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Key Points:
- Winter liquid water drainage is discovered in a frozen proglacial river draining Greenland's Isunguata Sermia outlet glacier
- No winter drainage is found in proglacial rivers draining neighboring Russell, Leverett, Ørkendalen, and Isorlersuup outlet glaciers
- Seasonal and/or interannual meltwater retention and a deep, spatially pervasive subglacial trough may enable winter export from Isunguata Sermia

Supporting Information:
- Supporting Information S1

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Direct Observation of Winter Meltwater Drainage From the Greenland Ice Sheet

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Abstract Meltwater runoff from the Greenland Ice Sheet (GrIS) significantly contributes to sea level rise and is the dominant driver of enhanced mass loss. While most melt occurs during summer, little is known about its seasonal and/or interannual retention within the GrIS. Here, we document evidence of runoff during winter, ~4 months after summer melt. Ground-penetrating radar and borehole surveys in the proglacial Isortoq River reveal slowly flowing water beneath >0.5 m of river ice. Geochemical analysis of this water indicates previous contact with the ice sheet bed. Comparable surveys in proglacial rivers draining four neighboring catchments found no winter drainage, despite a brief surface melt event ~10 days prior. We attribute the observed runoff to residual meltwater storage and release enabled by a >600 m deep trough beneath Isunguata Sermia, but not neighboring glaciers. We conclude that the GrIS bed can stay wet and drain small amounts of meltwater year-round.

Plain Language Summary Meltwater runoff from the Greenland Ice Sheet substantially contributes to global sea level rise. Summer melting of the ice sheet surface produces most of this runoff, which flows over and into the ice sheet before emerging at its edge. Current climate and ice sheet models assume rapid evacuation of this meltwater to the ocean with a shutdown of ice sheet drainage in winter. Using ground-penetrating radar and borehole measurements through seasonal ice cover in rivers draining the ice sheet, we find modest winter meltwater export in the Isortoq River, which drains a large area of the southwestern Greenland Ice Sheet. This signifies active subglacial hydrological processes year-round.

1. Introduction

The Greenland Ice Sheet (GrIS) is losing mass at an accelerating rate (Nerem et al., 2018; Rignot et al., 2011; Shepherd et al., 2012), primarily due to increases in surface meltwater runoff (van den Broeke et al., 2009, 2016). This is important, because GrIS runoff significantly contributes to global sea level rise (van den Broeke et al., 2016) and thus the vulnerability of coastal population centers (e.g., Hauer et al., 2016). Despite recent increases in surface melt and runoff, process-level understanding of GrIS hydrology remains deficient, especially outside of the summer melt season. In particular, the temporal and volumetric partitioning between supraglacial meltwater production, englacial/subglacial retention, and ocean-going runoff remains poorly understood (e.g., Chu, 2014; Rennermalm, Moustafa, et al., 2013).

Virtually all runoff from the ablation zone of the GrIS occurs during the summer melt season. Such estimates are derived from regional climate models (RCMs), which assume that meltwater at the ice surface runs off to the ocean without impoundment or delay (Smith et al., 2017). However, volumetric mismatches between RCM runoff and field-measured proglacial meltwater outflow suggest that meltwater can be retained within the ice sheet and that the hydrologic routing of meltwater from the ice surface, through the ice sheet, and to the ocean is complex and poorly constrained (Rennermalm, Smith, et al., 2013; Smith et al., 2015).

RCM simulations from Modèle Atmosphérique Régional (MAR) (Fettweis et al., 2017) version 3.8 (data acquired from: ftp://ftp.climato.be/fettweis/) find that approximately one third of total GrIS runoff derives from southwestern Greenland (see supporting information Text S1 and Figure S1; GrIS drainage regions from ice sheet mass balance intercomparison exercise (IMBIE) 2016, link: http://imbie.org/imbie-2016/drainage-basins/), where supraglacial meltwater is routed into moulins (Smith et al., 2015; Yang & Smith, 2016) and a seasonally evolving subglacial hydrologic network (e.g., Andrews et al., 2014). The volume of surface meltwater penetration to the ice sheet bed modulates subglacial water pressures, drainage efficiency, and ice dynamics on seasonal time scales (e.g., Catania & Neumann, 2010; Colgan et al., 2011; Cowton et al., 2013; Joughin et al., 2008; Tedesco et al., 2013). An unknown fraction of this meltwater is seasonally retained (e.g., Chu et al., 2016; Lindbäck et al., 2015; Overeem et al., 2015), while the rest is subglacially exported into proglacial rivers and the ocean (e.g., Ahlstrøm et al., 2017; van As et al., 2017, 2018). Despite GrIS surface melt being predominantly a summer phenomenon, winter temperatures around Greenland are increasing faster than the annual average (see supporting information Text S7, Figure S5, and Tables S6–S7; outlet glacier temperature data from MAR (Fettweis et al., 2017) version 3.8), and pan-Arctic winter melt events are increasingly common (Graham et al., 2017; Moore, 2016). In Greenland, anomalously high winter temperatures made international headlines in 2018 (Samenow, 2018), while winter surface melt has been detected using both satellite data and climate models (Oltmanns et al., 2019).

