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Modeling the future ice discharge of a small tidewater glacier, West Greenland

C23B-0609

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ABSTRACT

Sermeq (Glacier) Avannarleq, a small tidewater glacier in western Greenland, exhibits a strong annual velocity cycle, with a summer speedup event that contributes ~ 13 % of annual net displacement (discharge) across the grounding line. We examine the response of this glacier to a reasonable surface mass balance perturbation and a wide range of basal sliding forcings to assess its future surface mass balance and ice dynamic contributions to sea level rise. While mass loss along the flowline due to ice discharge likely exceeded mass loss due to surface ablation prior to 2000, our model suggests that mass loss due to surface ablation will approximately double the mass loss due to terminal ice discharge by the year 2035. Additionally, the ensemble of basal sliding scenarios suggests that ice discharge across the grounding line will likely decrease over the next 25 years. This decrease in terminal ice discharge is due to a decrease in deformational velocity as the ice thins, which outpaces increases in basal sliding velocity. We speculate that surface ablation will likely become the dominant sea level rise component for tidewater glaciers in dynamic settings where deformational velocity is currently greater than basal sliding velocity.

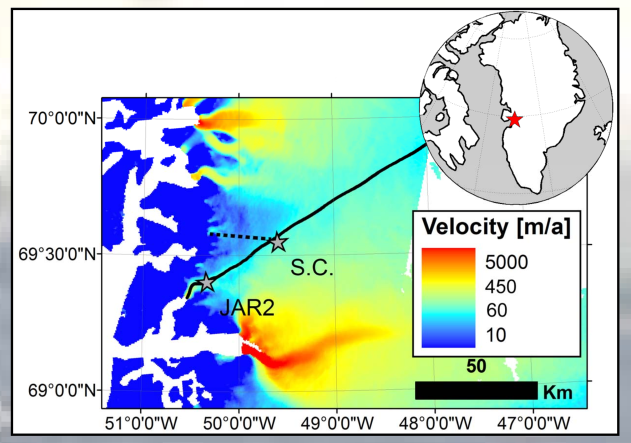

Figure 1 – *The Sermeq Avannarleq flowline (black line) overlaid on winter 2005/06 InSAR surface velocity[1]. Locations of JAR2 station and Swiss Camp are denoted with stars.*

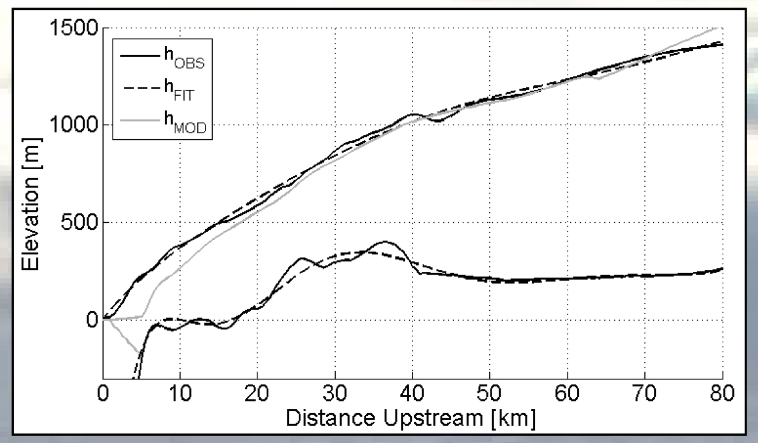

Figure 2 – *Observed ice surface[2] and bedrock elevations[3,4] with high-order polynomial fits. Equilibrium ice geometry is shown following a 1000 year spin-up.*

INTRODUCTION

Generally, the future ice dynamic sea level rise contribution of the Greenland Ice Sheet is regarded as more difficult to forecast than its surface mass balance counterpart[5,6]. Modeling suggests that continued low elevation thinning and high elevation thickening will result in increased ice discharge across the equilibrium line due to a steepening of the ablation zone[7]. Additionally, tidewater glacier ice discharge has been found to be highly sensitive to perturbations to the calving front that are subsequently propagated upstream via longitudinal coupling[8,9,10]. Significant uncertainty also surrounds a possible non-linear response to enhanced melt season basal sliding velocities[11,12]. In an attempt to assess the potential contribution of these processes to future tidewater glacier ice discharge, we examine the response of a small tidewater glacier in western Greenland to a reasonable surface mass balance perturbation and a wide range of basal sliding scenarios.

