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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 GPS-derived ice motion on the southwest Greenland Ice Sheet 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

Abstract (150 words max)

Surface melting can alter 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 (i.e. moulin input) and GPS-derived ice surface motion for Rio Behar, a ~60 km^2 moulin-terminating supraglacial river catchment the southwest Greenland ablation zone. Short-term accelerations in ice speed correlate strongly with lag-corrected measures of surface mass loss, specifically supraglacial river discharge ($r= 0.9$; $p<0.001$). 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 melting 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 meltwater runoff measurements from a large supraglacial river draining the ice sheet surface, just upstream of its plummet 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 align with 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. Meierbachtol et al., 2013; Van de Wal et al., 2008; Zwally et al., 2002; Bartholomew et al., 2012*). 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 governing the link between GrIS supraglacial meltwater runoff, ice sheet basal pressures, and ice sliding remain under intense study (*Davison et al., 2019; Nienow et al., 2017; Williams et al. 2020*).

Traditional basal sliding law formulations linking subglacial pressure and ice motion assume steady-state cavities at the bed (e.g. *Bindschadler, 1983; Schoof, 2005; Gagliardini et al., 2007*). However, observational research suggests that subglacial 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 speed) 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, ΔS). GrIS horizontal ice sliding speed broadly covaries with vertical surface uplift over the time scale of a melt season (e.g., *Hoffman et al., 2011; Bartholomew et al., 2010; Bartholomew et al., 2012*), 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 confounding factors impeding calculation of basal uplift from ice surface elevation measurements (see *Andrews et al., 2018* and *Hoffman et al., 2011*). 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 alpine glaciers (e.g. *Bartholomaus et al., 2008; 2011*).

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 measurements of surface energy balance and ablation (*Fausto and van As, 2019*), and with proglacial discharges from permanent river gauging stations located downstream (*Rennermalm et al., 2013b; 2017; van As et al., 2018; 2019*). Horizontal GPS positions provide ice surface speed variations, and vertical GPS positions and their first derivative provide proxies for subglacial storage S and rate-of-change ΔS, respectively. We also compute alternate, qualitative proxies for S and ΔS by differencing normalized supraglacial and proglacial discharge hydrographs (adapted from *Bartholomaus et al., 2008, 2011* and *McGrath et al., 2011*). We conclude that diurnal cycles in moulin input influence local ice speed variations through their influence on ΔS, confirming that transient water storage and cavity growth are important drivers of subglacial basal pressure and short-term ice motion.

