The Underwater Sounds of Glaciers

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The underwater sounds of glaciers are a powerful remote sensing tool for monitoring changing conditions in polar regions.

Introduction and Motivation

The stability of major ice sheets in polar regions are linked to sea level rise and the input of fresh meltwater into sensitive regions of the thermohaline circulation system (the oceanic salt and heat conveyor belt), two critical issues related to global change. Estimates of the future contributions to sea level rise from the melting of glaciers in Greenland alone range from 0.3 m to 3 m for the year 2100 (Berwyn, 2018). Moreover, the recent acceleration of mass loss from the Greenland ice sheet (GrIS), which quadrupled from 1992–2001 to 2002–2011 (**Figure 1**), led to a global mean sea level rise of 7-8 mm between 1992 and 2011 (Shepherd et al., 2012). Global glacier melt (small glaciers, ice caps, and ice sheets) currently contributes almost 1 mm/yr to the total sea level rise (Zemp et al., 2019). In addition to contributing to sea level rise, the freshening of surface waters affects global-scale heat transport by weakening the Atlantic meridional overturning circulation (Bamber et al., 2012). For these and other reasons, understanding the mass loss of glaciers is an important problem.

Here we focus on studying the behavior of tidewater glaciers using the various sounds they make in the ocean as they flow, melt, and break apart. However, before discussing the acoustics, we present some preliminaries about the glaciers themselves to introduce terminology and describe the processes that generate noise. Tidewater glaciers are valley glaciers flowing from their accumulation zones in the snowfields to the ocean over a journey that can take hundreds to thousands of years. Tidewater glaciers may flow short distances from local high mountain peaks (such as

Figure 1. *Cumulative ice mass loss (and sea level equivalent [SLE]) from Greenland derived as annual averages from 18 recent studies. Gt, gigatonnes. Reproduced from IPCC (2013, Figure 4.15). See main text and Appendix 4.A of IPCC (2013) for details.*

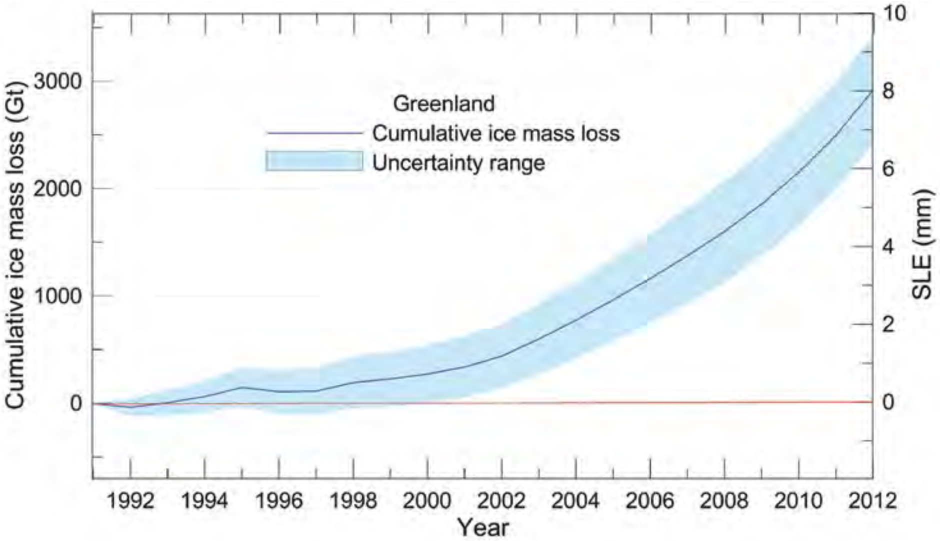

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Figure 2. *Photograph of a tidewater glacier. Snowfall in the accumulation zone feeds the glacier that ends with its terminus in the fjord. Photograph by Dale Stokes.*

in Alaska) or from more distant ice fields and ice sheets (such as in Greenland or on the Antarctic peninsula). **Figure 2** is a photograph of the tidewater glacier Samarinvågen taken from a boat in Hornsund Fjord, southwestern Svalbard (an archipelago in the Arctic Ocean situated about midway between Norway and the North Pole). Snowfall in the mountainous accumulation zone feeds the glacier, which flows downhill and ends in the fjord. The ice cliff in the ocean is known as the glacier terminus.

