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Oceans Melting Greenland

Early Results from NASA's Ocean-Ice Mission in Greenland

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Photo taken from Greenland's southwestern coastline in July and August 2015 during Phase 1 of the TerraSond/*Cape Race* bathymetry survey. *From https://omg.jpl.nasa.gov/portal/gallery/2015-survey-p1*

ABSTRACT. Melting of the Greenland Ice Sheet represents a major uncertainty in projecting future rates of global sea level rise. Much of this uncertainty is related to a lack of knowledge about subsurface ocean hydrographic properties, particularly heat content, how these properties are modified across the continental shelf, and about the extent to which the ocean interacts with glaciers. Early results from NASA's five-year Oceans Melting Greenland (OMG) mission, based on extensive hydrographic and bathymetric surveys, suggest that many glaciers terminate in deep water and are hence vulnerable to increased melting due to ocean-ice interaction. OMG will track ocean conditions and ice loss at glaciers around Greenland through the year 2020, providing critical information about ocean-driven Greenland ice mass loss in a warming climate.

INTRODUCTION

Melting of the Greenland Ice Sheet

The acceleration of global mean sea level rise over the past several decades has been driven, in part, by increased melting of the Greenland Ice Sheet (Nerem et al., 2010). Greenland ice mass loss has increased sharply since the 1990s due to a combination of increased ice discharge and surface melting/runoff (Howat et al., 2007; Enderlin et al., 2014). Over the satellite altimetry period (1992–present), the rate of global mean sea level rise has nearly doubled relative to its twentieth century average to 3.2 mm yr^{-1}, with ~0.75 mm yr^{-1} now attributable to the net transfer of water from the melting of Greenland's grounded ice (Shepherd et al., 2012; Church et al., 2013; Watkins et al., 2015).

Since 2003, Greenland Ice Sheet mass loss has been greatest in its southeast and northwest parts where widespread glacial acceleration has also been observed (Moon et al., 2012). Glacier acceleration has been attributed to several factors, including reduced basal and lateral sidewall resistive stresses following terminus retreat and reduced ice mélange back stress (Vieli and Nick, 2011; Joughin et al., 2012). Both glacier front retreat and diminished ice mélange (a mix of icebergs and sea ice) may be attributed to increased submarine melting and calving following the warming of ocean waters on Greenland's continental shelf and proximate offshore basins beginning in the late 1990s (Holland et al., 2008; Straneo et al., 2013; Straneo and Heimbach, 2013). Warming ocean waters in Greenland's extreme northwest and northeast has also been implicated in the calving and retreat of the Petermann, Humboldt, and Zachariæ Isstrøm Glaciers (Box and Decker, 2011; Münchow et al., 2014; Mouginot et al., 2015). While it is very likely that a warming ocean is an important factor for Greenland Ice Sheet mass loss, quantifying its contribution relative to other possible factors, such as atmospheric warming and increased surface melting, is a major outstanding research challenge for the community (Truffer and Motyka, 2016).

Given the logistical challenges associated with observing the ocean surrounding Greenland (sea ice, harsh weather, iceberg-chocked fjords), it is unsurprising that relatively few in situ ocean measurements have been made close to the ice sheet (Straneo et al., 2012). The pathways of ocean currents transporting heat to Greenland's glacial fjords are shaped by seafloor geometry (Gladish et al., 2015a,b), yet large gaps exist in observations of seafloor shape and depth. Recent progress has been made in monitoring large-scale ice volume and mass changes (e.g., van den Broeke et al., 2009; McMillan et al., 2016) but not at the spatial resolutions required to characterize changes in individual glaciers. Despite increased interest in better understanding the processes linking ocean warming and ice sheet mass loss, observations of ocean temperatures and changes in glaciers near ocean-ice interfaces are available for only a small number of fjord systems. More detailed surveys are needed to understand basic processes such as how water masses are modified as they move toward the ice sheet and to provide the diversity of observations required so that local findings about ocean-ice interaction can be generalized across Greenland's more than 200 marine-terminating glaciers.

Dynamic changes in the marine-terminating glaciers of Greenland and Antarctica were cited by the 2007 and 2013 Intergovernmental Panel on Climate Change reports as being the largest source of uncertainty in sea level rise projections (Lemke et al., 2007; Church et al., 2013). NASA's Oceans Melting Greenland (OMG) mission will provide the first opportunity to quantify the relationship between a warming ocean and ice loss in Greenland by collecting observations from 2015 through 2020 that address each of these knowledge gaps. Specifically, our goal is improved understanding of how ocean hydrographic variability around the ice sheet impacts glacial melt rates, thinning, and retreat. OMG's investigations into Greenland ocean-ice sheet interaction will lead to new insights about past sea level changes and reduce the uncertainties in our future projections of sea level rise.

OMG: A GREENLAND-WIDE EXPERIMENT

The OMG mission is guided by the overarching science question: *To what extent is the ocean melting Greenland's glaciers from below?* To address this question, the mission formulated the following approach:

1. Observe the year-to-year changes in the temperature, volume, and extent of warm, salty Atlantic Water on the continental shelf.
2. Observe the year-to-year changes in the extent and height of all marine-terminating glaciers.
3. Observe submarine topography (bathymetry) to reveal the complex network of underwater troughs and canyons connecting glacial fjords with the continental shelf.
4. Investigate the relationship between the observed variations in Atlantic Water properties and glacier extent and height.

Airborne eXpendable conductivity, temperature, and depth (AXCTD) surveys will be conducted in September of each year to observe interannual variations in the hydrographic properties of Atlantic Water on the shelf, and an interferometric radar will provide annual measurements of the extent and height of marine-terminating glaciers. Bathymetric observations will be made using ship-based sonars and airborne gravimetry. Statistical analysis of these data and a suite of variable-resolution data-assimilating ocean general circulation models will be utilized to make new quantitative estimates of ice sheet mass loss as a function of ocean warming.

The Ocean

The Greenland Ice Sheet is surrounded by the North Atlantic subpolar gyre (which spans the Labrador and Irminger Seas), Baffin Bay, the Arctic Ocean, and the Greenland Sea (Figure 1a). A boundary current system circulates clockwise around Greenland's periphery from Fram Strait in the northeast to Nares Sound in the northwest (Figure 1b). These boundary currents carry two distinct water masses: cold, fresh water that is relatively light and of Arctic origin (hereafter Polar Water), and warm, salty water that is denser and originates in the subtropics (hereafter Atlantic Water). During its transit in the boundary currents around Greenland, warm Atlantic Water progressively loses most of its heat through lateral mixing and exchange with the relatively colder offshore basins (Rignot et al., 2012a; Straneo et al., 2012; Kawasaki and Hasumi, 2014).

At select locations, deep (>500 m) submarine canyons also known as cross-shelf troughs cross the shallow (<200 m) continental shelf. Conserving potential vorticity and essentially following contours of constant depth, dense Atlantic Water diverges from the boundary current and is steered into these canyons where it flows toward the ice sheet beneath the buoyant Polar Water layer. Where these canyons are continuous with glacial fjords, Atlantic Water may penetrate to the ocean-glacier interface.

