Subtemperate sliding reduces period of ice stream variability in a simple model

Logan MANN[1], Colin MEYER[1], Alexander ROBEL[2], Elisa MANTELLI[3,4]

[1] *Thayer School of Engineering, Dartmouth College*

[2] *School of Earth and Atmospheric Sciences, Georgia Institute of Technology*

[3] *Department of Earth and Environmental Sciences, Ludwig-Maximillians-Universitẗ München*

[4] *Glaciology Section, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany*

Correspondence: Logan Mann <logan.e.mann.th@dartmouth.edu>

ABSTRACT. Understanding the formation and evolution of fast flowing ice streams is essential to projecting the centennial-scale response of ice sheets to climate forcings. Slow flowing glaciers or stagnant ice streams can slide at low velocities over a bed that is below the bulk melting point of ice, dissipating small amounts of frictional heat. This phenomenon is typically referred to as subtemperate sliding, and it complicates the assumed dichotomy between frozen and thawed beds embedded in many large-scale process-based ice sheet models. In this study, we allow for subtemperate sliding in a simple ice stream box model to investigate frictional heat dissipation at frozen ice-bed interfaces. We find that including subtemperate sliding leads to non-negligible frictional heat dissipation, which can accelerate sliding and lead to runaway acceleration of stagnant ice streams. These results suggest that subtemperate sliding and the associated thermo-frictional feedback occurs in longer timescales characterizing Heinrich events. On shorter, centennial timescales, subtemperate sliding is likely an important physical process to

consider in modeling the potential reactivation of stagnant ice streams like Kamb Ice Stream.

BACKGROUND

The Greenland and Antarctic ice sheets have distinct regions of fast ice flow, called ice streams, separated by slow flowing ice ridges. Ice streams were also present in paleo ice sheets during the last glacial period (Hubbard and others, 2009; Stokes and others, 2014; Clark and Spagnolo, 2016; Greenwood and others, 2017). Ice streams are the primary ice drainage networks for ice sheets and are currently responsible for the majority of discharge from the West Antarctic Ice Sheet (Oppenheimer, 1998; Bamber and others, 2000; Smith and others, 2020). Many drainage catchments, like the Siple Coast of West Antarctica, are organized into a parallel array of ice streams that display complex spatial patterns that are not primarily controlled by bed topography (Shabtaie and Bentley, 1987, 1988; Retzlaff and others, 1993). Instead, the flow of these ice streams may be governed primarily by thermal conditions along the bed and within shear margins. Radar observations typically indicate wet beds for active ice streams and frozen beds beneath ice ridges and inactive ice streams (with the exception of Kamb Ice Stream) Bentley and others (1998). In addition, the glaciological indicators of Siple Coast ice flow demonstrates a complex history, indicating an unsteady evolution of the ice stream system, suggesting thermal and hydrologic controls (Catania and others, 2012).

Understanding the thermomechanics of fast ice stream flow is key to projecting the centennial-scale response of ice sheets to climate forcing. Ice streams experience geometric changes, through thinning or thickening, lateral boundary migration, flow reorganization, or other complex spatial changes (Bindschadler and Vornberger, 1998; Fahnestock and others, 2001). They also experience kinematic changes, such as stagnation or reactivation. Stagnation is evidenced by relict fast flow morphologies in currently slow moving ice streams, like Kamb Ice Stream in West Antarctica (Rose, 1979; Catania and others, 2006), and more recent observations of slowdown in fast flowing ice streams, like Whillans Ice Stream (Joughin and Tulaczyk, 2002; Beem and others, 2014). The opposite may also occur: slow, stagnant ice streams can accelerate (Engelhardt and Kamb, 1997; Bougamont and others, 2015). New ice streams could possibly form in seemingly inactive catchments, like those in the colder regions of East Antarctica (Dawson and others, 2022, 2024).

