



OCEAN ACOUSTICS IN THE CHANGING ARCTIC

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Recent changes in ice cover and ocean stratification have been so large that acoustic measurements made during the Cold War no longer reflect current conditions.

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Interest in Arctic acoustics began in the early years of the Cold War when nuclear-powered submarines capable of operating for extended periods under the ice were first developed.¹ In 1958 the first operational nuclear submarine, the USS *Nautilus*, reached the North Pole. Shortly thereafter, military and academic scientists conducted Arctic acoustics research from ice islands and seasonal camps on the ice. The knowledge they gained was used to support submarine operations and develop antisubmarine warfare. Research at those ice camps continues today, but military interest in Arctic acoustics waned in the early 1990s at the end of the Cold War.

Researchers, however, are increasingly interested in the dramatic changes occurring in the Arctic Ocean in response to rising atmospheric concentrations of carbon dioxide and other greenhouse gases (see the article by Martin Jeffries, James Overland, and Don Perovich, *PHYSICS TODAY*, October 2013, page 35). Surface air temperature in the Arctic has warmed at more than twice the global rate over the past 50 years, and sea ice extent and thickness have declined dramatically.² Moreover, ocean stratification is changing as warmer waters encroach into the Arctic from the North Atlantic and North Pacific Oceans. Those changes have also affected acoustic propagation and ambient sound.

The rapidly changing Arctic Ocean

Since 1979, satellites with passive microwave sensors have measured the extent of sea ice—the area of the ocean that has at least 15% ice cover. Data from the US National Snow and Ice Data Center indicate that the monthly average sea-ice extent at its minimum in September declined from 7.67 million km² in 1984 to 4.32 million km² in 2019. (The lowest extent of 3.4 million km² of ice observed so far occurred on 16 September 2012.) Although sea ice varies considerably from year to year, a linear fit to the data from 1979–2019 yields a decline in the September monthly average of 12.9% per decade. The winter ice extent is also declining, albeit more slowly.

The presence of multiyear ice that survives the summer melt season is closely related to ice thickness and volume. Using a combination of satellite data and drifting buoys to derive the formation, movement, persistence, and disappearance of sea ice, researchers can estimate the age of multiyear ice. Figure 1 shows that the area covered by sea ice four years of age or older declined from 2.7 million km² in September 1984 to 53 000 km² in September 2019. The disappearance of multiyear ice has affected not only the average ice thickness but also pressure ridges atop the ice and ice keels that extend into the ocean, both of which form when large packs of floating ice floes collide. Old multiyear ice has larger pressure ridges than first-year ice, and the keels can extend tens of meters down. But those deep keels are disappearing with the multiyear ice.

The changes the Arctic is experiencing come in part from the warm, salty water of the Atlantic Ocean that enters the Arctic through the Barents Sea and the Fram Strait between Greenland and Spitsbergen, the largest island of the Svalbard archipelago. That water sinks and forms the relatively warm Atlantic layer approximately 150–900 m deep, as shown in figure 2. The Atlantic water makes its way throughout the Arctic Ocean: The bathymetry of the deep Arctic basin margins and ridges guides the water as it travels counterclockwise and deeper in the basin. Data from 1950 to 2010 show that since the 1970s the temperature of the Atlantic water has been steadily warming.³

In addition to the warming Atlantic layer, the western Arctic is influenced by waters entering from the Pacific Ocean through the shallow Bering Strait. Those waters comprise the relatively fresh Pacific Summer Water (PSW), between approximately 40 m and 100 m deep and having a local temperature and sound speed maximum, and the more saline Pacific Winter Water (PWW), characterized by a local temperature and sound speed minimum. Starting in 2000, the PSW warmed and thickened, and the depth of the PWW increased from 150 m to 200 m.⁴

Central Arctic acoustics

In general, sound speed increases monotonically with depth in the eastern central Arctic. As figure 2 shows, the sound speed profile is therefore upward refracting. As sound propagates, it interacts repeatedly with the ice. Some of the acoustic energy reflects with each interaction, some is scattered by the rough ice, and the rest is converted to compressional and shear waves within the ice. The resulting energy losses increase with frequency, which effectively makes the Arctic waveguide a low-pass filter.