Circulation in front of a glacier may be strongly affected by the injection of a fresh, buoyant outflow of meltwater from its base (known as subglacial discharge). Subglacial discharge is primarily sourced from accumulated surface meltwater from across glacial drainage basins. Because it is relatively light, the outflow rises quickly along the ice face in the form of a turbulent plume. As it ascends, the plume may entrain warm Atlantic Water, enhancing the rate of ocean heat transfer to the ice and thereby increasing subaqueous melting (Motyka et al., 2003; Jenkins, 2011; Sciascia et al., 2013; Xu et al., 2013).

While the North Atlantic is arguably the most studied region of the world ocean, previous research has mainly focused on processes in the offshore basins such as deep convection and dense water mass formation (e.g., The Lab Sea Group, 1998; Pickart et al., 2002). Argo profiling floats provide abundant temperature (T) and salinity (S) measurements in the upper 2,000 m, but their design precludes sampling on Greenland's shallow shelves. Oceanographic field programs to collect data on the relationship between hydrographic variability and Greenland's glaciers have focused on a small number of major fjords. Of these, only Ilulissat

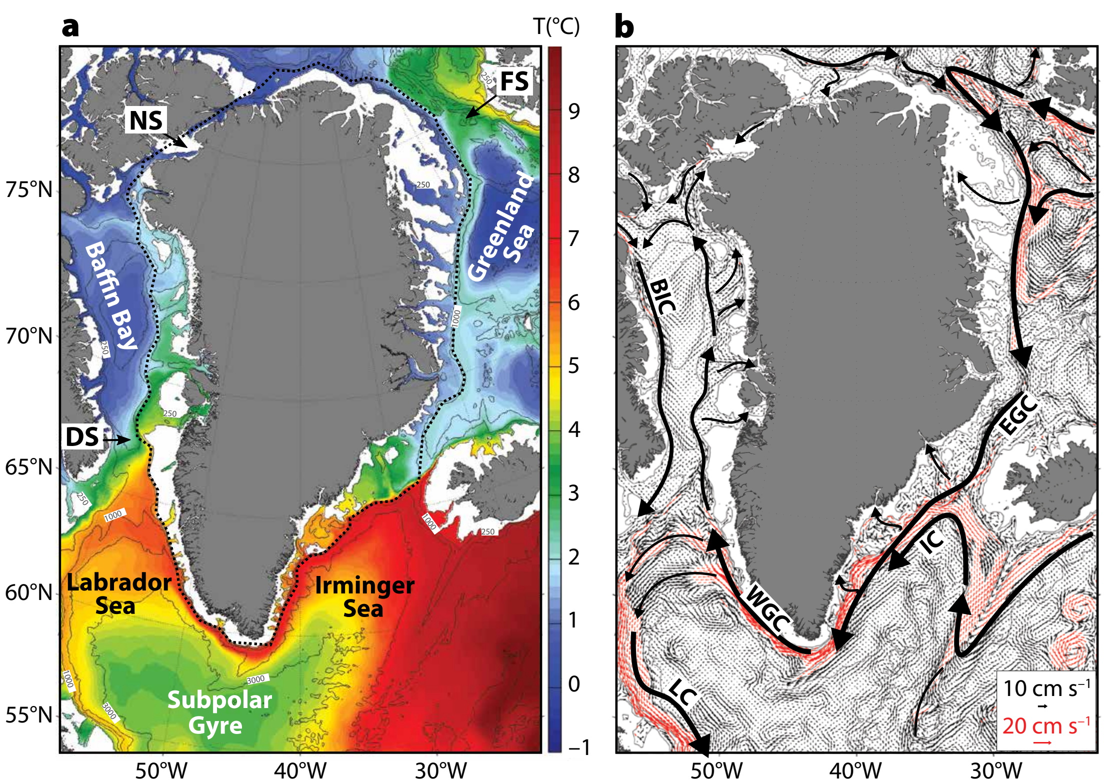

FIGURE 1. (a) Ocean temperature at 250 m from a 4 km horizontal resolution simulation by the MITgcm ocean circulation model (Rignot et al., 2012a). The boundary of Greenland's shelf is denoted by the dotted line, roughly corresponding to the 1,000 m depth contour. The locations of Fram Strait (FS), Davis Strait (DS), and Nares Strait (NS) are also indicated. (b) Annual mean ocean velocity at 250 m from the same simulation, depicting major currents: East Greenland Current (EGC), West Greenland Current (WGC), Irminger Current (IC), Baffin Island Current (BIC), and Labrador Current (LC).

Fjord in West Greenland (Gladish et al., 2015b) and Sermilik Fjord in Southeast Greenland (Vaňková and Holland, 2016) have been targeted with repeat CTD surveys and instrumented with seafloor moorings for more than five years.

Each year from 2016 through 2020, OMG will collect 250 full-depth profiles of temperature and salinity on the shelf and in fjords around Greenland using AXCTD sensors. The scientific objective of the AXCTD campaign (OMG, 2016a) is to measure the interannual variability of Atlantic Water on Greenland's continental shelf to enable the formulation of quantitative relationships between changing ocean temperatures and melting of marine-terminating glaciers.

Deployment of an AXCTD is performed manually by a flight engineer through a tube installed in the lower aft fuselage of a modified NASA G-III aircraft. Following release, the AXCTD parachutes to the ocean surface, whereupon its instrument package separates from the floating communication module and descends at a known rate to the seafloor trailing a wire. During its descent, the instrument package continually transmits data through the wire to the communication module, which relays the data to the aircraft via radio. The entire AXCTD unit self-scuttles once the instrument package reaches the seafloor. As AXCTDs require open water to operate, AXCTD campaigns are scheduled for late summer/early fall—coinciding with the annual sea ice extent minimum—and drop sites exclude narrow fjords with high concentrations of sea ice, icebergs, or ice mélange.

To design the AXCTD sampling strategy, a regional, 4 km horizontal resolution configuration of the Massachusetts Institute of Technology ocean-ice general circulation model (MITgcm) was analyzed to characterize ocean temperature and salinity correlation length scales on Greenland's continental shelf (see Rignot et al., 2012a). A roughly 50 km probe spacing was found to be sufficient to capture the mean spatial patterns of hydrographic variability on the shelf. After excluding most of the southwest shelf because of its small number of marine-terminating glaciers and all of the northern Arctic Ocean-facing shelf because of extensive multiyear sea ice, we determined that the spatial patterns of hydrographic variability over the remaining shelf could be inferred from about 225 spatially distributed vertical profiles of temperature and salinity.