An improved understanding of these processes can also help in reconstructing past ice sheet changes. Heinrich events were periods of intense discharge from the ice streams of the Laurentide (and possibly others) ice sheet, which occurred approximately every 6-8 thousand years during glacial periods, as evidenced by Ice Rafted Debris (IRD) within marine sediments (Heinrich, 1988; Bond and others, 1993; Hemming, 2004). These events potentially offer paleohistorical precedent for changes observed in contemporary ice sheets. There is a longstanding debate over the relative influence of internal ice sheet dynamical processes (MacAyeal, 1993a; Alley and MacAyeal, 1994; Tulaczyk and others, 2000b; Robel and others, 2013, 2014; Bougamont and others, 2011; Sayag and Tziperman, 2009, 2011) versus oceanic and other external climate forcings (Ganopolski and Rahmstorf, 2001; Hulbe and others, 2004; Shaffer and others, 2004; Marcott and others, 2011; Alvarez-Solas and others, 2013; Bassis and others, 2017; Edwards and others, 2022; Mann and others, 2021) in driving Heinrich events. A comprehensive theory of ice sheet change could leverage the data preserved in the geological record to enhance our understanding of modern changes in the Antarctic and Greenland ice sheets. However, the details of thermally controlled ice flow remain active areas of research.

Feedbacks mediated by basal sliding are a possible mechanism for ice stream formation and evolution. Hydraulic feedbacks can occur when basal temperatures are at the pressure melting point: faster sliding leads to frictional heat dissipation, meltwater generation, and thus even faster sliding (Fowler and Schiavi, 1998; Sayag and Tziperman, 2008; Bougamont and others, 2011; Kyrke-Smith and others, 2014). Thermo-frictional feedbacks also occur, in the absence of a developed drainage network, at temperatures below the bulk melting point if subtemperate sliding is taken into account: small amounts of slip mediated by regelation and premelting dissipate heat along the bed, which in turn raises basal temperature, thus leading to even faster sliding. These instabilities could complicate the assumptions embedded in large scale, process-based ice sheet models that are used to make ice loss and sea level rise projections (Seroussi and others, 2020, 2023). Approaches that invert for basal friction from surface observations can reproduce the present day flow field, including modern ice stream features (MacAyeal, 1993b; Ranganathan and others, 2021), by means of a spatially variable friction coefficient. However, if frictional parameterizations are held static over long model runs, they may overconstrain the model towards present-day behavior, without enabling unsteady processes that could reorganize the flow field. Coupling ice sheet models to subglacial hydrology models is a promising approach (Sommers and others, 2024). However, increases in model complexity come with a trade-off in terms of additional degrees of freedom and computational expense, increasing the potential for overparameterization. Ultimately, ice sheet models will require both a more expansive observational record and a more complete physical representation of subglacial processes to generate credible long-term climate predictions (Aschwanden and others, 2021). This study examines the temporal dynamics of thermo-frictional feedbacks at the bed, with a simple, spatially lumped, coupled ice sheet-hydrology model.

MATHEMATICAL FORMULATION OF SUBTEMPERATE SLIDING

Ice sheet models apply sliding laws to capture the dynamics of ice-bed interfaces or match observations through empirical functions with tunable parameters. Sliding laws relate the subglacial slip velocity, u_b, to the resistive shear stress at the ice-bed interface, τ_b, and the effective pressure, N. Approaches that seek to capture thermal effects incorporate the bed temperature, T_b, to specify some relationship for friction at the bed arising from the bed's thermal state, $u_b = (\tau_b, N, T_b)$. This often takes the form of a 'hard-switch' (e.g., Hutter and Olunloyo, 1981; Barcilon and MacAyeal, 1993; Payne and Baldwin, 2000; Payne and others, 2000; Moore and others, 2009),

$$u_b = \begin{cases} f(\tau_b, N), & \text{if } T_b = T_m \\ 0, & \text{if } T_b < T_m \end{cases}, \qquad (1)$$

