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Key Points:
- Bathymetry mapping extending to ice fronts essential in Greenland fjords
- Fjords are far deeper than expected and host warm, salty waters where deep enough
- Many glaciers are retreated in shallow waters in otherwise deep fjords

Supporting Information:
- Supporting Information S1

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Bathymetry data reveal glaciers vulnerable to ice-ocean interaction in Uummannaq and Vaigat glacial fjords, west Greenland

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Abstract Marine-terminating glaciers play a critical role in controlling Greenland's ice sheet mass balance. Their frontal margins interact vigorously with the ocean, but our understanding of this interaction is limited, in part, by a lack of bathymetry data. Here we present a multibeam echo sounding survey of 14 glacial fjords in the Uummannaq and Vaigat fjords, west Greenland, which extends from the continental shelf to the glacier fronts. The data reveal valleys with shallow sills, overdeepenings (>1300 m) from glacial erosion, and seafloor depths 100–1000 m deeper than in existing charts. Where fjords are deep enough, we detect the pervasive presence of warm, salty Atlantic Water (AW) (>2.5°C) with high melt potential, but we also find numerous glaciers grounded on shallow (<200 m) sills, standing in cold (<1°C) waters in otherwise deep fjords, i.e., with reduced melt potential. Bathymetric observations extending to the glacier fronts are critical to understand the glacier evolution.

1. Introduction

The mass balance of the Greenland ice sheet is controlled by the rate of ice discharge of its 240 marine-terminating glaciers into the ocean [*Rignot and Mouginot*, 2012] and its regime of surface mass balance. Surface runoff has more than doubled since the 1980s [*Ettema et al.*, 2009], and ice discharge into the ocean has increased considerably in some places, although not in others, to yield a complex spatial pattern of mass loss [*Moon et al.*, 2012]. Many posit that the glacier changes have been triggered by an increase in subaqueous melting of the glacier fronts due to increased temperatures of the relatively warm, salty, subsurface waters of tropical origin (hereafter Atlantic Water, AW) [*Holland et al.*, 2008; *Murray et al.*, 2010; *Straneo et al.*, 2010; *Rignot et al.*, 2010; *Christoffersen et al.*, 2011; *Motyka et al.*, 2011; *Rignot et al.*, 2012] and an increase of turbulent heat exchange at the ice-ocean interface fueled by greater surface melt and corresponding subglacial discharge [*Xu et al.*, 2013]. Around Greenland, the ocean waters comprise a shallow layer of cold (<1°C), fresh Polar Water (PW) in the upper 100 m and, if the fjords are sufficiently deep, a denser layer of AW (>2.5°C) below 250 m.

Our understanding of the role of bathymetry in controlling the access of AW into the fjords has been limited by a lack of bathymetry and temperature data [*Murray et al.*, 2010; *Schjoth et al.*, 2012; *Sutherland et al.*, 2013; *Straneo and Heimbach*, 2013]. Deeper fjords permit the intrusion of AW toward the glaciers. Conversely, shallow sills created by former glacier advances, fjord narrowing, or shoaling may limit the access of subsurface AW to the glacier faces and leave the glaciers exposed to PW [*Christoffersen et al.*, 2011; *Mortensen et al.*, 2011; *Chauche et al.*, 2014; *Gladish et al.*, 2015]. The most recent international compilation of Arctic bathymetry (International Bathymetry Chart of the Arctic Version 3 (IBCAO3)) [*Jakobsson et al.*, 2012] does not include inner fjord bathymetry because few data exist, especially near the glacier fronts where navigation is difficult and complicated by the presence of icebergs.

Here we present a nearly complete bathymetry survey of 14 glacial fjords, part of two large systems in central west Greenland, assembled from multibeam echo sounding data (MBES) collected by several research groups over the years 2007–2014 (Figure 1). The first system, Uummannaq Fjord (UF), one of the largest in