During the Cold War, sound waves could only propagate to ranges in excess of a few hundred kilometers at frequencies below 30 Hz or wavelengths greater than 50 m because of losses due to interaction with the ice.⁵ With the reduction in the amount of multiyear ice and the disappearance of the associated deep keels, higher-frequency sound can now propagate to greater ranges, but long-range propagation is still limited to relatively low frequencies. At very low frequencies, however,

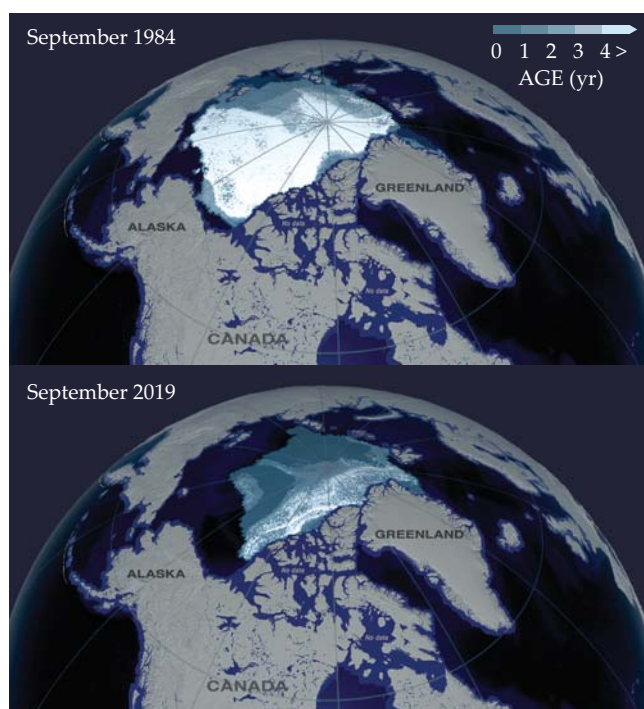


FIGURE 1. THE AGE OF ARCTIC SEA ICE in (top) September 1984 and (bottom) September 2019. The dark blue color represents first-year ice; the white, ice at least four years old. (NASA Scientific Visualization Studio, 2019.)

the sound begins to interact with the seafloor and lose energy to it. The resulting losses increase as frequency decreases, so only sound waves above a lower-frequency bound of 5–10 Hz can propagate over long distances.

Acoustic propagation in the western Arctic differs from that in the eastern Arctic because of the water from the Pacific. Sound speed increases with depth except for the sound speed minimum at the depth of the PWW, which forms an acoustic duct, visible in figure 2, that traps the sound energy and allows it to propagate over long distances without interacting with the ice cover or the seafloor. As the PSW has warmed and thickened in recent years, the sound-speed duct—sometimes referred to as the Beaufort Duct—has strengthened. An acoustic navigation and communication system deployed in the Beaufort Sea achieved ranges in excess of 400 km using 900 Hz sources deployed 100 m deep in the duct.⁶ But the duct is sufficiently weak that signals at frequencies below a few hundred hertz are no longer fully confined to the duct and lose energy by interacting with the ice cover.

Various physical properties of the sea ice, including porosity, brine content, Poisson's ratio, Young's modulus, and the shear modulus, affect acoustic propagation. Those properties differ between first-year sea ice—the primary type in the modern Arctic—and multiyear sea ice. Compared with first-year

ice, sound waves travel faster through multiyear ice primarily because of its lower brine content, which results from summer-melt processes. The shear-wave speed of first-year sea ice can be lower than the sound speed of the underlying seawater and consequently increase the transmission of sound out of the water column and into the sea-ice layer. Multiple studies have shown that the elastic properties of sea ice, particularly shear-wave attenuation, have the greatest influence on the surface reflection coefficient.⁷

However, the effects of the intrinsic properties of sea ice can be dominated by the effects of acoustic scattering because the under-ice surface has a rough topography.⁸ Scattering of acoustic waves depends on the length scales present in the surface's roughness relative to the acoustic wavelength. Multiyear ice ridges can be significantly larger than first-year ice ones.⁹

Differences in roughness are possible even in the absence of ice ridges. The smooth underside of undeformed first-year ice differs from that of rugged multiyear ice, which is made by surface pools melting at uneven rates during previous summers. Increased roughness can cause additional coupling of acoustic energy from the ocean waveguide into the sea ice layer. The relative importance of the intrinsic reflection loss and the scattering loss depends on the acoustic frequency and the characteristics of the ice cover, which are variable in space and time.

