Moulin density controls the timing of peak pressurization within the Greenland Ice Sheet's subglacial drainage system

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Key Points:

- Larger catchments within the Greenland Ice Sheet's ablation area impart significant delays on the timing of meltwater delivery to moulins
- Peak moulin head occurred 1–3.25 hours later at higher elevations
- Peak moulin head and sliding speeds are not coincident where moulin density is low

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Abstract

Links between hydrology and sliding of the Greenland Ice Sheet (GrIS) are poorly understood. Here, we monitored meltwater's propagation through the entire glacial hydrologic system for catchments at different elevations by quantifying the lag cascade as daily meltwater pulses traveled through the supraglacial, englacial, and subglacial drainage systems. We found that meltwater's residence time within supraglacial catchments—depending upon area, snow cover, and degree of channelization—controls the timing of peak moulin head, resulting in the two hour later peak observed at higher-elevations. Unlike at lower elevations where peak moulin head and sliding coincided, at higher elevations peak sliding lagged moulin head by ~ 2.8 hours. This delay was likely caused by the area's lower moulin density, which required diurnal pressure oscillations to migrate further away from subglacial conduits to elicit the observed velocity response. These observations highlight the supraglacial drainage system's control on coupling GrIS hydrology and sliding.

Plain Language Summary

Each summer, melting snow and ice collects within stream and rivers on the Greenland Ice Sheet's surface until reaching crevasses or moulins—near-vertical conduits that penetrate the entire ice thickness—where this meltwater can lubricate the bed, causing the overlying ice to slide more rapidly. Despite the important role of meltwater in modulating sliding speeds, little is known about how relationships between melting and sliding vary spatially or through time. Here, we take the novel approach of monitoring meltwater's propagation through the entire glacial hydraulic system at two elevations. We find that longer delays in the timing of meltwater delivery to moulins draining larger, higher-elevation catchments, caused peak moulin water level (i.e., peak pressurization) to occur two hours later in the day than at smaller, lower-elevation catchments. Unlike at lower elevations where peak moulin water level and sliding coincided, at higher elevations sliding lagged peak moulin water level by 2.8 hours. This delay was likely caused by the fewer number of moulins which require a single moulin to pressurize a larger proportion area. This work reveals the importance of the supraglacial drainage system in imparting controlling the timing of meltwater reaching the bed and its relationship with sliding.

1 Introduction

Accurate predictions of the Greenland Ice Sheet's (GrIS) future contributions to sea level rise require a good understanding of the dynamic links between melting, subglacial water pressures, and ice motion. Meltwater produced on the ice sheet's surface flows through complex networks of supraglacial streams and rivers that ultimately empty into crevasses or moulins (Rennermalm et al., 2013; Smith et al., 2015; Yang & Smith, 2016). Moulins are vertical conduits that penetrate the entire ice thickness and connect to the most efficient parts of the dynamic subglacial drainage system (Gulley et al., 2012). Meltwater inputs to moulins modulate subglacial water pressures and basal traction, which controls sliding (Andrews et al., 2014; Bartholomaus et al., 2007). Accordingly, the supraglacial, englacial, and subglacial drainage systems are inherently linked, meaning that changes in any of these components can impact ice motion. Despite the hydraulic system's interconnections, most studies of glacial hydrological systems have focused on one component at a time, resulting in critical gaps in our understanding of links between changes in hydrology and ice motion.

Large scale ice sheet models exclude key components of the glacial hydrologic system when investigating the ice-dynamic response to melting (Goelzer et al., 2020). Frequently, the supraglacial drainage system is overlooked under the assumption that meltwater delivery to the subglacial drainage system is coincident with peak melting across the ablation area. Such simplifications contrast with observations that reveal significant heterogeneity in the timing of meltwater delivery to moulins (King, 2018; Yang & Smith, 2016; Yang et al., 2018), which can lag peak melting by up to 16 hours for the largest catchments (Smith et al., 2017). Observations show temporal lags between peak melting and peak sliding speeds increase with elevation and distance from the ice sheet's margin (Hoffman et al., 2011), suggesting there should be spatiotemporal differences in the hydro-dynamic coupling throughout the GrIS ablation area. These lags are likely caused by longer delays in the timing of meltwater delivery to moulins with larger catchment areas, which similarly increase with elevation as moulin density decreases (Clason et al., 2015; Yang et al., 2018). Even though the importance of meltwater inputs on sliding is well documented, how differences in the timing of meltwater delivery to moulins and their spatial distribution impact sliding has not been fully investigated.

