Supraglacial river forcing of subglacial water storage and diurnal ice sheet motion

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Key Points:

- We present coincident field measurements of supraglacial river discharge and ice sheet motion on the southwest Greenland ablation zone
- The measurements are obtained upstream of a major moulin, enabling study of how supraglacial meltwater runoff influences subglacial hydrology and ice motion

- Recorded ice velocities are strongly correlated with measurements of supraglacial river discharge acquired hourly over the 7-day study period
- Differencing of supra- and proglacial discharge hydrographs suggests that diurnal fluctuations in subglacial water storage drive short-term variations in ice motion

Key Points

- We measure supraglacial river discharge entering a major moulin simultaneously with local accelerations in ice sheet motion
- Recorded ice speeds are strongly correlated with diurnal cycles of moulin input over the 7-day field experiment period
- Differencing supra- and proglacial hydrographs suggests diurnal fluctuations in subglacial water storage drive short-term ice motion

Abstract (150 words max)

Surface melting impacts ice sheet sliding by supplying water to the bed, but subglacial processes driving ice accelerations are complex. We examine linkages between surface runoff, transient subglacial water storage, and short-term ice motion from 168 consecutive hourly measurements of meltwater discharge (moulin input) and GPS-derived ice surface motion for Rio Behar, a ~60 km^2 moulin-terminating supraglacial river catchment on the southwest Greenland Ice Sheet. Short-term accelerations in ice speed correlate strongly with lag-corrected measures of supraglacial river discharge (r= 0.9, 'C= 0.7, p<0.01). Though our 7-day record cannot address seasonal-scale forcing, diurnal ice accelerations align with normalized differenced supraglacial and proglacial discharge, a proxy for subglacial storage change, better than GPS-derived ice surface uplift. These observations counter theoretical steady-state basal sliding laws and suggest that moulin- and proglacially induced fluctuations in subglacial water storage, rather than absolute subglacial water storage, drive short-term ice accelerations.

Plain Language Summary

The importance of surface meltwater runoff to Greenland ice sheet subglacial hydrology and ice sliding dynamics is widely recognized but poorly constrained by field observations. We present 168 consecutive hours of rare in-situ discharge measurements in a large supraglacial river draining the ice sheet surface, just upstream of where it plummets into a major moulin. GPS measurements of ice surface motion record brief accelerations in ice sliding speed that follow daily cycles in meltwater entering the moulin. By comparing these measurements with proglacial river discharges leaving the ice sheet, we identify daily fluctuations in subglacial water storage that track short-term accelerations in ice motion. These findings affirm the importance of supraglacial rivers to subglacial water pressure and ice dynamics, even in relatively thick ice >40 km inland from the ice terminus.

1. Introduction

Accurate models of ice-sheet response to climate change require good physical understanding of interactions between surface melting, subglacial hydrology, and ice dynamics (e.g., *Bell, 2008; Chu, 2014; Davison et al., 2019*). On the Greenland Ice Sheet (GrIS) ablation zone, surface melting activates a perennial hydrologic system of supraglacial streams, rivers, and lakes (*Irvine-Fynn et al., 2011; Rennermalm et al., 2013a; Lampkin and VanderBerg, 2014; Pitcher and Smith, 2019*), which commonly drain into moulins forming a dynamic subglacial drainage system that modifies basal pressures and ice motion (*e.g. Zwally et al., 2002; Van de Wal et al., 2008; Bartholomew et al., 2012; Meierbachtol et al., 2013*). While early concerns about warming-induced runaway sliding now seem unfounded (e.g. *Tedstone, et al., 2013; 2015; van de Wal et al., 2015; Flowers, 2018*), physical processes linking GrIS supraglacial meltwater runoff, ice sheet basal pressures, and ice sliding remain under intense study (*Nienow et al., 2017; Davison et al., 2019; Williams et al. 2020*), particularly processes governing englacial connectivity and subglacial evolution due to surface melting (e.g. *Poinar et al., 2015; Stevens et al., 2015; Christoffersen et al., 2018*).

Traditional basal sliding law formulations linking subglacial pressure and ice motion assume steady-state basal cavities (e.g. *Bindschadler, 1983; Schoof, 2005; Gagliardini et al., 2007*). However, observational research suggests that cavities constantly undergo transient evolution in response to fluctuations in supraglacial meltwater supply and subglacial channelization (*Iken et al., 1983; Bartholomaus et al., 2008; Hoffman et al., 2011; Cowton et al., 2016; Andrews et al., 2018*). If so, highest subglacial water pressures (and therefore ice sliding speeds) should occur when transient cavities are growing fastest, not when they are largest (*Iken et al., 1983; Cowton et al., 2016*).