Hydrographic measurements on the shelf at depths below the Polar Water temperature minimum and above the Atlantic Water temperature maximum only provide indirect information about Atlantic Water properties. Therefore, AXCTD drops sites were preferentially situated in deeper troughs (>350 m) where possible. In addition, we avoided locations where the ocean simulations indicated energetic turbulent circulation manifesting as large hydrographic variations over short time periods and distances. By avoiding these high-variability regions and targeting deeper troughs, the large-scale interannual variations of Atlantic Water temperature and salinity will be captured with our AXCTD sampling strategy (see Figure 2).

Greenland's Glaciers

The Greenland Ice Sheet has more than 200 land-terminating and marine-terminating outlet glaciers that drain ice from its interior outward toward the coast. The southeast, west, and northwest sectors of the ice sheet are characterized by marine-terminating glaciers without significant floating ice tongues. The few marine-terminating glaciers with floating extensions longer than a few kilometers are found in North and Northeast Greenland. The southwest sector of the ice sheet is predominantly drained by slow-moving, land-terminating glaciers.

The flow of marine-terminating glaciers has been shown to be highly sensitive to changes in ocean temperature and circulation. Following a sufficiently large

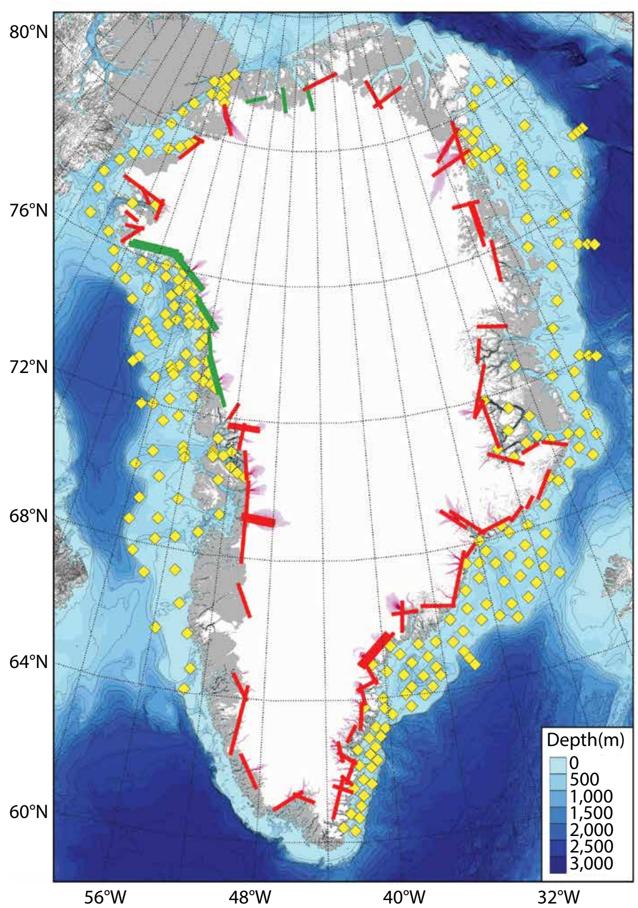

FIGURE 2. The sampling strategy for the yearly Airborne eXpendable conductivity, temperature, and depth (AXCTD) and Glacier and Ice Surface Topography Interferometer (GLISTIN-A) campaigns. Over most of the continental shelf, AXCTD probe spacing (represented by yellow diamonds) is approximately 50 km, adequate to resolve the large-scale spatial variations of Atlantic Water. AXCTD campaigns will take place in late September and early October when seasonal sea ice cover is near its annual minimum. GLISTIN-A swaths, shown as red 10 km bands are located across or near the faces of most of Greenland's marine-terminating glaciers. Green swaths in the northwest and north sector are lines that were missed in the March 2015 survey due to instrument problems.

increase in submarine melt rate, a glacier can exhibit dynamic destabilization that triggers a rapid flow acceleration, thinning, or retreat until a new, dynamically stable geometric configuration is achieved (Meier and Post, 1987). Exactly how any individual glacier responds to submarine melt rate perturbations depends on several factors, including fjord and bedrock geometry, bed composition, ice rheology, and subglacial water transport (Nick et al., 2009; Rignot et al., 2016a,b). In general, ocean-induced ice flow acceleration and dynamic thinning are greatest in the vicinity of glacier termini where ice flow is concentrated in narrow fjords.

The ice element of OMG consists of annual surveys of glacier surface elevation (OMG, 2016b) using NASA's high-resolution airborne Glacier and Ice Surface Topography Interferometer, GLISTIN-A, hereafter GLISTIN (Moller et al., 2011). OMG uses the GLISTIN radar to map the entire periphery of the Greenland Ice Sheet where glaciers terminate in the ocean. The first survey, conducted in March 2016, provides a baseline against which future changes in glacier surface topography will be determined.

Repeat measurements of four parameters are commonly assessed to quantify glacier changes: surface elevation, frontal position, ice flow velocity, and ice mass (gravity). Of these four parameters, GLISTIN directly measures two, changes in surface elevation and changes in frontal position. Changes in glacier mass can be inferred by combining GLISTIN ice elevation and frontal change measurements with estimates of changes in the firn (granular snow) air content of the ice column.

Installed on a NASA G-III aircraft, the GLISTIN Ka-band radar returns surface elevation data in 10–12 km wide swaths bounded within its 15°–50° off-nadir look angle range. GLISTIN can achieve a 20 cm vertical precision at a horizontal resolution of 3 m in the near range (15° off-nadir) and 38 m in the far range (50° off-nadir), independent of cloud conditions or solar illumination. GLISTIN's systematic errors from volume scattering average about 30 cm under dry snow conditions (Hensley et al., 2016). We anticipate that the effect of systematic errors on estimates of interannual surface elevation change may be somewhat mitigated because systematic errors could largely cancel after differencing observations collected at the same time of year. Comparisons between coincident or nearly coincident surface elevations measured by GLISTIN and NASA's Airborne Topographic Mapper laser altimeter flown during Operation IceBridge will be made to refine GLISTIN uncertainty estimates.

To maximize the radar energy backscatter, GLISTIN campaigns are flown in late winter before the onset of the spring melt season, as dry frozen surfaces are more reflective than wet melting surfaces. Opting for GLISTIN involved compromising among spatial coverage, spatial resolution, and vertical precision to achieve the mission requirement of observing highly heterogeneous surface elevation changes along the ice sheet periphery. GLISTIN's lower vertical accuracy relative to laser altimetry is offset by its significantly wider swath, higher spatial resolution, and insensitivity to cloud conditions and solar illumination.

Final calibration of GLISTIN elevation maps will use stationary targets such as rocky outcroppings and near-stationary targets such as slowly changing ice surfaces wherever possible. Fortuitously, elevation data from suitable calibration targets are abundant, thanks to Airborne Topographic Mapper campaigns.

As the orientation of glacier flow lines vary and the spatial distribution of front locations is complex, defining straight radar flight lines to map multiple glaciers in a single swath requires trade-offs. Glaciers are prioritized by considering ice volume discharge, retreat/advance history, and proximity to other glaciers with dissimilar retreat and advance histories. The highest priority is assigned to retreating and thinning glaciers with large volume discharges that are proximate to glaciers with dissimilar retreat patterns. A small number of the highest priority glaciers are allocated multiple parallel lines (e.g., Jakobshavn Isbræ) or overlapping perpendicular lines near their termini (e.g., Zachariæ Isstrøm and 79N).