Here we take a novel and holistic approach to understanding relationships between melting and sliding on the GrIS by quantifying lags in meltwater propagation through each component of the glacial hydraulic system. We established two field camps at different elevations—a lower elevation field camp, Low Camp, and a higher-elevation camp, High Camp—where we measured the timing of daily peaks in melting, meltwater delivery to moulins, moulin hydraulic head (the water level within the moulin with respect to sea level), and surface ice velocity. We use these observations to investigate how differences in the physical characteristics of supraglacial drainage basins control lags between peak meltwater production and delivery to moulins and how these differences impact sliding.

2 Data and Methods

2.1 Field Sites

In July 2017, we established two camps within the ablation area of Sermeq Avannarleq in west Greenland: a lower elevation site *Low Camp* and a higher-elevation site *High Camp* at elevations of 779 and 947 m.a.s.l., respectively (Figure 1; Table S2; Ice thicknesses of 503 and 790 m (Morlighem et al., 2017)). We monitored meltwater propagation within an internally drained catchment at each elevation, the moulins of which we refer to as JEME (at Low Camp), and RADI (at High Camp) (Figure 1b–c). To constrain the timing and magnitude of daily melting we installed an automatic weather station at each camp (Text S4), supplementing our observations with data from the nearby GC-NET station JAR1 (Figure 1; Steffen et al., 1996). We monitored the timing of meltwater delivery to each catchment's terminal moulin using ultrasonic water level sensors positioned approximately 30 m upstream of each moulin (Figures S1–S4). We measured moulin water level by directly instrumenting moulins with pressure transducers, allowing us to monitor pressure fluctuations within the most hydraulically connected parts of the subglacial drainage system. On 21 July we instrumented Low Camp's JEME moulin (69.474°N, -49.825°E) which drained $\sim$0.2 km^2 (Figure 1; Table S1). On 29 July we instrumented High Camp's Radical moulin (RADI; 69.543°N, -49.693°E) which drained $\sim$16.7 km^2 (Figure 1; Tables S1 and S3). Finally, we monitored ice motion by installing several global navigation satellite system (GNSS) stations at both camps (Text S6).

In 2018 we returned to the field to expand our observations. Before the onset of melting, we installed a seismic station to measure glaciohydraulic tremor amplitude, a proxy for the discharge and pressure gradient within subglacial conduits (Text S7; Bartholomaus et al., 2015; Gimbert et al., 2016), within Low Camp's main catchment JEME. On 10 July, we instrumented the newly formed PIRA moulin which drained the same catchment as JEME moulin the previous year (catchment area $\sim$0.2 km^2; Figure S3). PIRA moulin formed in approximately the same location as JEME moulin was before it had advected $\sim$90 m downglacier over the winter. To further constrain catchment area induced delays in meltwater delivery to moulins, we instrumented two auxiliary catchments with supraglacial stream gauges: JNIH catchment at Low Camp (July 2017; area $\sim$1.1 km^2), and SBPI catchment at High Camp (August 2018; $\sim$2.4 km^2; Figure 1).