Ambient sound

The sources and propagation of ambient sound in the Arctic differ substantially from those at lower latitudes. In temperate environments, low-frequency sound (20–500 Hz) is predominantly caused by distant shipping, and higher-frequency sound (500–100 000 Hz) is mostly from spray and bubbles associated with breaking waves. Ambient sound in the Arctic, however, is highly variable in space and time: It shows strong seasonal variations correlated to annual changes in ice cover. For example, anthropogenic sounds occur more frequently

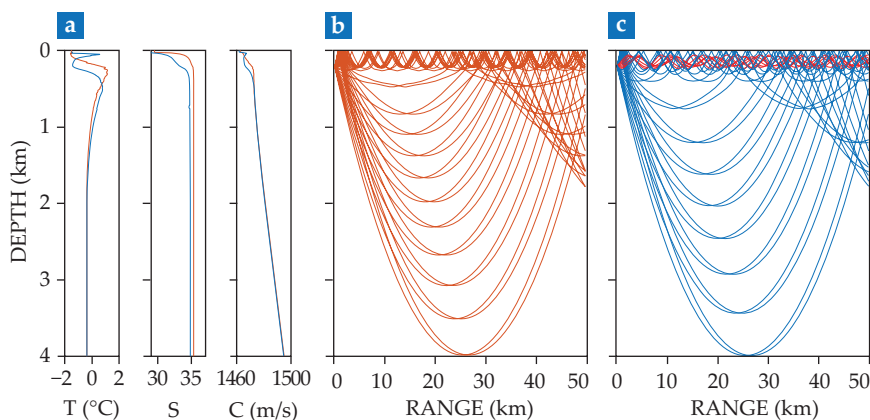
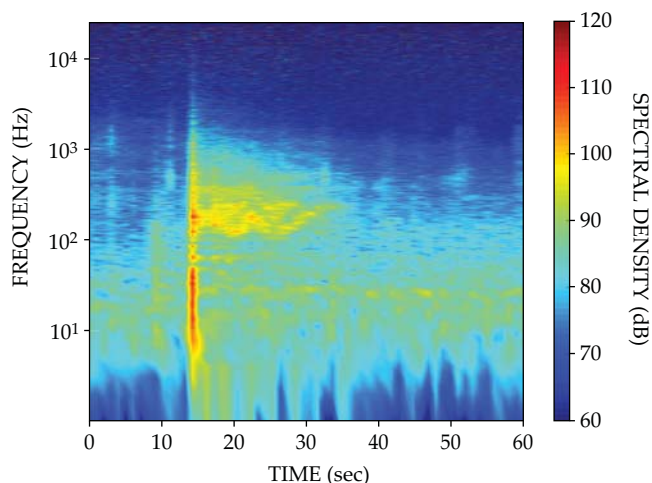


FIGURE 2. (a) THE TEMPERATURE (T), SALINITY (S), AND SOUND SPEED (C) PROFILES in the western (blue line) and eastern (orange line) Arctic Ocean were measured with Ice-Tethered Profiler instruments. Geometric ray paths for transmissions were generated from an acoustic source at 200 m depth in the (b) eastern and (c) western Arctic. Rays with positive (upward) and negative (downward) launch angles of the same magnitude give rise to the closely spaced ray pairs. In the western Arctic, a subset of the rays' paths that are contained in the Beaufort sound-speed duct are shown in red. (Data from R. Krishfield et al., *J. Atmos. Ocean. Tech.* **25**, 2091, 2008; J. M. Toole et al., *Oceanography* **24**, 126, 2011.)



during the summer months when large portions of the Arctic Ocean are ice free. Additionally, observations of marine mammal vocalizations are correlated to species-specific seasonal migratory patterns, which often follow the ice edge.