where sliding can only occur when the temperature of the bed is at the pressure-melting point of ice, $T_b = T_m$ (i.e., temperate). When the temperature of the bed is below the pressure-melting point, $T_b < T_m$ (i.e. subtemperate; Raymond, 1996; Robel and others, 2013), a no-slip boundary condition is applied. As an alternative to the no-slip condition, some models apply a hard-switch from slow to fast sliding when the bed reaches the melting point (Brinkerhoff and Johnson, 2015). The hard-switch approach may be acceptable in mechanical models of ice flow so long as horizontal length scales comparable with the ice thickness are resolved (i.e., Stokes mechanics are employed), but coupling to a thermal model inevitably leads to mathematical inconsistencies and numerical difficulties (Mantelli and others, 2019a). If ice flows from a non-sliding, sub-freezing region to a sliding, temperate one, ice flux must be conserved at the spatial onset of sliding, requiring a decrease in along-flow pressure gradient and surface slope. The subsequent reduction in vertical shear reduces the rate of heat dissipation, which should lead to refreezing. This leads to the paradoxical result that the thermal onset of sliding must cause a drawdown of cold ice, shutting down sliding at any potential onset location (Fowler and Larson, 1980; Fowler, 2001). Mantelli and others (2019a) expanded on this concept with a boundary layer analysis of the flow near the frozen-temperate transition to demonstrate that there is no mechanism for heat dissipation at realistic Pèclet numbers that can balance the downward advection of cold ice without refreezing. Therefore, an abrupt onset of sliding is entirely impossible under conditions likely to exist for terrestrial ice sheets.

Instead, Mantelli and Schoof (2019b) conclude that, for a laterally/radially uniform ice sheet, the onset of sliding must occur over horizontal length scales asymptotically larger than the ice thickness, so that the speed-up is never localized over shorter distances where advection dominates. In their analysis, they adopt a subtemperate sliding law in a similar form proposed by Fowler (1986)

$$u_b = f(\tau_b, N)g(T_b) \tag{2}$$

where $g(T_b)$ is some continuous function of the bed temperature, such that sliding may occur at temperatures in a narrow range below the melting point. Subtemperate sliding may be physically justified by either regelation and premelting for hard beds (Shreve, 1984; Rempel and Meyer, 2019; McCarthy and others, 2017) or till deformation for soft beds (Meyer and others, 2018; Zoet and Iverson, 2020; Hansen and others, 2024; Meyer and others, 2024). Subtemperate sliding has been observed in the field (Shreve, 1984; Echelmeyer and Zhongxiang, 1987; Cuffey and others, 1999), but its implications are not entirely understood.

In this study, we adapt the ice stream model from Robel and others (2013) (hereafter, R13), a simple box model (model description and parameters in Supplement S1), to include subtemperate sliding. The R13 model simulates the dynamics and temporal variability of ice stream flow by coupling ice stream hydrology to ice stream dynamics in a spatially lumped system of 2 Ordinary Differential Equations: a prognostic equation describing the evolution of a spatially averaged ice thickness, h, as a balance of accumulation and ice flux, and an evolution equation for water content, w, in a permeable bed as a balance of basal melt and drainage. The R13 model has been used in various forms to investigate ice stream variability under the influence of stochastic climate forcings (Mantelli and others, 2016), frozen fringe and sediment freeze-on (Meyer and others, 2019), and synchronization of Heinrich and DO events through ice ocean interactions (Mann and others, 2021). R13 assumes a plastic Coulomb-type friction law, such that no slip occurs when driving stress, τ_d, does not exceed a yield stress, τ_y, determined by the subglacial hydrology model. When the bed thaws, water saturates the till leading to a reduction of the yield stress and a rapid onset of fast flow. During these surges, the centerline sliding velocity is calculated with an approximation derived by Raymond (1996). Here, we modify the sliding law from R13 by replacing their equation (5) in Robel and others (2013) so as to enable subtemperate sliding when $T_b < T_m$ and $\tau_d < \tau_y$, allowing a continuous