The position and velocity of the glacier terminus are the net result of ice outflow, which drives the terminus onward, with melting and calving that erode it. Net mass loss of a glacier occurs when ablation (melting or calving) at the terminus exceeds the accumulation of new snow at high elevations. Any increase in the twin processes of melting and calving unbalanced by increases in snow accumulation will drive the retreat of the glacier terminus from the ocean toward land. The relative importance of melting and calving to glacial retreat is currently debated and is likely changeable, depending on ocean temperature; local winds and other atmospheric processes; and glacier flow dynamics. Models for glacial stability are sensitive to the roles of melting and calving in glacial ablation. Thus, quantifying models and understanding their responses to warming atmospheric and oceanic conditions are active areas of research.

There are no methods for the direct observation of submarine melt rates for tidewater glaciers. The terminus of a tidewater glacier or a floating sheet of ice is a dangerous place to work. This is because calving produces falling ice followed by a mini tsunami, both of which are hazardous, and so it is considered unsafe to get within a few hundred meters of the terminus of any glacier. Some glaciers are known to produce bigger calving events than others, and all glaciers should be approached with care. Moreover, the glacier surface is typically fractured by crevasses, making work on the ice surface dangerous or impossible as well. For these reasons, remote sensing techniques are primarily used to study terminus behavior.

Many satellite and airborne remote sensing techniques produce reliable and accurate estimates of average bulk ice mass loss, but measuring the melt rate relative to the calving rate of a glacier terminus remains a challenging problem. Current techniques include estimates of underwater melt rates based on calculations of heat flux to the glacier or numerical models of circulation within the fjord. Calculations of heat flux require observations of water temperature, salinity, and velocity in front of the glacier on short timescales. In the absence of these data, which are challenging to obtain, assumptions must be made about the distributions of glacially modified seawater and the temperature, salinity, and flow of the seawater around the glacier terminus, including poorly understood turbulent processes. Thermohaline structure is dynamic around a glacier terminus. As a result, tidally pumped seawater interacts with meltwater from the terminus and icebergs and buoyancy-driven, outflow plumes to create space- and time-varying freshwater lenses in the bay in which strength and structure vary over time and geographic location.

For example, in Svalbard, there is typically a strong seasonality to the strength of the thermohaline circulation and also to glacier melting because the ocean temperatures can show large variations. In Alaska, such processes also occur in winter because there is not as much seasonality to ocean temperatures. In Antarctica, the warmth of the ocean water varies in different ways that are not necessarily seasonally linked and can also show a dependence on weather patterns and sea ice conditions. The bottom line is that models of melt rate based on measurements and models of thermohaline structure will likely have to accommodate a variable range of conditions depending on geographic region.

Making long-term measurements of both calving and melting on the highly resolved timescales necessary for developing predictive models of retreat is an outstanding and difficult problem. Accomplishing this for multiple tidewater glaciers is even more difficult. In response to these monitoring challenges, in 2008, Wolfgang Berger and colleagues organized a workshop in Bremen, Germany, to propose the use of hydroacoustics to study tidewater glaciers, culminating in the publication of a correspondence note (see Schulz et al., 2008). They suggested that "Hydroacoustics could be used for passive listening — for example, to calving, iceberg collision, tidal flow, sediment transport and wind action — as well as active echo-sounding (for example Doppler detection of water and ice motions)" (Schulz et al., 2008). At the same time, some of the first measurements to record calving events were being made at Hansbreen Glacier in Svalbard (Tegowski et al., 2011) and the Meares Glacier, Prince William Sound, AK (Pettit, 2012).