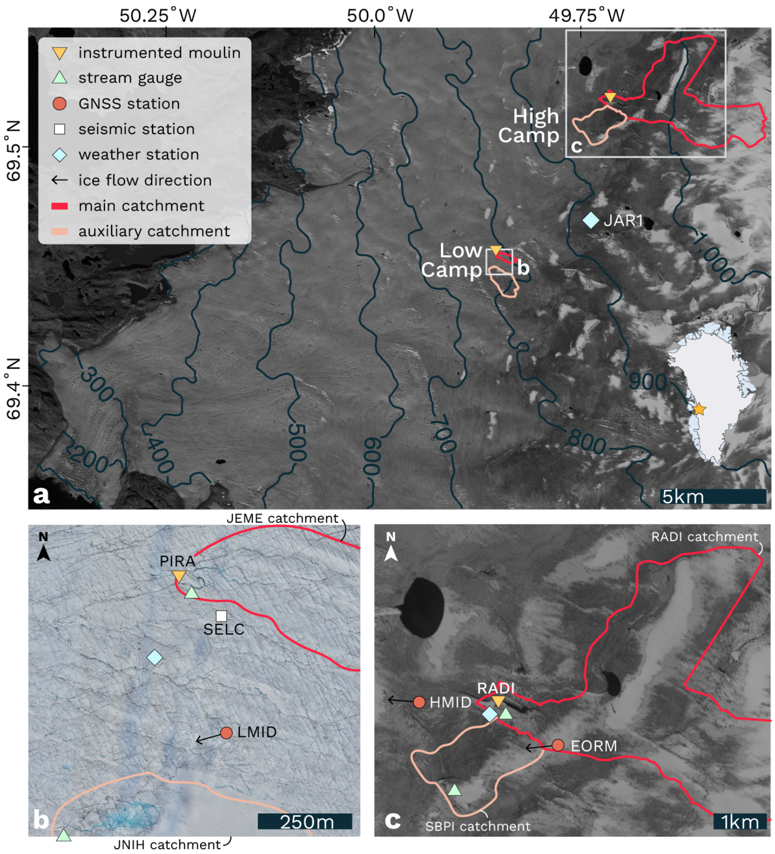

Figure 1. Sermeq Avannarleq field sites. (a) Sentinel-2 imagery from 10 Aug 2018 showing the full extent of the catchments studied at Low Camp and High Camp. (b) July 2018 drone orthophoto showing Low Camp, our main catchment JEME is outlined in red. PIRA (yellow triangle) and JEME moulins draining this catchment were located in the same position in 2017 and 2018 (Figures S1, S3–S4). (c) High Camp zoom in showing instrumented moulin RADI (yellow) with outlined catchment (Figures S2 and S5).

3 Results

The instruments deployed during the 2017 and 2018 melt seasons allowed us to monitor and constrain the timing of meltwater propagation through the glacial hydraulic system for catchments at Low Camp and High Camp. We deployed the first instruments in July 2017 after the melt season had already begun and the snowline had retreated past both our lower and higher-elevation sites.

3.1 Meltwater production

We used recorded meteorological measurements and the enhanced temperature-index model by Pellicciotti et al. (2005) to calculate melt rates to constrain the timing of peak meltwater production (Text S3; Figures 3a, S9a–S11a). Melting peaked simultaneously across our study area (Figure 2), occurring around 13:30±1.4 hours local time (henceforth all times are reported in local time (UTC-02:00). The timing and magnitude of peak melting was most strongly correlated with incoming solar radiation (Text S3). A comparison between calculated melt rate and ice surface ablation recorded at Low Camp (Text S3; 13 July–19 August 2017) shows good agreement with peak ablation occurring 13:30±