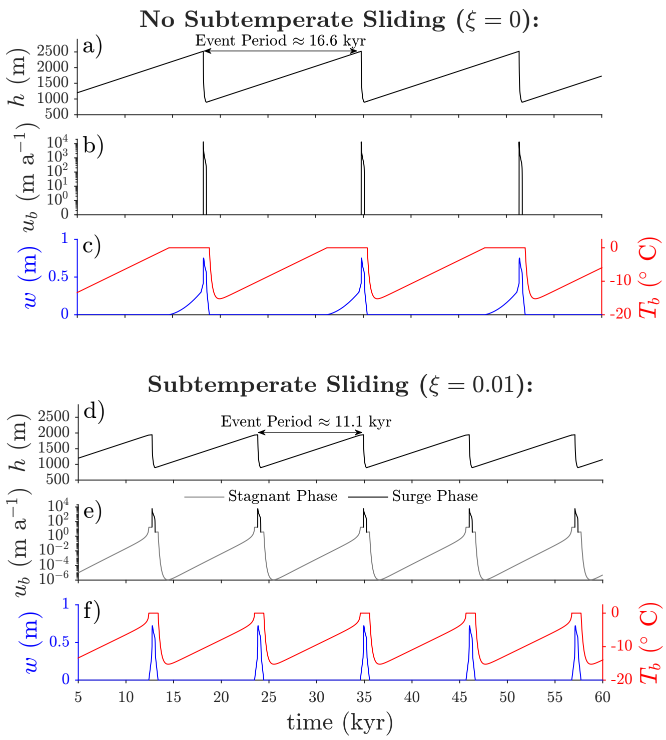

Fig. 1. (a-c) depicts simulation results without subtemperate sliding ($\xi = 0$). (d-f) depicts results with modest subtemperate sliding ($\xi = 0.01$). Panels display temporal evolution of: ice thickness, h, subglacial slip velocity, u_b, (Plotted on a logarithmic scale. Note that a cutoff is imposed at 10^{-1} m/yr, for the purpose of representing 0 velocity in the no-slip case), subglacial water content (blue), w, and bed temperature (red), T_b. Parameters: Surface Temperature, $T_s = -30$ °C, Geothermal heat, $G = 0.03$ W/m^2, Premelting Temperature range, $T_0 = 1$ °C. All variables plotted as a function of time.

transition to surging behavior when $\tau_d > \tau_y$.

$$u_b = C\tau_b^m e^{\frac{T_b - T_m}{T_0}} + \frac{A_g W^{n+1}}{4^n(n+1)h^n}\max(\tau_d - \tau_y, 0)^n. \tag{3}$$

In the first term, C and m are the friction coefficient and exponent in a Weertman sliding law. The exponential coefficient allows significant subtemperate sliding in a temperature range, T_0, below the melting temperature, T_m, that we call the premelting temperature range. A_g is the Glen's law rate factor (fluidity parameter), n is the rheological exponent (taken here to be $n = 3$, corresponding to shear-thinning flow), W is the width of an ice stream, and h is the ice stream thickness. R13 embeds an assumption of negligible vertical shear which our model also adopts, under the premise that it should be insignificant to the dynamical evolution of this system. Vertical shear in transitions from slow flowing to fast flowing ice streams could be incoporated, as in Warburton and others (2023), but we contend as in R13 that the sliding velocity primarily determines the temporal evolution of the system.

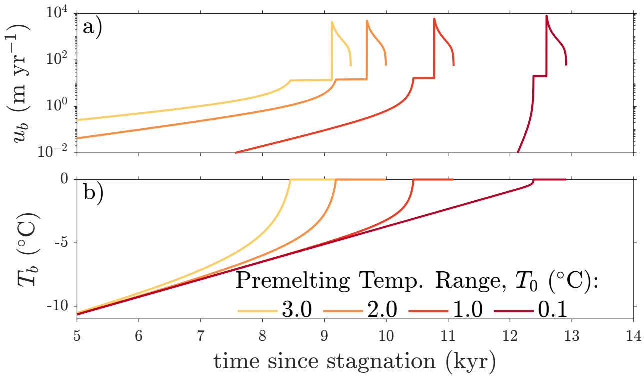

Fig. 2. Temporal evolution of a) ice velocity, u_b, and b) bed temperature, T_b, given different values of the premelting temperature range, T_0, (Color coded).

RESULTS

The sliding law originally implemented in the R13 model (their eq. 5) produces two distinct flow regimes with either steady streaming or oscillating ice flow velocities. In the steady-streaming regime, warm surface temperatures, T_s, and/or high geothermal heat fluxes, G, allow the system to come to a steady state with constant sliding velocity, u_b. In the oscillatory regime, relatively low geothermal heat and/or surface temperatures lead to periodic oscillations between stagnant ($u_b = 0$) and active ($u_b > 0$, generally much higher than in steady-streaming regime) ice stream phases, similar to MacAyeal (1993a).