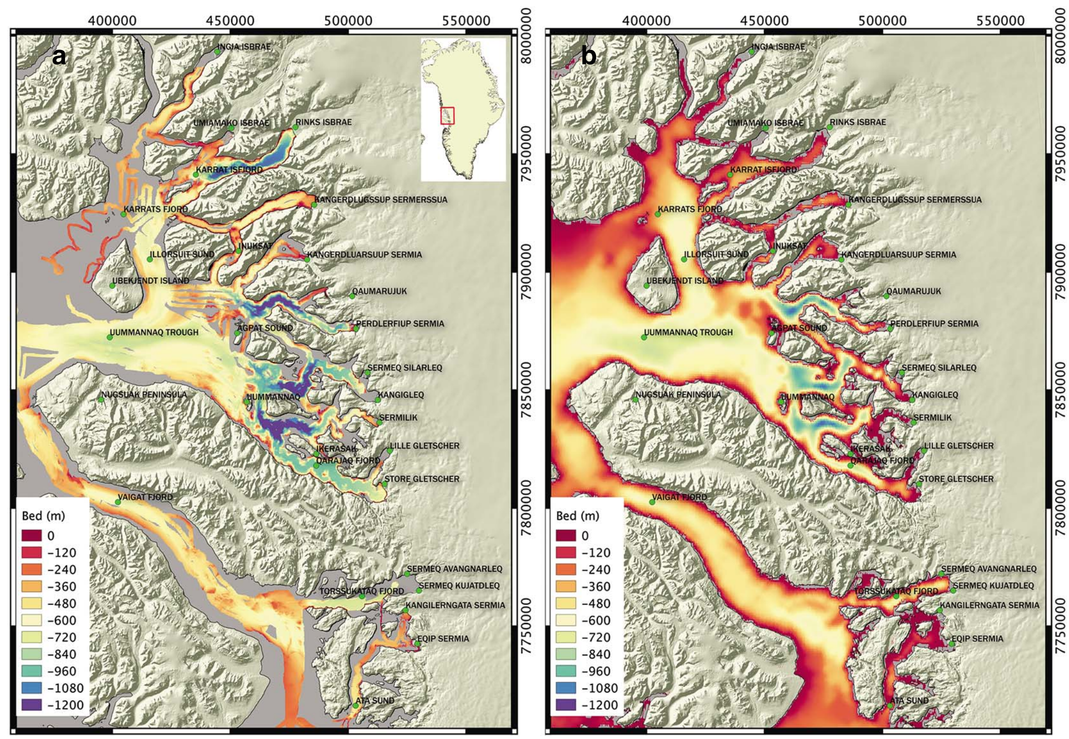

Figure 1. Bathymetry of Uummannaq and Vaigat fjords, west Greenland from (a) multibeam echo sounding data (MBES) acquired in 2007–2014 and (b) IBCAO3 [*Jakobsson et al.*, 2012] with bed elevation color coded from red (sea level) to blue (< −1200 m). Land ice mask (shaded) is from 2007. Glacier, fjord, and island names are black. Grey denotes no bathymetry data. Inset shows location in Greenland. UTM zone 22 unit in meters.

Greenland, hosts 10 outlet glaciers. The second, Vaigat Fjord (VF), which includes Ata Sund and Torssukatak Fjord, hosts another four major outlet glaciers. Seafloor mapping extends from the continental shelf to the base of the glacier faces, which is unprecedented at that scale. Temperature and salinity data were collected in all of the fjords to assess the presence and properties of AW. We compare our results with IBCAO3 to quantify the improvement in fjord mapping and discuss the results in terms of their impact on ice-ocean interaction and recent glacier variation. We conclude on the importance of these observations to improve our understanding of the evolution of marine-terminating glaciers in Greenland.

2. Data and Methods

In August 2012, 2013, and 2014, we deployed a Reson 8160 MBES system operating at 50 KHz with a typical range of 3000 m on board the *Esle* (2012) and *Cape Race* (2013–2014) vessels. The Reson 8160 was operated with a NAVCOM 3050 differential GPS unit with submeter position accuracy and an Applanix POSMV inertial navigation system, which provided real time vessel attitude and position. The data were acquired using the QINSy software and processed using the CARIS HIPS software. Calibration of sound speed in water was performed using conductivity temperature depth (CTD) data obtained at regular intervals during the cruise and by surveying a set of topographic features on the seafloor at multiple look angles. Bathymetry was binned on a 25 m grid, with a nominal vertical precision of 1–2 m. Each survey started in Ilulissat and proceeded through Ata Sund, Torssukataq Fjord, VF, and UF, extending to the glacier termini.

These data are complemented with MBES data of the continental shelf from cruise JR175 of the RRS *James Clark Ross* [*Ó Cofaigh et al.*, 2013] which used a Konsberg-Simrad EM120 system operating at 12 kHz, with an angular coverage of up to 150° and 191 beams per ping. The data were processed using the Kongsberg-Simrad NEPTUNE postprocessing software. Data were acquired on the continental shelf from Jakobshavn Isbrae to VF and the northern end of UF toward Rinks Isbrae in August–September 2009. As for all other data, calibration of the sound speed relied on CTD casts taken at regular intervals during the survey.