Subglacial meltwater flows from areas of high to low pressure (Cuffey & Paterson, 2010; Shreve, 1972), in cavities, in channels, in thin films, and/or as groundwater in sediment/bedrock (Ravier & Buoncristiani, 2017). Channelized flow requires sufficient meltwater supply to the basal drainage system to maintain melt rates along conduit walls that exceed closure (Meierbachtol et al., 2013). During winter, surface runoff input to the bed ceases and conduits close via deformation and creep (Schoof, 2010). In theory, a cessation of meltwater runoff and closure of conduits during the following weeks should preclude ocean-going meltwater export. However, evidence of supraglacial, englacial, and subglacial meltwater storage at seasonal and interannual time scales raises questions about the validity of this assumption (Chu et al., 2016; Forster et al., 2014; Kendrick et al., 2018; Koenig et al., 2015; Rennermalm, Smith, et al., 2013). To our knowledge, it is currently unknown whether residual GrIS meltwater drainage into proglacial rivers occurs during winter.

To test the assumption of a shutdown of subglacial hydrologic processes during winter, we deployed to southwest Greenland in February 2015 to investigate four proglacial rivers draining the Greenland Ice Sheet through five outlet glaciers, namely, (1) Isunguata Sermia, (2) Russell, (3) Leverett, (4) Ørkendalen, and (5) Isorlersuup (Figure 1). These five adjoining glaciers develop complex summer supraglacial stream networks that drain meltwater via moulins to the bed and ultimately the proglacial Isortoq, Sandflugtdalen, Ørkendalen, and Watson Rivers (Figure 1a). Flowing liquid water was discovered beneath the seasonal ice cover in the Isortoq River, but not the other rivers surveyed in situ. Here, we document the discovery of this modest winter (December, January, and February or DJF) proglacial outflow, including its estimated flux, spatial distribution, and geochemistry, and discuss plausible explanations for its presence as well as broader scientific implications.

2. Discovery of GrIS Winter Water Export

2.1. Mapping and Measuring Winter Flux

On 12 February 2015, we discovered slowly flowing water beneath proglacial Isortoq River ice ~1 km downstream from the Isunguata Sermia glacier terminus (Figure 2d). A transect was established orthogonal to the channel flow direction, and a sled-mounted 400 MHz ground-penetrating radar (GPR) was dragged across the frozen river surface (Figure 2a). Resultant GPR profiles reveal four significant bright reflectors (Figure S4) indicative of meltwater-filled conduits. Three bright reflectors were located at stations 84–92 m along the transect, and one was located at stations 126–128 m along the transect (Figure 2c; GPR data available from Pitcher et al., 2020).

To aid interpretation of GPR data, 11 boreholes were mechanically drilled through the river ice using a 5 cm diameter Kovacs ice auger (Figures 2d and 2e). Meltwater was discovered beneath approximately 53 cm of river ice in one borehole (location: 67.1914°N, −50.3699°W), that coincided with a bright reflector (88–90 m along orthogonal transect, Figure 2c; borehole data available from Pitcher et al., 2020). A gas-powered Jiffy Model 30 Ice Drill was then used to excavate a larger (~25 cm diameter) borehole