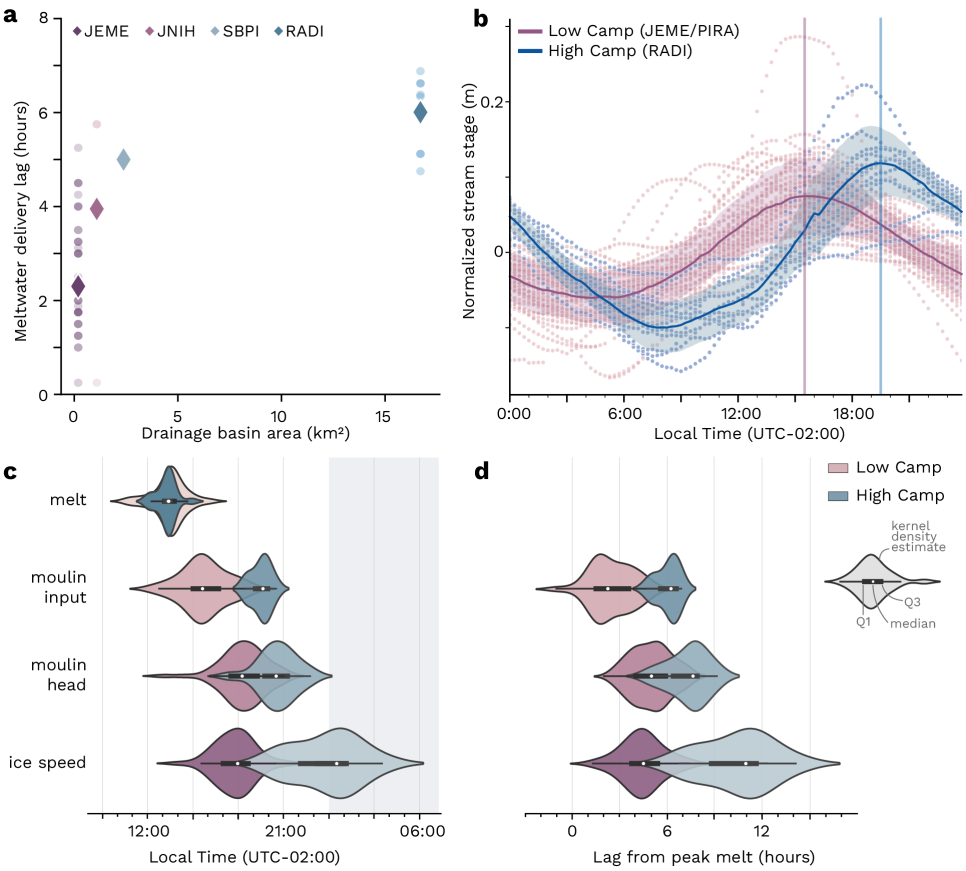

Figure 2. (a) Peak melting to meltwater delivery lag with respect to catchment area. Diamonds mark mean values with dots representing individual observations. (b) Normalized daily supraglacial stream stage for our catchments at Low Camp (purple) and High Camp (blue) primary catchments. The mean timing of diurnal peaks are marked with vertical lines. (c) Box plots overlaid by height-normalized kernel density estimates showing the timing of peak melting, meltwater delivery to moulins, moulin head, and ice speed for Low Camp (purple) and High Camp (Blue) during the 2017 melt season. (d) same as in c but shown as lag from peak melting.

3.5 hours (Figures S7–S8). Over the same time period air temperature peaked two hours later, around 15:30±3.3 hours (Figure S7). Moreover, peak melting occurred consistently around 13:30 at both Low Camp and High Camp over the 2017 and 2018 melt seasons. Due to the similarity in observations between weather stations, we use a single timeseries of peak melting to quantify lags across all variables.

3.2 Meltwater delivery to moulins

Of the physical characteristics considered, catchment area exerted the strongest control on the timing of peak meltwater delivery to moulins. At Low Camp's main catchment JEME (0.2 km^2), meltwater delivery peaked around 15:30 (Figure 2b–c), lagging peak melt by 2.4 ± 1.6 hours over the period of 2 July–9 August 2017 (Figure 2d; Table S3). At High Camp's much larger RADI catchment (16.8 km^2), meltwater delivery peaked around 19:45, lagging peak melt by 6.5 ± 1.8 hours (Figure 2 and S11) over the period of 5–16 August 2017. The longer residence time of meltwater within the supraglacial drainage system at the larger, higher-elevation RADI catchment ultimately caused moulin input to peak four hours later in the day at RADI when compared to the smaller and lower-elevation JEME catchment (Figure 2b–c). Importantly, all of the underlying data used to generate the aforementioned timing of peak meltwater delivery for JEME and RADI catchments were collected during bare-ice conditions (see Figures S1 and S2 for photos of surface conditions). Bare-ice conditions therefore eliminate the influence of the seasonal snowpack on the timing of peak meltwater to moulins reported here.

Observations from our two auxiliary catchments confirm the pattern of longer lags between peak melting and peak meltwater delivery to moulins with increased catchment area (Figure 2a; Table S1). At Low Camp's JNIH (1.1 km^2; 13–20 July 2017) peak meltwater delivery lagged peak melting by 4.2 ± 1.8 hours, and by 5.0 ± 1.3 hours at High Camp's SBPI (2.4 km^2; August 2018). Altogether, observations from four catchments indicate there are increasing delays in the timing of meltwater delivery to larger, higher-elevation catchments (Figure 2a) within this sector of the western GrIS.