A third set of MBES data was acquired in June–July 2007 by Cruise MSM 05/03 on board the R/V *Maria S. Merian* [*Weinrebe et al.*, 2009] also using a Kongsberg-Simrad EM120 system. The data were processed using the MB-system software [*Caress et al.*, 1996]. The survey spanned from Nuuk Fjord to the south to UF to the north. A second survey covered Jakobshavn Fjord in 2008 [*Schumann et al.*, 2012].

A fourth data set collected in 2013 aboard the Minna Martek using a pole-mounted Reson Seabat 7111 MBES in conjunction with an Applanix POS/MV 320 model positioning and orientation system. Data were acquired using the QINSy software and processed with the CARIS HIPS. The survey spanned Rinks and Kangerdluarsuup.

The data are merged and mosaicked together at 100 m spacing on a Universal Transverse Mercator grid zone 22 north (UTM22N) (Figure 1a). In areas of overlap, we find an excellent agreement (within a few meters) between the Cape Race, JR175 and Minna Martek surveys, but we note disparities of about 5–10 m in the middle of UF with the MSM 05/03 survey which did not employ the same precision processing for correcting beam pointing errors. The merged data are compared with IBCAO3 (Figure 1b and S1). IBCAO3 (International Bathymetry Chart of the Arctic Version 3) was released in 2012 using all available data north of 64°N at 500 m spacing [*Jakobsson et al.*, 2012].

In 2012–2014, we collected CTD casts from the continental shelf to the glacier fronts: 33 casts in 2012, 74 in 2013, and 33 in 2014, to a maximum depth of 600 m. The data were filtered and averaged in 5 m bins. The precision in temperature is 0.002°C and 0.002 practical salinity unit for salinity. Here we only employ CTD data from year 2013 along pathways toward the glaciers following the lines of deepest seafloor to highlight changes in water properties from the shelf to the glacier fronts (Figure S2). Temperature data obtained at discrete locations are linearly interpolated along the pathways (Figure 2).

Background on glacier history is provided by glacier front positions extracted from Landsat multispectral scanner images in 1975 until Landsat 8 and aerial photography from 1964 [*Carbonell and Bauer*, 1968] (Figure S3). We manually traced the ice front positions in Landsat imagery going back to 1976 and registered the aerial photography from the 1960s with Landsat-8 data to track down the evolution of ice front positions since 1964, with a 10 year interval between 1964 and 1985, several years between 1985 and 1999, and yearly intervals thereafter. The positions of all the glacier fronts within the survey area, spanning from the end of the Little Ice Age until 1920, are described in *Weidick* [1968].

UF holds 10 marine-terminating glaciers that drain an area of 89,500 km^2. The average surface mass balance for the years 1961–1990 for the UF drainage is 28 $\pm$ 2 Gt/yr [*Ettema et al.*, 2009]. Combining ice velocity [*Rignot and Mouginot*, 2012] and ice thickness from NASA Operation IceBridge, we estimate a total outflow of 38 $\pm$ 2 Gt/yr in 2011. VF holds four marine-terminating glaciers with a drainage area of 37,200 km^2. The 1961–1990 average surface mass balance is 8 $\pm$ 1 Gt/yr. The outflow in year 2011 was 13 $\pm$ 1 Gt/yr. Together, the two fjord systems therefore drain 8% of Greenland's area, control 9% of its total surface mass balance, and supply 9% of its total ice discharge.

3. Results

A main feature of Uummannaq is the 62 km wide Uummannaq Trough (UT) that extends south of Ubekjendt island, across the entire continental shelf, with depths of 700 to 800 m (Figure 1a). Marine geophysical and geological data acquired from the outer shelf and slope region of UT show that a grounded, fast-flowing outlet glacier reached the shelf edge and delivered sediments to a trough mouth fan at the Last Glacial Maximum [*Ó Cofaigh et al.*, 2013; *Dowdeswell et al.*, 2014]. East of Ubekjendt island, the trough splits into several fjords. The deepest sector (1480 m) is found at the entrance of Qarajaq Fjord (Figure 1a), east of Uummannaq Island. This sector is an overdeepened trough, i.e., an area where glacial erosion has excavated the landscape well below what would be expected from other processes (Figure 2e). The deepest overdeepening is found at the confluence of Sermilik and Qarajaq fjords. We posit that paleo–ice streams merged in that sector to produce higher flow rates, hence higher basal friction and erosion rates. Qarajaq Fjord shoals to 800 m depth to the east and remains relatively flat for another 120 km toward Store Gletscher. The fjord shallows to 280 m toward Lille Gletscher versus 550 m for Store [*Rignot et al.*, 2015].