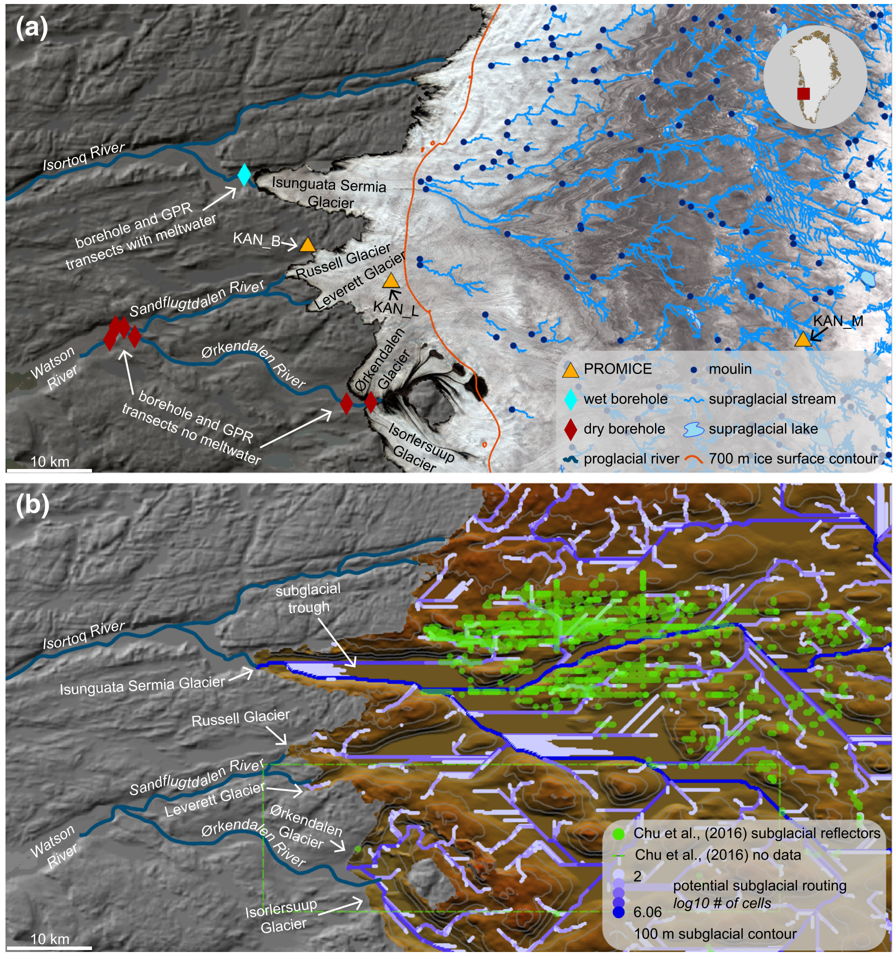

Figure 1. Field surveys (diamonds) were conducted in four frozen proglacial rivers during February 2015. Each river drains subglacial meltwater from the Greenland Ice Sheet to the ocean. (a) During the summer melt season, a supraglacial hydrologic network develops on the ice surface ablation zone and delivers meltwater via moulins (navy dots) to englacial/subglacial conduits (mapped by Yang et al. (2018). Cyan-colored diamond indicates where water was discovered in the proglacial Isortoq River on 12 February 2015. Red diamonds indicate in situ location where no meltwater was found. (b) The basal topography beneath the ice sheet (Morlighem et al., 2017), with green dots showing locations of subglacial meltwater storage as mapped using IceBridge Multichannel Coherent Radar Depth Sounder data and green dashed line denoting the no-data area (Chu et al., 2016). Proglacial land surface topography, shown as shaded relied, is from the 100 m resolution ArcticDEM Mosaic (Porter et al., 2018).

(Figure 2b), and the under-ice water velocity was approximated using a USGS Type AAMH Ice Current Meter (see note in Table S1 about low flow instrument limits). The slowly moving flow produced at least one rotation per 2 min, enabling rough estimation of a flow velocity of at least 1 to 3 cm s^{-1} (see Table S1). The GPR data were then used to estimate the height and width of these conduits (see Text S2). The individual under-ice conduit cross-sectional areas of the four conduits were 684–1,533, 969–1,720, 6,468–8,995, and 7,260–7,689 cm^2, with a cumulative cross-sectional area in the range of 1.54 to 1.99 m^2 (see Text S2, Figure S4, and Table S2). Given these areas, and assuming a constant flow velocity in all conduits, we estimate an approximate instantaneous water flux of 20 to 60 l s^{-1} (see Table S3).

To confirm the presence of an elongated water-filled conduit, we collected nine 25 m long GPR transects at distances of approximately 6, 14, 20, and 26 m upstream and 18, 28, 41, 64, and 101 m downstream from the wet borehole (Figure 2e; see Text S2 for discussion of geolocation uncertainty). These GPR surveys also reveal bright reflectors (teal diamonds, Figure 2e) indicative of meltwater-filled under-ice conduits persisting at least 90 m downstream (Figures 2d and 2e). To our knowledge, this is the first documentation of winter flow of a Greenlandic proglacial river.