Evidence for transient cavity evolution is drawn primarily from GPS-derived correlations of horizontal ice speed with vertical ice surface uplift (interpreted as a proxy for total subglacial water storage, *S*) or its first derivative (interpreted as subglacial water storage rate-of-change, L'*S*). GrIS horizontal ice sliding speed broadly covaries with vertical surface uplift over seasonal time scales (e.g., *Bartholomew et al., 2010; 2012; Hoffman et al., 2011*), but variations at shorter timescales tend to correlate better with its derivative (*Hoffman et al., 2011; Cowton et al., 2016; Andrews et al., 2018*). Such correlations are typically weak and spatially variable due to a range of factors confounding estimation of basal uplift from ice surface elevation measurements (*Hoffman et al., 2011; Andrews et al., 2018*). Therefore, it is difficult to infer interactions between surface melting, subglacial water storage, cavity growth, and ice motion for the GrIS, despite previous success on mountain glaciers (e.g. *Bartholomaus et al., 2008; 2011; Armstrong and Anderson, 2020*)

To study the links among supraglacial runoff, subglacial water storage fluctuations, and short-term ice motion, we present in situ measurements of moulin input (i.e. supraglacial discharge), ice surface speed, and ice surface uplift for Rio Behar, a large supraglacial river on the GrIS mid-elevation (>1200 m a.s.l.) ablation zone (**Figure 1**). We compare daily cycles in these variables with PROMICE automated weather station (AWS) measurements of surface energy balance and ablation (*Fausto and van As, 2019*), and with proglacial river discharges from three gauging stations downstream (*Rennermalm et al., 2017; Tedstone et al., 2017; van As et al., 2019*). We present GPS measurements of horizontal ice surface speed and vertical uplift, and use them to estimate subglacial storage *S* and rate-of-change L'*S*, respectively. We also compute alternate proxies for *S* and L'*S* by differencing normalized supraglacial and proglacial discharge hydrographs (adapted from *Bartholomaus et al., 2008, 2011; McGrath et al., 2011; Armstrong and Anderson, 2020*). We conclude that diurnal cycles in supraglacial river discharge drive ice accelerations through L'*S*, confirming that transient water storage and cavity growth are important influences on GrIS subglacial basal pressure and short-term ice motion.

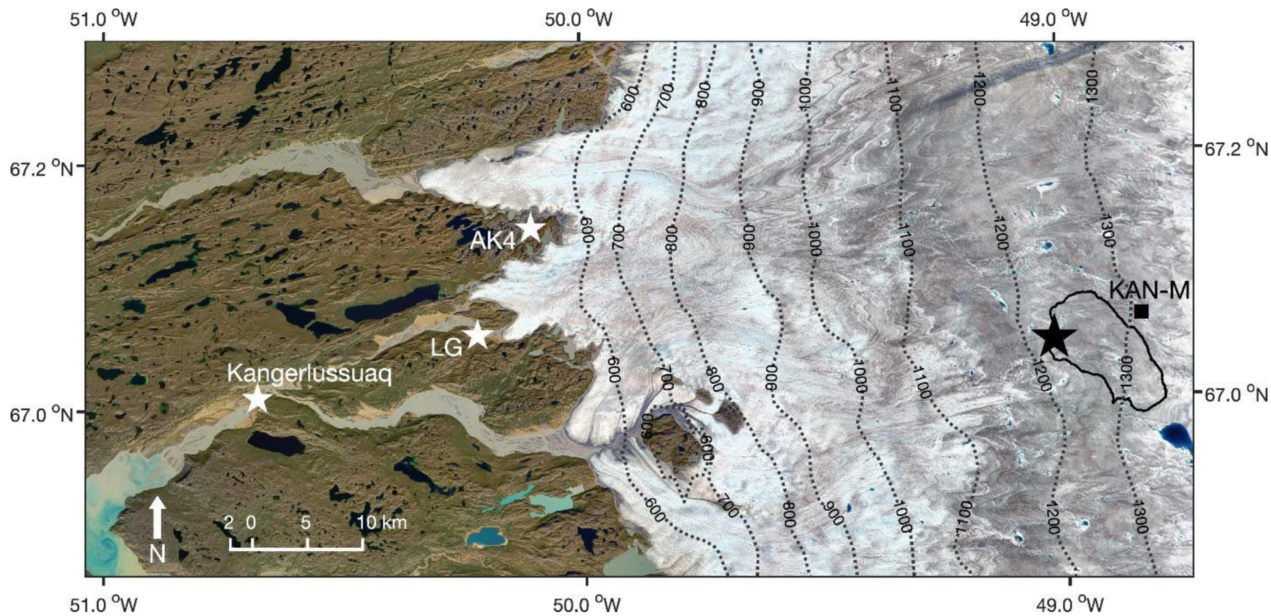

Figure 1: Study area in southwest Greenland. Black star shows location of our GPS measurements of ice surface motion and Acoustic Doppler Current Profiler (ADCP) measurements of moulin input (supraglacial discharge) in Rio Behar, a large supraglacial river penetrating the ice sheet >40 km from the ice edge. Field work was conducted ~750 m upstream of the Rio Behar terminal moulin. Black outline delineates the surface catchment (60.02 km^2 in July 2016). White stars locate proglacial river gauging stations; black square locates PROMICE KAN_M automated weather station. Background is a 26 July 2016 true-color Landsat-8 satellite image.

