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Listening to Glaciers: Passive Hydroacoustics Near Marine-Terminating Glaciers

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The catastrophic breakup of the Larsen B Ice Shelf in the Weddell Sea in 2002 paints a vivid portrait of the effects of glacier-climate interactions. This event, along with other unexpected episodes of rapid mass loss from marine-terminating glaciers (i.e., tidewater glaciers, outlet glaciers, ice streams, ice shelves) sparked intensified study of the boundaries where marine-terminating glaciers interact with the ocean. These dynamic and dangerous boundaries require creative methods of observation and measurement. Toward this effort, we take advantage of the exceptional sound-propagating properties of seawater to record and interpret sounds generated at these glacial ice-ocean boundaries from distances safe for instrument deployment and operation.

Ambient noise in the ocean varies temporally and spatially depending on water properties, bathymetry, ocean-surface conditions, fish and marine mammal sounds, and human-generated noise (Medwin, 2005). Our measurements from both autonomous hydrophone moorings and near-surface recordings, performed offshore Alaska and the Antarctic Peninsula, demonstrate that, compared to other oceanic environments, tidewater glacier fjords can be continuously loud, particularly in the band between 1 and 3 kHz (Figure 1, top right; Pettit et al., 2011; Pettit, 2012). Glacial ice-ocean boundary processes (including, but not limited to, iceberg calving, glacier ice melt, and subglacial freshwater discharge) produce similar types of sound in all glacier-dominated environments, although the intensity and frequency content varies.

The character of these sounds and their temporal and spatial variations provide constraints on three glacier-ice-ocean processes that previously proved difficult to quantify. First, from small subaerial splashes to the largest full-thickness events, *iceberg calving* generates acoustic energy. Quantitative resolution of this process is important because calving can affect upstream dynamics, trigger disintegration of a floating ice shelf, or induce acceleration of grounded ice, contributing to sea level rise. Second, acoustic observations may be useful for quantifying the *submarine melt rate* of ice at the terminus of a glacier or in a sub-ice-shelf cavity, which is a critical boundary condition for modeling both ice flow and ocean water circulation. Finally, acoustic measurements have potential to resolve variability in *freshwater discharge* from the subglacial hydrological system, a process that to date has completely evaded direct, quantitative measurement. Observations of sediment-laden upwelling plumes at calving margins qualitatively confirm that rivers, similar to those emanating from land-terminating glaciers, exist underneath marine-terminating glaciers. The discharge from these subglacial rivers has a diurnal cycle with occasional floods due to drainage of upstream supraglacial or subglacial lakes (Fountain and Walder, 1998).

ICEBERG CALVING. Any visitor to a calving glacier knows the explosive sound produced as a calved block hits the water. The underwater sounds from such an event, however, are more complex and cover four orders of magnitude in frequency (Pettit, 2012). As measured for a subaerial event in Alaska, low and infrasound frequencies potentially associated with slip at the ice-rock interface initiate the event and persist after the falling of the block due to wave interaction at the surface and seiche activity. The release (30–80 Hz) and subsequent impact of the block on the water (~ 100–600 Hz) generate short-lived signals. High-intensity, high-frequency sounds from surface wave action and spray take minutes to dissipate. Although patterns exist, every event generates different acoustic emissions depending on the geometry and timing of the event. Further, these acoustic emissions appear to evolve differently from seismic emissions for the same event. It is likely that submarine and full-thickness events also emit similarly complex sequences of broadband sounds during their interactions with the water column. Many calving events produce a mini tsunami (Burton et al., 2011), which results in infrasonic pressure waves in the water (Pettit, 2012). In extreme cases, calving events and tsunamis positively feed back on each other, causing ice shelf disintegration (MacAyeal et al., 2003, 2009).

ICE MELT. Examination of individual waveforms shows that the 1–3 kHz peak in intensity is composed of many small events with characteristics similar to that shown in the "Acoustic Event" waveform (Figure 1, top left). One possible mechanism for generating these events and the corresponding narrow band of high-intensity sound is the release of trapped air as glacier ice melts. Glacier ice forms as snow compresses over tens to hundreds of years, trapping air in pore spaces along grain boundaries. This process creates a uniform distribution of pore sizes and pressures within the ice (Spencer et al., 2006), which may lead to generation of the narrow band of frequencies emitted as the ice melts.

FRESHWATER DISCHARGE. A recent mooring deployment in Icy Bay, Alaska, shows a distinctive diurnal signal at 100 Hz (Figure 1, bottom right). This signal is not attributable to instrumentation, tides, or other nonglaciogenic processes. Our preliminary interpretation that freshwater discharge is responsible for the signal is based on the known diurnal variability of discharge from terrestrial glaciers, which exhibits a delayed maximum discharge due to the time required for surface meltwater to navigate the englacial and subglacial pathways (Fountain and Walder, 1998). Based on seismic studies, we expect this process to emit low-frequency sound as the water resonates in cracks and cavities (hydraulic transients) and induces fracturing in the ice (West et al., 2010).