Using Ambient Sound to Study Glaciers

The idea of using ambient sound to study the ocean and the things in it, sometimes called "passive acoustics," has been around for awhile and has proven effective at providing information across a diverse range of phenomena including the study of breaking surface waves, monitoring reef ecology, studying marine animals (Mann, 2012), monitoring volcanoes (Matoza and Fee, 2018), and probing the ocean interior structure, to name a few. Active acoustics has a much longer history. Indeed, it is arguably the most important tool ever developed to probe the ocean interior and seafloor. However, the ideas that emerged from Schultz at el. (2008) and the initial measurements made an important contribution in pointing out that these powerful tools could be applied to a pressing and difficult measurement problem in polar regions: the monitoring of tidewater glaciers with hydroacoustics.

Hydroacoustics, more commonly referred to as underwater acoustics in North America, offers some practical advantages for monitoring tidewater glaciers over more traditional methods. Active acoustic sensing can provide data about the structure of a glacier terminus that would be virtually impossible to acquire otherwise (e.g., Sutherland and Straneo, 2012). This would include water motions in the glacier bay, which can be complicated by meltwater outflows and direct melting of the terminus interacting with tidally pumped circulation. The concept of passive listening is also attractive because it provides an opportunity to monitor ice-ocean interactions on long timescales with robust and cost-effective technology and without introducing artificial signals into the ocean. Although it may not be immediately obvious that hydrophones can survive for extended periods in a glacial bay, which is subject to the passage of icebergs that may extend from the sea surface to the seafloor and is often covered with sea ice during the winter months, several groups have now demonstrated that year-long recordings of ambient noise are possible.

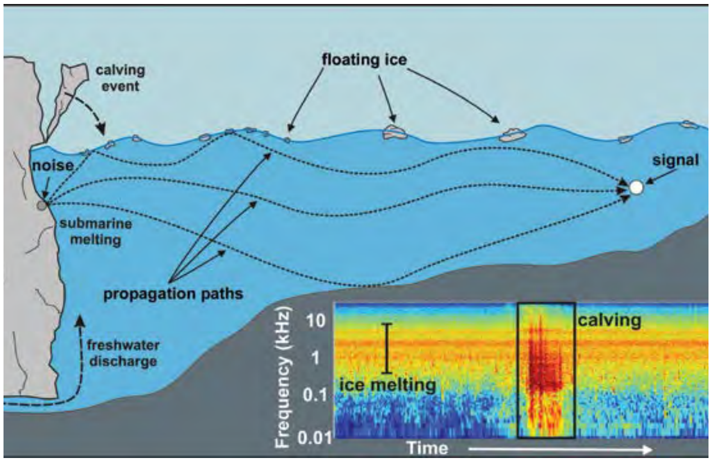
The subject of polar underwater acoustics, both active and passive, is a large and important field with a history dating well back into the last century. The breadth and scope of it lie well beyond our reach in this article. However, here we offer some highlights from the new and developing field of tidewater glacier acoustics along with some interesting results from a closely related topic, iceberg acoustics.

The Underwater Soundscape Near a Glacier Terminus

The bays of tidewater glaciers are one of the noisiest places in the ocean (Pettit et al., 2015). Calving icebergs, wave-iceberg interactions, freshwater outflows and melting glacier ice all contribute to the underwater soundscape (see bit.ly/347NuVF). The variability of sound sources, in both frequency and time, are prominent features of the soundscape.

