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Emerging Technology Monitors Ice-Sea Interface at Outlet Glaciers

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Recent melting in Greenland and Antarctica has led to concerns about the long-term stability of these ice sheets and their potential contributions to future sea level rise. Marine-terminating outlet glaciers play a key role in the dynamics of these ice sheets; recent mass losses are likely related to increased influx of warmer water to the base of outlet glaciers, as evidenced by the fact that changes in ocean currents, calving front retreats, glacial thinning, mass redistribution based on satellite gravity data, and accelerating coastal uplift are roughly concurrent [e.g., *Holland et al.*, 2008; *Wouters et al.*, 2008; *Jiang et al.*, 2010; *Straneo et al.*, 2012; *Bevis et al.*, 2012]. However, collecting quantitative measurements within the dynamic environment of marine outlet glaciers is challenging. Oceanographic measurements are limited in iceberg-laden fjords. Measuring ice flow speeds near the calving front is similarly challenging; satellite methods lack temporal resolution (satellite revisit times are several days or longer), while GPS gives limited spatial resolution, a problem for assessing changes near the highly variable calving front.

Breiðamerkurjökull (Breida), a large outlet glacier for Vatnajökull, Iceland's main ice cap, presents an opportunity to study glacial dynamics in a setting that is more accessible for in situ measurements. Breida and the tidal lagoon (Jökulsárlón) it empties into on the south side of the island produce numerous icebergs and play an important role in the country's tourism industry. Its scenery is a famous backdrop for many films and television programs. Like many marine-terminating outlet glaciers in the Northern Hemisphere, the calving front has retreated in the past decade—in Breida's case by several kilometers. A recent project at Breida tested new in situ technologies for studying the dynamics of marine-terminating outlet glaciers and the role of warming ocean water in melting them. These technologies include a bottom-stationed ocean profiler (BSOP) for measurement of water properties near the calving front (Figure 1) and a terrestrial radar interferometer (TRI) for measuring glacier flow speeds (Figure 2).

TRI and BSOP in Detail

Designed and built by Gamma Remote Sensing AG, TRI generates radar phase and amplitude images out to a range of 10 kilometers. It operates at Ku band (1.7-centimeter wavelength) and has an effective displacement precision of 1 millimeter or better [*Werner et al.*, 2008]. Ice displacement in the radar line of sight (LOS) direction is measured by phase comparisons of the radar signal between successive images. Corresponding velocity uncertainties depend on the amounts of tropospheric water vapor present (which refracts and slows the signal), sampling interval, and averaging time, but a typical value for these combined uncertainties is 0.1 meter per day or smaller for 1-hour averages. Motion perpendicular to the radar LOS is estimated using a technique that tracks surficial features of the ice such as crevasses as they move. The system has one transmitting and two receiving antennas and can generate three-dimensional digital elevation models of the glacier surface. TRI is similar in many respects to the satellite interferometric synthetic aperture radar technique [*Massonnet and Feigl*, 1998] but repeats its measurements at intervals of several minutes or less, providing excellent spatial and temporal resolution of ice velocity.