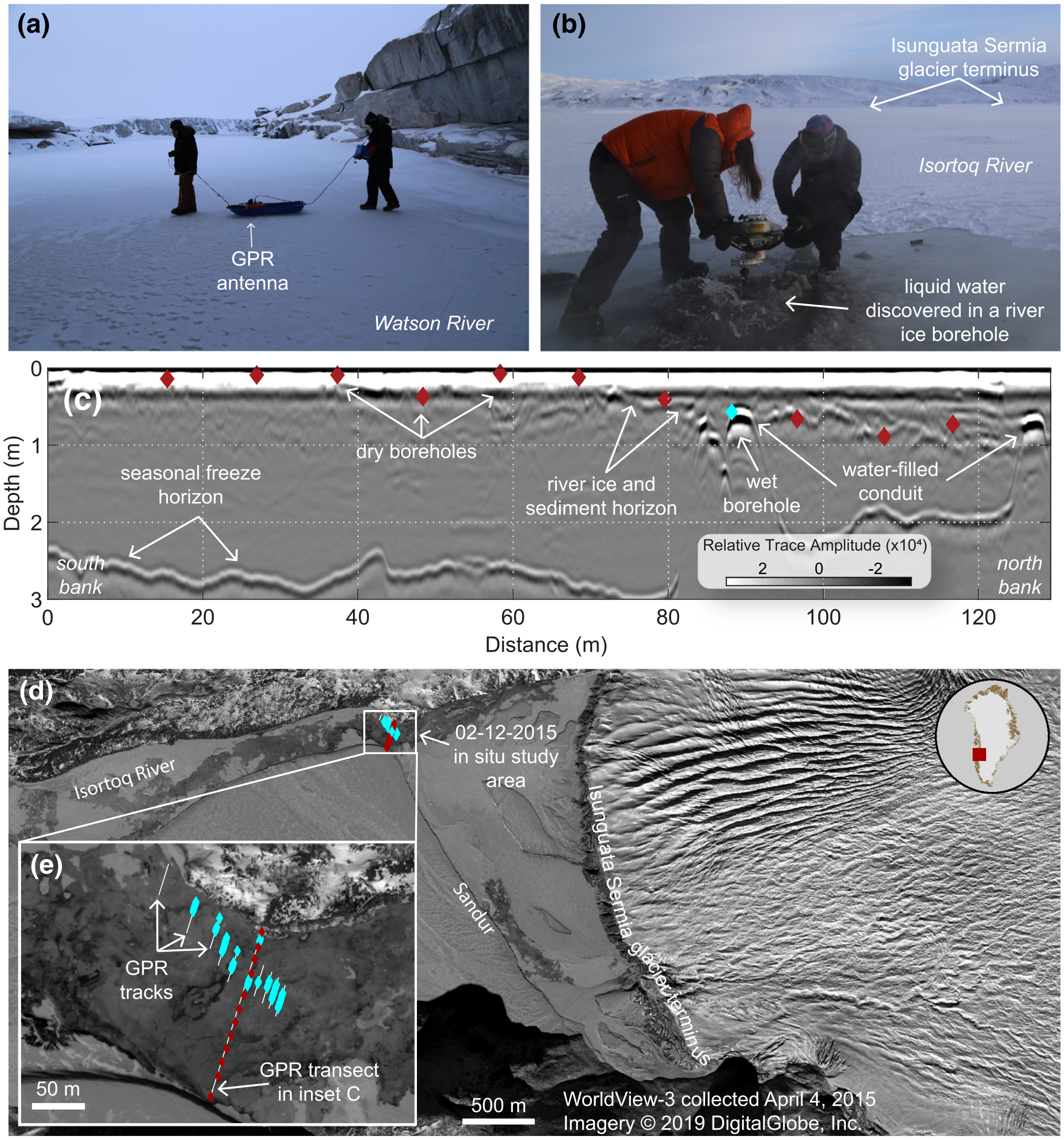

Figure 2. Ground-penetrating radar (GPR) transect (a) and boreholes across the Watson River near Kangerlussuaq indicate this proglacial river to be frozen to the bed. (b) On 12 February 2015 slowly flowing liquid water was discovered beneath the seasonal ice cover of the proglacial Isortoq River draining the Isunguata Sermia outlet glacier. (c) Long GPR transect across the frozen proglacial Isortoq River identifies four bright reflectors interpreted as water-filled conduits, one 126–128 m and the other three 84–92 m from the south bank. The latter was validated via an in situ borehole (cyan diamond, b) and its longitudinal continuity confirmed through short GPR transects upstream and downstream of the water-filled borehole (d, e). Red diamonds indicate river ice thickness measured in situ as the distance from the river ice surface to dry proglacial channel bed in the boreholes. Other cyan diamonds (d, e) signify liquid water, as interpreted from bright radar reflectors in GPR transects.