Figure 3 gives an overview of noise sources in the bay of a tidewater glacier terminus and boundary and waveguide effects influencing sound propagation (note that the spectrogram in **Figure 3**, ***inset***, is from the video referenced above). The noise

Figure 3. *Noise sources and propagation effects shaping the soundscape around the terminus of a tidewater glacier.* ***Inset:*** *spectrogram of sound versus frequency (in kHz on a log scale) and time (total duration of 1 minute) showing a calving event and noise radiated by melting glacier ice in the bay of Hansbreen Glacier.*



of iceberg calving is mostly evident in the sub-500-Hz band and persists for several seconds, whereas the noise of melting glacier ice dominates the noise from around 1 kHz to several tens of kilohertz or higher and is generated without interruption. Other intermittent noise sources include breaking waves on the fjord shoreline, marine mammal vocalizations, rain, wave-iceberg interactions, and the sounds of iceberg disintegration. Noise from freshwater outflows from the glacier terminus is thought to generate sound at frequencies below 100 Hz, but not much is known about this source of sound at the present time. Anthropogenic noise from cruise ships, small transport vehicles, and acoustic sensors such as echo sounders and acoustic Doppler profilers can also be present.

The mechanical and acoustical properties of glacier ice play an important role in determining the character of the underwater soundscape in the bay of a glacier terminus. Ice mechanical properties, combined with ocean temperature and other factors such as rain, control how frequently calving events occur, the range of iceberg sizes produced, and the integrity of the ice block as it impacts the sea surface. All these parameters influence the underwater sound of calving.

Remarkably, most glacier ice contains numerous, small bubbles of compressed air (see **Figure 4**), giving it unique acoustical properties. Trapped at the base of the firm layer in the accumulation zone of the glacier, the bubbles become compacted and pressurized over time by the overburden pressure of accumulating ice above. Gas pressure in glacier bubbles in western Greenland can exceed 2 MPa or 20 atmospheres (e.g., a car tire is typically pressurized to around 2 atmospheres; Scholander and Nutt, 1960). Ice-containing bubbles with such high pressures behave in interesting ways. When collected from a terminus bay directly after a calving event, extreme examples of ice containing high-pressure bubbles may fracture explosively during boat transport or fracture into large sections while being cut for processing. The sounds made by the pressurized air bubbles as they escape are coined "Bergy seltzer" (e.g., see bit.ly/2ZgOqbm), and cubes of glacier ice have been used to both chill and enliven beverages with their pops and cracks.

The subject of air bubbles trapped in glacier ice is complicated by many factors including, for example, bubble size and density that depend on the snowfall rate in the glacier accumulation zone; bubbles that can be altered (or removed entirely) if the glacier ice melts and refreezes; and the bubble shape that varies from almost spherical to ellipsoidal or even more distorted depending on shear in the ice flow. Notwithstanding the details of bubble production, transport, and heterogeneous distribution, their presence in glacier ice is ubiquitous.

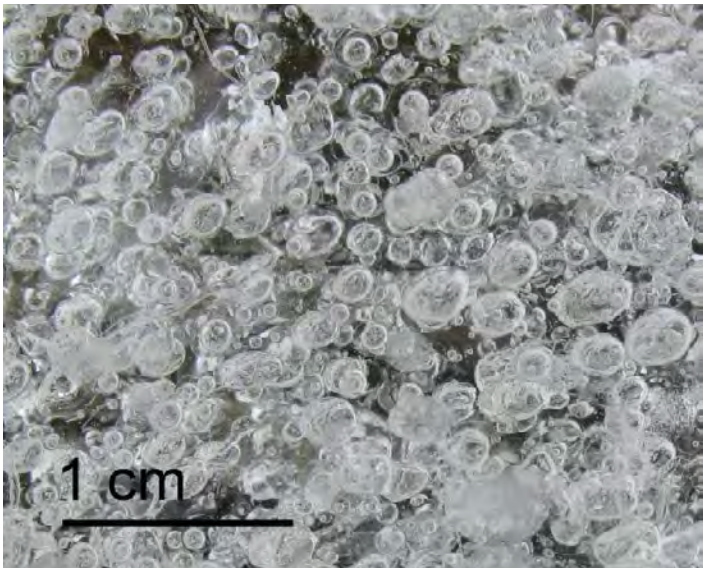


Figure 4. *A section of glacier ice showing the inclusion of many small air bubbles.*

The journey of a bubble trapped in glacier ice may take hundreds to thousands of years, but when the terminus bay is finally reached, the bubbles are released into the ocean. The release of bubbles under high pressure by melting ice can be explosive, creating a loud and impulsive burst of sound. The cacophony from millions of bubbles ejected into the ocean every second can be heard up to several kilometers from a glacier terminus (see the band of frequencies labeled "ice melting" in **Figure 3**, ***inset***). The bubbles also influence the transmission of sound through the glacier ice (e.g., Meyer et al., 2019).