North of Ikerasaq, the 1450 m deep fjord rises to 800 m deep at the entrance of Sermilik Fjord (Figure 2d). Sermilik Fjord shoals to 400 m about 25 km from the glacier snout and then 100 m about 2.5 km from the snout. The glacier is grounded at only 20–80 m, entirely within the cold, fresh Polar Water layer (Figure 3b).

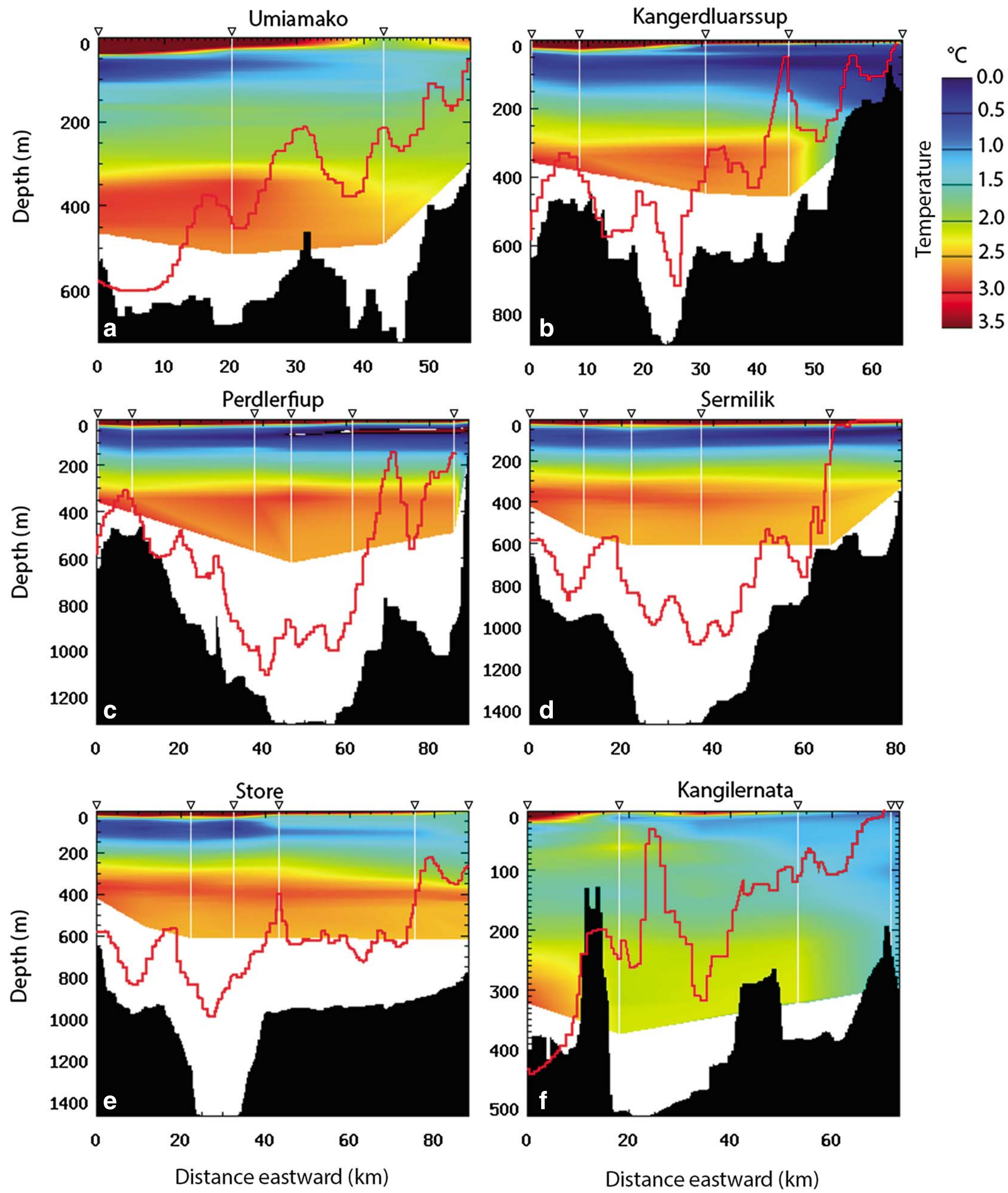

Figure 2. Bathymetry from MBES data (in black) acquired in 2012–2014 starting from the west moving east toward the glacier fronts, with IBCAO3 bed elevation in red, and potential temperature from CTD color coded from blue (0°C) to red (+3.5°C) going from north to south with (a) Umiamako Isbrae, (b) Kangerdluarssuup Sermerssua, (c) Perdlerfiup Sermia, (d) Sermilik, (e) Store, and (f) Kangilerngata with CTD cast location as triangle. White denotes no temperature data.

A second over deepening >1300 m is found to the north of Uummannaq Island, toward Sermeq Silarleq and Kangigleq Sermia. The fjord remains 800 m deep until the junction with the terminal valley of Sermeq Silarleq. The ice front of Silarleq is chocked up with icebergs and debris that block icebergs emitted from the east by Kangigleq Sermia. Both fjords become shallower near the ice fronts.

To the north, the next set of fjords is separated from UT by an 80 km wide, shallow area named Agpat Sound (Figure 1a). Its deepest part lies to the north (400 m) versus depths of 200–300 m at the center and south. The seafloor over deepens to 1200 m toward Perdlerfiup Sermia for 80 km (Figure 2c). About 5 km from the ice front, the seafloor abruptly rises to 150–200 m. The glacier front stands in shallow (100 m), cold, and fresh waters (Figure 3a).