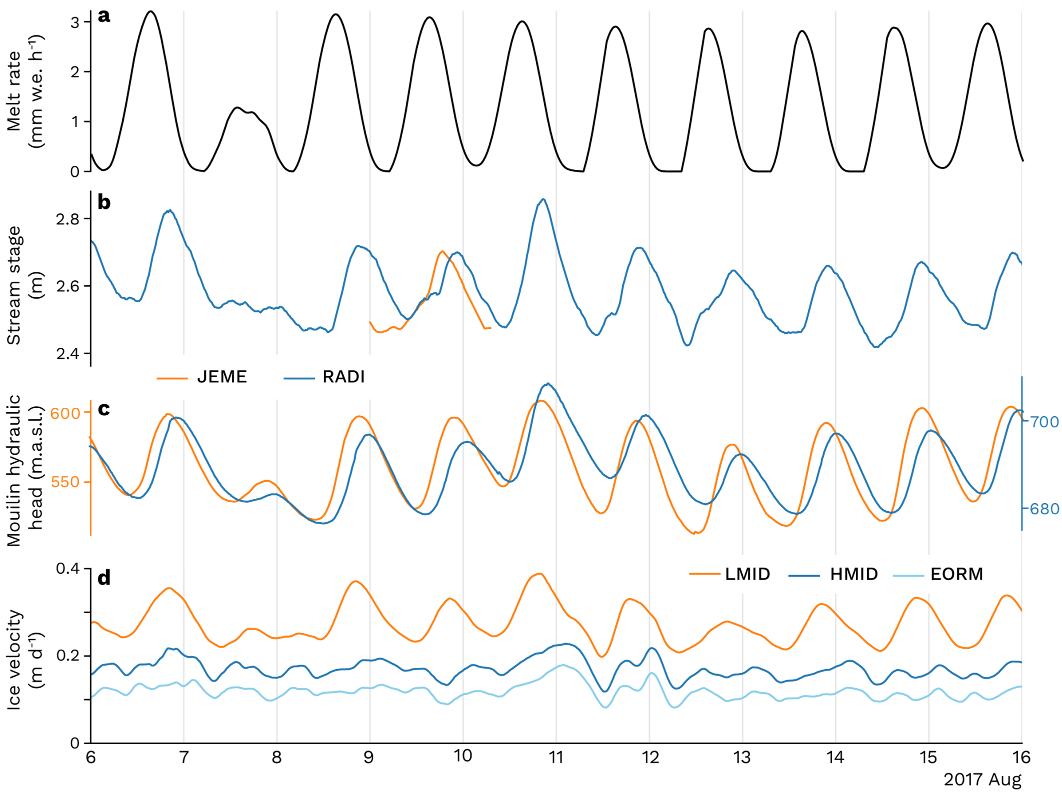

Figure 3. Comparison between Low Camp measurements (orange) and High Camp measurements (blue). (a) Meltwater production (b) supraglacial stream stage about an arbitrary datum. (c) Moulin hydraulic head from JEME moulin (left axis, orange) and RADI moulin (right axis, blue). The two axes are shown to highlight the phase-shift between the two timeseries (see Figure S12 for a single axes). (d) Along-flow ice velocity. Extended timeseries are shown in Figures S9 and S11.

3.3 Moulin hydraulic head and sliding

Coincident timeseries of moulin head from August 2017 (Figures 3, S9c–S11c) constrain the timing of peak pressures within the subglacial drainage system for Low Camp and High Camp moulins. The lag between peak meltwater delivery to moulins and peak moulin head was similar, approximately two hours, at both sites (Figures 2c–d and S15). However, the longer delay in meltwater delivery caused High Camp's RADI moulin's water level to peak 1–3.25 hours later in the day than at the lower-elevation JEME moulin (Figure S15). This delay resulted in a clear phase shift between the moulin head timeseries from JEME and RADI moulins (Figure 3c).

We find a strong agreement between the timing of peak moulin head and peak sliding speed at Low Camp that is not observed at High Camp. For example, peak sliding speed at Low Camp coincided with peak moulin head but lagged peak melting by 4.6 ± 1.7 hours (Figure 2d). This pattern was observed during 2017 and 2018 with peak sliding lagging peak moulin head by -0.4 ± 1.5 hours ($n = 21$) for JEME and -0.3 ± 2.3 hours ($n = 28$) for PIRA (i.e., sliding precedes head). In contrast, at High Camp peak sliding lagged (i.e. followed) peak moulin head by 2.8 ± 2.0 and 3.0 ± 1.2 hours for GNSS stations EORM and HMID respectively. Ultimately sliding peaked 2.2–7.6 hours later at High Camp than at Low Camp throughout the 2017 melt season (Figure 3d).