The GLISTIN survey plan captures nearly all of Greenland's marine-terminating glaciers in 82 swaths with an average length of 103 km covering ~85,000 km^2.

Bathymetry and the Ocean-Ice Relationship

Seafloor geometry plays a major role in determining whether subsurface Atlantic Water reaches marine-terminating glaciers. Deep troughs excavated from the seafloor by advancing glaciers during earlier glacial periods allow warm, salty Atlantic Water to cross the shelf beneath a shallow layer of cold, less saline Polar Water. In some locations, these deep troughs are interrupted by shallow sills, uneroded bedrock, or terminal moraines created by debris accumulated by glaciers in more advanced positions. These sills can isolate tidewater glaciers from Atlantic Water by blocking or retarding its transport into the fjords (Gladish et al., 2015a,b). Abrupt bathymetric features may also influence turbulent mixing rates and thus water modification over the continental shelf and in the trough-fjord systems.

Consequently, detailed knowledge of the continental shelf and fjord bathymetry is essential for ascertaining which glaciers are vulnerable to interannual Atlantic Water temperature variations. Despite the importance of bathymetric data, large gaps remain on the inner continental shelf, and reliable measurements are nonexistent for the vast majority of fjords. This lack of data is most acute within ~50 km of the coast between the inner shelf and glacier termini where sea ice, icebergs, ice mélange, and dangerous uncharted rocks and shoals have impeded past charting efforts.

The recent compilation of high-resolution fjord bathymetry collected over a 10-year period in the Uummannaq and

Vaigat Fjords of Central West Greenland provides a compelling demonstration of the importance of thoroughly mapping fjord bathymetry for interpreting past and predicting future ocean-ice interaction (Rignot et al., 2016a). Indeed, the success of these mapping efforts inspired OMG's bathymetric campaigns (OMG, 2016c).

In summer 2015, OMG conducted its first seafloor measurement campaign: a ship-based multibeam sonar survey to map key regions of the shelf and glacial fjords in Northwest Greenland. The mission's first airborne gravimetry survey followed in the spring of 2016, focusing on a band along the inner shelf in the same region (see Figure 3a).

The sonar and gravimetry campaigns are complementary. Airborne gravimetry can quickly map gravitational anomalies along an aircraft flight line but requires a spatial averaging kernel of ~1.5 km to reduce measurement uncertainties to acceptable levels. The acquisition of sonar bathymetry is slower, but its spatial and vertical resolutions are superior. Thus, narrow fjords and glacier faces are best mapped using sonar while large areas of open water outside of fjords and away from other coastal features are efficiently mapped using airborne gravity.

The mission's primary sonar is a multibeam echosounder that was mounted on the hulls of M/V *Cape Race* in 2015 and R/V *Neptune* in 2016 under a contract with TerraSond Ltd. The multibeam sonar emits beams in a 150-degree swath from the port and starboard sides of the vessel to progressively map a corridor of the seafloor. Depending on seafloor and sea-state conditions, the sonar's swath width ranges between three and four times the water depth. Differential GPS data as well as pitch, roll, heave, and heading sensors are used to correct the raw soundings based on vessel attitude at the time of the sonar ping. Profiles of seawater sound speed calculated using CTD data are used to convert the raw time-of-flight measurements to a corrected range.

A single beam echosounder survey supplements the multibeam effort. Operated by the Oceans Research Project on the R/V *Ault* (2015 and 2016) sailboat, this survey mapped Inglefield Gulf and Murchison Sound in northern Baffin Bay. Unlike the wide swath mapped by the multibeam sonar, the single beam sonar traces a narrow profile of seafloor depth directly beneath the vessel.