2. Data and Methods

2.1 Observational data

In July 2016 the Rio Behar terminal moulin was located at 67.047°N, -49.033°W, with an upstream drainage catchment of ~60.2 km^2 and mean surface elevation >1200 m (**Figure 1**). We established a field camp to measure moulin meltwater input and ice surface motion ~750 m upstream (~67.050°N, -49.018°W). During 5-13 July 2016 we collected 174 measurements of supraglacial river discharge using a SonTek RiverSurveyor M9 Acoustic Doppler Current Profiler (ADCP) and methods of *Smith et al. (2017)*. A Tyrolean cableway was suspended over the river to safely and repeatedly tow the ADCP back and forth across the channel every hour (**Figures S1-S4**). In total 847 ADCP transects were acquired, of which 677 later passed rigorous quality-assurance screening and were used to compute 168 consecutive hourly discharge measurements from 6-13 July (**Text S1-S3, Figure S5, Tables S1-S2, Datasets S1-S2**).

Simultaneous measurements of ice surface motion were collected every 5-s using a Trimble R7 GPS receiver and Trimble Zephyr Geodetic antenna anchored 3m into the ice to prevent its movement from ablation (67.048°N, -49.018 °W, elevation 1211.43 m). On-ice kinematic GPS positions were later estimated using carrier-phase differential processing relative to a bedrock mounted base station (~47 km baseline, 67.150°N, -50.058°W, elevation 581.19) and final International GNSS Service satellite orbits (*Chen, 1998; Estey and Meertens, 1999; Hoffman et al., 2011; Andrews al. 2014; 2018*; **Text S4**). To assess surface melt processes, simultaneous measurements of 2-m air temperature, energy balance, and ablation were obtained from the nearby PROMICE KAN_M AWS (*Fausto and van As, 2019*, **Text S5**). Proglacial river discharges were obtained from gauges at Qinnguata Kuussua/Watson River in Kangerlussuaq (*van As et al., 2019*), its northern tributary Akuliarusiarsuup Kuua (AK4) near the ice terminus (*Rennermalm et al., 2017*, AK4 station), and a discontinued gauge near Leverett Glacier (*Tedstone et al., 2017*) (**Figure 1**). Lagged correlation coefficients (e.g. *Flowers et al., 2016; Armstrong and Anderson, 2020*) were used to quantify links between these variables and GPS-derived ice motion, and to compute proglacial timing delays between the ice edge and Kangerlussuaq (**Text S6, S8**).

2.2 Proxies for *S* and A*S*

GPS-derived vertical positions and their first derivative were used to estimate subglacial storage *S* and rate-of-change L'*S* (e.g. *Bartholomew et al., 2012; Cowton et al., 2016;* **Text S7**). Proxies for *S* and L'*S* were also computed by adapting a meltwater input-output approach (*Bartholomaus et al. 2008; 2011; McGrath et al. 2011; Armstrong and Anderson, 2020*) comparing relative timings of supra- and proglacial river discharge hydrographs (**Text S7**). Hydrographs were normalized and differenced (supraglacial minus proglacial) to assess their relative timings and shapes at Rio Behar moulin and at the ice edge. These "discharge-difference" proxies are unitless and do not satisfy mass conservation. They characterize instantaneous net water storage changes, not subglacial routing delays and/or storages known to retard proglacial discharges longer than 24 h (e.g. *Chandler et al., 2013; Rennermalm et al., 2013b; Smith et al., 2015; Chu et al., 2016; van As et al., 2017; Pitcher et al. 2020*). From dye tracing experiments, subglacial routing from ~1300 m elevation takes 1-3 days (*Chandler et al. 2013,* site L57), or ~2-5 days from proglacial hydrograph analysis (*van As et al., 2017*). Such subglacial delays and storages are irrelevant to our purpose here, which is simply to characterize instantaneous subglacial conditions at our field site, not Lagrangian transport to the ice edge. Descriptions of all data, methods, and uncertainties are presented in **SI** (**Text S1-S9, Figures S7-S14, Tables S1-S5**).