3.4 Glacio-hydraulic tremor amplitude

To investigate how transient surface conditions (i.e., seasonal snowpack removal and supraglacial drainage network evolution) within Low Camp's JEME catchment influence the timing of meltwater delivery to moulins, we utilize observations of glacio-hydraulic tremor amplitude to supplement stream stage observations which only cover 11 July and 20 August 2018 during bare-ice conditions (Figure 4 and S10). Our tremor amplitude timeseries spanned the entire duration of the melt season, from 5 June through the end of August 2018 ($n = 62$ for diurnal extrema picks). Peak meltwater delivery to PIRA moulin coincided with peak tremor amplitude (Figure S13; Text S4 and S7), which occurs when subglacial pressure gradients within moulin-connected subglacial channels are increasing most rapidly (Gimbert et al., 2016). From the monthly breakdown of diurnal extrema peaks shown in Figure 4, tremor amplitude peaked earlier in the day as the melt season progressed, lagging peak melting by 6.1 ± 2.2, 3.5 ± 2.5, and 1.4 ± 2.5 hours in June, July, and August respectively. Stream stage observations agree, with the lag between peak melting and peak meltwater delivery decreasing by 54 minutes between July and August 2018.

4 Discussion

4.1 Controls on the timing of peak moulin head

By constraining the timing of peak meltwater delivery to moulins within five GrIS catchments, we show that differences in the physical characteristics of catchments—area, snowpack extent, and supraglacial drainage efficiency—induce non-trivial heterogeneity in the timing of meltwater delivery to moulins. Lags between peak melting and peak meltwater delivery to moulins increased with catchment area (Figure 2a), resulting in longer delays in the timing of meltwater delivery to larger, higher-elevation catchments. This is expected because meltwater must be transported greater distances over the ice surface before reaching the catchment's terminal moulin (Sherman, 1932). Previous works have shown a positive relationship between catchment area and delays in meltwater delivery through applying traditional hydrological theory to supraglacial catchment throughout the GrIS ablation area (King, 2018; Smith et al., 2017; Yang & Smith, 2016; Yang et al., 2018). In considering 799 catchments in SW Greenland, Smith et al. (2017) showed that catchments with areas 0.4–244.9 km^2 could produce lags between peak melting and meltwater delivery to moulins of 0.4–9.5 hours. Our observations show that even a more limited range of catchment sizes (0.2–16.8 km^2) can induce differences of over four hours in the timing of meltwater delivery to moulins, thereby inducing a similar offset in timing of peak moulin head across the ablation area.

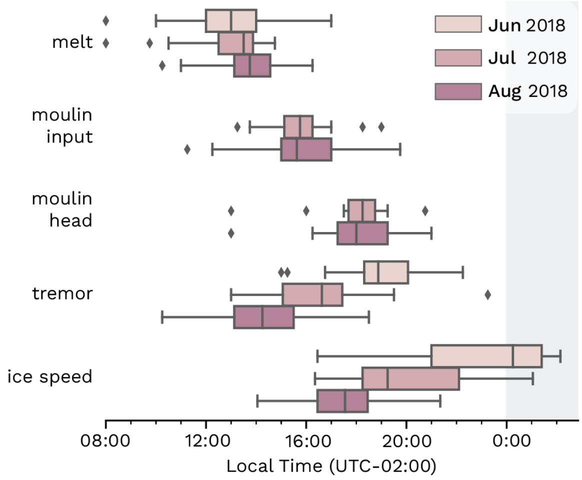

Figure 4. Seasonal shifts in meltwater propagation timing. Box and whisker plots show the monthly distribution of daily peaks in melting, meltwater input to PIRA moulin (stream stage), PIRA moulin head, tremor amplitude, and ice speed of Low Camp's JEME catchment during the 2018 melt season. Shading corresponding to the month of the underlying data for June (lightest), July (mid-tone), and August (darkest). Gray diamonds mark outliers, and the center line corresponds to median values. Shading as in Figure 2.