BSOP makes vertical profiles of salinity, temperature, and depth. It remains on

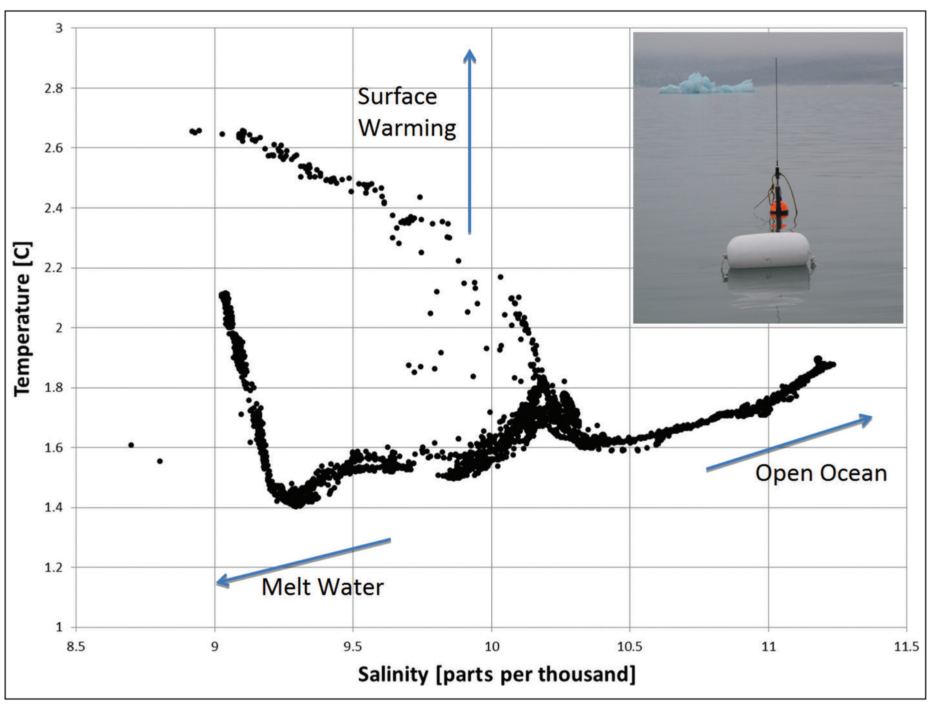

Fig. 1. Temperature-salinity data acquired in a series of profiles between the surface and 100 meters depth by the bottom-stationed ocean profiler (BSOP) over a 48-hour period. Despite limited range of values in this well-mixed lagoon, three components can be identified: cold, fresh meltwater; warmer, high-salinity open ocean; and warm, mixed surface layer. The inset shows BSOP at the surface with an iceberg in the background. The white float is approximately 40 centimeters long.