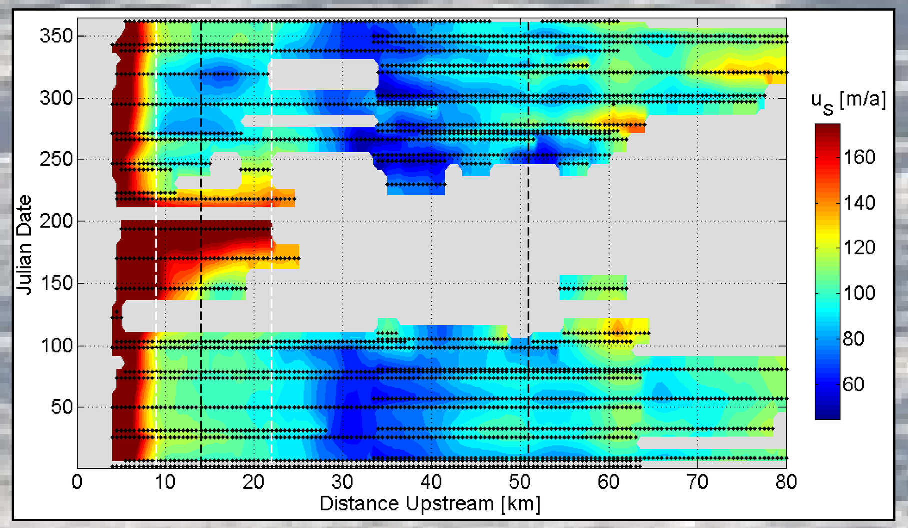

Figure 3 – *Time-space plot of ice surface velocity[9] cycle along the terminal 80 km of the flowline (color bar range: u_S < 175 m/a). Dots indicate individual InSAR velocity observations. Vertical black lines denote the locations of JAR2 station and Swiss Camp. Vertical white dashed lines delimit the data shown in Figure 4.*

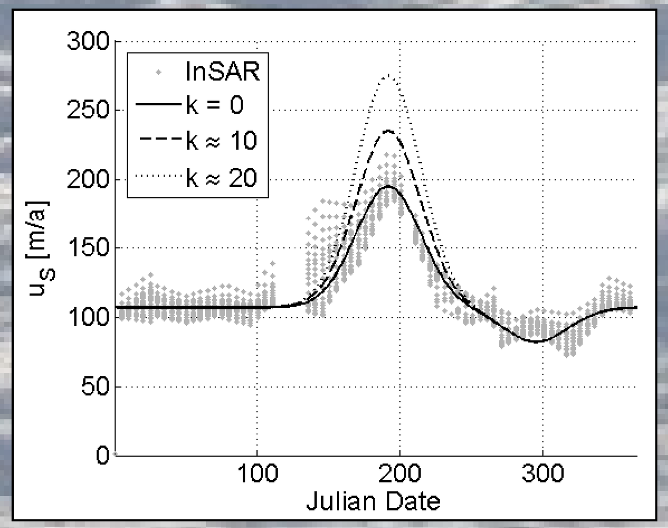

Figure 4 – *Observed annual ice surface velocity[9] cycle in the vicinity of JAR2 station (grey dots). Lines approximate annual velocity cycles that integrate to the annual net ice displacements consistent with the various k scenarios.*