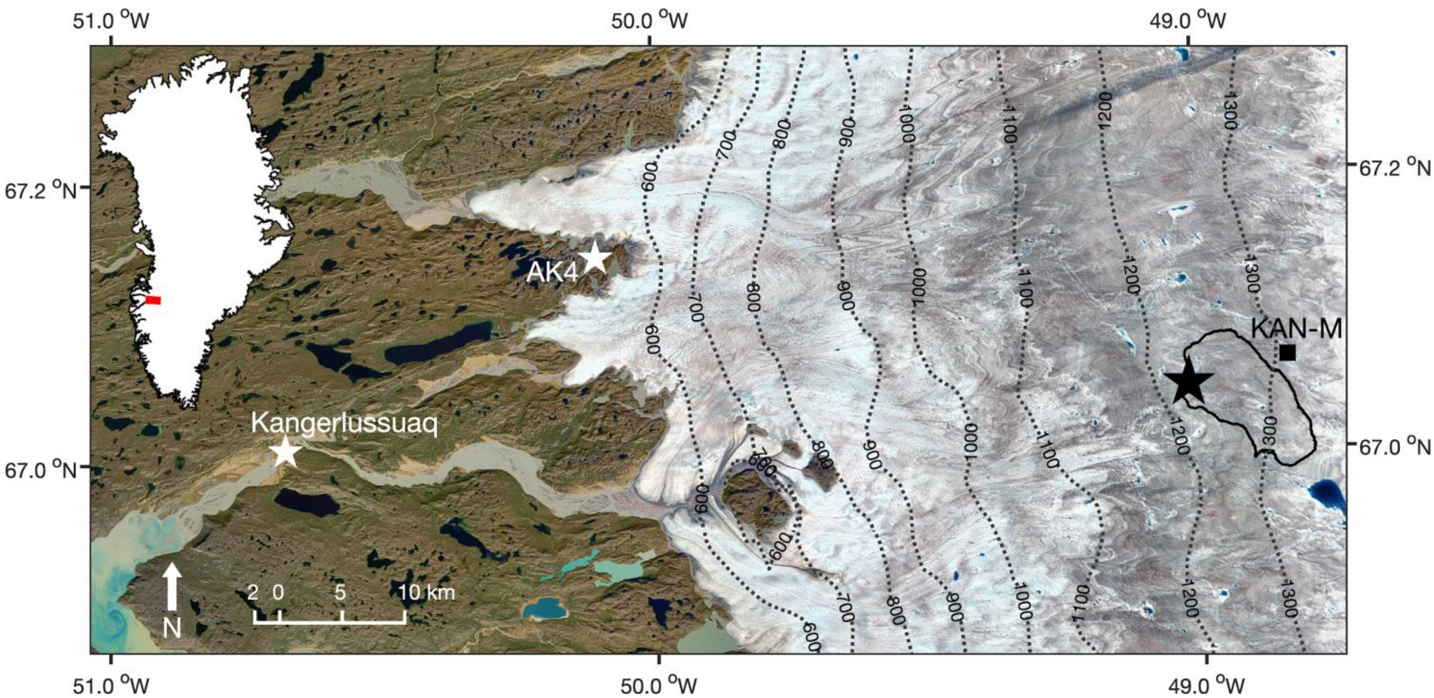


Figure 1: Study area in southwest Greenland. Black star shows location of our GPS measurements of ice surface motion and Acoustic Doppler Current Profiler (ADCP) measurements of moulin input (supraglacial discharge) in Rio Behar, a large supraglacial river penetrating the ice sheet >40 km from the ice edge. Measurements were acquired ~750 m upstream of the Rio Behar terminal moulin from 5-14 July 2017. Black outline denotes the Rio Behar surface catchment (60.02 km^2 in July 2016). White stars show locations of the PROMICE KAN_M automated weather station (black square) and two permanent gauging stations in proglacial rivers. 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 monitor moulin meltwater input ~750 m upstream (location ~67.0499°N, -49. 0180°W) and ice surface motion. Field operations were carried out from 5-14 July 2016, with 168 consecutive hourly measurements of supraglacial river discharge collected 6-13 July 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 (**Figures S1-S4**). A total of 847 ADCP transects were acquired, of which 677 later passed rigorous quality-assurance screening and were used to compute 174 hourly in situ discharge measurements (**Figure S5, Tables S1-S2, Datasets S1-S3**).

Simultaneous measurements of ice surface motion were collected every 5 seconds using a Trimble R7 GPS receiver and Trimble Zephyr Geodetic antenna anchored in the ice (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 (67.150°N, -50.058°W, elevation 581.19) and final International GNSS Service satellite orbits (*Chen, 1998; Estey & Meertens, 1999; Hoffman et al., 2011; Andrews al. 2014; 2018*; see SI). To assess surface melt processes, simultaneous measurements of 2-m air temperature, energy balance, and ice ablation were obtained using the nearby PROMICE KAN_M automated weather station (AWS) (*Fausto and van As, 2019*). To assess proglacial water outflow, hourly discharges were obtained from permanent river gauges at Qinnguata Kuussua (Watson River) in Kangerlussuaq (*van As et al., 2019*), and its northern tributary Akuliarusiarsuup Kuua near the ice terminus (*Rennermalm et al., 2017*, AK4 station 67.146°N, 50.107°W). Lagged correlation coefficients were used to quantify links among these various forcing variables with GPS-derived ice motion.

2.2 Proxies for *S* and Δ*S*

GPS-derived vertical positions and their first derivative were used to estimate subglacial storage *S* and rate-of-change Δ*S* (e.g. *Cowton et al., 2016; Bartholomew et al., 2012;* see **SI**). Proxies for *S* and Δ*S* were also computed by adapting a meltwater input-output approach (*Bartholomaus et al. 2008; 2011; McGrath et al. 2011*) comparing relative timings of supra- and proglacial discharge hydrographs (see **SI**). 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 so should be used qualitatively (i.e. for visual comparison of peak *S* and *ΔS* timing with accelerations in ice speed). They also characterize instantaneous net water storage, not subglacial routing delays and/or storages known to retard proglacial discharges longer than 24 h (e.g. *Chandler et al., 2013; Chu et al., 2016; Pitcher et al. 2020; Rennermalm et al., 2013b; Smith et al., 2015; van As et al., 2017*). Dye tracing experiments, for example, show that 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. Complete description of these data and methods are presented in **SI**.