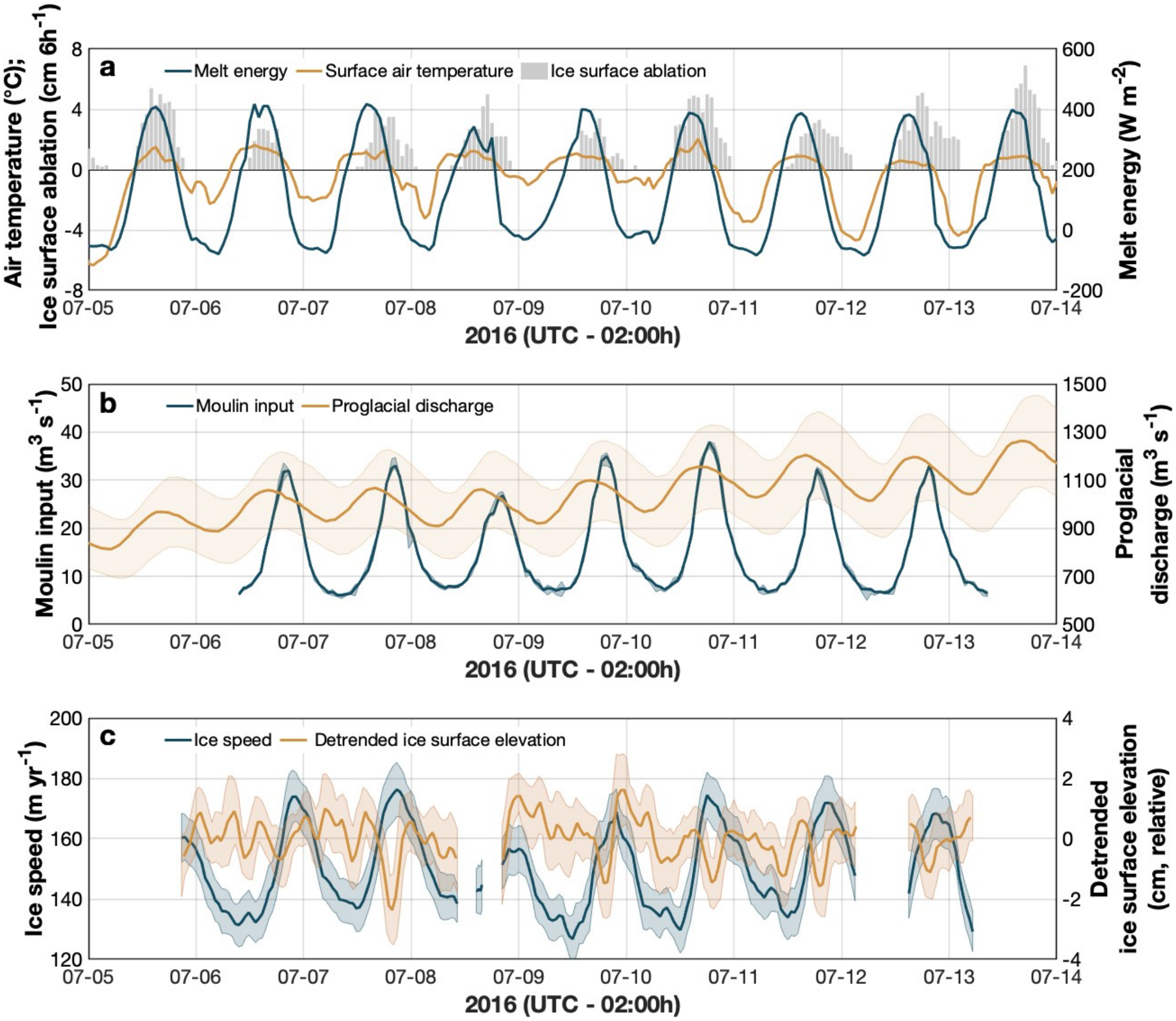

Figure 2: In situ measurements of (a) melt energy, air temperature, and ice ablation from KAN_M; (b) Rio Behar moulin input (supraglacial discharge) and proglacial discharge; (c) ice surface speed and elevation. Colored envelopes (b, c) represent measurement uncertainties.

3. Results

3.1 Correlations of ice speed with other variables

We find strong diurnal cycles in all variables except surface elevation, with daily accelerations in horizontal ice speed closely tracking moulin input and melt energy (**Figure 2; Table S3**). A consistent progression is observed in the timing of daily peaks, with melt energy and air temperatures peaking near local solar noon, followed by sequential peaks in ice ablation, moulin input, ice speed, and proglacial discharge (**Figure 3**). The timing of daily peaks is most consistent for melt energy, moulin input, ice speed, and proglacial discharge, whereas peaks in air temperature, ablation, and especially ice surface elevation are more variable as indicated by their peak timing range (**Table S3**).

