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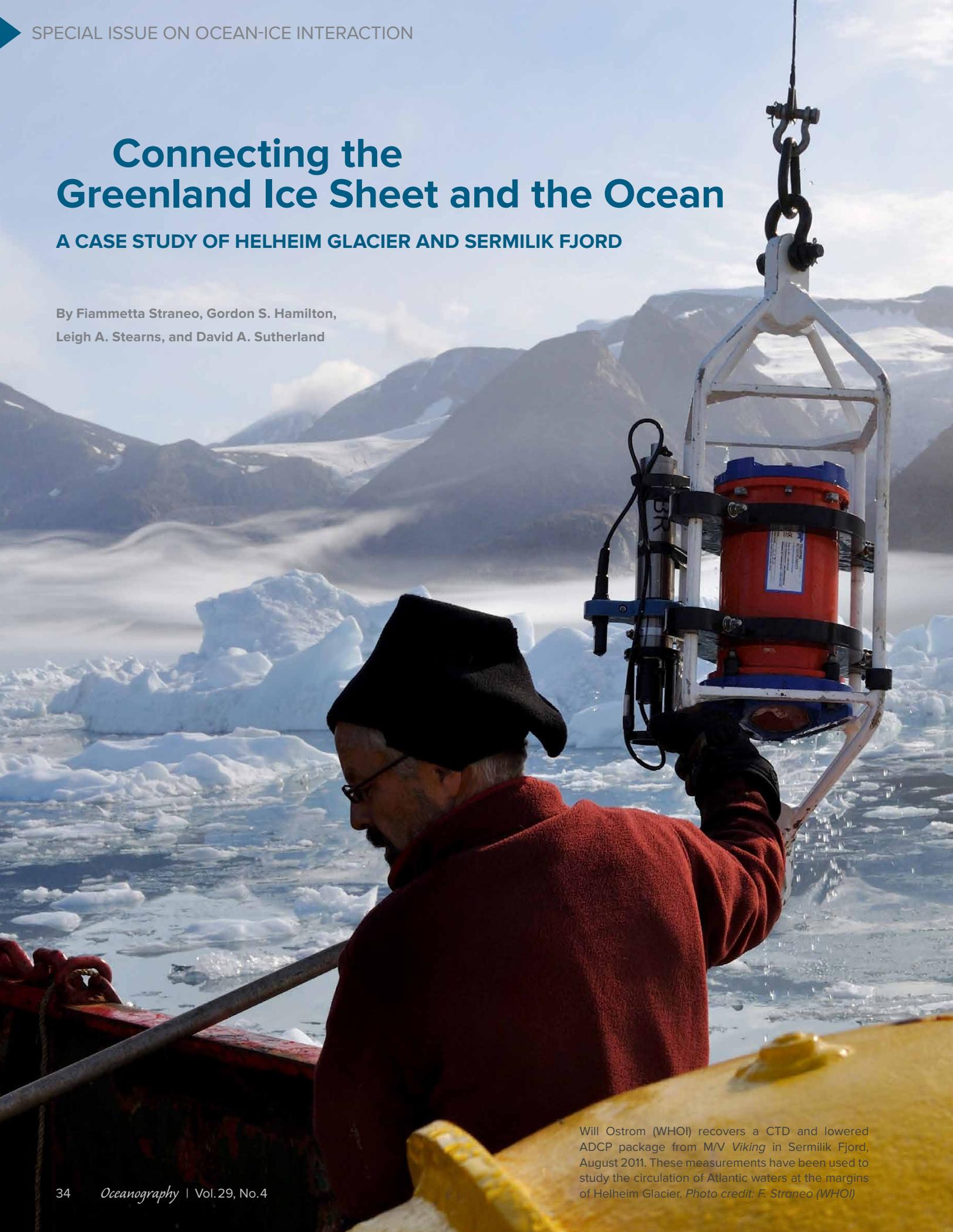
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Connecting the Greenland Ice Sheet and the Ocean

A CASE STUDY OF HELHEIM GLACIER AND SERMILIK FJORD

By Fiammetta Straneo, Gordon S. Hamilton,
Leigh A. Stearns, and David A. Sutherland



Will Ostrom (WHOI) recovers a CTD and lowered ADCP package from M/V *Viking* in Sermilik Fjord, August 2011. These measurements have been used to study the circulation of Atlantic waters at the margins of Helheim Glacier. Photo credit: F. Straneo (WHOI)

ABSTRACT. The rapid ice loss from the Greenland Ice Sheet that began in the late 1990s sparked an interest in glacier/ocean exchanges both because an increase in submarine melting of the glacier is a potential trigger of glacier retreat and because the increasing freshwater discharge can affect the regional ocean's circulation and ecosystems. An interdisciplinary field project focused on the Helheim Glacier-Sermilik Fjord system began in 2008 and has continued to date. We found that warm, Atlantic Water flows into the fjord, drives melting of the glacier, and is regularly replenished through shelf-forced and glacier-driven circulations. In summer, the release of surface melt at the base of the glacier has a pronounced impact on local ocean circulation, the properties of the glacier, and its melt rate. Measurements taken in the fjord indicate that it is virtually impossible to derive submarine melt rates from hydrographic (including moored) data due to the fjord's pronounced water mass variability and uncertain contribution from iceberg melt. Efforts to correlate glacier behavior with ocean forcing on seasonal and interannual time scales yield no straightforward connections, likely because of a dependence on a wider range of parameters, including subglacial discharge and bedrock geometry. This project emphasizes the need for sustained long-term measurements of multiple glacier/ocean/atmosphere systems to understand the different dynamics that control their evolution.

INTRODUCTION

Ice loss from the Greenland Ice Sheet (GrIS) quadrupled from the 1992–2001 period compared to 2002–2011 and contributed 7.5 ± 1.8 mm to sea level rise over the entire 19 years (Shepherd et al., 2012). The ice loss is due to both an increase in surface melt, largely driven by rising air temperatures over Greenland (Hanna et al., 2012), and a speedup and retreat of glaciers in Southeast and West Greenland (Howat and Eddy, 2011). These rapid, unpredicted changes sparked an interest in ice sheet-ocean interactions in Greenland, in particular, in mechanisms governing the exchange of heat and freshwater at the marine margins of outlet glaciers for two reasons. First, an increase in submarine melting, potentially associated with the warming of the subpolar North Atlantic, is considered a likely trigger for glacier retreat (Holland et al., 2008; Motyka et al., 2011; Straneo et al. 2013; Straneo and Heimbach, 2013). Thus, understanding what oceanic, atmospheric, and glaciological processes influence melt rates at glacier termini is key to interpreting past events and predicting future changes. Second, the increased freshwater discharge into the

North Atlantic associated with the ice loss (Bamber et al., 2012; Enderlin et al., 2014) has the potential to affect dense water formation, the Atlantic Meridional Overturning Circulation, and marine ecosystems via freshening and nutrient input. Given that freshwater discharge from Greenland is projected to increase in the coming decades (Franco et al., 2013), understanding how, where, and when the freshwater is exported is key to projecting its impact on regional waters and the large-scale ocean.