Remote Sensing Using Ambient Sound

Can underwater sound in the bays of tidewater glaciers be used to study glacier-ocean interactions, particularly melting, calving, and outflow? Specifically, can ice mass lost from calving and melting and outflow rate be quantified from measurements of their underwater sound signatures?

A hydrophone is placed on in the water column some distance from the glacier terminus and used to record underwater sound, perhaps over a year-long period. The noise signal contains information about the intensity and statistics of underwater noise sources, which include the splashing sounds of calving events, bubbles bursting out of the glacier terminus as it melts, and low-frequency sounds generated by ice fracture, movement, and submarine freshwater outflow. But the signal also contains other sources such as the sounds of melting and disintegrating icebergs along with other potential sources such as ships, marine mammals, breaking waves, and rain. Moreover, the sound is influenced by propagation effects in the ocean waveguide and reflection from the terminus. The ocean waveguide contains the usual complications that arise when considering the propagation of sound through the ocean, which include scattering and coherent reflection from the sea surface and seafloor and scattering and refraction from the thermohaline structure in the ocean interior (see the article by Dall'Osto in this issue of *Acoustics Today*).

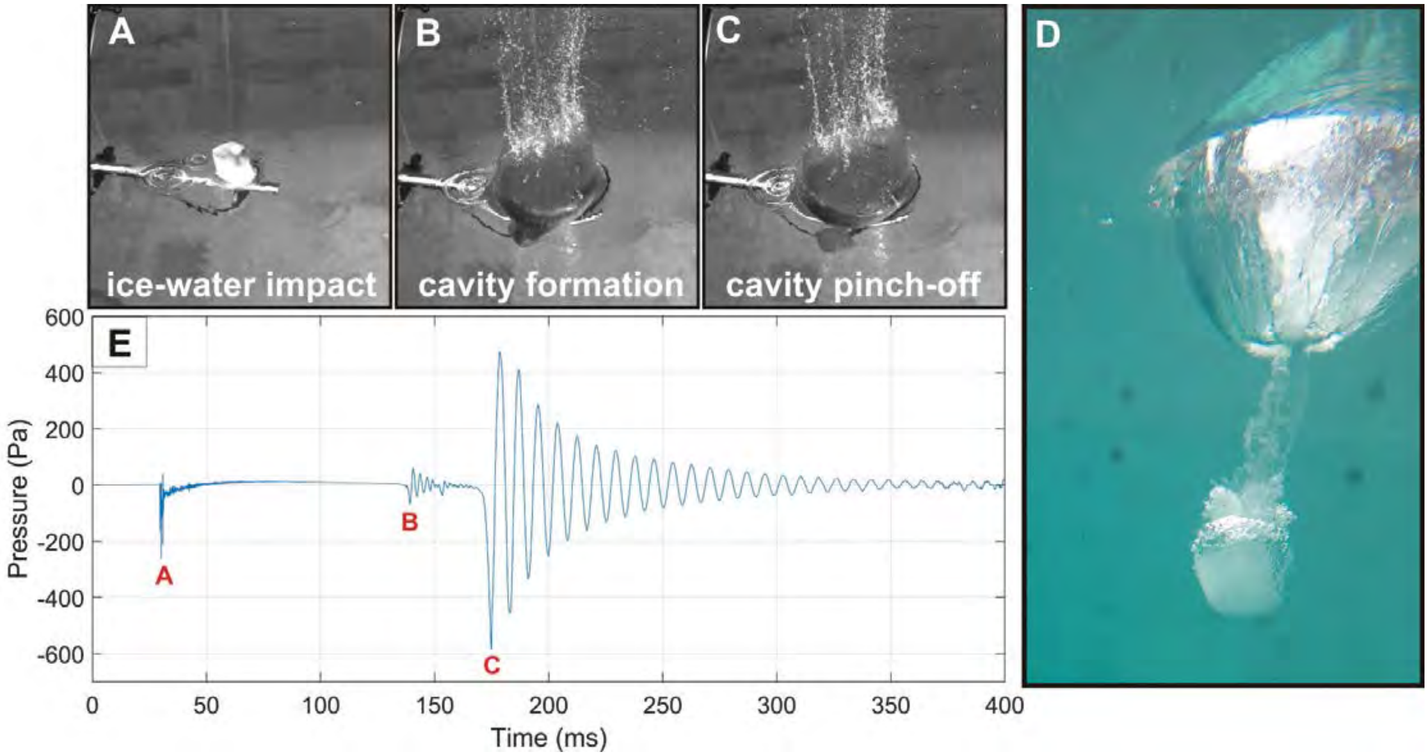
Recent progress has been made toward using the sounds of both calving and ice melting to quantify ice mass loss and melt rates from a glacier terminus. Here we discuss each of these topics in greater detail.