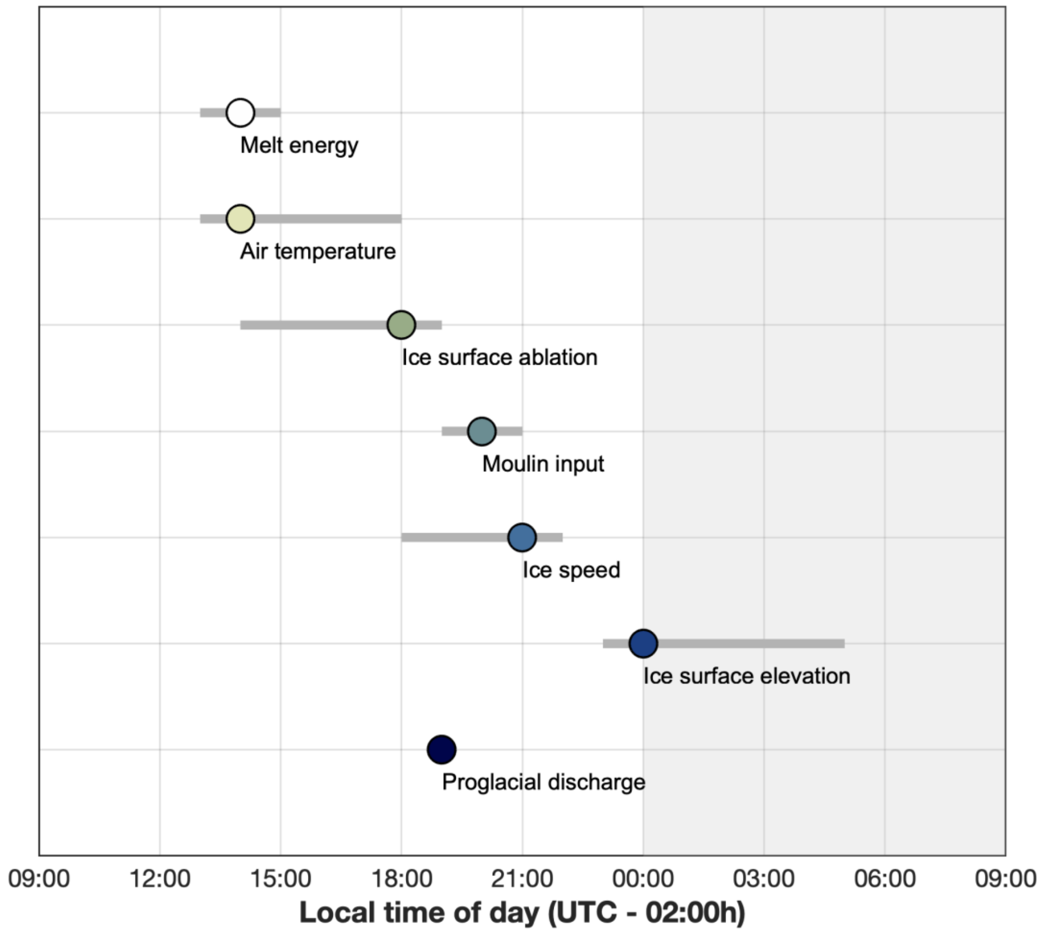

Figure 3: Mean daily peak timing (circles) and timing range (grey bars) of observed variables. Diurnal cycles in melt energy and air temperatures peak around solar noon, followed by peaks in ice ablation, proglacial discharge, moulin input, ice speed, and ice surface uplift. GPS-derived daily peaks in uplift are temporally variable (Table S3). Peak proglacial discharge has little timing variability and is shifted -5h earlier to account for the timing offset between Kangerlussuaq and the ice edge. This figure presents only the timing of daily peaks, not subglacial routing delays and/or storages of meltwater.

After lagging our GPS-derived horizontal ice speed time-series to correct for its mean timing offsets with the other variables, we compute correlations between potential forcing variables and ice speed using Pearson's r, which assumes a linear relationship, and Mann-Kendall's τ, which does not assume a linear relationship between variables. We find that ice speed correlates strongly with moulin input (r=0.90, τ=0.70), melt energy (r=0.90, τ=0.67), and proglacial discharge (r=0.88, τ=0.71) (**Figure 4, Table S4**). We find moderately strong correlations with ice surface ablation (r=0.74, τ=0.59) and air temperature (r=0.70, τ=0.54), drivers of melt energy and runoff, respectively. Lowest correlation is found for detrended ice surface elevation (i.e. uplift, r=0.36, τ=0.24, **Table S4; Figure 4e**). All correlations are statistically significant (p<0.01). Unlike melt energy (which turns negative, implying nocturnal refreezing), moulin input persists throughout the night. Because i) moulin input closely tracks (and derives from) melt energy; ii) virtually all surface runoff generated within Rio Behar catchment flows to its terminal moulin; and iii) an observed 6h time lag between peak melt energy and peak supraglacial discharge (**Table S3**) is similar to a previously calculated catchment routing delay for Rio Behar (i.e. estimated time-to-peak t_p=5.5h, *Smith et al., 2017*) we infer that supraglacial river discharge, a product of catchment-integrated melt energy, is the dominant supraglacial forcing variable driving our locally recorded ice speed variations.