Even prior to the acceleration, the limited number of floating ice tongues in Greenland meant that the surface area over which ice and ocean interacted was small. Today, the bulk of heat and freshwater exchange between the GrIS and the ocean occurs at the margins of outlet glaciers terminating at the heads of long, deep fjords that have little or no floating portion. This includes the largest glacier systems draining the GrIS ranked by ice flux: Jakobshavn Isbrae in West Greenland and Kangerdlugssuaq and Helheim Glaciers (Figure 1) in Southeast Greenland. In the cases of either floating ice tongues or mostly vertical glacier fronts, the glacier-ocean interfaces at

the heads of narrow fjords act as bottlenecks for the exchange of heat and freshwater between two much larger bodies. For an outlet glacier, the relevant body is the catchment basin—an ice sheet's equivalent to a watershed. Catchment basins are bounded at their upper limits by topographic divides and, for large glaciers in Greenland, can vary in size from 10,000 km² to 100,000 km² (Rignot and Kanagaratnam, 2006; Figure 1a). For the fjord, the relevant body comprises the continental shelf and the neighboring oceanic region, which can be hundreds to thousands of kilometers wide (Figure 1a). While Greenland is drained by numerous outlet glaciers, about 77% of the ice sheet's total discharge occurs through just 15 glaciers (Enderlin et al., 2014). Thus, it is through a handful of these relatively narrow outlet glaciers and fjords that the bulk of the heat and mass exchange between the Greenland Ice Sheet and the subpolar ocean occurs.

Glacier-ocean interactions were poorly studied until recently. This was, in part, because the GrIS was thought to be sensitive mainly to surface air temperature changes, with response times on the order of centuries or millennia (Ridley et al., 2005; Gregory and Huybrechts, 2006). Also, the freshwater contribution of the GrIS to the North Atlantic Ocean was deemed negligible compared to the much greater, and more variable, Arctic freshwater export (Dickson et al., 2007; Haine et al., 2015). It was not until the rapid retreat of outlet glaciers started in the late 1990s that interest in understanding the connections between the ice sheet and surrounding ocean surged. For the ice sheet, the first step was to establish if (and how) oceanic changes had induced an increase in submarine melting that, in turn, had triggered glacier retreat. Because subpolar North Atlantic warming was tied to a thickening and warming of Atlantic waters (Bersch et al., 2007), the initial focus was to establish

whether Atlantic waters reached the margins of the ice sheet. Observations from Greenland's glacial fjords were scarce at that time, however, and fjords were not resolved by even the highest resolution regional ocean models, due to their small scales and to the lack of appropriate bathymetry. Hence, addressing this question required data from the fjords.

It was in this scientific context that, in July 2008, the authors initiated oceanic, glaciological, and atmospheric observations of one major glacier/fjord system in Southeast Greenland, Helheim Glacier and Sermilik Fjord (Figure 1). What started as an unfunded collaboration among oceanographers and glaciologists has continued to the present through multiple projects funded by federal agencies, the scientists' institutions, and private foundations. In this synthesis, we summarize the lessons we have learned from working in the fjord, including determining how to make measurements in an unusually challenging environment, and from investigating simple correlations between the variability of fjord and glacier. The goal is not to duplicate recent reviews that summarize the state of knowledge (e.g., Straneo et al., 2013; Straneo and Cenedese, 2015; Truffer and Motyka, 2016), but rather to focus on our own efforts to unravel one glacier/fjord system in Greenland.

HELHEIM GLACIER AND SERMILIK FJORD

Glaciological Setting: The Southeastern Flank of the Greenland Ice Sheet and Helheim Glacier

Helheim Glacier (66.38°N, 38.8°W; Figure 1) is one of Greenland's largest outlet glaciers. Its catchment encompasses ~4% (~48,000 km²) of the ice sheet's total area. Between 2000 and 2012, the glacier itself accounted for ~20% of the ice sheet's mass discharge (Enderlin et al., 2014). The inland boundary of the glacier's catchment is ~200 km from the coast at an elevation of ~2,500 m. This region receives some of Greenland's highest snowfall totals (>1 m yr⁻¹ w.e. [water equivalent]; Burgess et al., 2010). Ice in the catchment converges ~50 km from the coast into the channelized flow of the outlet glacier. Mass is eventually discharged through a ~6 km wide rock-walled channel near the glacier terminus, where flow speeds reach ~25 m d⁻¹ (Nettles et al., 2008). The glacier terminates in ~600 m of water at the head of Sermilik Fjord, ~100 km from the open ocean (Figure 1b,c).

The terminus of Helheim Glacier maintained an approximately stable position at the head of Sermilik Fjord for several decades, but between 2002 and 2005, it rapidly retreated by 7 km (Figure 1b; Howat et al., 2007). This retreat was

accompanied by an almost doubling of its flow speed (Rignot and Kanagaratnam, 2006) and sustained rapid thinning in excess of 90 m yr⁻¹ (Stearns and Hamilton, 2007) that created a distinctive "bathtub ring" at the lateral margins of the glacier (Figure 2). In all, ice loss from Helheim Glacier alone between 2002 and 2005 led to a rise in sea level of 0.5 mm (Stearns and Hamilton, 2007). Since then, flow speeds have decelerated from their 2005 peak (Moon et al., 2012) but remain above pre-2002 levels. Similarly, while the glacier has thickened (Csatho et al., 2014) and re-advanced beyond its 2005 minimum position, it is still thinner and its terminus position is still retreated with respect to pre-2002 levels. Seasonally, the glacier's terminus advances and retreats by 1–2 km (Figures 1c and 2; Schild and Hamilton, 2013).

Oceanographic Setting: The East Greenland Shelf and the Irminger Sea

Sermilik Fjord is connected to the continental shelf ("shelf" hereafter) of Southeast Greenland, which, in turn, forms one of the boundaries of the Irminger Sea, a basin within the subpolar North Atlantic. Cold, fresh water exported from Fram Strait (Polar Water, PW) flows equatorward along the shelf, transported primarily by the East