The Sounds of Iceberg Calving

Anyone who has observed an iceberg calving event can attest to its drama; booms and cracks accompany an ice fracture event followed by a splashing ocean entrance and the formation of a mini tsunami. The impact of many tons of ice on the sea surface also creates underwater noise. The two first studies of the underwater sound signature of calving events were conducted independently in Svalbard (see bit.ly/347NuVF; Tegowski et al., 2011) and Alaska (Pettit, 2012). The underwater sound of calving from above the waterline (subaerial calving) is most pronounced at frequencies below 1,000 Hz (see **Figure 3**, ***inset***). Calving noise typically persists for several seconds and is energetic and clearly discernable above other, more persistent sources. There are distinct phases of a calving event that generate sound: (1) infrasound rumble at the onset followed by (2) ice fracturing and cracking, (3) block-water impact, (4) iceberg oscillations, and (5) surface wave action.

Of these various processes, water entry is the most energetic and spectacular. **Figure 5** illustrates three phases of sound

Figure 5. *The sounds produced by a block of ice falling into a pool of water.* ***A-D****: distinct, sound-producing phases of block impact: ice-water impact (****A****), cavity formation (****B****), and cavity pinch-off (****C*** *and* ***D****).* ***E:*** *these phases are annotated in a time-series plot of acoustic pressure.* ***E: red letters****, letter designation in* ***A-D****. The most energetic phase of sound production occurs with cavity pinch-off, photographed both above the water surface (****C****) and below the water surface (****D****).*



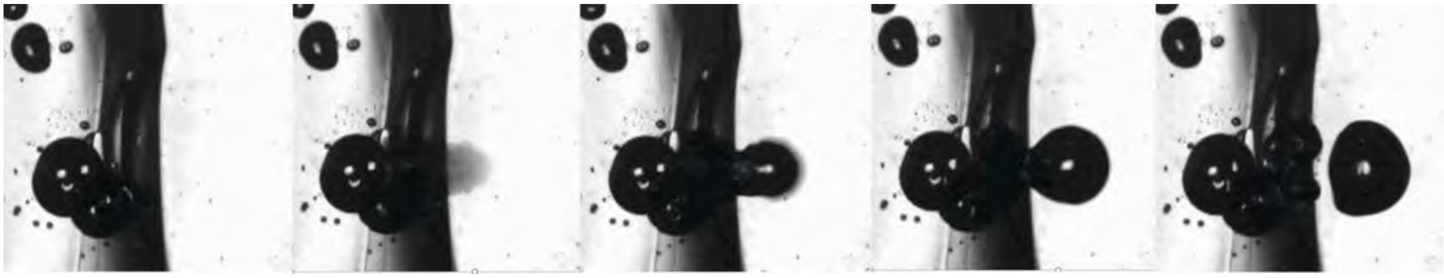


Figure 6. A sequence of images showing a bubble exploding out of melting glacier ice. Image scale is roughly 1 cm on a side. The interframe time interval between the first 3 frames is 500 μs.