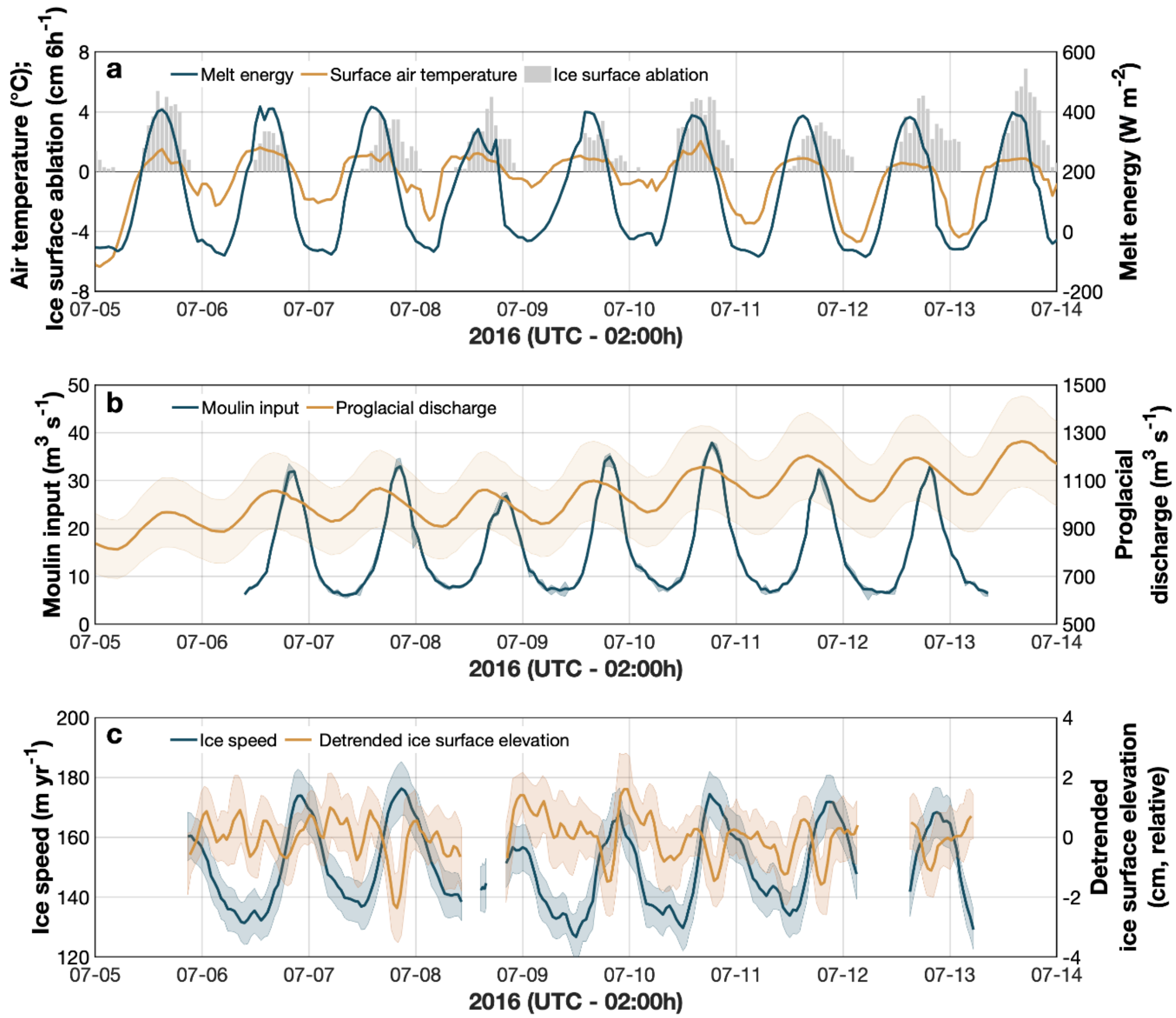