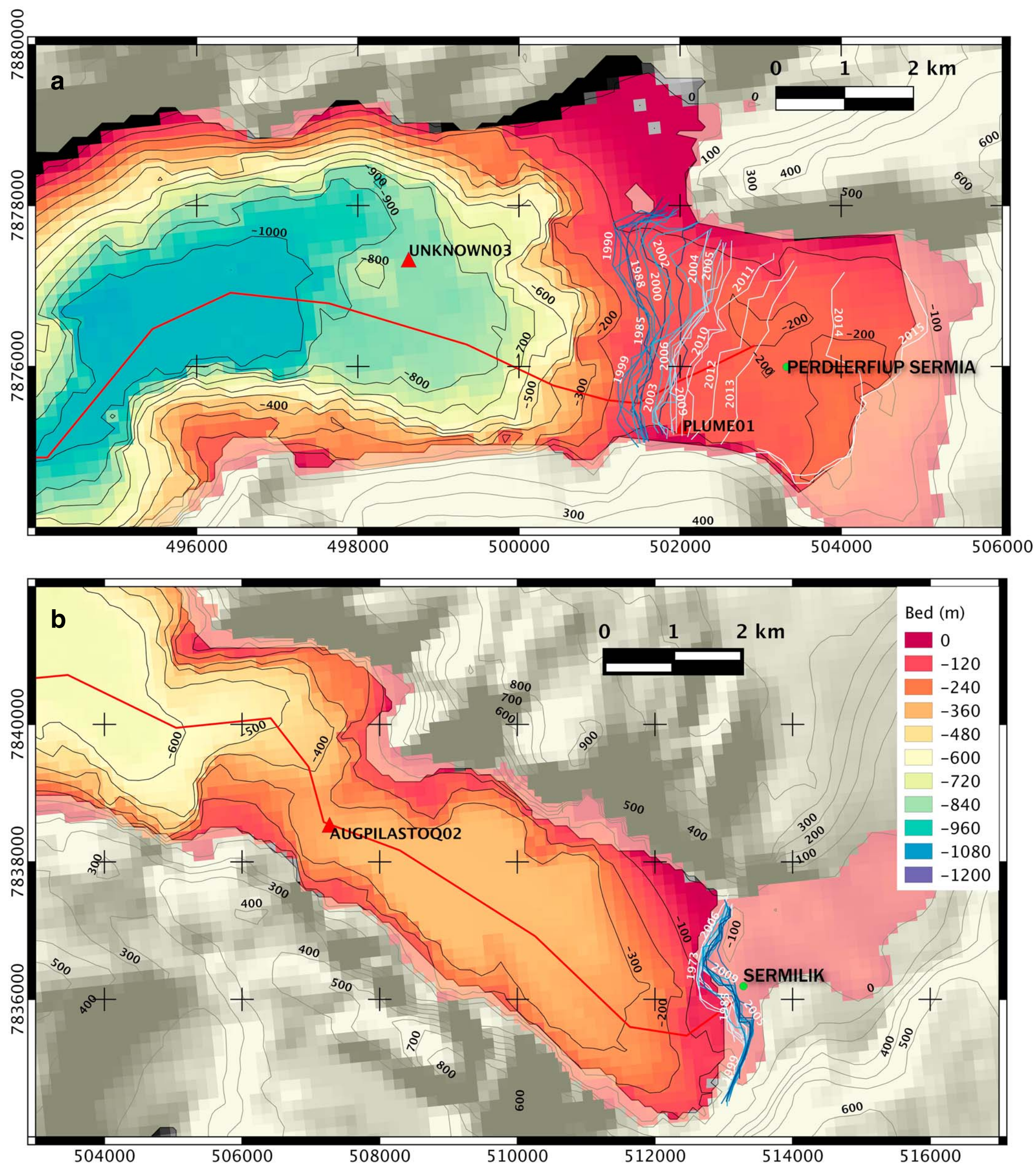

Figure 3. Bathymetry from MBES data with 100 m contour levels in (a) Perdlerfiup Fjord and (b) Sermilik Fjord showing glaciers grounded in shallow waters in otherwise deep (>800 m) fjords. CTD locations from year 2013 are red triangles with name in black. Red line denotes the profile used in Figure 2. Bed elevation (same color code) inland of the calving front is from *Morlighem et al.* [2014]. Ice front positions from 1964 to 2015 are color coded from blue to white and labeled by year.

Directly to the north, Kangerdluarsuup Fjord is 500–600 m deep for 70 km, with no over deepening, until the sea floor rises to 200 m depth about 25 km from the ice front. Kangerdluarsuup Sermia stands in shallow (100–150 m), cold, and fresh waters (Figure 2b).

The next fjord, leading to Kangerdlugssup Sermerssua, is connected to UT to the south via Inuksat, a 500–600 m deep fjord with three sills at 300 m depth and via an unnamed fjord to the west uniformly 400 m deep (Figure 1a). Kangerdlugssup Fjord is uniformly deep at 500–550 m for 80 km until the seafloor quickly rises to 340 m depth about 10 km from the glacier front. The glacier stands in water only 250 m deep.

The northern branch of UT connects to Karrat Isfjord to the north via the 500–650 m deep Illorsuit Sund. The entrance to Karrat Isfjord is 600 m deep, 5 km wide, with a sill at 400 m depth about 160 km from the ice front of Rinks Isbrae (Figure 1a). To the east, the fjord deepens to 1100 m. A sill at 650 m depth is present 8 km from the ice front of Rinks. Rinks is the thickest glacier in the area, standing in water >1000 m deep and with an ice front