The timing of meltwater delivery to moulins within individual catchments evolves over the course of the melt season as the seasonal snowpack melts and then as efficient supraglacial stream networks form (Lampkin & Vanderberg, 2014; Willis et al., 2002; Yang et al., 2018). Early in the 2018 melt season (i.e., the first few weeks following the melt season's initiation on 6 June), snow cover was likely responsible for the increase in meltwater's residence time within the supraglacial drainage system as indicated by the difference in peak tremor amplitude and sliding velocity between June and July (Figure 4). This increased residence time would have delayed meltwater delivery to the Low Camp moulin PIRA during the first few weeks of the 2018 melt season as the snowline quickly retreated upglacier (Text S9). This approximately three hour increase is similar to previous work on Haut Glacier d'Arolla's La Vierge catchment (0.11 km^2) where Willis et al. (2002) showed the seasonal snowpack could increase the lag between peak melting and peak meltwater delivery by more than two hours. Despite being snow-free by July 2018, peak meltwater delivery to PIRA moulin decreased by 1–1.75 hours between July and August. This shorter residence time of meltwater within the supraglacial drainage system is likely attributed to increased supraglacial drainage density where small tributaries drain into well-developed streams and rivers which quickly transport meltwater to the catchment's terminal moulin (e.g., Yang & Smith, 2016).

By including direct measurements of moulin head within the primary catchments considered in this study, we identified a two hour lag between peak meltwater delivery and moulin head. The lag between peak meltwater delivery and moulin head was consistent throughout the melt season and between sites despite significant differences in the magnitude and timing of peak meltwater delivery to the moulins themselves (Figure 2c–d). This contrasts previous assumptions that peak meltwater delivery and moulin head would occurr simultaneously (e.g., McGrath et al., 2011). While our observations cannot be extrapolated to every moulin on the GrIS, they do demonstrate that there is a delay inherent to the coupled englacial-subglacial drainage system that controls the absolute timing of peak moulin head and therefore the timing of peak pressurization within moulin-connected parts of the subglacial drainage system.

4.2 Local relationships between effective pressure and ice motion

Lags between peak melting and peak sliding speed increased with distance from the ice sheet margin, echoing the pattern established by Hoffman et al. (2011). At Low Camp, peak moulin head and peak sliding speed were nearly coincident, indicating daily peaks in moulin head control the timing of peak subglacial water pressure and sliding. At High Camp, longer delays in meltwater delivery caused moulin head to peak 1–3.25 hours later than at Low Camp (Figure 3). However, this delay does not entirely account for the later timing of peak sliding, which lagged peak moulin head by up to 3.5 hours. Accordingly, the timing of peak moulin head was only partially responsible for the later timing of peak sliding. Instead the timing offset between peak pressure within the moulin-connected drainage system and peak sliding speed indicates there is a difference in the relationship between effective pressure (ice overburden pressure minus subglacial water pressure) and sliding at higher elevations that was not observed lower on the ice sheet.

The spatial distribution and density of moulins control the development of the subglacial drainage system by determining where meltwater is delivered to the bed and thus where subglacial conduits form (Banwell et al., 2016; Gulley et al., 2012). When moulin head is high, subglacial conduits become pressurized relative to the surrounding distributed drainage system, driving water out laterally away from the conduits and into neighboring linked-cavities (Bartholomaus et al., 2007; Hubbard et al., 1995; Rada & Schoof, 2018; Werder et al., 2013). As higher pressures migrate out into the distributed system, basal traction is reduced over a larger area of the bed, thereby promoting sliding. Because sliding is controlled by the areally integrated basal traction over three to eight ice thicknesses (Gudmundsson, 2003), peak sliding should occur when high pressures cover the largest area of the bed. At lower elevations on the ice sheet where moulin density is high (e.g., Low Camp's primary catchment with more than 10 moulins per km^2; Figure S4), closely spaced subglacial conduits work in tandem to quickly pressurize a large area of the bed. However, at higher elevations where moulin density is much lower (e.g., High Camp with 1–3 moulins per km^2; Figure S5), sliding will be more coupled to the pressure change emanating from an individual conduit as it migrates into the distributed system. Modeling work by Werder et al. (2013) showed that the diurnal pressurization of a single conduit can extend up to two kilometers into the distributed system, with the water pressure perturbation amplitude decreasing with distance away from the conduit, while also incurring a progressive phase lag of up to six hours. In this paradigm, the finite diffusion speed of the pressure change within the conduit at the base of RADI moulin could produce the two hour lag between peak moulin head and peak sliding observed at our higher-elevation site.