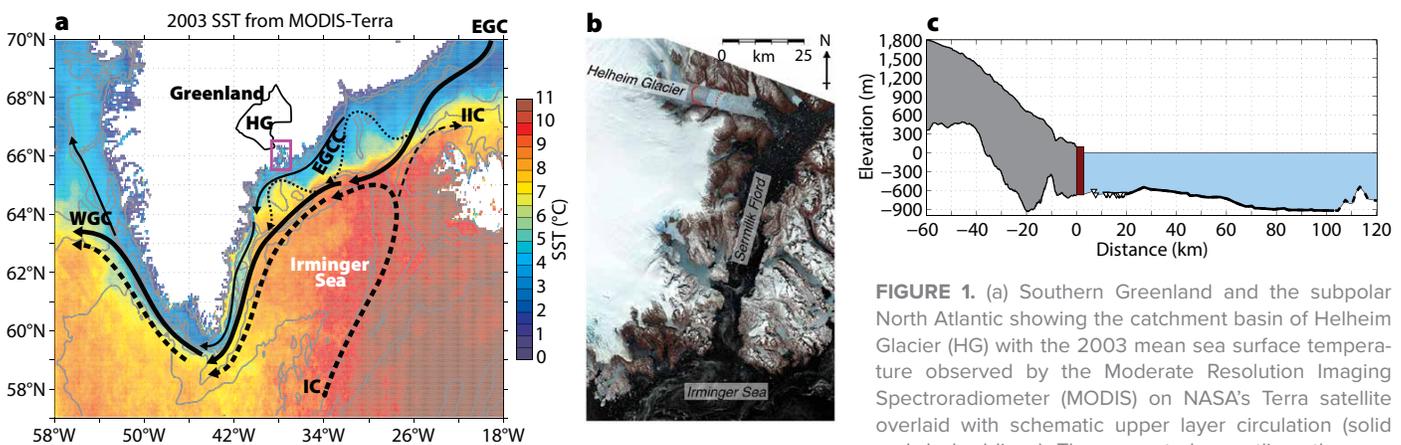


FIGURE 1. (a) Southern Greenland and the subpolar North Atlantic showing the catchment basin of Helheim Glacier (HG) with the 2003 mean sea surface temperature observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite overlaid with schematic upper layer circulation (solid and dashed lines). The magenta box outlines the area shown in b. (b) Portion of Landsat-8 satellite image (acquired May 15, 2016) showing Helheim Glacier and Sermilik Fjord. The dashed red line shows the pre-retreat terminus position of August 2002, and the solid red line is the minimum terminus position, reached in August 2005. (c) Helheim Glacier centerline thickness (gray) from Morlighem et al. (2014) where $x = 0$ is a mean terminus position. For $x > 0$ km, the black line shows bathymetry along the center of the fjord (Schjøth et al., 2012), with estimated depths for outside the mouth and under the ice mélange (triangles, from expendable CTD [XCTD] profiles). The red shaded area shows the mean seasonal extent of Helheim Glacier advance/retreat.

Greenland Current (EGC; Rudels et al. 2005; Sutherland and Pickart, 2008). Farther offshore, the Irminger Current transports warm, salty water (Atlantic Water, AW) from the subtropical region along the continental slope (Våge et al., 2011). This simplified scenario largely breaks down near Sermilik Fjord where deep troughs cut across the wide shelf and funnel warm water toward the Greenland coast (Murray et al., 2010; Sutherland et al., 2013), and an inner branch of the EGC, the East Greenland Coastal Current (EGCC; Figure 1a), flows near the coast (Sutherland and Pickart, 2008).

Until recently, variabilities in the EGC, EGCC, and AW intrusions on the shelf were largely unknown. Estimates of the upstream variability for the shelf's source waters exist thanks to a decade-long moored array in Fram Strait, which shows that the volume and freshwater transports of the EGC peak in late winter and are minimum in summer and that interannual variations are relatively small (de Steur et al., 2009). For the AW, offshore measurements have shown that the subpolar North Atlantic, which includes the Labrador and Irminger Seas, warmed from the early 1990s into the 2000s (Bersch et al., 2007; Våge et al., 2011). A recent study of the Irminger Sea suggests that this region may have started cooling since 2010 (de Jong and de Steur, 2016).

MEASUREMENTS FROM SERMILIK FJORD

Water Properties and Bathymetry

Prompted by the rapid retreat of Helheim Glacier, we set out in July 2008 to investigate what role, if any, the ocean had played in triggering the retreat. An initial goal was to establish if AW reached the fjord and the glacier. Key to establishing this was determining if a sill isolated Helheim Glacier from the deep troughs on the shelf where summer surveys had revealed the presence of AW. Using a small, locally chartered vessel (*M/V Sabina*, Figure 3) equipped with a portable conductivity, temperature, depth (CTD) profiler on a motorized fishing

reel, an externally mounted single beam echosounder, and an acoustic Doppler current profiler (ADCP), we found that there was no sill at the mouth of the fjord. As a result, the salinity, temperature, and density structure inside the deep fjord (Straneo et al., 2010; Figure 4a,b) mimicked the PW/AW layering on the shelf, with PW filling the upper ~150 m of the fjord and AW the remainder of the water column. A follow-on survey in September 2008 confirmed a similar PW/AW distribution. Differences in the fjord properties between July and September suggested that the fjord's upper 400 m had been renewed through shelf-fjord exchange, which, combined with velocity observations of fast, strongly sheared flows, provided the first glimpse of the complex circulation inside this fjord. Still, the small vessel used in 2008 was unable to reach far into the fjord due to increasing iceberg density, leaving open the possibility that an inner sill existed, which might block the AW from reaching Helheim Glacier.

It was not until August 2009 that we were able to unequivocally show that AW reaches and drives melting of Helheim Glacier. *M/V Arctic Sunrise* was able to negotiate leads in the ice in order to reach the seaward edge of the proglacial ice mélange (a mixture of icebergs, bergy bits, and sea ice found in front of the glacier; Figure 2), roughly 20 km from the

glacier terminus. Furthermore, using the ship's helicopter, we deployed expendable ("X") probes, including XBTs (expendable bathythermographs), XCTDs (expendable CTDs), and XCPs (expendable current profilers) in sporadic leads found in the ice mélange (Figure 3). These probes provided the first measurements of temperature, salinity, and velocity within a few kilometers of Helheim Glacier. In addition, expendable probes deployed from a small boat and a helicopter the following winter (March 2010) provided the first wintertime measurements (Straneo et al., 2011). These probes also provided unique estimates of bathymetry in the ice-covered region that is impenetrable to vessels. Both the sparsely mapped bathymetry and the ocean properties suggest that there is no shallow sill in the vicinity of Helheim Glacier that would block the AW inflow (Figure 1c).

Since 2009, a compilation of bathymetric data collected by scientists from several different nations (Schjøth et al., 2012) and soundings from tagged seals (Sutherland et al., 2013) have resulted in a relatively robust bathymetry for Sermilik Fjord from the mouth to the seaward edge of the mélange (Figure 4d). The resolution on the shelf outside the fjord, however, remains coarse, and the only bathymetry from the ice mélange-covered portion of the fjord is drawn from measurements by

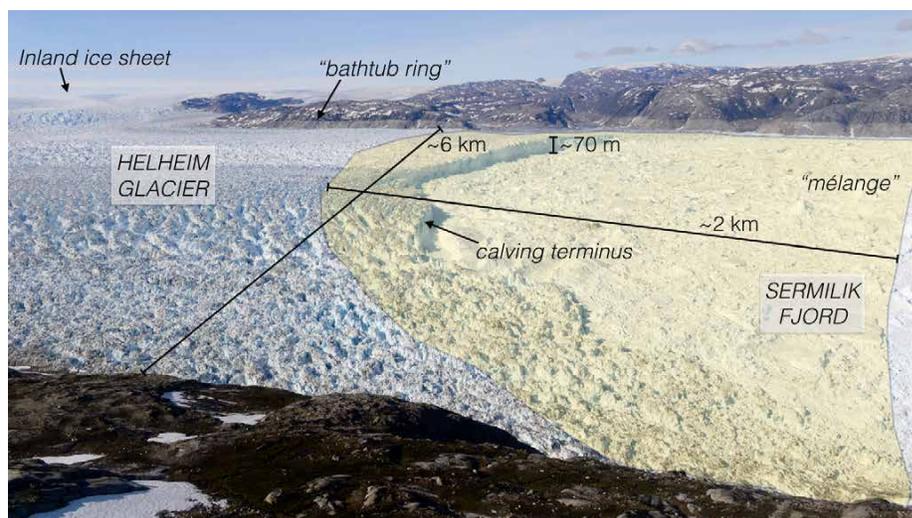


FIGURE 2. Oblique photo of Helheim Glacier (July 2015) showing the near-terminus study region and the approximate range of seasonal variability in terminus positions. *Photo credit: G. Hamilton*

a limited number of expendable probes (Figure 1c). Collectively, these data suggest that AW flows into the fjord via deep troughs on the shelf, in particular, through a trough near the mouth of the fjord that is perpendicular to the fjord axis (Figure 4d).