partially afloat. Umiamako Fjord to the north shares the same narrow entrance to Karrat Isfjord, but its sea floor rises to 400 m depth. We find a sill at 200 m depth, about 25 km from the 2012 ice front position (Figure 2a). The fjord is often choked up with icebergs and debris in the last 15 km. Finally, the last fjord connects with Ingia Isbrae, a small glacier draining from an ice cap, via a channel 450–500 m deep.

VF, south of UF and Nugsuak Peninsula, is 500 m deep at the center with a 300 m sill on its northwest entrance where the fjord deglaciated 10 kyr ago [*Funder et al.*, 2011]. The fjord over deepens to 600 m to the east at the junction with Disko Bay. VF extends to the east into Torssukataq Fjord which hosts Sermeq Avangnarleq and Kujatdleq. The entrance of Torssukataq Fjord is marked by a 300 m sill [*Weinrebe et al.*, 2009]. The fjord is uniformly 700–800 m deep but shallows near the glaciers. Waters immediately near these ice fronts are rarely ice free. Avangnarleq has an ice draft about 250–350 m deep versus 500 m for Kujatdleq [*Morlighem et al.*, 2014].

South of Vaigat, Ata Sund is connected to Disko Bay via a 150–200 m sill (Figure 2f). Ata Sund is 500 m deep before the seafloor rises to 200 m depth at the junction with Eqip Fjord to the east. Eqip Sermia has a shallow (<300 m) fjord, often stranded with icebergs, with an island in the middle, and a glacier front in waters 100–250 m deep. North of Eqip Sermia, Kangilerngata Sermia stands in water 300 m deep. We detect a 200 m deep sill about 7 km from the 2012 ice front position (Figure 2f). The area between Kangilerngata Sermia and Torssukataq Fjord is shallow.