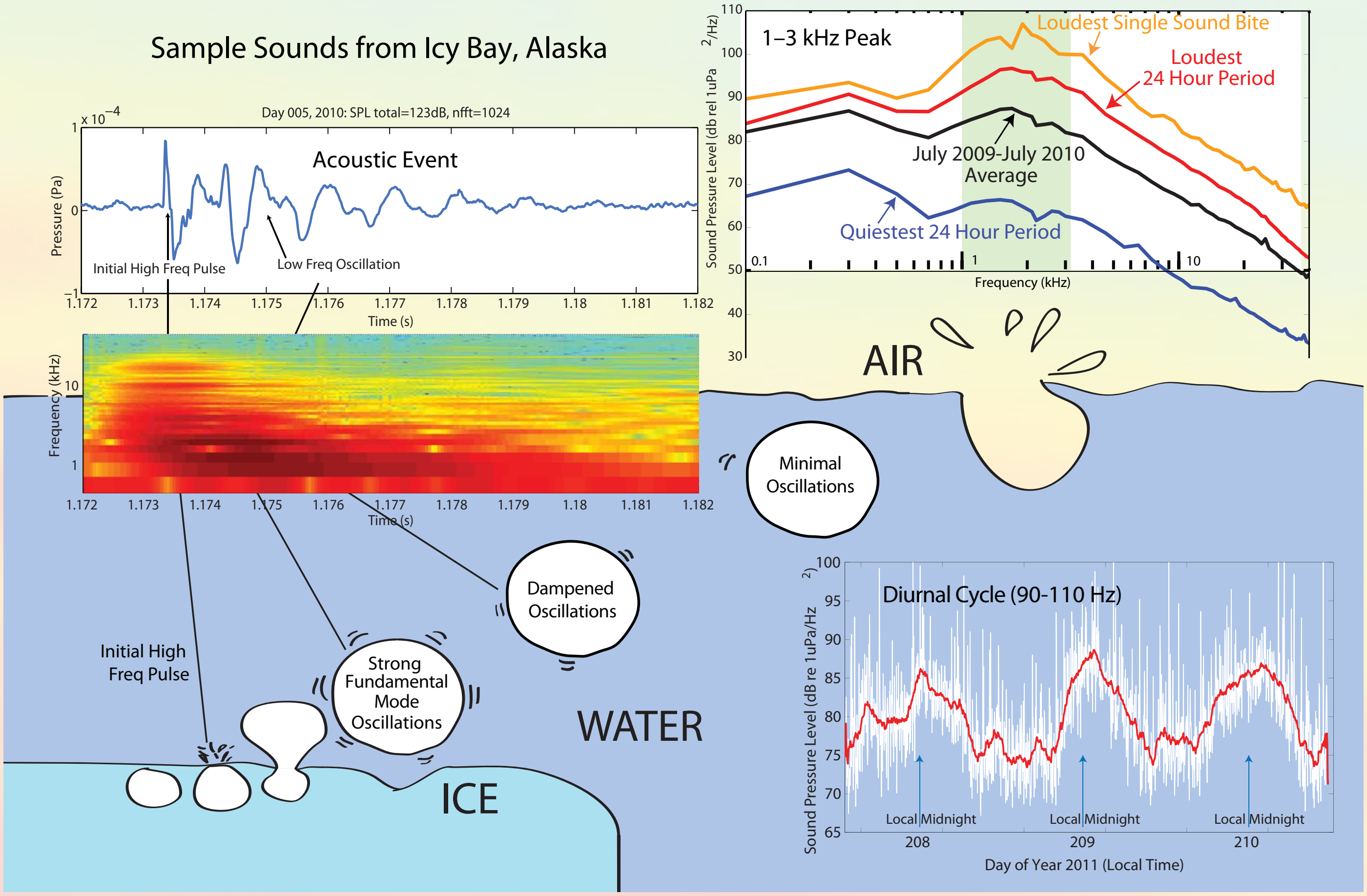

Figure 1. (top right) The "1–3 kHz Peak" shows the average sound pressure levels in a tidewater glacier fjord. (top left) The "Acoustic Event" shows an example of the amplitude and spectrogram of a bubble recorded in Icy Bay, Alaska. The background diagram shows the stages of bubble oscillation, beginning when the ice shatters and air is released into the water (initial high-frequency pulse). The bubble is loudest just after formation (strong fundamental mode oscillation), and, finally, the bubble quiets as oscillations are damped. (bottom right) The "Diurnal Cycle" shows the 100 Hz signal during a three-day period in late July 2011 that we interpret as freshwater discharge from the glacier.

Exploring ocean environments using passive underwater acoustics is a growing field. The Antarctic glacier-ice ocean boundaries are still largely unexplored in this way. The preliminary results of our ongoing studies show intriguing sounds at these boundaries, leading us toward novel methods for measuring variability in glacier ice melt rates, calving rates, and freshwater discharge. As this article went to press, RVIB *Nathaniel B. Palmer* was deploying the first hydrophone in the Larsen A Embayment (results expected in mid-2013), leveraging the efficient sound transmissions of water to study a challenging process from an easier vantage point.

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