4.3 Implications

Our results reinforce previous observations of spatially inhomogeneous patterns of GrIS ice motion driven by areas with direct hydraulic connections to the bed, while highlighting the added complexity induced by the differences in timing of peak moulin head throughout the ablation area. Longitudinal flow coupling acts over a range of length-scales, explaining acceleration in areas of the GrIS without direct hydraulic connections to the bed (Price et al., 2008; Ryser et al., 2014). Areas without direct hydraulic connections (i.e., without moulins), respond passively to ice motion induced by pressure fluctuations within moulin-connected parts of the subglacial drainage system (Ryser et al., 2014). At our lower elevation site, moulin head and sliding speeds peaked consistently earlier than at higher elevations. Accordingly, when peak pressurization (or "slipperiness") was reached at lower elevations, upglacier areas were still resisting flow, and vice versa. This observed offset in the timing of peak pressurization may then produce different patterns of ice deformation, stress transfer, and basal motion, than would be expected if all areas with moulins experienced peak pressurization coincidentally.

Alpine glaciers have been frequently used as analogues to the GrIS, yet their usefulness remains a point of debate. Fundamental relationships between hydrology and ice motion identified within alpine environments diverge with distance inland as the ice thickens, surface slopes flatten, and moulin density decreases. Our results demonstrate the correlation between moulin head and peak sliding initially identified on alpine glaciers (Iken, 1972) seems to hold in areas with high moulin density (e.g., Low Camp). This relationship likely remains intact in this area because closely-spaced moulins are able to feed water simultaneously to the entirety of the ice sheet bed (Andrews et al., 2014). However, at higher elevations where moulin density is low (e.g., High Camp), the same correlation between moulin head and peak sliding is not observed. Accordingly, the straightforward coupling between effective pressure and ice motion derived from studies on alpine glaciers breaks down for inland reaches of the GrIS ablation area. Resolving the distinct processes governing hydrodynamic coupling within these areas will be more important as the GrIS ablation area continues to expand further inland as the climate warms (Noël et al., 2019).

5 Conclusions

Our observations suggest the supraglacial drainage system controls hydrodynamic coupling by two mechanisms: by creating delays in meltwater routing that propagate through the englacial and subglacial drainage systems and by controlling the spatial distribution of moulins which affects relationships between effective pressure and sliding. Because moulin density and catchment area are inherently linked, these processes work together to produce the progressively later timing daily peak sliding speeds with increasing distance from the ice sheet's margin. Given the role of the supraglacial drainage system in controlling the timing of peak subglacial pressurization, we would expect the well-documented heterogeneity of supraglacial catchments (King, 2018; Smith et al., 2017; Yang & Smith, 2016) to produce widespread variability in the timing of peak pressurization experienced within different regions of the subglacial drainage system. How these complex patterns of subglacial pressurization influence ice flow need to be considered in order to determine how the GrIS will respond to increased melting under future climatic warming.

Acknowledgments

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Data Availability Statement

The data sets and code used in this study are openly available. Meteorological and hydrological data sets are archived with the National Science Foundation's Arctic Data Center through the MoVE project's portal: `http://arcticdata.io/catalog/portals/moulin` (Mejia, Trunz, Covington, & Gulley, 2020; Mejia, Trunz, Covington, Gulley, & Breithaupt, 2020; Mejia et al., 2021). GC-Net weather station data from JAR1 is available from (Steffen et al., 1996) and is also archived with (Mejia et al., 2021) for convenience. Data from our on-ice GNSS stations and the base stations used during processing are archived through UNAVCO's GAGE Facility (Fahnestock et al., 2006; Mejia, Gulley, & Dixon, 2020). The Python module created to pick diurnal extrema is archived with Zenodo (see Mejia, 2022).

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