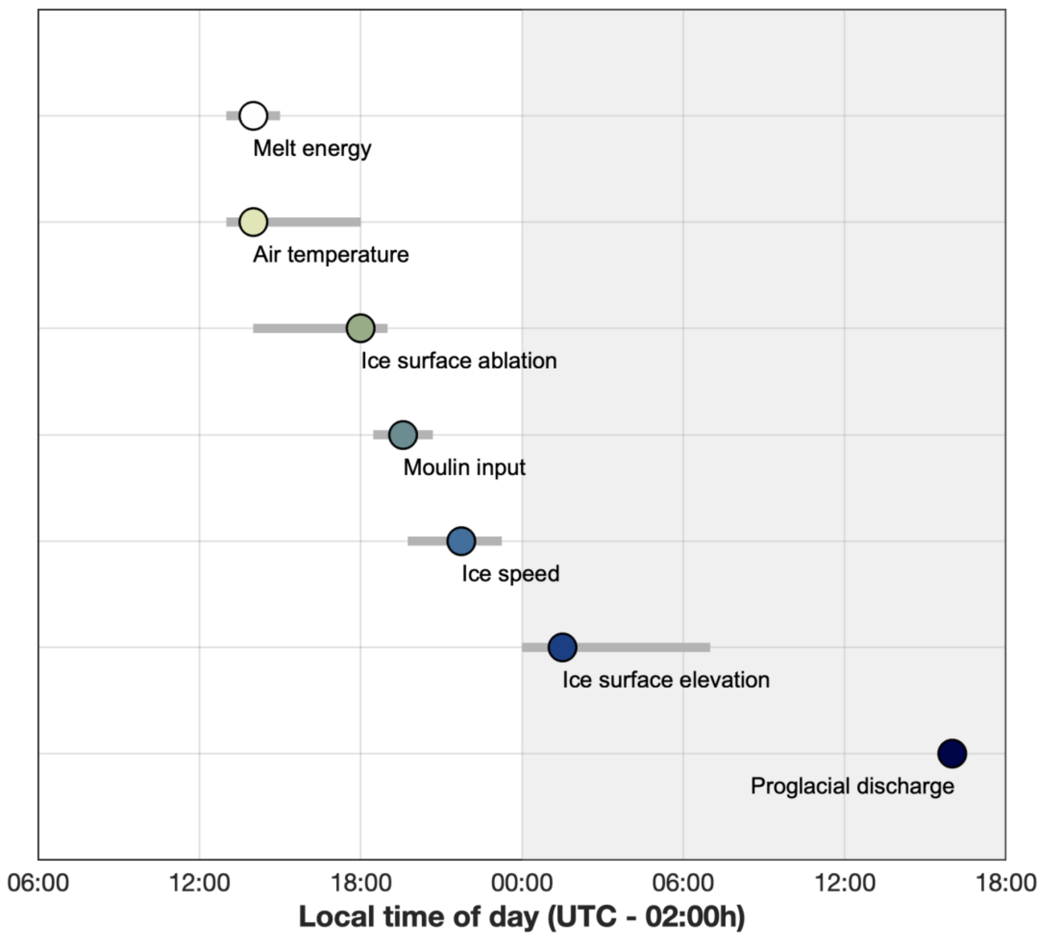