STUDY SITE

Sermeq (Glacier) Avannarleq is a relatively small (width ≈ 4 km) tidewater glacier that calves into a northern branch of Jakobshavn Fiord (Figure 1). Given the proximity of Sermeq Avannarleq to Jakobshavn Isbrae, multiple 2005 and 2006 InSAR-derived ice surface velocity profiles are available for the terminal portion of the Sermeq Avannarleq flowline[9]. Temporal interpolation between these profiles yields a time-space velocity plot (Figure 3). The region in the vicinity of JAR2 station (km 8.5 to 22) exhibits a distinct annual ice velocity cycle. This cycle consists of a summer speedup event, in which velocities increase above winter velocity (~ 195 versus 107 m/a), followed by a fall slowdown event, in which velocities decrease below winter velocity (~ 82 versus 107 m/a; Figure 4). The summer speedup contributes an additional ~ 14 m of displacement over background winter displacement (~ 13 % of annual).

MODEL OVERVIEW

We infer a range of basal sliding velocities by differencing a range of modeled ice surface velocities due to internal deformation from the observed winter ice surface velocity along the profile[9]. Deformational ice surface velocity is modeled using the shallow ice approximation and smoothed ice surface[2] and bedrock elevation[3,4] profiles (Figure 2). We employ a range basal ice temperatures (T_{pmp} to T_{pmp}–5K) and Wisconsinan enhancement factors[13,14] (2 to 4) to yield a range of temperature-dependent flow law parameter values[15]. We incorporate the 25th, 50th and 75th percentiles from the resultant range of basal sliding velocities to represent "low", "moderate" and "high" basal sliding scenarios, respectively, in the 1D (depth-integrated) flowline model (Figure 5).

In all simulations the longitudinally-coupled[16] model is spun-up for 1000 years in an equilibrium climate (60 and 100 % of present-day surface ablation and accumulation respectively) and then forced with an observed trend in surface mass balance and a variety of basal sliding scenarios for 25 years. We modify a steady-state basal ice temperature solution for the flowline (*Phillips et al.*, in preparation), which suggests that basal ice temperature is at the pressure-melting-point downstream of the equilibrium line, by forcing basal ice temperatures to the pressure melting point as the equilibrium line is forced upstream.

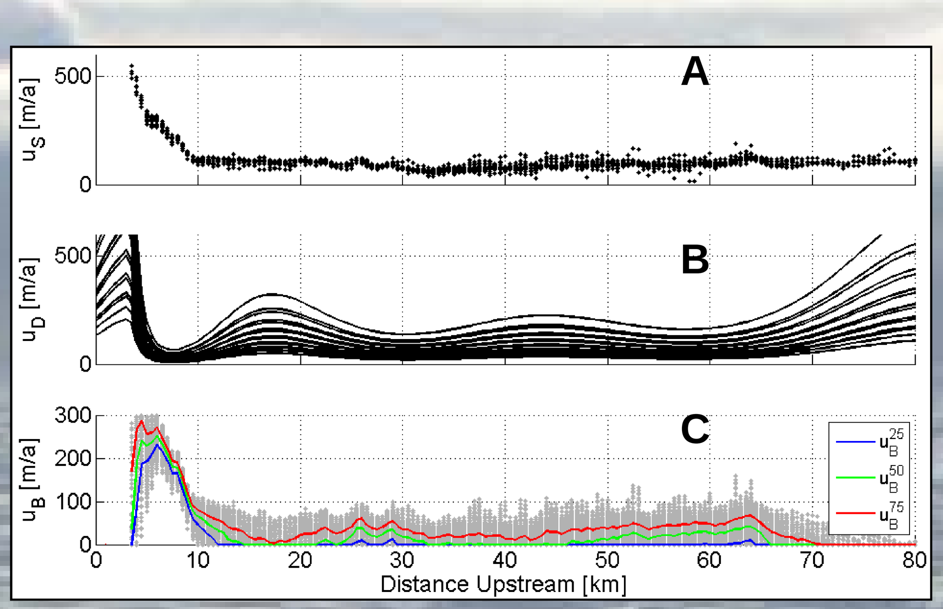

Figure 5 – A: *Observed winter ice surface velocity[9] along the terminal 80 km of the flowline (u_S).* B: *Modeled profiles of ice surface velocity due to internal deformation (u_D) under various flow law parameter assumptions.* C: *Range of inferred basal sliding velocities (u_B; dots) with specific percentiles denoted (lines).*