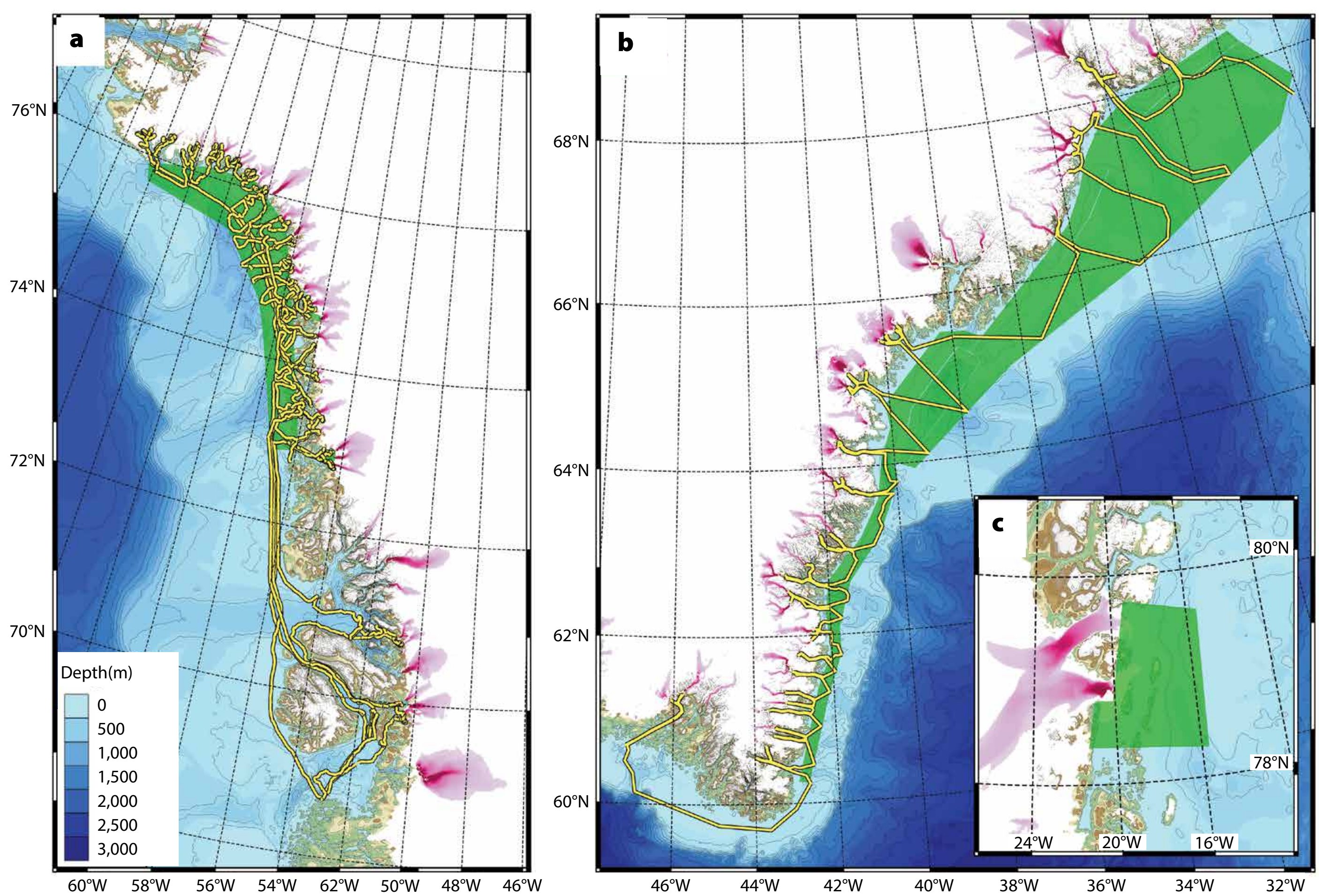

FIGURE 3. The sampling strategy for the multibeam sonar ship survey, shown as yellow lines, and airborne gravimetry (AIRGRAV) campaigns, indicated by green polygons. The multibeam survey in the (a) northwest (7,800 km) occurred in August 2015 while the (b) southeast survey (5,510 km) occurred in September 2016. Green polygons show AIRGRAV survey regions. Line spacing within the AIRGRAV polygons are generally 4 km offshore, reducing to 2 km closer to the coast. In the (c) northeast sector, no ship survey is possible and the AIRGRAV survey line spacing is 2 km.

The seafloor mapping campaign around the ice sheet focuses on three areas with numerous marine-terminating glaciers: the northwest, the southeast, and the northeast. Existing bathymetric data in these sectors are mainly limited to the outer and mid shelves, leaving the inner shelves and fjords almost entirely unmapped (Jakobsson et al., 2012).

The objectives of the sonar survey are twofold: (1) to provide high-precision ground-truth bathymetry to calibrate the gravimetry data, and (2) to provide improved seafloor geometry for the ocean general circulation model. The plan involves a combination of alongshore and cross-shelf survey lines that extend from the offshore edges of the airborne gravity areas to the glacier termini. The final ship survey includes ~9,000 linear kilometers over 45 days in the northwest and ~5,500 linear kilometers over 28 days in the southeast.

The OMG airborne bathymetry survey (OMG, 2016d) is accomplished using the AIRGRAV gravimeter owned and operated by Sander Geophysics Ltd (SGL). AIRGRAV has three orthogonal accelerometers mounted on a three-axis gyro-stabilized Schuler-tuned inertial platform installed in the cabin of a Twin Otter aircraft. Precision positioning of the aircraft is determined through dual frequency GPS and differential GPS.

Free-air gravity anomalies measured by AIRGRAV arise from variations in mass beneath the aircraft. A major component of the mass signal comprises the changing proportion of seawater to rock beneath the aircraft as the seafloor depth varies. Seafloor depth can be inferred by inverting the observed gravity anomalies. An accurate inversion of seafloor depth from gravity data requires knowledge of the spatially varying seafloor density. For this mission, seafloor density is estimated using ground-truth sonar data and prior geological findings about the composition of Greenland's shelf.

AIRGRAV survey regions correspond to the unmapped areas of the inner to mid shelves in the northwest, southeast, and northeast sectors. Logistical challenges precluded a complementary sonar survey in the northeast sector around Zachariæ Isstrøm and 79N, neighboring glaciers with dissimilar dynamical behaviors (Box and Decker, 2011; Moon et al., 2012; Mouginot et al., 2015). The AIRGRAV survey consisted of multiple parallel alongshore flight lines separated by 2 km near the coast and 4 km further offshore. This flight line spacing strategy allowed a considerable fraction of the data-poor shelf to be mapped while also ensuring that the resolution of the nearshore bathymetry was adequate for merging with the sonar data.

Numerical Modeling

The ocean data collected by OMG will provide unprecedented large-scale synoptic snapshots of the hydrographic state around the Greenland Ice Sheet. To better understand how warm Atlantic Water reaches glacier termini, OMG will use global and regional configurations of the MITgcm (Marshall et al., 1997).

Specifically, OMG will leverage global ocean state estimates (dynamical syntheses of in situ and remotely sensed ocean and ice data with numerical models) developed by the Estimating the Circulation and Climate of the Ocean (ECCO) consortium. On the global scale, the ECCO Version 4 Central Production (V4-CP) synthesis provides an excellent reconstruction of basin-scale ocean variability from 1992 to present at 40 km horizontal resolution (Forget et al., 2015). While useful for capturing observed basin-scale warming in the North Atlantic Ocean since the mid-1990s, the horizontal resolution of the V4-CP is inadequate for simulating Greenland's narrow and energetic boundary currents and cross-shelf circulation and heat transport. Because explicitly simulating these currents is required for studying ocean heat transport to the ice sheet, we will downscale the 40 km V4-CP state estimate into a series of nested, regional model configurations with a progressively finer horizontal resolution.

When configured with new bathymetry measurements from our sonar and AIRGRAV surveys, these ocean model simulations will be used to investigate how temperature and salinity in the fjords are modulated by the large-scale temperature and salinity variations on the shelf and in the more distant offshore basins. In addition, fjord temperature variability in the simulations will be compared with observations of ice loss from individual glaciers measured during our GLISTIN surveys to further explore the relationship between ocean warming and ice loss.

PRELIMINARY RESULTS FROM THE MISSION

Next, we present a preliminary analysis of some of the data collected to date by the OMG mission. Note that the airborne remote-sensing gravimetry and radar data are still undergoing post-processing for calibration and error correction.

Ocean Bathymetry

Sonar Survey

In 2015, OMG collected sonar bathymetry data in central west and northwest Greenland using two vessels. M/V *Cape Race*, equipped with a multibeam sonar, collected swath bathymetry along 9,000 linear kilometers on the inner shelf and in numerous glacial fjords. *Cape Race* and R/V *Ault*, the latter equipped with a single beam sonar, collected data between southern Disko Bay (68°N) and the Savissuaq glaciers in northern Melville Bay (76°N, 67°W). Additional single beam data were collected further north to Dodge Glacier (78.2°N, 72.7°W).

Figure 3 shows the 2015 *Cape Race* survey, including the many deep channels that were discovered on the inner shelf and mapped along their often sinuous paths. Not all fjords could be mapped to the glacier faces due to the presence of icebergs and ice mélange, and poor weather limited offshore mapping in Melville Bay.

Even after discovery, not all deep channels connecting the cross-shelf troughs with glacial fjords could be completely mapped. One such example is shown in the inset of Figure 4a near 74.5°N, 57°W where two deep (>500 m) channels were found. Despite surveying these channels during several alongshore crossings and following them inshore toward Hayes Glacier, a large area between them remained unmapped.