Figure 2: In situ measurements of (a) melt energy, air temperature, and ice ablation from PROMICE KAN_M; (b) Rio Behar moulin input (supraglacial river discharge) and proglacial discharge at Kangerlussuaq; (c) Rio Behar ice surface speed and elevation. Colored envelopes (b, c) represent measurement uncertainties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

3. Results

3.1 Correlations of ice speed with other variables

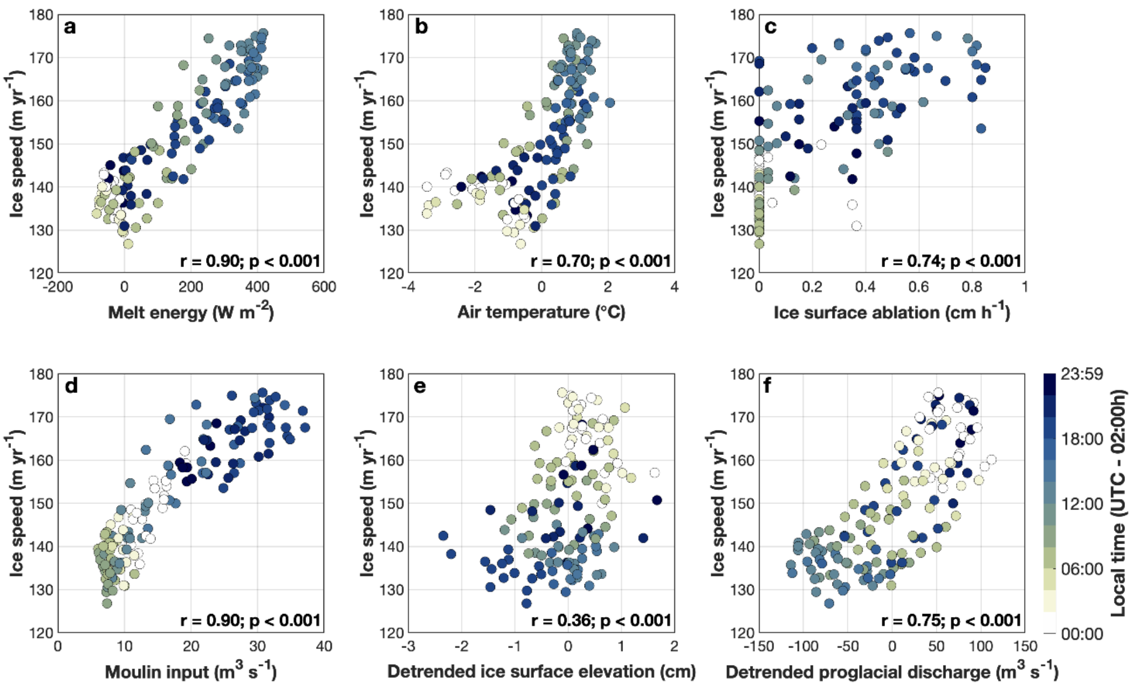
We find strong diurnal cycles in all variables except surface elevation, with daily accelerations in horizontal ice speed closely tracking melt energy and moulin input (**Figure 2**). A consistent progression is observed in the timing of daily peaks, with melt energy and air temperatures peaking near 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 velocity, and proglacial discharge, whereas peaks in



air temperature, ablation, and ice surface elevation are more temporally variable (**Figure 3**).

Figure 3: Mean daily timing (circles) and timing range (earliest to latest, grey bars) of daily peaks in observed variables. Diurnal cycles in melt energy and air temperatures peak around solar noon, followed by peaks in ice ablation, moulin meltwater input, ice surface speed, ice surface uplift, and proglacial discharge. Peak proglacial discharge displays no timing variability and is here shifted -8h to account for the mean timing difference between peak daily discharge observed at Kangerlussuaq versus at the ice edge (see SI). Note that this figure presents only the timing of daily peaks, not subglacial routing and/or storages known to delay proglacial discharges longer than 24h.

After lagging our GPS-derived horizontal ice speed time-series to correct for mean timing differences with the other variables, we find ice speed correlates most strongly with melt energy and moulin input (r=0.9, **Figures 4a, 4d**). Moderately strong correlations are found for air temperature (r=0.71, **Figure 4b**) and ice surface ablation rate (r=0.75, **Figure 4c**), drivers of melt energy and runoff, respectively. Lower correlations are found for detrended proglacial discharge (r=0.74, **Figure 2b**) and detrended ice surface elevation (i.e. uplift, r=0.37, **Figure 4e**). All correlations are statistically significant (p<0.01). Unlike melt energy (which turns negative, suggesting nocturnal refreezing), moulin input persists at low levels throughout the night. Because i) moulin input closely tracks (and derives from) melt energy; ii) virtually all meltwater runoff generated within Rio Behar catchment flows to its moulin; and iii) the observed +5h timing difference between peak melt energy and peak supraglacial discharge 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 a dominant forcing variable driving our locally recorded ice-speed variations.

Figure 4. Correlations between ice speed and other observed variables, after correcting for the mean differences in daily peak timing shown in Figure 3 (timing differences in parentheses): (a) melt energy (-7h); (b) air temperature (-7h); (c) ablation (-4h); (d) moulin input (-2h); (e) ice surface elevation (+6h); (f) proglacial discharge (+19h at the ice sheet edge). Linear correlations (*r*) and statistical probability values (*p*) are shown in the bottom right corner of each plot. Strongest correlations with ice speed are found for melt energy and moulin input.