Direct evidence that AW was melting the underside of Helheim Glacier came from comparative analysis of temperature/salinity (T/S) properties from the profiles collected near the glacier and inside the fjord. Specifically, these data showed that the AW near the glacier had been modified (cooled and freshened), which is indicative of ice melting in ocean waters (Jenkins, 1999). A comparison of the March and August surveys, however, also revealed one striking difference. Specifically, the August survey provided the first evidence that large amounts of meltwater produced by surface melting over the glacier's catchment basin were being discharged at depth through Helheim's subglacial hydrologic system. The transformation of ocean properties induced by this discharge (subglacial discharge, hereafter) is distinct from that

induced by submarine melting because it does not involve the release of latent heat to melt the ice (Straneo et al., 2011; Jenkins, 1999).

Another important finding from these surveys concerned the export of meltwater from the glacier, including submarine melt and subglacial discharge. Because this meltwater is buoyant with respect to the ambient water and most of it is released at depth, it rises as a buoyant, turbulent plume at the edge of the ice and rapidly entrains ambient water. The result is the formation of a new water class—glacially modified water (GMW)—that can equilibrate subsurface. For Sermilik Fjord, both our observations and a modeling study showed that the equilibration depth for GMW (and hence the depth at which it is exported) varies as a function of the subglacial discharge, the submarine melt, and the background ocean stratification (Sciascia et al., 2013). A key implication of this finding is that meltwater released from Helheim Glacier is not exported as a fresh anomaly at the surface but rather as GMW distributed over a range of depths.

Moored Measurements in an Iceberg-Choked Fjord

Key to demonstrating any link between ocean and glacier variability is understanding what controls the variability of submarine melt of Helheim Glacier. One aspect of this question involved understanding what controlled the circulation of AW within the fjord and, potentially, quantifying the heat transport to the glacier. At that time, the circulation within glacial fjords was largely thought to be an estuarine-like two-layer circulation consisting of inflowing ocean (ambient) water at depth and outflowing GMW at the surface (Motyka et al., 2003). However, unlike traditional estuaries, a glacial fjord releases buoyant meltwater at depth that drives this circulation, and it can give rise to positive feedback; for example, an increase in AW temperature resulting in more melting will drive an increased transport toward the glacier that will, in turn, result in increased melting (Motyka et al., 2011).

Synoptic hydrographic and velocity surveys provided crucial information on glacier-ocean exchanges but, because



FIGURE 3. Oceanographic measurements in Sermilik Fjord. (a) *M/V Sabina*, the vessel used in 2008. (b) Expendable conductivity, temperature probes deployed from a helicopter have provided temperature and salinity profiles, as well as bathymetry near the glacier. (c) Mooring operations next to an iceberg, from *M/V Arctic Sunrise*, August 2009. (d) Mooring recovery in the fjord using *M/V Fox*, August 2012. Photo credits: (a) F. Straneo, (b) M. Cape, (c) N. Cobbing, (d) D. Sutherland

of their short duration, failed to capture any temporal variability within the fjord or allow us to identify mean circulation patterns. In particular, the observed flows differed from the expected estuarine circulation, but it was unclear whether this was because of temporal variability or because the fjord's mean circulation was not a simple estuarine one. Furthermore, without knowing the mean fjord circulation and its variability, it was challenging to determine the significance of any estimated heat flux toward the glacier and of the implied melt rate (e.g., Sutherland and Straneo, 2012). The need to quantify (and investigate) both the mean circulation and the variability in the fjord led us to deploy moorings in the fjord.

Moored measurements in glacial fjords such as Sermilik are far from trivial. Larger moorings that can carry ADCPs to measure velocities and properties at multiple depths require bigger vessels that, in turn, are less maneuverable in the iceberg-clogged fjord (Figures 2 and 3). From 2009 to present, with various degrees of success, we have deployed moorings from a local ferry,

M/V *Johanna Kristina*; a Greenpeace icebreaker, M/V *Arctic Sunrise*; a converted fishing boat, M/V *Fox*; a former Russian tugboat, M/V *Viking*; and an icebreaker previously used for fisheries research, M/V *Adolf Jensen*. Depending on the vessel, the captain, the ice cover, and the time available, our ability to penetrate far into the fjord toward the glacier has varied considerably. The closer to the glacier, the harder it is to both deploy and recover moorings. Locations that are accessible one year may not be accessible the following year(s) when the moorings need to be recovered. One particular example is SF1, a mooring carrying an ADCP and multiple SBE-37 MicroCAT sensors, which was deployed in the northern part of the fjord in August 2011. Recovery the following year failed when the captain of the vessel decided to turn back just 5 km from the mooring because of the large icebergs in the region. Ironically, that same evening, SF1 was hit by an iceberg whose draft exceeded 500 m (in 610 m of water), which caused the subsurface float to implode and the entire mooring to shatter to the seafloor (Figure 5). It took

12 hours of dragging among drifting icebergs a year later to recover it, an achievement that surprises us still to this day!

The presence of deep-drafted icebergs (many exceeding 300 m) in Sermilik Fjord (Enderlin and Hamilton, 2014; Andres et al. 2015) means that any instrument or mooring component located in the upper 300 m is likely to suffer iceberg damage. Six out of 40 moorings we deployed over eight years were lost either because they disappeared (presumably displaced by an iceberg) or because they lost their flotation and we could not recover them. While velocity can be obtained using ADCPs located at safer depths (>350 m), temperature and salinity require in situ measurements. In addition, high sediment deposition (due in part to melting of drifting icebergs) causes acoustic mooring releases to seize up. Still, moorings deployed in Sermilik Fjord and on the nearby shelf have provided invaluable information on the hourly to interannual variability within the fjord, and on the fjord's circulation and its drivers (see below). Having a continuous record of ocean properties offers