production by the impact of a small ice block dropped into a pool. The first contact between the block and water surface generates a short-duration, high-frequency impulse followed by the creation of an air cavity. The moment of cavity pinch-off from the water surface cavity pinch-off is marked by the onset of breathing mode oscillations of the newly created air bubble.

Calving events do not always originate above the water. Buoyancy forces combined with ice fracture can lead to blocks of ice detaching from the submerged glacier terminus, an event known as submarine calving. The frequency of occurrence of submarine calving and its contribution to the overall loss of ice from tidewater glaciers are poorly understood. Icebergs from submarine calving events have no airborne detachment noise. Instead, they emerge unexpectedly on the surface a few hundred meters from the glacier terminus, presenting a significant hazard for any boats too close to the ice cliff. However, submarine calving events generate underwater noise and are easily detected with hydrophones. As with subaerial calving, there are distinct stages of underwater noise production: a series of cracks announcing the separation of the ice block from the underwater part of the terminus followed by emergence noise as the iceberg breeches the surface.

Can the underwater noise of calving be used to quantify calving ice flux? Perhaps, if impact noise can be directly related to the volume and mass of falling ice blocks. Glowacki et al. (2015) analyzed 10 subaerial calving events from Hans Glacier, Svalbard, that had been observed with a digital camera and a hydrophone to test the idea. The kinetic energies of impacting icebergs were estimated from time-lapse images of the glacier terminus and then correlated with the resulting acoustic emissions recorded at frequencies below 200 Hz. A model assuming a simple power law relationship between impact energy and underwater noise production explained 93% of the variability seen in the dataset. These results from a single glacier demonstrated that hydroacoustic monitoring of iceberg calving fluxes might be possible in the future.

The Sounds of Melting Glacier Ice

Melting glacier ice sounds a bit like bacon frying (or snapping shrimp, if you have ever heard them in the ocean; see, e.g., bit.ly/2RtTKEj). This is because the explosive release of gas from a pressurized bubble makes a loud and impulsive popping noise. Urick (1971) appears to have published the first measurements of noise from melting glacier ice, and attributed the sound produced to "...the explosion of tiny air bubbles entrapped in the ice under pressure and released as melting occurs."

A typical sequence of events for the explosive release of a bubble from a block of glacier ice melting in the laboratory is shown in **Figure 6** as a series of high-speed photographic images. The scene is backlit, and the bubbles appear as dark, roughly circular regions within the ice. A bubble approximately 4 mm in diameter can be seen emerging from the ice from left to right in the bottom half of the 4 right-hand images. The timescale of the main part of the release event is less than a frame in duration (see the blurred, emerging bubble in the second image from the left), which is 500 μs (see, e.g., youtu.be/0Bilzdsi42E; youtu.be/6EHaD_169eU).

Bubble release events like the one shown in **Figure 6** and the videos can create peak pressures of over 100 Pa and an exponentially decaying sinusoidal waveform associated with the natural oscillations of an acoustically excited bubble. The superposition of many such events from a melting glacier terminus creates a random pressure signal with a broad peak in the frequency range of 1-3 kHz that can be heard underwater several kilometers from the ice cliff.

To relate this signal to the ice melt rate requires information about the density of the bubbles in the ice along with the knowledge of the distribution of gas pressures within the bubbles. A final, critical piece of information required is the fraction of trapped bubbles that are released explosively. This number presumably depends on the ice microcrystalline properties, including its tensile strength and fracture toughness, which can vary with temperature and ice history at the terminus. The pressure differential across the bubble cap ice film, which is the difference in pressure between the gas in the bubble and the external pressure, is also important. The external pressure is equal to the hydrostatic pressure of the ocean at the depth of the glacier ice if it is below the sea surface and exposed to the ocean.