Ultimately, the *Cape Race* survey exceeded expectations and included major successes such as mapping to the faces of several major marine-terminating glaciers: Sermeq Silarleq, Kangigleq, Upernavik, Nunatakassap Sermia, Qeqertarsuup Sermia, Ussing Braeer, Cornell, Illullip Sermia, Alison, Hayes, Steenstrup, Dietrichson, Sverdrup, Nansen, Rink, Docker Smith, Gade, Carlos, Yngvar Nielsen Brae, Helland, and Savissuaq. Of these, collection of data in Upernavik Fjord stands apart as a particularly remarkable achievement given the exceptional challenge of safely navigating the extremely heavy ice conditions caused by the fjord's numerous calving glaciers.

Airborne Gravimetry Survey

The AIRGRAV campaign was completed in 2016 and consisted of the successful mapping of the three survey regions shown in Figure 3, totaling 25,000 km^2 in the northwest, 100,000 km^2 in the southeast, and 15,000 km^2 in the northeast. The uncorrected free air gravitational anomalies in the northwest and southeast sectors are plotted in Figure 4 beneath the sonar data, where it exists.

At the largest scales, the gravitational anomaly fields are dominated by gradients that result from geological variations in shelf density, which will be removed during processing. On smaller scales, however, useful information can be gleaned even from the raw data. To illustrate, we show the gravitational anomalies in the vicinity of the two deep partially mapped channels on the inner shelf near 74.5°N, 57°W (Figure 4a). The negative gravitational anomaly pattern matches the locations of the deep channels mapped by *Cape Race*. The gravitational anomaly data in the sonar data gap between the deep channels clearly indicate the existence of a curving continuation of a connecting channel. Based on this early result, we are confident that our AIRGRAV data will prove useful for filling in many of the remaining gaps in the shelf bathymetry data.

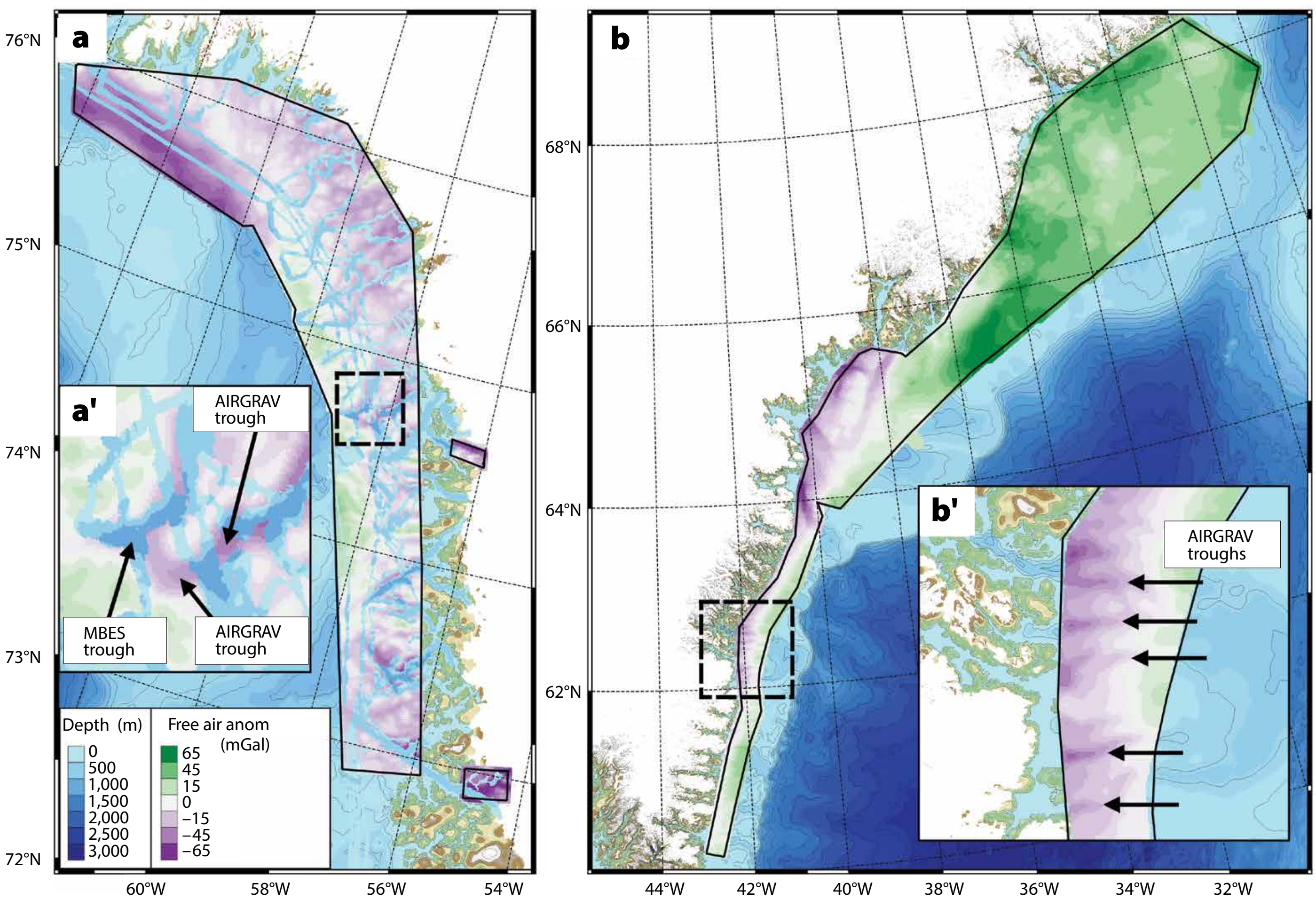

FIGURE 4. Free air gravitational anomalies measured by AIRGRAV and bathymetry from multibeam sonar in the (a) northwest and (b) southeast sectors. AIRGRAV anomalies clearly indicate the continuation of a deep trough partially mapped by M/V *Cape Race* in the northwest (a') and several deep troughs emanating offshore from fjords in the southeast (b'). Location of insets (a') and (b') are marked as dashed boxes in (a) and (b), respectively. Large gradients in gravitational anomalies in the alongshelf direction are mainly due to geological variations of shelf density, which will be removed during processing.

Ocean Hydrography

During the ship surveys, 377 CTD casts were taken, many in fjords with no known prior hydrographic measurements. Altogether, these data constitute a major new contribution to the small existing set of ocean temperature and salinity measurements in Greenland's northwest sector.

In Baffin Bay, six major cross-shelf troughs connect the outer shelf break with Greenland's inner shelf and fjords between Disko Bay (68°N) and Inglefield Gulf (77°N) (see Figure 3a). The warmest Atlantic Water is found at depth along the southern margin of each trough, consistent with the notion that Atlantic Water follows the seafloor terrain toward the ice sheet after diverging from the poleward-flowing West Greenland Current. The maximum Atlantic Water temperatures in these troughs are remarkably stable, decreasing by only one degree from 3.5°C to 2.5°C over the 1,100 km between Disko Bay and Inglefield Gulf. Within each trough, temperatures of the mid-depth waters (~200 m) generally decrease by one-half to one degree from south to north and from the inner shelves toward the glaciers. Such cooling implies a modification of Atlantic Water during its transit with cooler neighboring waters, through both isopycnal mixing with Baffin Bay intermediate water (Gladish et al., 2015a) and diapycnal mixing with the overlying Polar Water near glacier fronts.