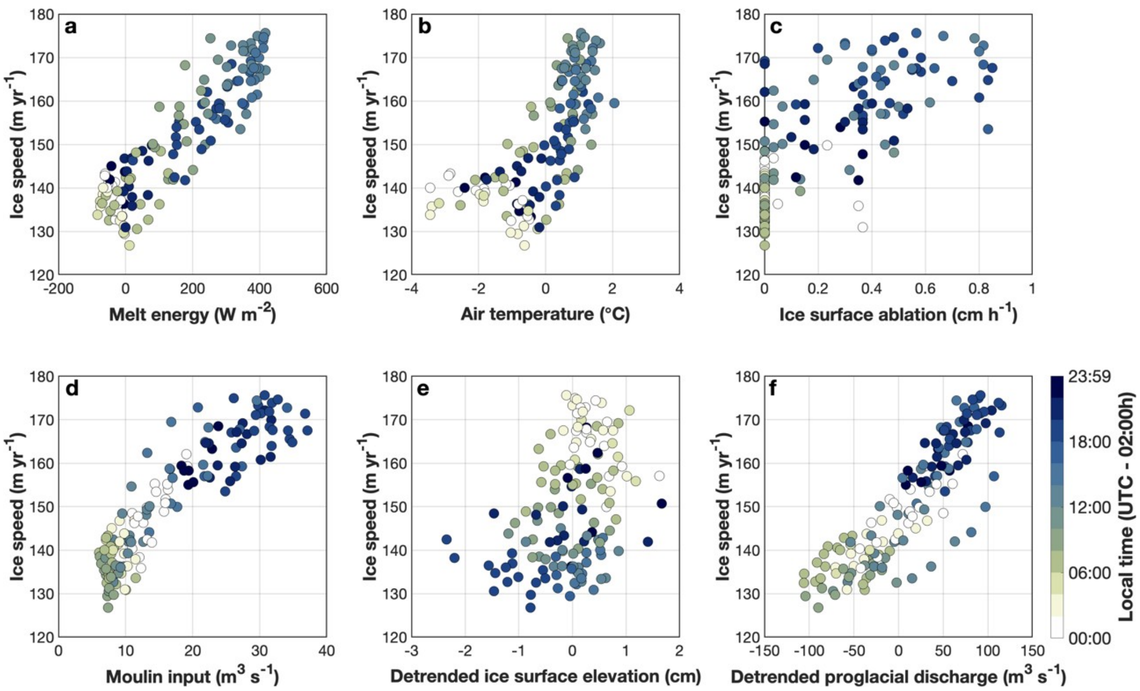

Figure 4. Correlations between ice speed and other variables, after correcting for their mean differences (values in parentheses) in daily peak timing: (a) melt energy (-7h); (b) air temperature (-8h); (c) ablation (-4h); (d) moulin input (-2h); (e) ice surface elevation (+6h); (f) proglacial discharge (-2h at terminus). Statistical correlations presented in Table S4. Moulin input displays strongest correlation with ice speed (r=0.90, τ=0.70, p<0.01).

3.2 Comparison of short-term ice accelerations with *S* and A*S*

To further investigate drivers of short-term ice speed variations, we test proxies of subglacial water storage *S* and rate-of-change L'*S* calculated from GPS-derived ice surface observations (following *Anderson et al., 2004; Harper et al., 2007; Howat et al., 2008; Hoffman et al., 2011; Cowton et al., 2016; Andrews et al., 2018*) and by differencing normalized hydrographs of supraglacial and proglacial river discharge (**Text S7-S9**). Implicit in the latter "discharge-difference" calculations are assumptions that englacial storage is negligible; that en/subglacial melting is negligible; that subglacial routing delays are irrelevant to instantaneous net storage; and that proglacial discharge reflects overall regional basal water pressure, allowing

Rio Behar moulin input to be compared with regional proglacial discharge despite its smaller spatial domain (60 km^2 vs. ~2800 km^2 to 1750 m a.s.l.) and absolute discharge magnitude (~6-38 m^3 s^{-1} vs. ~800-1300 m^3 s^{-1}).

Comparison of our observed horizontal ice speeds with both proxies for *S* and L'*S* suggests that L'*S* drives short-term accelerations in ice speed (**Figures 5, S11, S13, S14; Table S5**). This conclusion is clearest from the discharge-difference proxies, with L'*S* tracking ice as well or better than *S* (see **Figure 5c vs. 5b; S13c vs. S13b; S11, S14**). This same conclusion may be drawn, albeit less compellingly, from conventional GPS-derived *S* and L'*S* proxies (**Figure 5a vs. Figure 2c; S11d and S14d vs. b**). For both methods, L'*S* generally correlates with ice accelerations better than *S* (**Table S5**) suggesting that changes in subglacial water storage force short-term ice speed accelerations at our field site.