In Figure 1a-c, we show simulation results in the oscillatory regime without subtemperate sliding. When the ice sheet is thin, cold atmospheric temperatures conduct heat through the ice and away from the bed, maintaining a frozen till and gradual thickening of the ice stream, as a result of snowfall. Eventually, when the ice stream is thick enough to insulate the base and weaken the vertical temperature gradient, basal ice can warm to its pressure-melting point. When this meltwater eventually saturates the till to a critical void ratio, the till layer fails and the ice stream reactivates, thinning the ice stream, until the cycle begins again. Without subtemperate sliding, the ice stops sliding between surges, so there is no frictional heat dissipation. This means that the thermal evolution of the bed is only governed by the time required to 1) thicken the ice stream, insulating the bed to the pressure melting point and 2) generate sufficient meltwater to weaken the till layer.

With subtemperate sliding added (Figure 1d-f), the sliding law (Eq. 3) is now coupled with the basal thermal state of the ice stream, such that increasing the bed temperature continuously increases the sliding velocity. This results in a two-way feedback during both stagnant and active periods. We non-dimensionalize the sliding law, such that $\xi = C[\tau_d]^m/[u_b]$ represents a nondimensional friction coefficient for the subtemperate component of the sliding law and [·] brackets denote relevant scales. We choose values for this parameter such that the maximum subtemperate sliding velocity is $O(10^1)$ m/yr, compared to the $O(10^3)$ m/yr velocities that occur in a fast-flowing ice stream.

Despite an increase in net ice flux during stagnant periods, surges become more frequent and subtemperate sliding causes a ∼33% decrease in the oscillatory period compared to the same parameter regime in the R13 model (Figure 1). The evolution of sliding velocity, bed temperature, and till water content (Figure 1d-f) illustrates the cause of this earlier surging behavior: During the stagnant period, subtemperate sliding generates frictional heat, which is initially insignificant to the thermal balance, but it does slightly increase the subglacial slip velocity. Later in the stagnant phase, as velocity increases, frictional heat dissipation from subtemperate sliding becomes significant to the thermal balance, accelerating the warming of the bed. Eventually, frictional heating dominates the thermal balance of the bed and hastens the onset of rapid till deformation at $O(10^3)$ m/yr.

Next, we investigate the effect of the premelting temperature range, T_0. This value determines the temperature below the melting point at which subtemperate sliding is significant. The range of subtemperate sliding is related to the physics of premelting (Dash and others, 2006), but this connection has not yet been made nor has the influence on the ice sheet scale been articulated (see supplemental materials S3). In figure 2, we compare 4 different values of T_0. For all experiments temperature increases linearly in time, as ice thickens during the early stagnant period. However, once bed temperatures approach the T_0 range, thermal feedbacks initiate. Subtemperate sliding can accelerate the onset of a surge centuries or millennia early, depending on our choice of parameters.

Importance of subtemperate sliding across parameter space

Figure 1 shows that subtemperate sliding can substantially reduce the period between surges for a single parameter set. Here, we set out to determine: (1) whether these results hold with different parameters, and (2) whether subtemperate sliding can change the range of parameters under which oscillatory behavior occurs. To answer these questions, we run the model under a wider range of climatic and basal conditions to determine the oscillation period (the time between surges). The oscillation period is a useful metric for determining the change to the basic model behavior that occurs with subtemperate sliding, because it defines the temporal sensitivity to the parameter regime for oscillatory systems. As we show in Figure (3), we perform parameter sweeps through the surface temperature, T_s, and the subtemperate sliding parameter, ξ. Increasing the surface temperature, T_s, decreases the event period, until the regime changes