SURFACE BALANCE AND BASAL SLIDING FORCING

Following the 1000 year spin-up, we force both the surface mass balance and basal sliding velocity boundary conditions. Annual surface ablation (a_S) in the Sermeq Avannarleq ablation zone can be expressed as:

$$a_S = \gamma(h_S - h_S^{ela}) - a_S^{ela} \qquad \text{Equation 1}$$

where h_S is ice surface elevation, h_S^{ela} is equilibrium line altitude (1125 m)[17], a_S^{ela} is equilibrium line altitude surface ablation (0.4 m)[18], and γ is the surface ablation gradient (0.00372)[18]. *In situ* Greenland Climate Network data from Swiss Camp suggest that h_S^{ela} exhibits strong inter-annual variability (dh_S^{ela}/dt), ranging between -202 and +160 m/a over the period 2000 to 2009. We use dh_S^{ela}/dt = 6.5 m/a, the decade mean, as our surface ablation forcing and assume no change in surface accumulation. We force basal sliding velocity in a heuristic fashion, by assuming that basal sliding perturbation (Δu_B) is related to surface ablation perturbation (Δa_S) by a constant of proportionality (k):

$$\Delta u_B = k^*\Delta a_S \qquad \text{Equation 2}$$

We use a range of k values: from a "low" sensitivity scenario of k = 0 /a, representing complete accommodation of increased surface ablation by the glacier hydrology system[19], to a "high" sensitivity scenario of k = 20 /a, which implies a 1 m increase in a_S results in a 20 m/a increase in mean annual basal sliding velocity, with a "moderate" sensitivity scenario of k = 10 /a. As melt-induced displacement may be assumed to be limited to the melt season, k values of 10 and 20 /a correspond to ~ 45 and 90 % increases in summer speedup velocity at JAR2 station by forcing year 25 (Figure 4).