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

To further investigate drivers of ice speed variations, we test proxies of subglacial water storage *S* and rate-of-change Δ*S* calculated from GPS-derived ice surface observations (*Anderson et al., 2004; Andrews et al., 2018; Cowton et al., 2016; Harper et al., 2007; Hoffman et al., 2011; Howat et al., 2008*) and by differencing normalized hydrographs of supraglacial and proglacial river discharge (See **Methods** and **SI**). 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 distal (>40 km) 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 ΔS suggests that ΔS drives short-term accelerations in ice speed (**Figure 5b**). This conclusion is clearest from the discharge-difference proxies, with ΔS aligning better with ice speed peaks and ascents than S (see **Figure 5c** versus **Figure 5b**, see also **Figure S7)**. This same conclusion may be drawn, albeit less compellingly, from conventional GPS-derived S and ΔS proxies (i.e. **Figure 5a** versus **Figure 2c**; **Figure S7**). For both methods, peaks in ΔS generally align better with ice accelerations than peaks in S, suggesting that changes in subglacial water storage force short-term ice speed accelerations at our field site.

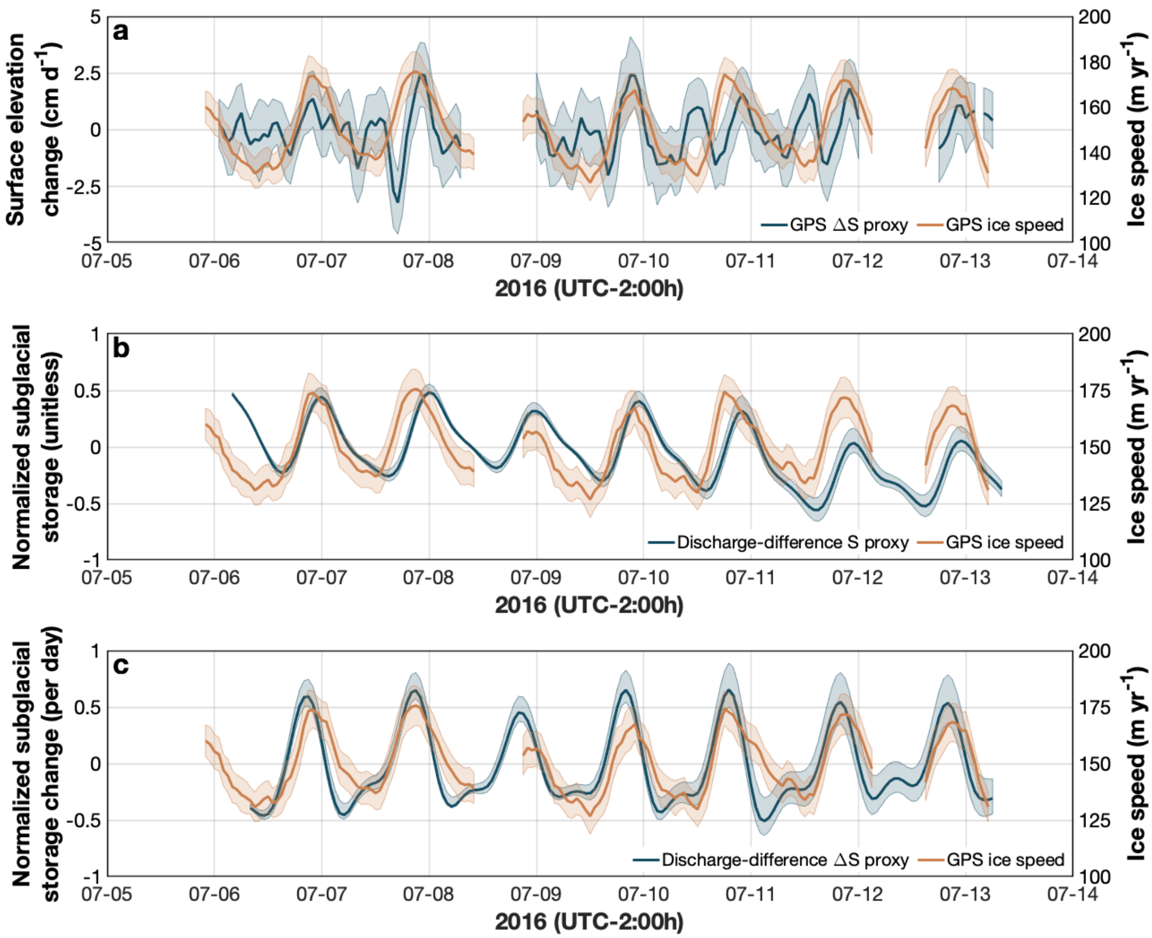


Figure 5. Comparison of horizontal ice speeds (blue line) with proxies for subglacial water storage (*S*) and its rate-of-change (Δ*S*): (a) Δ*S* as estimated from GPS-derived ice surface elevations; (b) *S* as estimated from normalized discharge-difference; (c) Δ*S* as estimated from normalized discharge-difference. See Figure 2(c) for *S* as estimated from GPS. Short-lived accelerations in ice speed generally align with peaks or ascents in *S* (c), see also (a); but not *S* (b), see also Figure 2(c). Peaks in Δ*S* capture peaks in ice speed more exclusively in (c) than (a),

and also some small secondary ice accelerations, suggesting that the discharge-difference proxy may more sensitively characterize subglacial water storage conditions than vertical GPS measurements.

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 (**Figure 3, Figure 4**). This finding supports previous work (*Andrews et al., 2014*) and the conclusion that over diurnal scales, supraglacial rivers impose a first-order control on subglacial water pressure fluctuations. Furthermore, while short-term accelerations in ice speed closely follow moulin input (**Figure 2, Figure 4**), they also tend to align with proxies for subglacial water storage change (ΔS) better than proxies for absolute storage (S) (**Figure 5, see also Figure 2c**), suggesting that nocturnal peaks in subglacial water storage drive subglacial basal pressure and short-term ice motion.