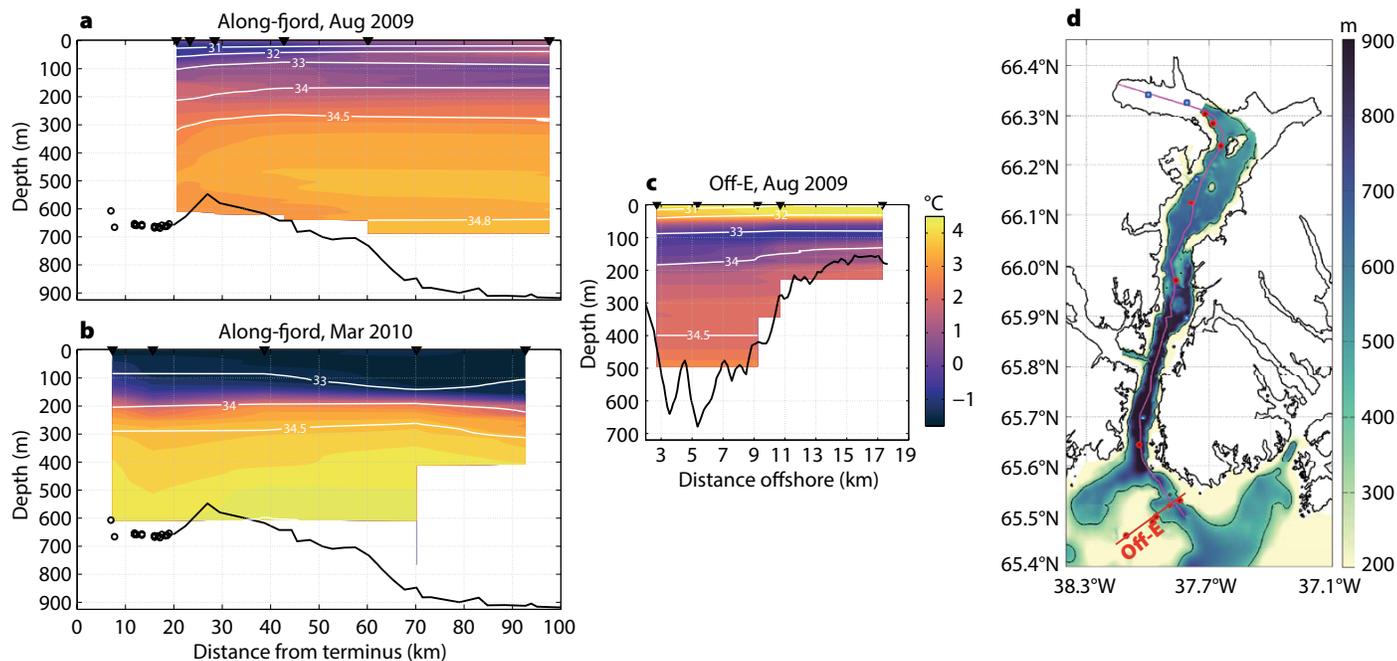


FIGURE 4. (a) Along-fjord section of potential temperature ($^{\circ}\text{C}$, color) with salinity contoured (white) during August 2009. Along-fjord distance and bathymetry are the same as in Figure 1. Black triangles show CTD cast locations. (b) Same as (a), but for March 2010. (c) Same as (a), but for a CTD section taken outside the fjord across the East Greenland Coastal Current (Harden et al., 2014) in August 2009. (d) Map of Sermilik Fjord bathymetry (Sutherland et al., 2014b) showing locations of along-fjord CTD casts (blue: winter, red: summer) and the CTD (Off-E) section outside the fjord's mouth. The black contour is the 400 m isobath, and the magenta line shows the along-fjord line used in this study.

the best chances for determining coincident changes in the glacier/fjord system and examining the cause and effect behind those coupled changes.

While icebergs pose a risk to mooring and ship-based operations, they also play several other roles in glacial fjords. Melting of icebergs can result in the addition of large amounts of meltwater to the head of the fjord, where iceberg density is larger (Enderlin et al., in press), which will contribute to the buoyancy-driven circulation. Icebergs are also part of the dense ice mélange that potentially buttresses the terminus and affects glacier variability (Amundson et al., 2010). Furthermore, icebergs can also act as drifters that move with the mean flow averaged over their keel depth. Since 2012, we have opportunistically deployed GPS-enabled trackers on large icebergs (most >500 m in waterline length) both to monitor their

movement and to act as proxies for inferring fjord circulation (Sutherland et al., 2014a). Outside of the mélange, the iceberg velocity is as variable as the currents in the upper few hundred meters (Jackson et al., 2014; Andres et al., 2015). Inside the mélange, icebergs move at speeds typical of Helheim Glacier's speed (Sutherland et al., 2014a), jumping forward periodically during calving events. Ironically, the iceberg that destroyed mooring SF1 was being tracked (Figure 5)!

Seasonal and Interannual Variability in the Fjord and Shelf

Moored measurements from Sermilik Fjord and the nearby shelf have shown these environments to be highly dynamic, with a pronounced variability on scales of days to a week (Harden et al., 2014; Jackson et al., 2014;). This variability is largely attributed to transiting low-pressure

systems that result in strong, northeasterly barrier winds on the shelf (Harden et al., 2014) as well as strong along-fjord wind events in the fjord (Oltmanns et al., 2014). Both wind events are stronger and more frequent between September and May, and the barrier winds in particular have large impacts on the fjord's circulation and properties. Explicitly, barrier winds result in a rapid exchange of properties between the shelf and the fjord that, in turn, allows longer-term changes (seasonal, interannual) on the shelf to propagate inside the fjord (Straneo et al., 2010; Jackson et al., 2014; Sutherland et al., 2014b). One additional consequence of this large variability is that caution must be used in interpreting short-term (days to a week) surveys as representative of a seasonal mean for a particular year.