A clear example of substantial Atlantic Water modification is illustrated for the trough originating near 72.2°N, 60.3°W, leading to the fjords between 73°N and 74°N. Assuming that the Atlantic Water in this trough flows toward the ice sheet along its southern flank, the first fjord it encounters is Upernavik Isfjord (73°N, 56.4°W; Figure 5a). The warmest Atlantic Water on the north-south CTD transect along the eastern edge of the trough is 2.9°C near the mouth of Upernavik Isfjord (Figure 5b). Progressing north in the trough to CTD N12, the Atlantic Water temperature at 350 m cools to 2.1°C and the depth of the temperature maximum increases to 475 m.

Our data indicate that interaction with glaciers is one likely cause of this Atlantic Water modification. CTDs collected in

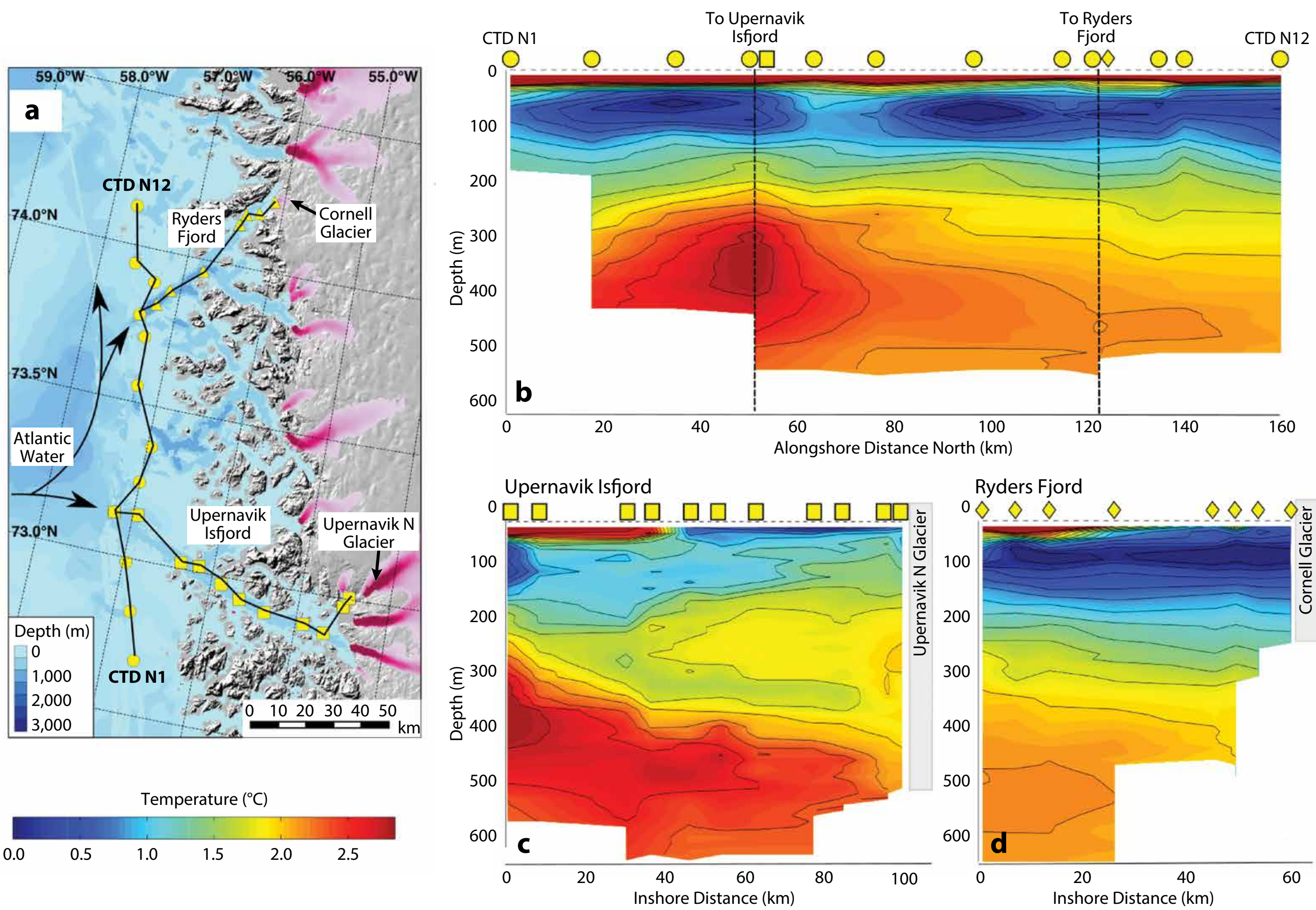

FIGURE 5. Ocean temperatures on the inner shelf and two fjords at the end of a major cross-shelf trough. Yellow symbols indicate CTD locations in (a). Atlantic Water likely approaches the inner fjord along the southern edge of the deep trough. (b) Some Atlantic Water flows into Upernavik Isfjord toward the glaciers while some continues north toward Cornell Glacier in Ryders Ford. Atlantic Waters are warmest near the entrance of Upernavik Isfjord (3.8°C at 350 m) and cooler at the entrance of Ryders Fjord (2°C at 350 m). Vigorous mixing from plumes of ascending fresh subglacial discharge likely enhances glacier melting at Upernavik North Glacier and warms the outflowing mid-depth waters. In contrast, no evidence of similar mixing and mid-depth warming is found at the shallower Cornell Glacier.

Upernavik Isfjord within a few kilometers of Upernavik North Glacier show evidence of significant vertical mixing near the ice face. It is likely that large volumes of buoyant subglacial meltwater enter the fjord from the glacier's base. The presence of anomalously warm waters (1°C–1.6°C) between 50 m and 150 m in the final 20 km of the fjord suggests that deeper Atlantic Water is entrained into the ascending plume and transported vertically into the Polar Water layer (see Figure 5c). The byproduct of mixing between subglacial discharge, ice meltwater, Atlantic Water, and Polar Water at the glacier face is a cooler, fresher, and more buoyant water mass. These modified waters dominate the mid-depth fjord outflow between 50 m and 300 m.

Not all fjords show a similar modification of Atlantic Water, however. The northernmost fjord in the trough, Ryders Fjord, leads to Cornell Glacier. In Ryders Fjord, there is no evidence of Atlantic Water mixing near the ocean-ice interface (Figure 5d). Indeed, temperatures in the upper 200 m of the fjord change very little over the fjord's final 15 km. Seafloor depths at Cornell Glacier (200–350 m) are much shallower than those at Upernavik North Glacier (>675 m). Consequently, it is unlikely that buoyant subglacial discharge from Cornell entrains Atlantic Water as it ascends.