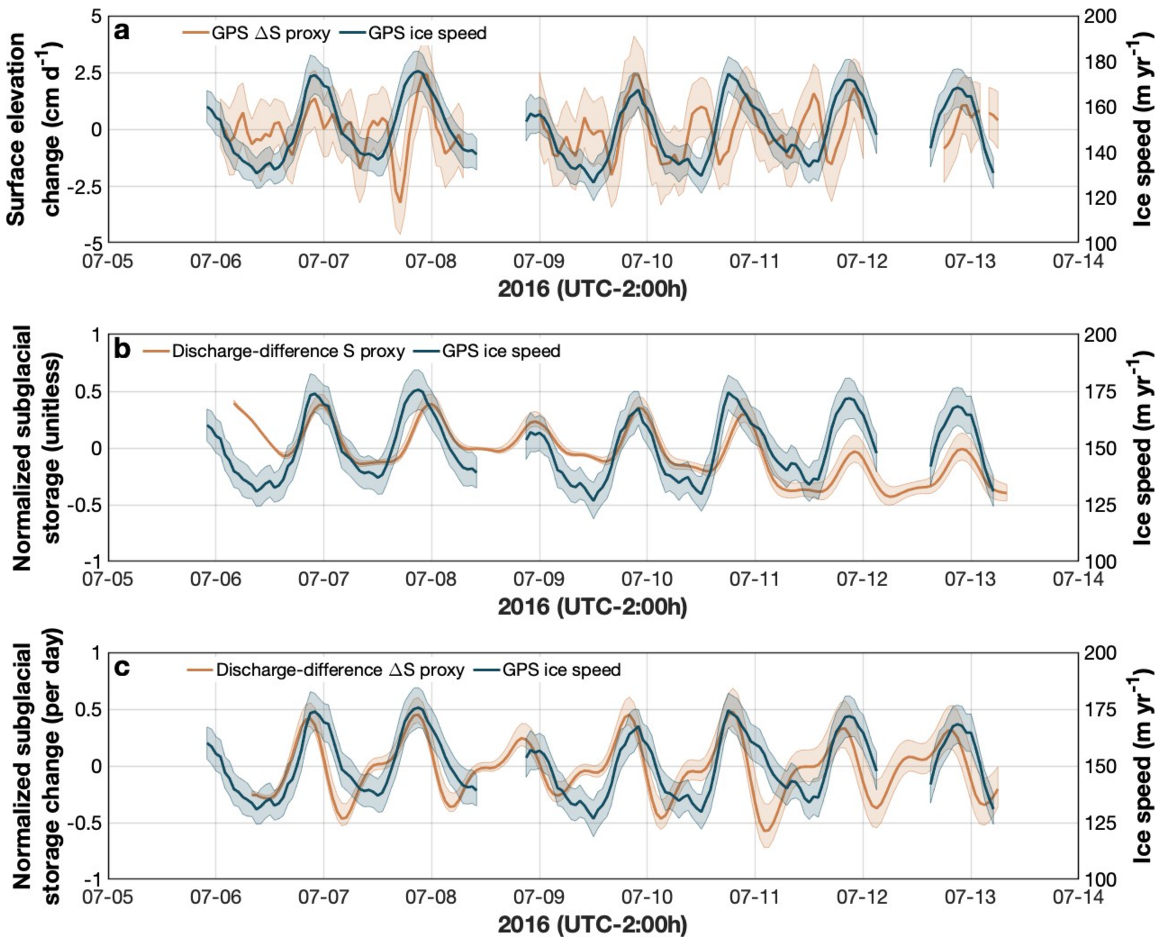

Figure 5. Comparison of horizontal ice speed (blue) with proxies for subglacial water storage (*S*) and storage rate-of-change (Δ*S*): (a) Δ*S* estimated from GPS-derived ice surface elevation; (b) *S* estimated from normalized discharge-difference; (c) Δ*S* estimated from normalized discharge-difference. See Figure 2(c) for *S* estimated from GPS. Brief accelerations in ice speed track Δ*S* better than *S*. Discharge-difference (c) tracks ice speed better than GPS (a). Figure S13 presents another version of this figure using AK4 proglacial discharges.

4. Discussion and conclusion

We find that diurnal cycles in moulin input (following the integrative and delaying effects of surface routing through the upstream catchment) are the primary driver of short-term accelerations in ice sliding velocity at our field site (**Figure 4**). This finding supports previous work (*Andrews et al., 2014*) and the conclusion that over diurnal scales, variability in supraglacial river input imposes a first-order control on subglacial water pressure fluctuations. Furthermore, while short-term accelerations in ice speed closely follow moulin input, they also tend to track proxies of subglacial water storage change (L'*S*) better than proxies of absolute storage (*S*) (**Figures 5, S11, S13, S14**), suggesting that nightly peaks in subglacial water storage drive subglacial basal pressure and short-term ice motion.

This conclusion is more evident in discharge-difference proxies than conventional GPS-derived proxies (e.g. **Figures 5c vs. 5a; S13c vs. S13a; S11, S14**). This is likely due to our inability to assess the impact of changes in the ice column due to variations in vertical strain, making our GPS-derived proxies susceptible to local and non-local forcings (e.g., *Price et al., 2008; Ryser et al., 2014*; see **Text S7**). Differencing supra- and proglacial hydrographs, therefore, may characterize subglacial water storage conditions more sensitively than small vertical ice surface elevation changes, which are inherently difficult to detect and have multiple sources of uncertainty (*Anderson et al., 2004; Andrews et al., 2018*). A discharge input-output approach (e.g. *Bartholomaus et al., 2008; 2011; McGrath et al., 2011*; *Armstrong and Anderson, 2020*), comparing moulin inputs with proglacial outputs, offers an alternate strategy for characterizing subglacial water storage and its link to basal sliding laws. Future studies, for example, could develop discharge-difference proxies over longer time scales and larger study areas by pairing surface-routed climate model output (e.g. *Smith et al., 2017; Yang et al., 2019*) with proglacial discharge records (*Rennermalm et al. 2017; van As et al., 2019*), to relate net increases/decreases in L'*S* to regional ice speed variations.