Borehole and GPR transect surveys were similarly conducted at five other locations during February 2015 (Figure 1a), namely, (1) beneath the Watson River bridge in Kangerlussuaq, (2) along a single-channel reach of the Watson River, (3) along the Sandflugtdalen tributary ~350 m upstream of its confluence into the Watson River, (4) along the Ørkendalen tributary ~1.9 km upstream of its confluence with the Watson River, and (5) near the Ørkendalen and Isorlersuup outlet glacier termini. These surveys, all within the Watson River proglacial watershed (Figure 1), revealed no liquid water. This suggests subglacial drainage of seasonally retained meltwater beneath Isunguata Sermia, but not its neighboring outlet glaciers to the south, at least at the time of the field visit.

2.2. Isortoq River Water Geochemistry

Isortoq River winter water samples were collected by lowering a 1 L polyethylene bottle on a line into the Isortoq River borehole. The water was supercooled, with a temperature of −2 °C. Bulk water samples were split into 8 × 125 ml unfiltered samples, and 4 × 30 ml filtered samples using a 0.45 μm syringe filter. Prior to filling, the collector and sample bottles were rinsed with river water. Samples of snow atop the river ice were collected at four locations surrounding the borehole, which were later melted and transferred into 16 × 30 ml sample bottles. All samples were refrigerated including during transport from Greenland to the United States for laboratory analysis. Opportunistic grab samples of Isortoq River water and Watson River water were also collected during previous summer melt seasons, when both rivers were ice- and snow-free (Figure S2 and Table S4).

Geochemical analysis of these winter Isortoq River water samples reveals high total dissolved solute (TDS) concentration and deviation from local snow samples. TDS concentrations and deviation from meteoric composition indicates that the Isortoq River water had been in contact with sediments or rocks and solutes derived partly from dissolution of minerals, signifying contact with glacial bedrock/sediment. Two of four snow samples had higher TDS concentrations than river water (Figure S2), which might be impacted by recrystallization and refreezing of older river water yet cannot be traced to a specific source or process with available data (Text S6). Stable isotope composition of δD and δO-18 (Figure S2), indicate high isotopic ratios for snow compared to river water, suggesting that the Isortoq River water samples were not sourced from local snow melt on the frozen river. Collectively, this geochemical evidence suggests that the under-ice proglacial river water has a unique chemical signature different from both winter snow samples and summer melt season proglacial Isortoq River water and has also been in contact with glacial bedrock/sediment (see Table S4 for geochemistry laboratory results).

3. Mechanisms Enabling GrIS Winter Meltwater Drainage

We hypothesize that the discovery of residual winter drainage in the Isortoq River is enabled by a >600 m deep subglacial trough which extends >20 km inland from the terminus of Isunguata Sermia (Figure 1b) (Jezek et al., 2013). Comparison of the subglacial topography beneath Isunguata Sermia, with that of Russell, Leverett, Ørkendalen, and Isorlersuup glaciers confirms that comparable troughs are not present beneath these neighboring glaciers (Figure 1b). Isunguata Sermia's subglacial trough and its potential subglacial drainage network (Figure 1b and Text S5) also intersect with IceBridge airborne radar (May 2010 and April 2011) mappings of bright subglacial reflectors, interpreted as likely locations of subglacial water storage (Chu et al., 2016), plotted as green dots in Figure 1b (also, see Figure S3 for summary of reflectors by ice surface elevation and thickness). There are uncertainties in both the subglacial topography data (Morlighem et al., 2017) and the parameters used for potential subglacial drainage network delineation (see Text S5, Figure S6 and Figure S7). Therefore, we present potential subglacial hydrologic networks as supplementary evidence to the deep, spatially pervasive, subglacial trough beneath Isunguata Sermia.

Discovery of residual winter drainage from Isunguata Sermia is also consistent with the possibility of seasonal and/or interannual retention of summer meltwater runoff and with previously suggested mismatches between observed and modeled proglacial outflow (Lindbäck et al., 2015; Rennermalm, Smith, et al., 2013; Smith et al., 2015). A similar mismatch is not present for the Watson River (which integrates all meltwater outflow from the Russell, Leverett, Ørkendalen, and Isorlersuup glaciers) (Lindbäck et al., 2015). Lag times between summer GrIS surface melt and proglacial runoff in the Watson River range from <24 hr to ~10 days, with no evidence for significant (winter) storage or retention (van As et al., 2017). While there are uncertainties in the data and parameters used to generate hydrologic catchment for individual glaciers (e.g., Ahlstrøm et al., 2005; Lindbäck et al., 2015; Pitcher et al., 2016) (Text S5 and Figures S6 and S7), this does suggest that previously reported mismatches between simulated runoff and observed outflow in the region may be unique to Isunguata Sermia.