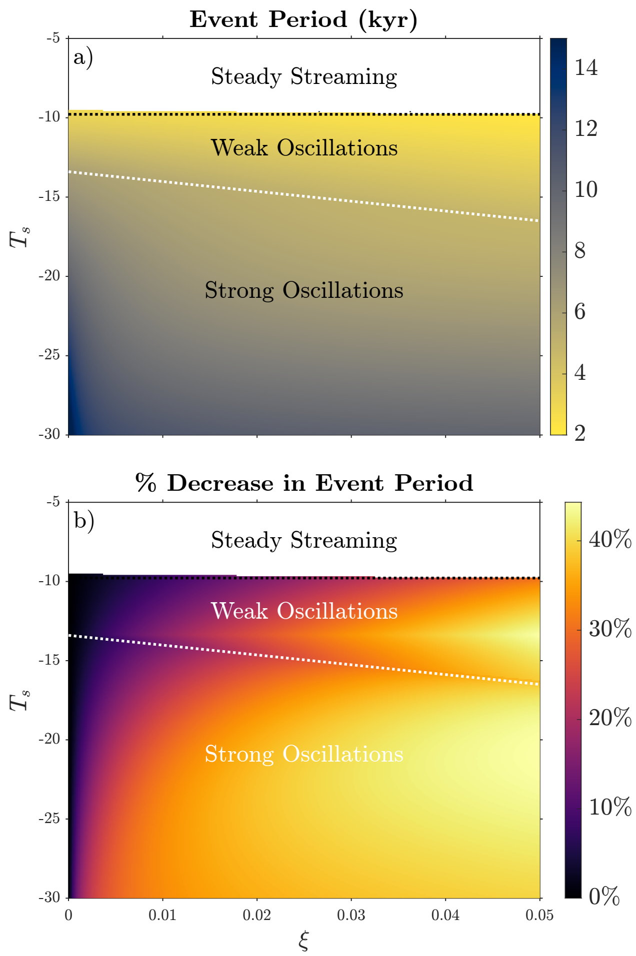

Fig. 3. Parameter sweep of R13 with subtemperate sliding for parameters: surface temperature, T_s, on the y-axis, and subtemperate sliding parameter, $\xi = C[\tau_d]^m/[u_b]$, on the x-axis. The white space represents the steady streaming region of parameter space, which has no event period. The top dotted line represents the stability boundary between oscillations and steady streaming, calculated in Supplement S2. The bottom dotted line represents the oscillation mode boundary, identified heuristically. a) Event period. b) percentage decrease in event period.

from an oscillatory regime to a steady streaming one. The white space above $T_s \approx -10$ °C represents steady streaming in parameter space, which necessarily has no event period, because the system reaches a steady state with constant velocity. Subtemperate sliding decreases event periods across broad swaths of parameter space, even with very small amounts of subtemperate sliding. This also remains true, for a wide range of premelting temperature ranges, T_0 (See Supplement S3).

The effect is particularly notable for ice streams with colder surface temperatures, characterized by strong oscillations. Small amounts of subtemperate sliding ($\xi \approx 0.01$; Figure 1) can lead to significant reductions in event period of around ~20-30%. Faster subtemperate sliding speeds, at the higher end of plausibility ($\xi \approx 0.05$), result in ~40% reductions in event period. For colder surface temperatures, the bed is subtemperate for almost all of the stagnant phase, allowing more time for thermal feedbacks to accelerate warming of basal ice, leading to a departure from results without subtemperate sliding ($\xi = 0$). This means that the oscillatory period is almost entirely dictated by the time required to warm the bed to the melting point.

Warmer surface temperatures are characterized by weak oscillations, in which the bed is almost always temperate during the stagnant phase. The oscillation mode boundary between strong and weak oscillations is particularly evident in Figure 3b (denoted by the lower dotted line), corresponding to a change in how the system responds to subtemperate sliding. Weak oscillations are primarily governed by changes in till water content caused by changes in the thermal heat budget. Despite this, sliding during the stagnant phase still significantly impacts the event period. Small amounts of sliding over stagnant temperate beds allows the dissipation of frictional heat, generating more meltwater and hastening the process of till saturation and failure. This leads to reductions in event period ranging up to 30%. Despite its impact on the event period, subtemperate sliding has little influence on the stability boundary between oscillations and steady streaming itself, plotted in Figure 3 as the top dotted line. We perform a stability analysis in the supplemental materials (S2) and show that, in agreement with these numerical results, subtemperate sliding is asymptotically small in its influence on the steady streaming boundary. For weak oscillations, subtemperate sliding will not significantly alter this stability boundary, because activations occur before heat dissipation becomes a dominant part of the basal heat budget, although they still impact the thermal evolution of the system.