This conclusion is more evident in discharge-difference proxies (**Figures 5b, 5c**) than conventional GPS-derived proxies (**Figures 2c, 5a**). The discharge-discharge ΔS proxy reflects quiescent periods better than GPS-derived ΔS, and may also reflect subglacial behavior associated with a secondary ice-speed peak on most days (**Figure 5c**). 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; 2018*). A meltwater input-output approach (here adapted from *Bartholomaus et al., 2008; 2011* and *McGrath et al., 2011*), comparing moulin inputs with proglacial outputs, offers an alternate strategy for characterizing subglacial water storage and their link to ice and 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 ΔS to ice speed variations. Our results, using normalized input and output without mass conservation, suggest that a true (i.e. mass-conserved) water balance may not even be necessary to infer qualitative relationships between subglacial water storage, subglacial pressures, and ice motion.

It is well-known that evolution of the subglacial system from inefficient to efficient states acts to modulate the ice dynamical response to supraglacial inputs (e.g. *Bartholomew et al., 2010; 2011; Hoffman et al., 2011*). Using two different methods, we find that peak or ascendant ΔS is associated with localized GrIS velocity accelerations (**Figure 5c**). This suggests that highest subglacial water pressures (and ice sliding speeds) occur when subglacial cavities are growing the fastest, not when their size 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 (*Hoffman et al., 2011; Andrews et al., 2018; Bartholomew et al., 2010; Nienow et al., 2017*). 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 (*Andrews et al., 2014, Bartholomew et al., 2010*) 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 variability in peak timings between Δ*S* and ice motion, as well as non-linear behavior on descending limbs (**Figure 5c**) are discussed further in **SI** (**Text S8**)

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 local subglacial channels are likely out of equilibrium with moulin input for large portions of the day, such that corresponding 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; King et al., 2016; Karlstrom and Yang, 2016; Crozier et al., 2018*), we submit 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

Supraglacial discharges, surface mass balance variables, ADCP and GPS data, and *S* and Δ*S* proxies are provided as summary tables (**Tables S1-S2**) and/or as Additional Supporting Information (**Datasets S1-S7**). 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*) and Akuliarusiarsuup Kuua (*Rennermalm et al., 2013b; 2017*) are available from https://doi.org/10.22008/promice/data/watson_river_discharge and https://doi.org/10.1594/PANGAEA.876357.

6. Acknowledgements

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Dedication

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

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