Seasonally, mooring measurements from the shelf show that PW transport is

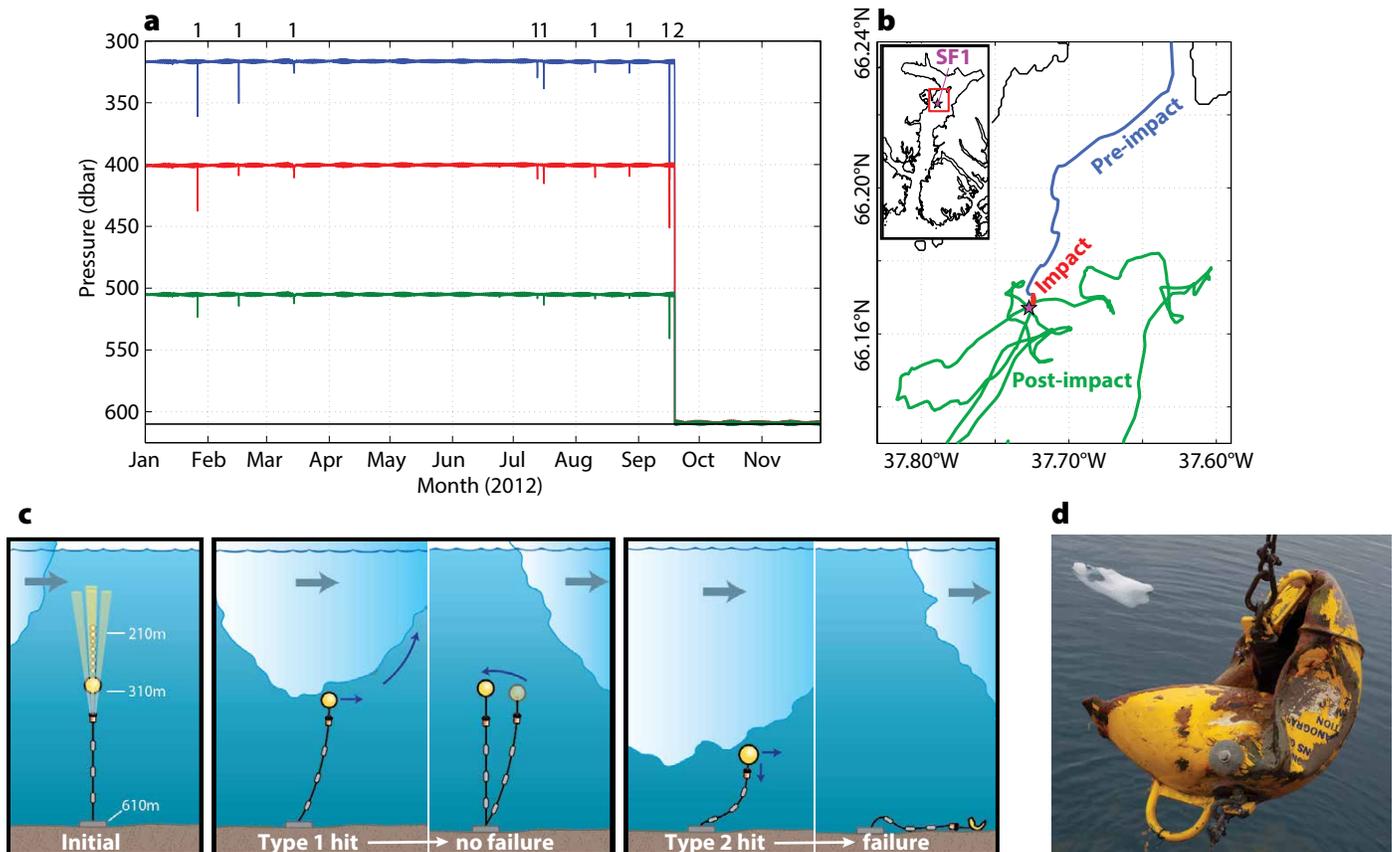


FIGURE 5. (a) Pressure records from three SBE-37 MicroCAT sensors on mooring SF1. The black line indicates the fjord depth at the mooring location. Numbers 1 or 2 refer to presumed iceberg hit types, as shown in panel c. (b) Zoom-in on Sermilik Fjord region where the mooring was located (red box in inset map) showing the track of the iceberg that passed over the mooring location (star). (c) Schematic of mooring SF1 and what happens as icebergs pass over with keel depths deeper than the shallowest instrument *Credit: Jack Cook, Woods Hole Oceanographic Institution* (d) Recovered float from mooring SF1. *Photo credit: F. Straneo*

reduced in summer and fall and increases in winter and spring, associated with a thickening of the warm AW layer in summer and fall, and thinning in winter and spring (Harden et al., 2014). This seasonal variability is corroborated by hydrography collected by tagged seals along the Southeast Greenland shelf (Sutherland et al., 2013). Moorings deployed mid-fjord (see Figure 4 for locations) since summer of 2009 show large seasonal variability in the upper ~300 m that in part mimics that of the shelf: thinning of the AW layer in winter/spring and thickening in summer/fall (Figure 6). However, fjord variability is also influenced by the export of GMW in the upper 100–200 m (Straneo et al., 2011; Jackson and Straneo, 2016). This is particularly true in late spring and summer, when subglacial discharge rates of 800–1,200 m³ s⁻¹ (e.g., from the regional model RACMO 2.3; see Jackson and Straneo, 2016) are diluted by mixing with AW, and the resulting GMW is exported as a relatively warm water mass in the upper layers (Straneo et al., 2011; Jackson and Straneo, 2016). Assuming a dilution ratio of subglacial discharge to ambient of 1:30, as recently estimated for a West Greenland glacier using noble gases (Beird et al., 2015), this will result in GMW summer export rates of ~0.025 Sv (1 Sv = 1.0 × 10⁶ m³ s⁻¹). This GMW contributes to the warming of waters above 200 m in the late spring/early summer recorded by moorings located mid-fjord (Figure 6), making the fjord waters warmer than the shelf waters (Figure 7). Beneath 300–400 m, it is challenging to discern any seasonal variability. The moored records from mid-fjord, and as close as 20 km from Helheim Glacier, do show is that AW is present year-round and year after year, and that temperature variations of 1°C at 500–600 m depth are not uncommon (Figure 6a,b).

In terms of circulation, moored velocity data show that between September and May, the circulation is dominated by shelf-forced flows, and no mean circulation is discernible. In summer, as the shelf-forced circulation decreases and the

buoyancy-driven circulation increases, a mean exchange flow emerges consisting of export of GMW in the upper layers and inflow of AW at depth (Jackson and Straneo, 2016). While qualitatively similar to the estuarine-type circulation proposed for glacial fjords (Motyka et al., 2003), this exchange flow is likely due to the combination of buoyancy-driven, shelf-driven, and locally driven flows.

Interannually, we found considerable variability in fjord properties. In particular, the 400–550 m average temperature mid-fjord shows rapid variations that exceed 1°C—some transient and some not (Figure 6a,b). Over the period of the observations, the fjord AW

cooled from the start of 2010 to the start of 2013, after which it regained much of its heat content.

SEASONAL AND INTERANNUAL VARIABILITY OF HELHEIM GLACIER

In parallel to the ocean monitoring, we have tracked the seasonal and interannual changes in Helheim Glacier using remote-sensing data sets. Our observations show clear annual cycles in flow speed and terminus position (Figure 7). Like many tidewater outlet glaciers, Helheim Glacier begins to accelerate and retreat in early spring. Its peak speeds and minimum terminus positions are