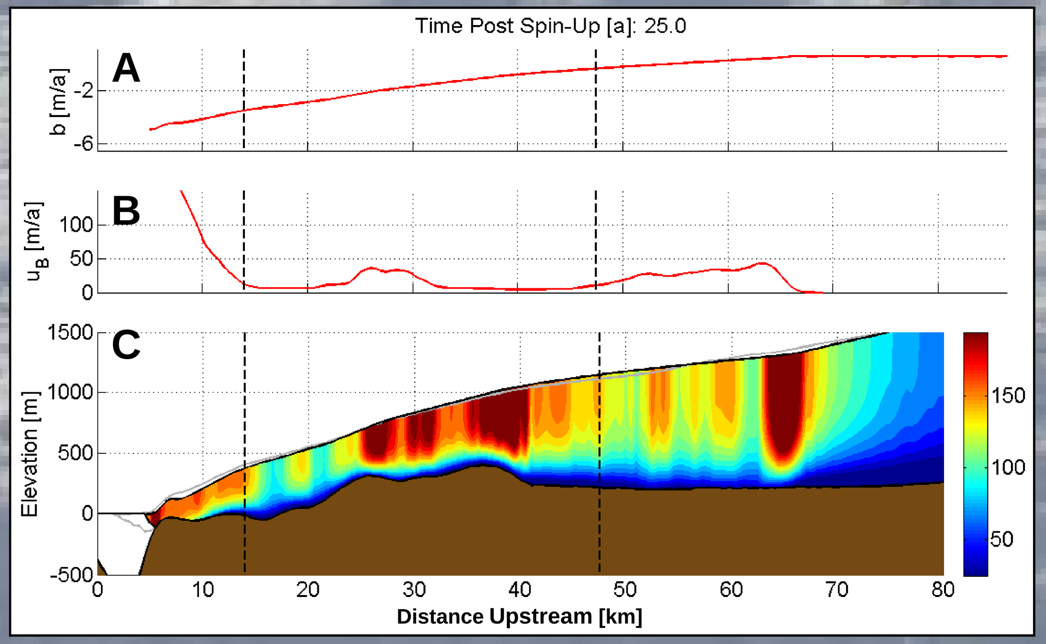

Figure 6 – *Terminal 80 km of the flowline in forcing year 25 (year ~ 2035), following a 1000 year spin-up. Vertical lines denote the positions of JAR2 station and Swiss Camp.* A: *Surface mass balance after a 162.5 m increase in equilibrium line altitude.* B: *Basal sliding velocity (scenario u_B^{50}, k = 10 /a).* C: *Horizontal velocity field (u; in m/a) within the ice (color bar range: 25 < u < 200). Grey lines denote equilibrium ice geometry at forcing year 0 (year ~ 2010).*

RESULTS

The 1D flowline model produces a reasonable equilibrium ice geometry for the Sermeq Avannarleq ablation zone following the 1000 year spin-up (Figures 2 and 6). To better understand the processes controlling flowline mass loss, we compare the ice discharge past JAR2 station (Q) with the sum of all surface ablation runoff that occurs upstream of JAR2 station ($\Sigma a_S F$; where F is a spatially variable retention fraction; Figure 7). While mass loss along the flowline due to ice discharge likely exceeded mass loss due to surface ablation prior to 2000, under our warming scenario and range of predicted basal sliding responses, mass loss due to surface ablation will approximately double the mass loss due to terminal ice discharge by the year 2035. The ensemble mean of the nine basal sliding scenarios suggests that ice discharge past JAR2 station will likely decrease over the next 25 years. Generally, the "high" basal sliding velocity scenarios (i.e. u_B^{75}) showed a greater decrease in ice discharge in response to the surface ablation and sliding forcings than the "low" basal sliding velocity scenarios (i.e. u_B^{25}).