Our finding of residual drainage from Isunguata Sermia is also consistent with regional contrasts in ice velocity. Subglacial hydrologic connectivity partially modulates ice velocity, with high connectivity associated with high basal traction and low flow speeds (Andrews et al., 2014). Unlike Isunguata Sermia, outlet glaciers draining into the Watson River watershed accelerate rapidly at the onset of the summer melt season

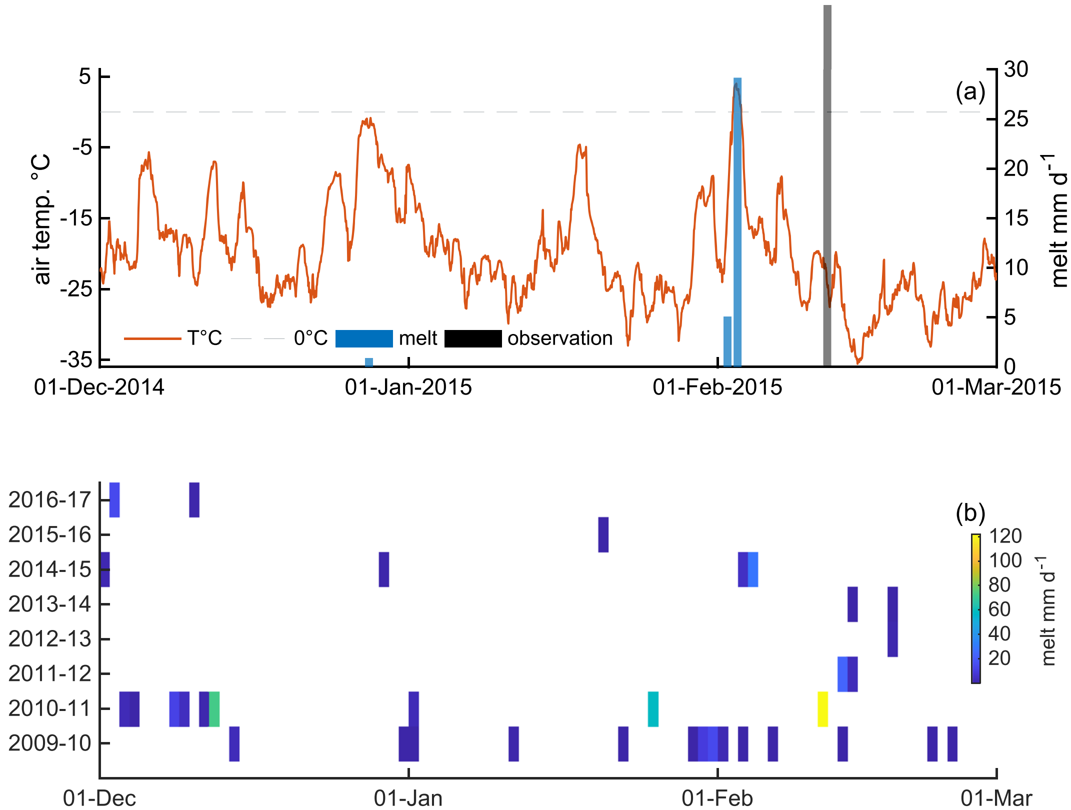

Figure 3. The glaciated region of our West Greenland study area experienced (a) above freezing temperatures (orange line) and surface melt (modeled, blue bars) on 2–3 February 2015, ~10 days prior to our field study (black bars). (b) Interrogation of a surface energy balance (SEB) melt model established for the K-Transect, representative of our study region of the Greenland Ice Sheet, finds that this February 2015 melt event was neither rare nor anomalously intense.

(Lindbäck et al., 2015). Similarly, our finding of a wet bed and residual winter drainage only from Isunguata Sermia suggests higher subglacial hydrologic connectivity, which should reduce associated velocity accelerations.

An alternate source of the residual outflow observed draining Isunguata Sermia could be the result of a brief winter surface melt event that occurred ~10 days prior to our borehole and GPR surveys (Figure 3). On February 2–3, 2015 a ~21 hr period of above-freezing conditions was recorded at the nearby KAN_L PROMICE meteorological station, with air temperatures briefly exceeding 4 °C (Figure 3a; data available at https://www.promice.dk/). An observation-fed surface energy balance (SEB) model (van As et al., 2017) simulates ~12 hr of surface melt with rates >29 mm day^{-1} at ice surface elevations up to 700 m during this period (Figure 3a). The occurrence of this melt event prior to our field study raises the possibility that surface melting might enable modest proglacial meltwater drainage during winter.