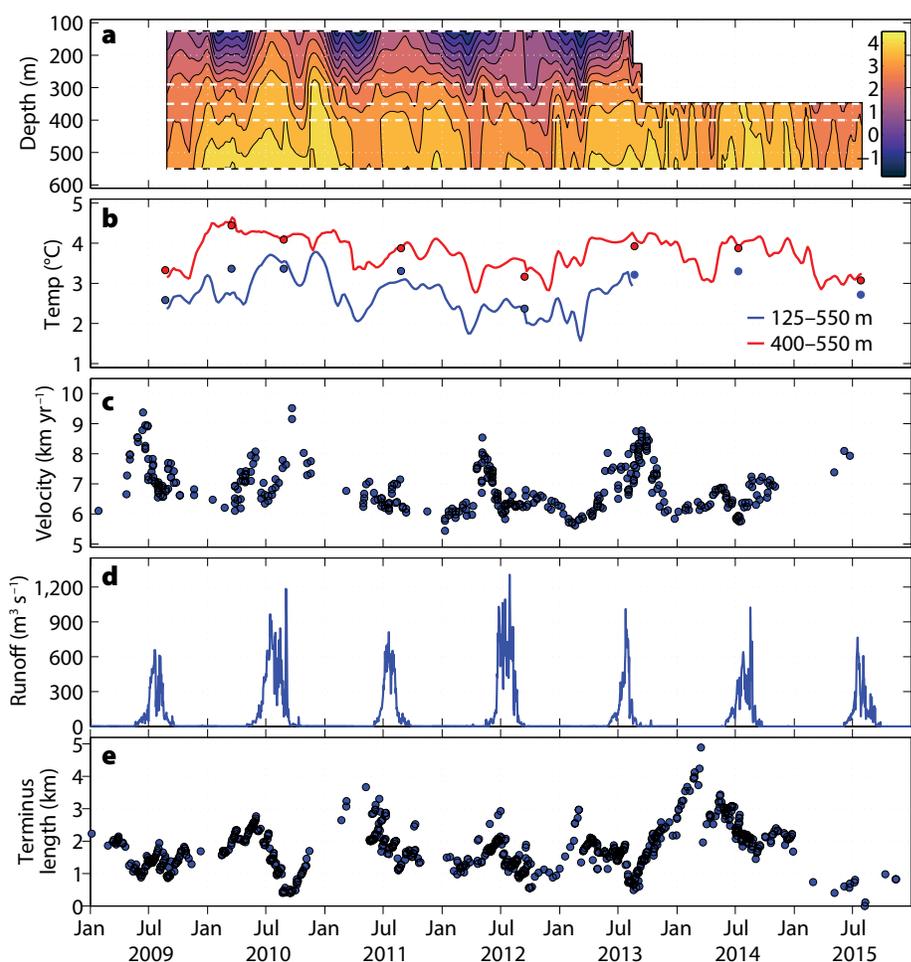


FIGURE 6. (a) Potential temperature (°C) time series from mid-fjord interpolated over available instrument depths (white dashed lines). (b) Potential temperature (°C) at mid-fjord averaged over two depth ranges, with colored dots showing the potential temperatures observed over the same depth range during each ship-based survey. (c) Glacier velocity (km yr⁻¹) width-averaged over the last 2 km of the terminus derived from radar (Joughin et al., 2011) and optical imagery (Howat, 2016; Rosenau et al., 2015). (d) Modeled runoff (m³ s⁻¹) for Helheim Glacier from 1 km downscaled RACMO v2.3 (Noël et al., 2016). (e) Width-averaged glacier terminus length (km) from a minimum position on August 8, 2015.

typically reached in late summer/fall (Figure 7). Superimposed on this seasonal cycle is a double peak in ice velocity (initial peak in May, after which the glacier decelerates until July, and a second larger peak in September). From year to year, however, there is considerable variability in the timing and magnitude of retreat (Schild and Hamilton, 2013).

DISCUSSION: LINKING GLACIER CHANGES TO OCEAN CHANGES

At the start of the Sermilik/Helheim project, we perhaps naively thought that knowledge of the seasonal to interannual variability in the fjord would provide key clues to interpreting the behavior of Helheim Glacier. Now, with an approximately seven-year record of properties in Sermilik Fjord, and improved understanding of what governs its variability, the problem seems more complex.

The main hypothesis we set out to test is whether Helheim Glacier's variability on seasonal or interannual time scales could be attributed to changes in submarine melting. One early objective was to determine if the observed warming

of the subpolar North Atlantic in the late 1990s had spread to the margins of Helheim Glacier. Given the absence of measurements from Sermilik Fjord, and the nearby shelf, the only way to answer this question was to determine if changes in the Irminger Sea propagated into the fjord. Based on the rapid exchange observed between the shelf and the fjord region, our findings suggest that as the Irminger Sea warmed in the late 1990s, the fjord also warmed (i.e., it is plausible that submarine melting increased at this time). Our observations, however, also indicate that submarine melting is not just a simple function of fjord temperatures.

Direct measurements of submarine melting at the edge of a calving glacier like Helheim are effectively impossible to obtain. Thus, we must rely either on indirect measurements or on parameterizations that link melting to measurable quantities. In practice, however, the indirect estimates are also challenging. On the glacier side, ice discharge cannot be effectively separated into calving and submarine melt components. On the ocean

side, melt rate estimates based on estimating heat transport across a fjord section (e.g., Motyka et al., 2003; Rignot et al., 2010) have very large uncertainties even when we attempt to remove the high-frequency fluctuations (Sutherland and Straneo, 2012). Indeed, from our moored record, it has become clear that estimates of melt rates for a glacial fjord with significant runoff (typical of Greenland) require closing both the heat and freshwater budgets and knowledge of the subglacial discharge (Jackson and Straneo, 2016). For Sermilik, flux estimates are statistically significant only in summer but, even then, submarine melt of the glacier face cannot easily be separated from iceberg melting within the fjord (Jackson and Straneo, 2016). Indeed, a recent study suggests that the latter might be larger than glacier melt during much of the year—in part because the submerged iceberg area is an order of magnitude larger than the submerged glacier area (Enderlin et al., in press). Similarly, our measurements indicate that the proposed idealized fjord circulations (such as the estuarine circulation), which could in principle be used to close the fjord's budgets, do not describe the observed circulation in Sermilik Fjord. Thus, testing the submarine melting hypothesis has to rely on postulated relations between submarine melting and measurable far-field quantities.

Melting of the glacier depends on the supply of available ocean heat to the ice. This supply is governed both by the ocean properties (temperature primarily) and by the mechanisms that govern the turbulent exchange across the ice/ocean boundary layer (e.g., Holland and Jenkins, 1999; Jenkins, 2011). In this region, the flow is thought to be dominated by the turbulent meltwater plume(s) (fed by submarine melt and/or subglacial discharge) at the glacier terminus. Recent theoretical and modeling studies highlight the fact that subglacial discharge can enhance melting by increasing the turbulent exchange (Jenkins, 2011; Xu et al., 2013; Sciascia et al., 2013). Indeed, a modeling study

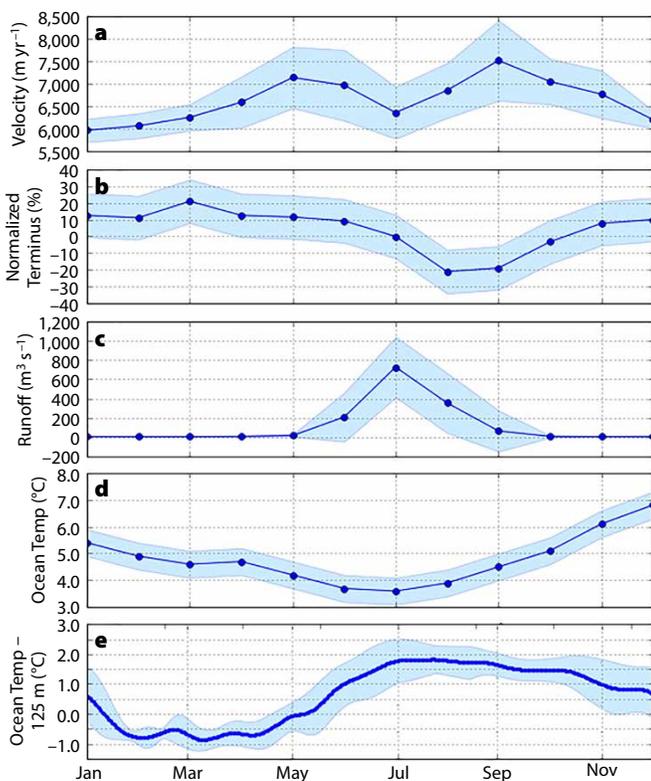


FIGURE 7. Seasonal variability of glaciological, atmospheric, and oceanic fields shown by monthly means for the period 2009 to 2015. The shading in every panel is \pm the standard deviation for each variable. (a) Width-averaged ice velocity near the terminus. (b) Terminus length, normalized by the minimum and maximum for each year. (c) Modeled runoff. (d) Seal-derived ocean temperature ($^{\circ}$ C) averaged over 0–400 m depth on the continental shelf outside the mouth of Sermilik Fjord (after Straneo et al., 2010). (e) Mid-fjord temperature at 125 m from moorings (monthly low passed).

based on the 2009 and 2010 Sermilik Fjord surveys showed summer melt rates, when subglacial discharge was present, to be an order of magnitude larger than non-summer melt rates (Sciascia et al., 2013). Even if these parameterizations have not been fully validated in the context of tidewater glaciers (see Straneo and Cenedese, 2015, for a review), they nonetheless provide a framework that relates submarine melting to external forcings. Based on these studies, we expect melt rates to increase with a warmer or thicker AW layer near the glacier and with increased subglacial discharge. However, the relative importance of these two factors is still unclear. Furthermore, our moorings do not measure the AW near the glacier but 30–50 km from the fjord. Thus, we rely on limited measurements showing that the AW variability in the along-fjord direction is small and assume that the AW near the glacier closely tracks that observed mid-fjord.