Comparison with IBCAO3 (Figure S1) shows a reasonable agreement on the continental shelf, along UT and VF but significant differences in the inner fjords (Figure 1b). Underestimation of the inner fjord depth in IBCAO3 ranges from a few hundred meters to thousand meters in Rinks Fjord. The MBES data indicates depths 200–400 m deeper than IBCAO3 in Ata Sund, 200–600 m in Torssukataq, 300–400 m in Qarajaq, 200–500 m in Silarleq, 600 m in Perdlerfiup, and 400 m in Ingia fjords.

Tracing water temperature along the lines of deepest seafloor from the continental shelf to the glacier fronts, we find AW (temperature > 2.5°C) in nearly all fjords that are deep enough (>300 m) (Figure 2). As noted above, several fjords become shallow near the glacier fronts, with CTD data indicating the presence of cold, fresh water. Glaciers standing in cold, relatively fresh water include Lille, Sermilik, Perdlerfiup, and Kangerluarssup. Several glaciers stand in water of intermediate temperature, e.g., Eqip and Ingia. The remainder glaciers stand in warm, salty AW, including Kangilerngata, Avangnarleq, Kujatdleq, Store, Silarleq, Rinks, and Umiamako.

The rate of ice front retreat varies significantly among the surveyed glaciers (Figure S3). We separate them into first-order (several kilometers), second-order (about 1 km), and third-order retreats (no retreat). First-order retreat glaciers include Ingia (6.8 km retreat since 2002), Umiamako (3.5 km retreat since 2002), Perdlerfiup (2.8 km retreat since 2002), Silarleq (5.2 km mostly from 2009 to 2012), Kangilergata (3.1 km retreat mostly since 2005–2010), and Eqip (2 km retreat in 2005–2014). Second-order retreat glaciers include Rinks (1.4 km retreat since 1964), Kangerdluarsuup (1.5 km since 1964), Lille (1.2 km since 1989), and Kujatleq (1 km since 1964). We report no retreat for Kangerlugsuup, Kangigleq, Sermilik, Store, and Avangnarleq since 1964. These latter glaciers encompass a wide range of depth (300 to 550 m) and ocean temperature (PW to AW). First-order retreat affects thinner glaciers with lower glacier speeds.

4. Discussion

The comparison of IBCAO3 and MBES data reveals major differences in the inner fjords, as expected, because IBCAO3 has few observational constraints in these areas. According to IBCAO3, all glaciers in UF and VF are grounded near or at sea level, whereas in reality the glaciers are grounded in waters 100 to 1000 m deep and 400 m deep on average. The existence of deep inner fjords is of importance for ice-ocean interaction because it suggests natural pathways for warm, salty, subsurface AW to reach the glaciers, whereas AW could not reach the glaciers based on IBCAO3. Indeed, we find that all the fjords that are deep enough host AW. This is consistent with the presence of AW in the fjords of Helheim, Kangerdlussuaq, and Jakobshavn [*Christoffersen et al.*, 2011; *Sutherland et al.*, 2013; *Gladish et al.*, 2015].

Bathymetry data extending to the ice fronts has rarely been acquired in Greenland due to the difficulty of navigating near calving fronts. For instance, there is no data in the last 10 km of Helheim or Kangerlugssuaq fjords in East Greenland because of persistent, thick ice melange [*Azetsu-Scott and Tan*, 1997; *Schjoth et al.*, 2012; *Sutherland et al.*, 2013]. Our survey reveals that fjord depth may change rapidly near ice fronts. We find many glacier termini grounded in relatively shallow waters at the end of deep fjords, e.g., Sermilik, Perdlerfiup, and Kangerlugsuup. These shallow waters are cold and fresh, therefore conducive to low rates of subaqueous melting. This configuration is common to many glaciers in our survey area, hence highlights the importance of extending bathymetry mapping to the glacier fronts to reveal potential barriers for subsurface, warm waters to reach the glaciers and better understand the level of interaction between ice and ocean at calving margins. Interestingly, these three glaciers had already retreated from the deeper fjords by 1850 [*Weidick*, 1968].

Fjord conditions vary significantly from one glacier to the next. Fjords routinely choked with iceberg debris include Sermeq Kujatdleq, Avangnarleq, Silarleq, Kangigleq, and Ingia. Our data suggest that these fjords are characteristically shallow near the ice fronts or with constrictive geometry (e.g., converging bay walls). In contrast, the fjords leading to Sermilik, Perdlerfiup, Kangerlussup, Kangerluarssuap, and Rinks are often ice free but also deep, which makes it easier for icebergs to exit the fjords. We suggest that heavy brash ice, icebergs, some with included debris, is not indicative of high iceberg production but instead reveals the presence of shallow seafloors, narrowing embayments, or fjord curvature that prevent the flushing of icebergs.