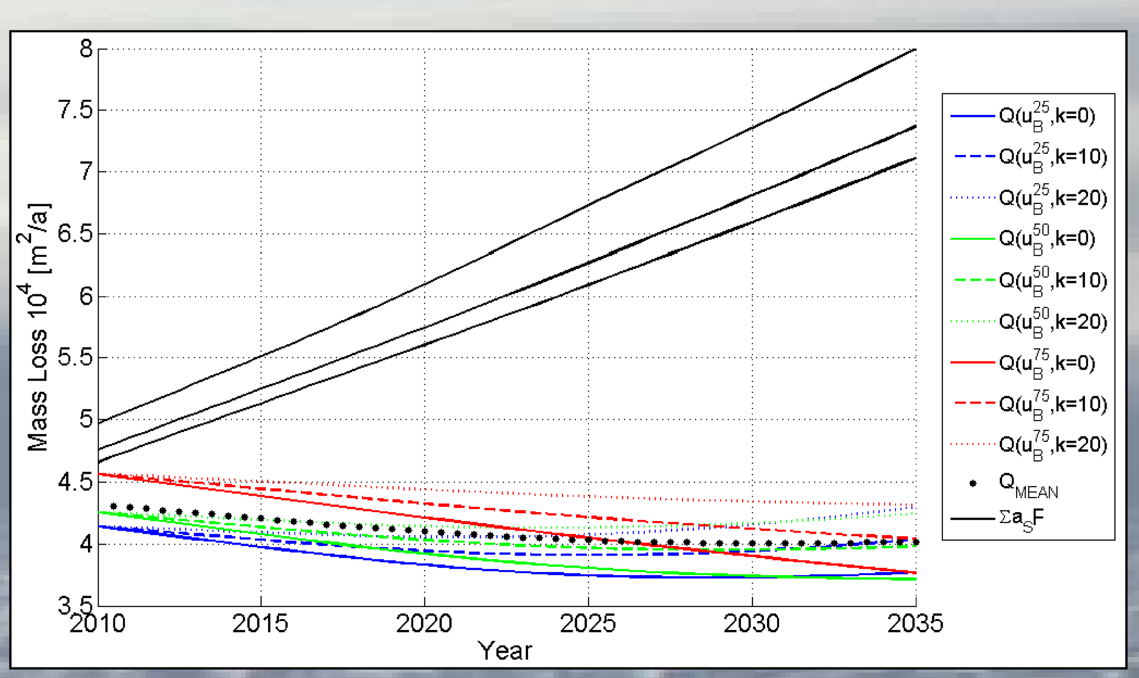

Figure 7 – *Modeled mass loss due to ice discharge past JAR2 station (Q; colored lines) and mass loss due to surface ablation runoff upstream of JAR2 station ($\Sigma a_S F$; all scenarios lumped in black lines) under various basal sliding scenarios, following a 1000 year spin-up to equilibrium (year ~ 2010).*

SUMMARY REMARKS

While the relatively large thinning and steepening of marginal ice due to surface ablation over the forcing period drives an increase in ice discharge across the equilibrium line (i.e. Swiss Camp; Figure 8)[7], it produces a decrease in ice discharge near the grounding line (i.e. JAR2). Our model predicts that decreases in deformational velocity, stemming from reductions in ice thickness, will outpace most reasonable increases in basal sliding velocity[20]. Long term records of *in situ* Greenland Ice Sheet marginal ice velocity are sparse, but the limited observations that exist suggest that ice velocities along the Kangerlussuaq Transect (~ 250 km south of Sermeq Avannarleq) have decreased over the last 17 years[19]. Thus, we speculate that surface mass balance will supersede ice dynamics as the dominate mass balance control of tidewater glaciers in dynamic settings where the majority of ice velocity is due to internal deformation (as opposed to basal sliding).

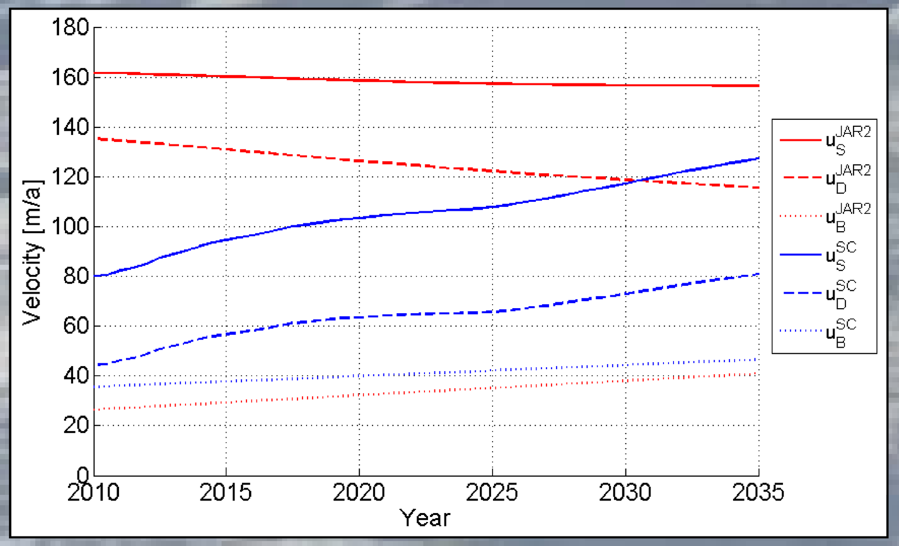

Figure 8 – *Modeled ice surface (u_S), deformational (u_D) and basal sliding (u_B) velocities at JAR2 and Swiss Camp over the 25 year forcing period (scenario u_B^{50}, k = 10 /a).*

Figure 9 – *QuickBird-2 multispectral image of the Sermeq Avannarleq terminus acquired 18 May 2009. Flowline nodes shown in red (dx = 500 m).*

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This work was supported by National Aeronautics and Space Administration (NASA) Cryospheric Science Program grants NNX08AT85G and NNX07AF15G to KS. WC thanks Natural Science and Engineering Research Council (NSERC) of Canada for support through a Post-Graduate Scholarship and the Cooperative Institute for Research in Environmental Sciences (CIRES) for support through a Graduate Research Fellowship.

Background Photo: Sermeq Avannarleq ablation zone, August 2009