Surface melting along the K-Transect (Figure 4a) occurred on average 4.5 days per year (i.e., 36 melt days over eight winters) from 2009–2017 (Figure 3b). The intensity of the 2–3 February 2015 surface melt event preceding our field study was above average but not a statistical outlier (i.e., total melt $< \mu \pm \sigma$, see Table S5). When analyzing the PROMICE record for all stations on the GrIS, only 4 of 20 stations did not have DJF positive degree days (PDD) (Figure 4a). Similarly, surface temperature/emissivity observations from the MODIS satellite record reveals pixels with temperatures ≥ -1 °C, indicative of surface melt conditions (Hall et al., 2018), during all winters over the period 2000–2019 (Figures 4b and 4d and Text S3). The MEaSUREs passive microwave satellite record (Mote, 2014) further reveals that the occurrence of GrIS winter surface melt increased (p value < 0.05; $r^2 = 0.27$) between 1979 and 2012 (Figures 4c and 4d and see Text S4). Collectively, these data sets suggest that brief episodes of winter surface melt are relatively common, both within our study area and across the margins of the GrIS.

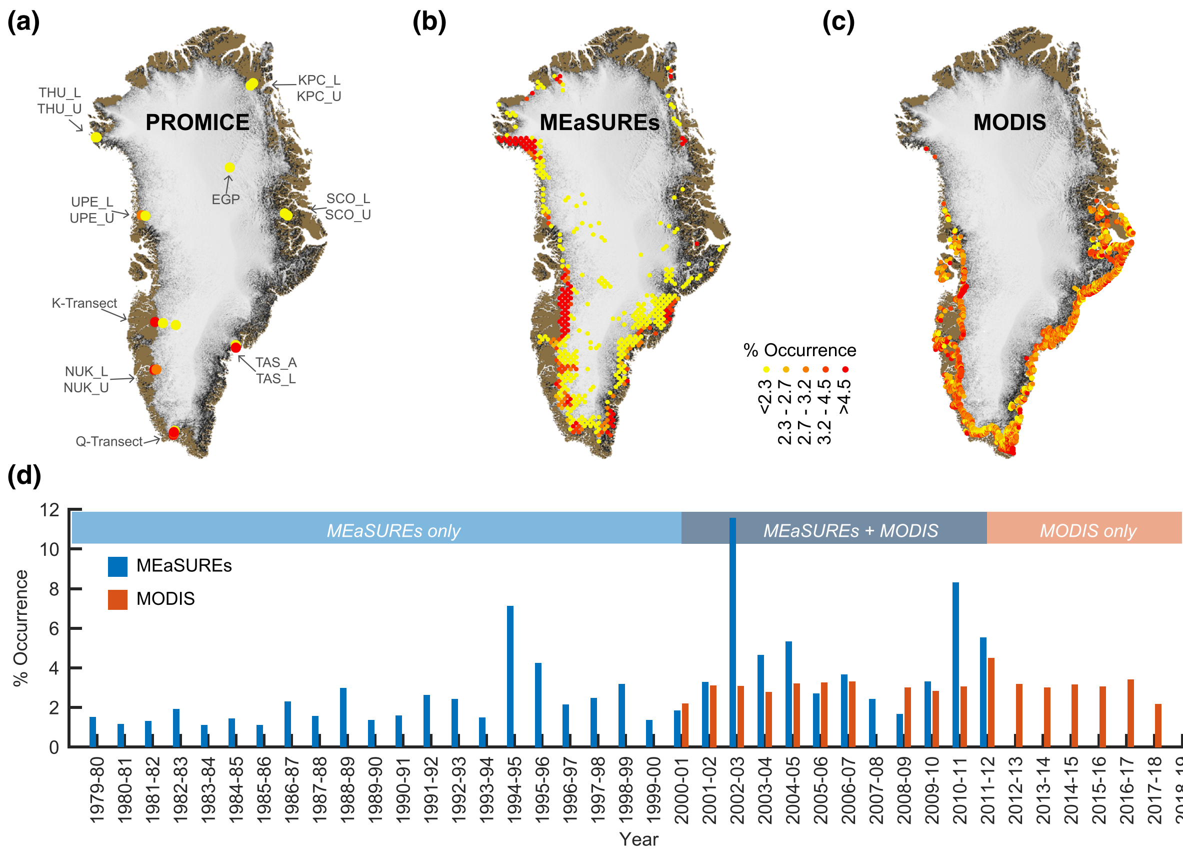

Figure 4. Winter surface melt on the Greenland Ice Sheet (GrIS) is relatively common, as determined from (a) PROMICE meteorological stations (2007–2018, record length is station dependent); (b) MEaSUREs brightness temperatures derived from microwave radiometer satellite data (1979–2012); and (c) MODIS Terra MOD11A1 land surface temperature/emissivity data (2000–2019). The (d) MODIS and MEaSUREs records indicate at least 1.1% occurrence (frequency of winter melt divided by the number of winter observations) of winter melt over their respective observation periods (orange tones in (a), (b), and (c)). (d) The percent occurrence of winter melt events also increased (p value < 0.05; r^2 = 0.27) across the 1979–2012 MEaSUREs record.