An alternate explanation for the absence of Atlantic Water modification in Ryders Fjord is that the volume of subglacial meltwater discharge at Cornell may be much less than that at Upernavik North. A less voluminous discharge plume at Cornell would entrain and mix less ambient water, resulting in an overall weaker overturning circulation. Finally, some of the greater Atlantic Water modification observed in Upernavik Isfjord could be due to differences in mechanical mixing from overturning icebergs: only the glaciers in Upernavik Isfjord have the potential to calve icebergs with drafts deep enough to penetrate the Atlantic Water layer. Ultimately, we anticipate that numerical ocean model simulations of the circulation within these newly mapped fjords will yield quantitative estimates of the relative importance of various physical processes responsible for establishing these distinct hydrographic cross sections.

Ice Survey

In March 2016, the mission's first GLISTIN survey of ice elevation was completed. Unfortunately, the survey was terminated before all planned lines could be flown because issues related to the instrument could not be resolved in the field. However, of the 80 planned lines, 68 were successfully flown (shown in Figure 2b), collecting measurements over 68,600 km^2. These data will serve as the baseline against which future changes will be measured.

As a preliminary example of the GLISTIN data that were collected, Figure 6 shows surface elevation in the vicinity of Jakobshavn Isbræ mapped by three long overlapping swaths oriented in the general direction of ice flow. Also shown is the 1 km yr^{-1} average ice surface speed contour (Rignot et al., 2012b; Joughin et al., 2014) within which the average rate of ice surface lowering exceeds 5 m yr^{-1} (Hurkmans et al., 2012). It is within this area of fast-flowing, rapidly lowering ice that future glacier acceleration is expected to have the largest impact on ice elevation.

OMG will quantify the mean elevation changes over all mapped glaciers as well as changes in glacier front positions. When combined with bathymetry data near the terminus, glacier volume

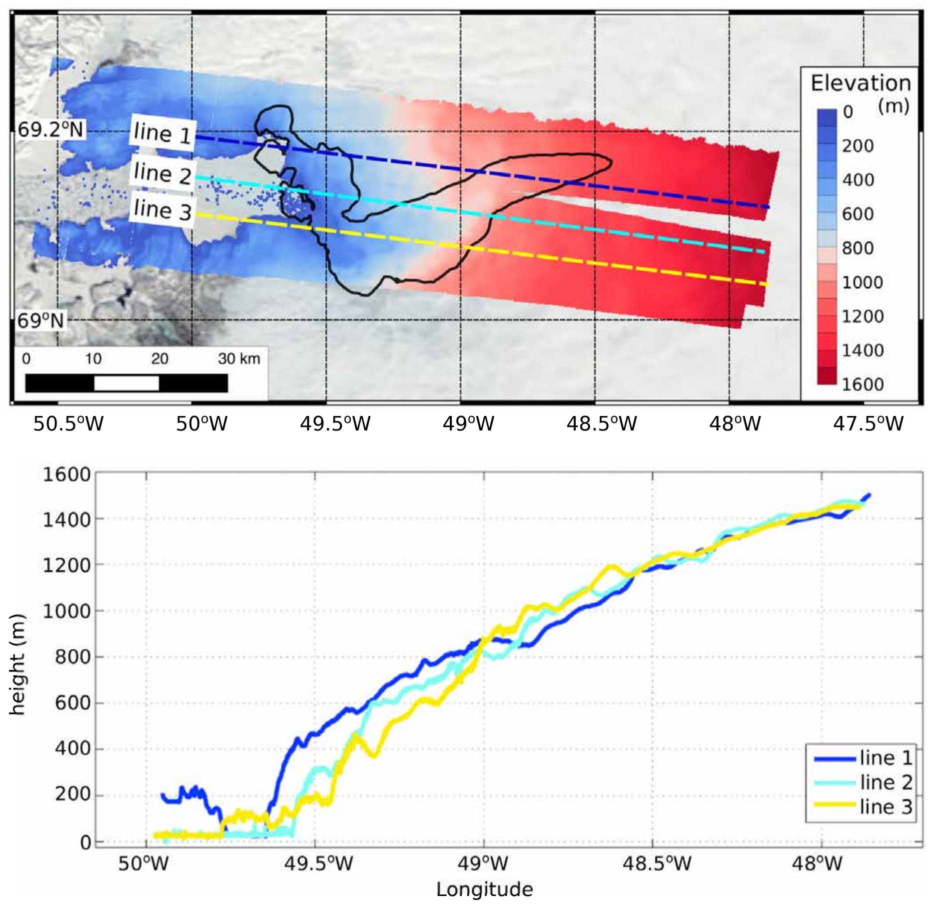

FIGURE 6. Surface elevation observed by the GLISTIN-A radar at Jakobshavn Isbræ. GLISTIN-A elevations are shown over Google Earth satellite imagery. The green contour denotes the region in which the glacier is flowing at speeds greater than 1 km per year, based on the ice velocity map of Rignot et al. (2012b). The mean elevation in this region is estimated to be 609 ± 10 m above the sea level in the fjord. Three along-track elevation profiles in the inset show that the glacier rises about 1,000 m over a distance of roughly 35 km from the front.

changes will be estimated with an accuracy comparable to that of laser altimetry. For Figure 6, the mean elevation within the contoured area is estimated to be 609 ± 10 m. This ±10 m elevation uncertainty is estimated from the RMS elevation differences between the overlapping swaths. We expect that elevation uncertainties will be reduced by a factor of two to three following further data calibration and bias correction.

Changes in the glacier slope are also an important dynamic quantity that will be observed annually by OMG's GLISTIN campaigns. In the case of Jakobshavn Isbræ, the glacier currently rises by ~1,000 m over the first 35 km upstream from the front.

SUMMARY AND DISCUSSION

The results of the first 1.5 years of the OMG mission, illustrated in Figures 4–6, demonstrate the mission's scope and its potential for improving our understanding of ocean-ice interactions in Greenland. Our preliminary ocean and bathymetry data provide important clues about how Atlantic Water changes as it moves north along Greenland's west coast and reveal which glaciers terminate in deep water and are thus susceptible to Atlantic Water warming. Data from our first GLISTIN campaign establish a baseline against which future changes in glacier volume will be computed for the vast majority of marine-terminating glaciers in Greenland.

Each year between now and 2020, OMG will observe changes in ice elevation for nearly all of Greenland's marine-terminating glaciers as well as changes in the hydrographic properties of Atlantic Water on the shelf. Through careful analysis of these data in conjunction with improved maps of seafloor bathymetry and results from high-resolution ocean model simulations, the OMG mission will provide new insights into the expected impact of future ocean-ice interactions on Greenland Ice Sheet mass loss.

In addition to its importance for addressing the key scientific questions of the OMG mission, the wide breadth of the observational campaigns is expected to draw interest across a variety of disciplines. NASA is committed to the full and open sharing of scientific data and data products with the research and application communities, private industry, academia, and the general public. All data collected through the OMG mission will be made freely available immediately after quality control and initial processing on the OMG website, https://omg.jpl.nasa.gov/portal.

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