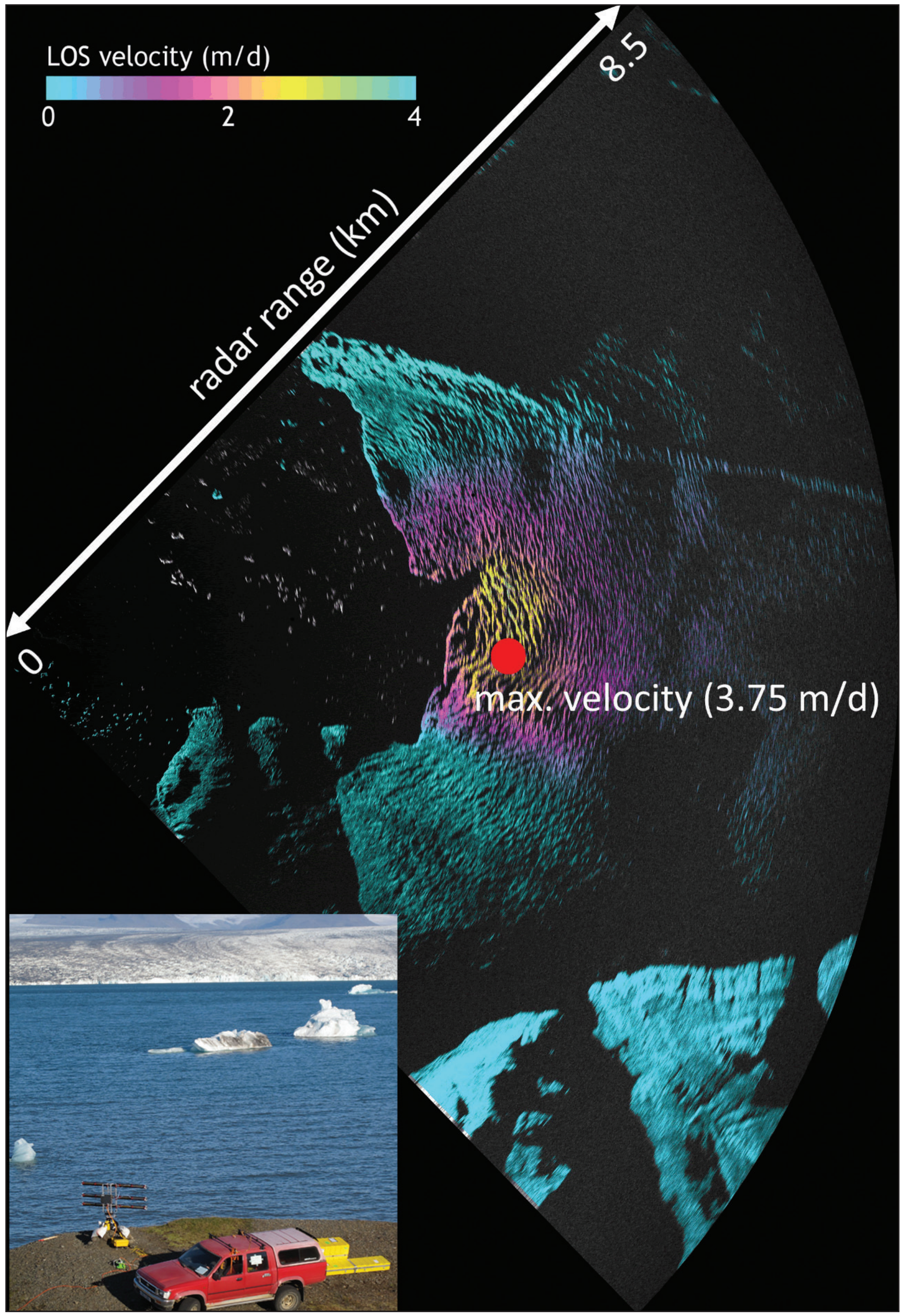

Fig. 2. Line of sight (LOS) interferometric ice velocity map (motion toward or away from the radar) produced by the terrestrial radar interferometer (TRI), located at zero radar range, superimposed on a radar backscatter amplitude image. Icebergs appear in the near field (0–4 kilometers) in the amplitude image; their velocity can be determined separately by feature tracking. Inset shows calving front of Breida emptying into Jökulsárlón, with TRI visible along the bottom of the image.

the bottom of the ocean most of the time, rising at preprogramed intervals. Data are transmitted via satellite during brief (several minutes) intervals at the surface. Spatial drift of the units is typically limited by their short time in the water column, though tethering to the seafloor is an option.

Concurrent Measurements Taken During Weeklong Test

TRI and BSOP were deployed at Breida and its fronting lagoon for a week in August 2012. TRI was set up on stable ground with good visibility of the glacier's terminal region.

Figure 1 shows combined temperature and salinity (T-S) data from a series of lagoon profiles taken with BSOP. The data show a limited range of temperature (1.4°C–2.7°C) and salinity (8.7–11.2 parts per thousand (ppt)), reflecting mixing between meltwater and ocean water, which enters the lagoon through a narrow channel. Despite the mixing, three components can be identified: an open ocean component (6°C, 35 ppt salinity); a colder freshwater component (0°C, 0 ppt salinity), which individual profiles show exists mainly at depths greater than 10 meters; and a warmer freshwater surface component (at depths greater than 10 meters), heated by the warm daytime summer atmosphere.

Figure 2 shows a velocity map of the glacier near the calving front acquired by TRI. The maximum speed of the glacier (3.75 meters per day) was recorded near the calving front and probably indicates the location of maximum topographic gradient of the underlying bedrock as the glacier approaches the sea.

Experience from this deployment is leading to improvements in both instruments. For TRI, a more efficient solar panel power system would facilitate longer deployment in remote areas. For BSOP, operation in a dense ice field provided special challenges. An iceberg dislodged the profiler from its tether, moved it several kilometers, and trapped it within a dense ice field. However, safety features allowed the unit to be retrieved unharmed and redeployed several more times during the survey's operational window. Modifications to BSOP will include higher-pressure-rated housings to allow deeper deployments (the Breida unit was limited to 200 meters depth), top endcap redesign and hardening for potential iceberg impacts, addition of a turbidity monitor to facilitate identification of subglacier meltwater close to the calving front, and battery upgrades to allow longer-mission duration (up to several months).

After more trials, TRI and BSOP can be concurrently deployed to more remote locations. This will potentially yield a wealth of new high-resolution data that will help scientists better understand the role of warming ocean currents on the stability of marine-terminating outlet glaciers and ice sheets.

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