4. Implications of GrIS Winter Surface Melt, Retention, Refreezing and Drainage

Regardless of the causal mechanism, our finding of mineral-rich liquid water draining from Isunguata Sermia during winter confirms that this outlet glacier maintains a wet bed year-round. This finding, which is consistent with Chu et al. (2016) IceBridge airborne radar reflector mappings (Figure 1b), supports the idea of subglacial water retention in some parts of the ice sheet but not others and consequent alteration of the overlying GrIS thermal structure. As retained meltwater refreezes, it releases latent heat and warms surrounding ice, raising basal temperatures, reducing ice viscosity, and promoting basal sliding (Phillips et al., 2013; Pitcher & Smith, 2019). This process, termed cryohydrologic warming (Phillips et al., 2010), may influence the long-term stability of the GrIS (Colgan et al., 2015). Field observations identify temperate basal ice at least 45 km from the Isunguata Sermia terminus, which can be partially explained by heat from refreezing, particularly within basal crevasses, which softens ice and enhances deformation (Harrington et al., 2015). The temporal and spatial pervasiveness of winter subglacial water, refreezing, and associated cryohydrologic warming is an important yet poorly constrained forcing on ice deformation, flow, and long-term ice sheet stability.

It is also important to consider the implication of potential winter subglacial drainage from marine terminating glaciers. During the summer melt season, subglacial drainage from marine terminating glaciers fuels submarine melting (Fried et al., 2015), which is a key control on ice dynamics (Cowton et al., 2019). The other process enhancing mass loss in marine terminating glaciers is the circulation of warm ocean waters to glacier termini (Holland et al., 2008), which similarly intensifies submarine melting (Rignot et al., 2010). Simulations suggest that ocean-fjord circulation in Greenland can result in winter melting in at least some outlet glaciers (Fraser et al., 2018). However, during the summer melt season, oceanographic and subglacial hydrologic forcings in unison result in submarine melting at rates an order of magnitude larger than during winter (Sciascia et al., 2013). This implies that if significant subglacial hydrologic drainage were to also occur during winter, it could similarly impact ice dynamics. Collectively, this suggests that subglacial hydrology may be an important control on the stability of marine terminating glaciers, not just during the summer melt season but year-round.

Recognition of winter retention and runoff is also important for RCM simulations of the GrIS contribution to global sea level rise. Currently, RCMs make the assumption that surface runoff flows into the ocean without impoundment, retention, or long-term delay (Smith et al., 2017). Recent work finds that bare ice hydrological routing and retention processes (e.g., Cooper et al., 2018) result in incorrect RCM simulation of meltwater delivery to moulins during the melt season (Smith et al., 2017). At a seasonal time scale, this may be unimportant for systems like the Watson River, where simulated annual runoff from tributary outlet glaciers closely matches annual Watson River discharge (Lindbäck et al., 2015; van As et al., 2017). However, the mismatch between simulated runoff and proglacial discharge for Isunguata Sermia (Lindbäck et al., 2015; Rennermalm, Smith, et al., 2013; Smith et al., 2015) suggests that current assumptions of instantaneous runoff transfer can yield inaccurate simulation of sea level rise contributions from some glaciers. Our discovery of residual winter drainage supports the idea that seasonal retention is an important yet poorly constrained term in RCMs (e.g., Rennermalm, Smith, et al., 2013; Smith et al., 2015), suggesting that field-based validations of RCM runoff using measurements of proglacial river discharge should avoid glaciers (such as Isunguata Sermia) that seasonally retain meltwater and have complex subglacial hydrologic networks, deep troughs, and thawed beds.

5. Conclusion

Our winter field study of proglacial rivers draining the southwestern Greenland Ice Sheet confirms that a wet glacial bed and residual subglacial drainage can occur even in February, at least when located downstream of a large, well-integrated, deep subglacial trough. We conclude that some fast-flowing land-terminating areas of the GrIS bed can experience basal cryohydrological warming and drain residual meltwater during winter. This supports the overall notion of ice sheet retention and/or delayed release of summer meltwater for at least several months after cessation of melt. Further studies are needed to document whether winter surface melt events are sufficient to activate GrIS subglacial hydrological processes and associated ice velocity accelerations in winter, but Automated Weather Station and satellite observations do confirm the ubiquity of such surface melt events. This is consistent with an overall pan-Arctic trend of increasing melt events in winter (Graham et al., 2017; Moore, 2016), and highlights a growing need for Arctic hydrologic investigations to be conducted during the cold season as well as summer.

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