The fraction of explosive bubble release events decreases at the differential bubble cap pressure decreases, and consequently hydrostatic pressure plays an important role in controlling the generation of sound by the glacier terminus. Hydrostatic pressure increases with increasing water depth, which tends to suppress the occurrence of explosive bubble release events and consequently decreases the noisiness of ice melting at greater depths. Measurements of the vertical directionality of the noise radiated by four glaciers in Hornsund fjord in southwestern Svalbard show that radiation is limited to a layer of ice that extends roughly 20 m below the sea surface. This effect is very important for the estimation of melt rates because the overall level of sound produced is significantly reduced from what the level would be if the entire melting terminus were generating noise.

Distant Connections

An account of glacier hydroacoustics would not be complete without mention of the "singing icebergs" (Müller et al., 2005). Icebergs can be kilometers or larger in scale, which is large enough to support flow within internal tunnel/crevasse systems and which is thought to create fluid flow-induced vibrations. The signals are in the same spectral band as the harmonic volcano tremor and have similarities in terms of their duration, magnitude, and spectral features.

Iceberg tremor signals observed in the Antarctic have been backtracked to icebergs over distances greater than 800 km. Icebergs of this scale also produce disintegration sounds when they break apart. These are short-duration, broadband signals in the frequency band of 1-440 Hz, with average sound pressure levels reaching ~220 dB root-mean-square (rms) re 1 μPa at 1 m (Dziak et al., 2013). Talandier et al. (2002) have reported hydroacoustic signals from large icebergs in the Ross Sea, Antarctica, detected by seismic stations in Polynesia, demonstrating that signals from large Antarctic icebergs are detectable at basin-scale ranges.

Challenges and Opportunities

Exploiting the natural sounds of tidewater glaciers to study their dynamics and ice-ocean interactions provides both difficult challenges and exciting opportunities. Notwithstanding the logistical difficulties of collecting a long-term data series of underwater sound in glacial bays, the greatest challenge lies in converting the sounds to quantitative signals, such as the average melt rate of a glacier terminus or the mass of ice lost through calving. The signal, whether from melting, calving, or some other process, is inevitably influenced by propagation through the ocean waveguide, which must be understood and accounted for. If this is possible, the equivalent source level then must be inverted for the geophysical process creating it. Natural variability in the sound generation mechanisms, caused by, for example, variation in the shape of an ice block and its angle of entry into the ocean or the microscale tensile strength of melting glacier ice, must be understood. Recent research has made some progress on these issues, but much work remains to be done. If successful, the vision of Schultz et al. (2008) for the hydroacoustic monitoring of tidewater glaciers may prove to be a powerful tool for understanding the fate of these critical systems.

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BioSketches

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Erin Pettit studies the dynamics of glaciers and ice sheets to better predict the impact of glacier change on land and ocean environments. Her research currently focuses on ice-ocean interactions and the stability of marine-terminating glaciers and ice shelves in Greenland, Antarctica, and Alaska. She is an associate professor at Oregon State University (Corvallis), founder and director of Inspiring Girls Expeditions, a fellow of Wings WorldQuest, and an emerging explorer with National Geographic. She has a BSc in mechanical engineering from Brown University (Providence, RI) and a PhD in geophysics from the University of Washington (Seattle).

Dale Stokes is a research oceanographer in the Marine Physical Laboratory, Scripps Institution of Oceanography, University of California, San Diego (La Jolla). He cofounded the Innovative Marine Technology Lab, Scripps Institution of Oceanography, with Grant Deane more than two decades ago and has extensive experience in laboratory and oceanographic field studies from the deep sea to shallow waters and from the tropics to both polar regions.