DISCUSSION

Theory and observations demonstrate that glaciers can slide when the bed is subtemperate (Shreve, 1984; Echelmeyer and Zhongxiang, 1987; Cuffey and others, 1999; Mantelli and others, 2019a). Thermally activated hard-switch sliding laws introduce physical inconsistencies into models, which must be corrected with a temperature-dependent subtemperate sliding law to investigate the onset of fast sliding (Mantelli and others, 2019a). When this friction law is introduced into ice flow models, it enables a feedback which can give rise to both temporal (Mantelli and Schoof, 2019b) and spatial (Schoof and Mantelli, 2021) instabilities. These temporal instabilities are challenging to model in spatially resolved models, because they involve all scales from the ice thickness to the ice sheet scale. Here we focus on the temporal instabilities arising from subtemperate sliding, but in a spatially lumped, rather than spatially resolved, ice stream model. This allows for a straightforward examination of the temporal evolution, in isolation from other processes.

Our results demonstrate that frictional heat during stagnant phases of ice stream flow can initiate a feedback loop, warming basal ice and accelerating the onset of fast sliding. This feedback proceeds as follows: (1) subtemperate sliding occurs during a period of stagnant ice stream flow with a subtemperate bed, (2) subtemperate sliding generates small amounts of frictional heat, and then (3) frictional heat increases the temperature of the bed, which accelerates sliding. The cycle then repeats. In our work, we show that this leads to a reduction in inter-surge period, changing the relevant parameter space for Heinrich events and other forms of ice stream variability. These results demonstrate a potential positive feedback in ice sheet flow. In ice stream systems, this feedback is hypothesized to play a major role in ice stream formation, reactivation of stagnant ice streams, and complex flow reorganization in regions like the Siple Coast. This has important implications on ice sheet models and sea level rise projections on centennial timescales. Thermal feedbacks at the bed are observed across a wide range of parameters in this study, demonstrating that this effect is not just a small contributor to ice discharge, but capable of dominating the temporal evolution of ice streams in both past and current ice sheets.

Kamb Ice Stream (KIS) has been identified as a possible source of increasing ice loss from the Siple Coast region of West Antarctica. The modeling experiments in Bougamont and others (2015) demonstrated a potential for KIS reactivation in the next century, using a traditional hard-switch sliding law. In this scenario, reactivation begins at the upstream tributaries of KIS in $\sim$50 yrs, and the trunk of KIS briefly reactivates at $\sim$ 100 yrs, before cold basal conditions slow the process down until $\sim$250 yrs. This leads to complex flow reorganization, causing mass balance projections for the Siple Coast region to become more negative, from +30 Gt yr^{-1} to -3 Gt yr^{-1} and adding $\sim$5 mm to sea level rise projections in the next century. Including the effects of subtemperate sliding in these experiments could accelerate this timeline or lead to entirely different reorganization scenarios, and figures 2-3 indicate that the timing of a KIS reactivation is subject to the parameters chosen.

However, using a spatially lumped model limits our ability to extend these results to the full spatio-temporal system. Yet, spatially lumped models are still useful in identifying the dynamical modes of ice stream variability, with important implications for spatially resolved models (Robel and others, 2014). Further, the presumption that oscillatory dynamics in subglacial till properties may explain systems like Kamb Ice Stream has not been proven. This limits our ability to draw firm conclusions about the dynamical causes of centennial-scale ice stream and ice sheet change.

This study offers multiple future avenues of investigation for the long term behavior of Antarctic ice streams. It could inform our analysis of critical transitions of the Antarctic ice sheet's dynamical behavior by correctly identifying the pertinent early indicators from changes in basal temperatures and surface velocities. For Heinrich events, these results provide a compelling mechanism for more abrupt and rapid discharge. Within glacial systems, subtemperate sliding may provide a heat source that can express itself in sudden changes to the dynamical behavior of an ice sheet on centennial timescales. Yet, our results should also be taken as cause for increased caution, as they demonstrate that thermally coupled ice sheet models are highly sensitive to poorly constrained parameters.

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