It is well-known that evolution of the subglacial system from inefficient to efficient states acts to modulate the ice dynamical response to supraglacial water inputs (e.g. *Bartholomew et al., 2010; 2011; Hoffman et al., 2011*). We find that peak or ascendant L'*S* is associated with localized GrIS velocity accelerations (**Figure 5c; Figure 13c**). This suggests that highest subglacial water pressure (and ice sliding speed) occurs when subglacial cavities are growing the fastest, not when their volume is largest (e.g. *Iken et al., 1983; Cowton et al., 2016*). As such, steady-state theoretical basal sliding laws – which assume a relationship between cavity size and subglacial pressure – do not accurately represent transient behavior of the subglacial system.

It is important to note that the strong correlation between moulin input and ice velocity reported here (**Figure 4d**) is unlikely to hold over an entire melt season. Previous work has clearly established that Greenland ice sliding velocities are strongly influenced by long-term seasonal evolution of the subglacial hydrological system (e.g. *Bartholomew et al., 2010; Hoffman et al., 2011; Nienow et al., 2017; Andrews et al., 2018*). Our short 7-day record captures neither the early nor late melt season, when subglacial efficiency (and associated ice speeds) undergo extensive changes. Subglacial evolution makes melt-driven proxies inappropriate for estimating ice motion over the entire melt season (*Bartholomew et al., 2010; Andrews et al., 2014*) or multiple years (*Tedstone et al., 2015; Davison et al., 2019*). Over short time scales, however, we find that diurnal cycles in moulin input are the primary driver of fluctuating subglacial water pressures and associated ice accelerations – even in relatively thick ice (~1 km) more than 40 km inland from the ice edge. Some slight differences in peak timings between L'*S* and ice motion, as well as some non-linear behavior on descending limbs (**Figure 5c, Figure 13c**) are discussed further in **Text S9**.

This study adds to a small but growing collection of GrIS supraglacial streamflow measurements (*Holmes 1955; Echelmeyer and Harrison 1990; Carver et al. 1994; McGrath et al. 2011; Chandler et al., 2013; Gleason et al. 2016; Smith et al., 2015; 2017*). With peak daily discharges of 26.59 – 37.61 m^3/s (**Table S2**), the discharges reported here are far larger than those collected in most supraglacial streams, but are typical for trunk supraglacial rivers in southwest Greenland (*Smith et al., 2015; 2017*). Nearly all of them terminate in moulins (*Smith et al., 2015; Yang and Smith, 2016*), and the high diurnal variability we observe (19.05 – 30.50 m^3/s, **Table S2**) signifies that their subglacial channels are likely out of equilibrium with supraglacial inputs for large portions of the day, such that associated accelerations in ice speed are driven by addition or removal of water outside of the channelized system.

Based on satellite mapping (e.g. *Yang and Smith, 2013; 2016; Lampkin and VanderBerg, 2014; Smith et al., 2015; Yang et al., 2015; 2016)* and topographic modeling (e.g. *Banwell et al. 2012; 2016; Karlstrom and Yang, 2016; King et al., 2016; Crozier et al., 2018*), we maintain that supraglacial rivers likely drive ice accelerations near hundreds of other terminal moulins as well. Process-level understanding and modeling of subglacial hydrology and associated ice dynamics should presume large, strongly diurnal inputs of meltwater entering hundreds of supraglacial river moulins distributed throughout Greenland's ablation zone. These inputs, countered by water output discharged beneath outlet glaciers, trigger short-term fluctuations in subglacial water storage that drive short-term accelerations in ice sheet motion.

5. Data Availability

Discharge data, surface mass balance data, ADCP and GPS data summaries, *S* and Δ*S* proxies, and a time-lapse camera video are available as tables (**Tables S1-S2**) and/or Additional Supporting Information (**Datasets S1-S7**). Original, full-resolution ADCP and GPS data will be archived at the Arctic Data Center (https://doi.org/10.18739/A2PN8XG5T). PROMICE KAN_M automated weather station data (*Fausto and van As, 2019*) are available from https://www.promice.org/PromiceDataPortal/. Proglacial river discharges for Qinnguata Kuussua/Watson River (*van As et al., 2019*), Akuliarusiarsuup Kuua (*Rennermalm et al., 2013b; 2017*), and Leverett Glacier (*Tedstone et al., 2017*) are available from https://doi.org/10.22008/promice/data/watson_river_discharge , https://doi.org/10.1594/PANGAEA.876357, and https://doi.org/10.5285/17c400f1-ed6d-4d5a-a51f-aad9ee61ce3d.

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Dedication

We dedicate this paper to the memory of Dr. Konrad Steffen (1952-2020).

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