Comparison of the 1964 and 2015 ice front positions reveals that several glaciers standing in AW have not retreated: Sermeq Kujatdleq, Avangnarleq, Store, Sermilik, Kangigleq, Kangerlussup, and Rinks. One possibility is that the rates of ice melt by the ocean are small compared to the rates of ice motion, i.e., changes in ocean temperature and increases in ice melt have not been large enough to counteract the advection of ice from upstream by the glaciers and dislodge them from their calving front positions. Sermeq Kujatdleq, Sermeq Avangnarleq, and Store Gletscher, for instance, flow at speeds averaging across the entire glacier width of 8.4 m/d, 5.3 m/d, and 10 m/d, respectively, versus an area average summer melt rate by the ocean estimated at 3 m/d for Store Gletscher [*Xu et al.*, 2013], 3 m/d for Kangerluarssap [*Fried et al.*, 2015], similar values for the other two glaciers, and lower modeled values in winter. A doubling or tripling of the rate of the summer ice melt would be necessary to make the melt rates comparable to the rates of ice advection and thereby enable glacier retreat.

In contrast, we find glaciers grounded in relatively shallow waters that have retreated significantly in recent years, e.g., Eqip Sermia, Kangilerngata, Umiamako Isbrae, and Ingia Isbrae. Kangilerngata started to retreat from a 300 m deep sill in 2002, with a fast retreat in 2005–2010. Eqip Sermia underwent a rapid retreat of its northern sector in 2005–2011 and its southern sector in 2012–2014. Umiamako and Ingia started to retreat in 2002. We find no obvious correlation between glacier depth at the terminus, ocean temperature, and retreat rates, i.e., thick glaciers standing in AW have not retreated faster than thin glaciers standing in cold, relatively fresh waters. Perdlerfiup and Eqip stand in relatively shallow, cold water but retreated (1.4 km in 2014–2015 alone for Perdlerfiup). Deeply grounded Store (550 m) and Rinks (900 m) stand in AW but have experienced no change since 1964. This suggests that the interpretation of the spatial and temporal patterns of glacier retreat involves more factors that just ocean temperature. In particular, it must also depend on the speed of ice melt by the ocean versus the calving speed of the glacier, the distribution of bed slopes in the ice front region, the width of the glacial valley, the exact shape of the calving faces, and the impact of glacier undercutting by the ocean on iceberg calving [e.g., *Rignot et al.*, 2015; *Fried et al.*, 2015].

One important application of the bathymetry data will be to bridge the gap between bed topography mapped beneath land ice and bathymetry on the continental shelf. Modern ice sheet bed topography is mapped using radar echo sounding data at megahertz frequencies, however with significant failure near glacier fronts, so thickness data have to be extended to the glacier fronts using mass conservation principles [*Morlighem et al.*, 2014]. Bathymetry provides a natural, precise, and reliable boundary for mass conservation techniques. Furthermore, extension of bathymetry mapping to recently ungrounded areas will help interpret recent changes in glacier dynamics. On longer time scales, the bathymetry data will help constrain the reconstruction of larger, Quaternary ice sheets from colder time periods.

5. Conclusions

We present the first relatively complete bathymetry mapping of two large fjord systems in west Greenland, which host a number of major outlet glaciers that control nearly 10% of the ice sheet discharge. The results show that actual bathymetry is drastically different from existing charts, especially in the inner fjords which are typically 100 m to 1000 m deeper. The presence of deep fjords permits the access of warm, salty AW to the glacier fronts, which yields high rates of ice melt into the ocean. Ice sheet numerical models using existing bathymetric charts will clearly underestimate—or ignore—the role of ice-ocean interaction because the inner fjords will be represented as too shallow. The survey also reveals that numerous glaciers are grounded on shallow sills, in relatively cold, fresh waters, in otherwise deep fjords, thereby highlighting the importance of extending bathymetry mapping to the glacier fronts to understand their melt regime into the ocean. Similarly, several glaciers grounded in PW have retreated recently, indicating that the presence of AW is not required to trigger glacier retreat. Similar data collected in other fjords are critical to understand the past, current, and future evolution of marine-terminating glaciers.

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