If we combine the glacier and ocean data, we observe that seasonally the pattern of glacier speed up and retreat is largely synchronized with the runoff/subglacial discharge cycle and, to some extent, with the mid-fjord temperature in the upper water column (Figure 7). This finding alone, however, does not validate or invalidate the submarine melt hypothesis. Specifically, the glacier's behavior could be due to increases in submarine melt as a result of increased subglacial discharge at the base of the glacier; alternatively, the onset and cessation of the seasonal speed up could indicate that Helheim Glacier is sensitive to subglacial water pressure when, in both early spring and late fall (corresponding to the onset and cessation of runoff, Figure 7c), an inefficient drainage system results in high basal water pressures. Furthermore, on a year-to-year basis, the magnitude and timing of acceleration and retreat are not easily correlated to patterns in runoff; this finding is consistent with analysis of a longer time series of Helheim Glacier terminus behavior by Schild and Hamilton (2013).

From the perspective of ocean temperature, Helheim Glacier's seasonal retreat roughly coincides with warming of mid-fjord temperatures in the upper 200 m (Figure 7e). Because these waters are warmer than those found on the shelf, and based on their properties, we attribute this warming to the upwelling and export of relatively warm GMW into the upper water column driven by subglacial discharge. This highlights the interplay of ocean variability and subglacial discharge in affecting conditions at the edge of Helheim Glacier. Interannually, the weak cooling of the AW from early 2010 to 2013 (Figure 6a,b) is perhaps consistent with the slowdown of Helheim Glacier over this same period (Figure 6c)—but given the limited length of the record, it is impossible to establish a significant correlation. Similarly, it is challenging to attribute interannual variations in the retreat to changes in subglacial discharge (Figure 6c,d). What we can say is that given the rapid exchange of properties between the shelf and the fjord, it is very likely that the fjord waters warmed (and submarine melting increased) as a result of the subpolar North Atlantic warming that occurred in the late 1990s.

Overall, our measurements also show that a seven-year time series is still too short to extract meaningful correlations between atmospheric forcing, ocean forcing, and glacier behavior. From year to year, both the glacier and the fjord exhibit considerable variability, but attempts to link them through simple hypotheses have failed. Likely, the interannual variability of Helheim Glacier is controlled by a number of forcings that are modulated by the glacier's geometry at its grounding line. Furthermore, bedrock topography and bathymetry are likely to exert a dominant control on the glacier's ability to advance and retreat.

From the perspective of meltwater export, our measurements show that much of Greenland's meltwater, in both summer and winter, is exported in the form of GMW, where the meltwater is strongly diluted by ambient water. This

result is consistent with a recent study using noble gases that shows meltwater constitutes 1%–5% by volume of the GMW near-terminus (Beaird et al., 2015). The distribution of GMW over several hundred meters in the upper layers of the fjord implies that care must be taken in prescribing Greenland meltwater as a relatively fresh surface boundary condition in ocean models addressing the impact of Greenland melt on ocean circulation (e.g., Boning et al., 2016). Seasonally, the export peaks in summer/fall when subglacial discharge contributes to mean exchange flow (Jackson and Straneo, 2016). At this time, GMW transiting the fjord contains a significant fraction of subglacial discharge compared to waters formed in winter, which mostly contain submarine melt (Straneo et al., 2011). Finally, it is likely that icebergs calved at the head of Sermilik Fjord melt considerably within the fjord, thus contributing large volumes of additional meltwater.

SUMMARY AND FUTURE OUTLOOK

Measurements obtained in Sermilik Fjord since 2008 have advanced our understanding of the properties, circulation, and forcings of a major Greenland glacial fjord. To date, these measurements have been used in 24 publications and three review papers. In addition to achieving bathymetric measurements on the shelf and the fjord, major findings include: the presence and rapid renewal of warm AW in the fjord, the subsurface export of glacially modified waters, the importance of subglacial discharge and ocean stratification for melting at the edge of the glacier, the importance of shelf-forced circulations, quantification of iceberg speed and melt rates, and quantification of meltwater export from the fjord in summer. Despite this progress, our understanding of how these findings translate into variations in the submarine melt rate at the edge of Helheim Glacier is still limited. Furthermore, we have shown that it is almost impossible to derive meaningful submarine glacier melt rates from

transport measurements in the fjord. Finally, the source of the variability in the fjord waters at depth is still largely unknown. In terms of attributing glacier response to ocean changes or, more specifically, to submarine melt variability, during our observational period it has been challenging to identify any simple links between glacier behavior, subglacial discharge, and ocean variability. We attribute this difficulty to the multitude of factors that affect glacier variability, including bedrock configuration, surface melt and other glaciological processes.

In terms of the export of meltwater from the fjords, our measurements show that meltwater is strongly modified in the near-glacier region through rapid, turbulent dilution by ambient water. The implication is that Greenland's meltwater enters the large-scale ocean circulation not necessarily as a surface, relatively fresh discharge but via the subsurface export of glacially modified waters. Furthermore, the timing and rate of export depend on the circulation within the fjord, including potential feedbacks with glacial discharge. Presently, there is no simple model that can provide export estimates for a range of fjords/glaciers; thus, improved understanding is needed to provide adequate boundary conditions for large-scale ocean models that take into account mass loss from the Greenland Ice Sheet.

Our combined analysis and observations indicate that long time series of oceanic, glaciological, and atmospheric variables are needed to fully understand the coupling between the ocean, the glacier, and the atmosphere. Recent efforts to establish a Greenland-wide Ice Sheet-Ocean Observing System (GrIOOS) would thus be very beneficial to our ability to interpret Greenland Ice Sheet variability and project future changes. The collection of such time series by several different systems is critical for testing simple mechanistic links, identifying relevant processes, and providing constraints for modeling experiments. Without these measurements

to inform our understanding, we would continue to struggle in testing empirical models of glacier-ocean interaction. Finally, working at the margins of a large glacier, such as Helheim, has required the progressive development and modification of traditional observational techniques and has benefited from multiple failures. Sharing of these experiences within the community has enabled many more groups to work successfully in Greenland's glacial fjords. 

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AUTHORS

Fiammetta Straneo (fstraneo@whoi.edu) is Senior Scientist, Woods Hole Oceanographic Institution, Woods Hole, MA, USA. **Gordon S. Hamilton** is Professor, Climate Change Institute & School of Earth & Climate Sciences, University of Maine, Orono, ME, USA. **Leigh A. Stearns** is Associate Professor, Department of Geology, University of Kansas, Lawrence, KS, USA. **David A. Sutherland** is Assistant Professor, Department of Geological Sciences, University of Oregon, Eugene, OR, USA.

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