During the winter and spring, the prevailing sound in ice-covered regions of the Arctic is largely generated when the ice cover deforms and fractures in response to wind, swell, currents, and thermal stresses.⁹ Figure 3 shows the acoustic response of one such cracking event. Ice-fracturing processes can create some of the loudest underwater environments, but under calm wind conditions the Arctic can be one of the quietest places in the world's oceans. For example, under-ice ambient sound can reach levels 30 dB higher or 20 dB lower than the same ice-free summer location.¹ Ambient sound measurements have historically had a broad peak around 15–20 Hz, which results from the band-pass nature of sound propagation from distant sources.

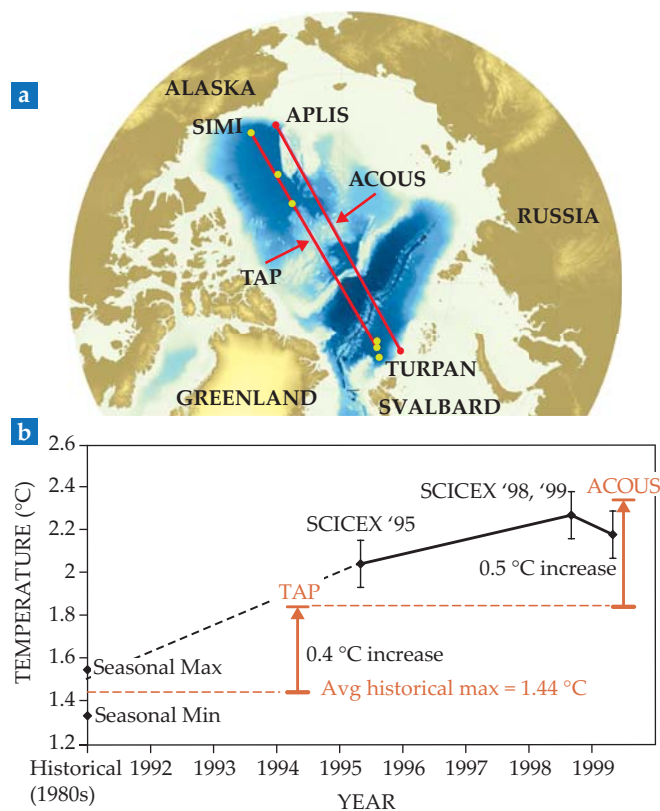


FIGURE 3. THIS TIME-FREQUENCY SIGNATURE of a local ice-cracking event approximately 400 m from the receiver was recorded on 16 March 2014 during the US Navy Arctic Submarine Laboratory Ice Experiment. The color bars are in dB relative to a reference level of $1 \mu\text{Pa}^2/\text{Hz}$. (Adapted from K. L. Williams et al., *IEEE J. Ocean. Eng.* **43**, 145, 2018.)

Several studies have compared historical ambient sound measurements with recent data.¹⁰ However, drawing conclusions from the comparisons is difficult given the high spatiotemporal variability of the Arctic sound field, the differing conditions under which the data sets were acquired, and the various metrics reported. Nevertheless, researchers expect the level and character of ambient sound in the Arctic to change as ice coverage and thickness decrease.

Changes in sound-generating mechanisms and acoustic propagation determine the evolving ambient sound field in the Arctic. Evidence already exists of an increase in anthropogenic activities from industries such as oil and gas exploration, fishing, shipping, tourism, and military activity. The once impassable Northwest Passage and the Northern Sea Route have recently seen increases in commercial ship traffic. Marine mammals are adapting to the changing conditions: Some species, such as Pacific Arctic beluga whales, are shifting their migratory patterns because of the longer ice-free season. Furthermore, the thinner and more mobile ice of the modern Arctic responds more readily to winds and is more easily broken up, which has increased wind-generated sound.

Acoustic remote sensing

Ocean acoustic tomography is a method that remotely senses the ocean interior by transmitting sound through it.¹¹ The speed at which sound travels depends on the ocean's temperature and velocity fields, and measurements of acoustic travel times therefore provide information on water temperature and current. Researchers use inverse methods on the measured travel times of the signals to infer the ocean's state. Travel times are inherently spatially integrating, which means they provide long-range horizontal and vertical averages and suppress the effects of small-scale oceanic variability that can contaminate point measurements. The application of long-range transmissions to measure ocean temperature is often referred to as acoustic thermometry.

During the Transarctic Acoustic Propagation (TAP) experiment in 1994, phase-modulated acoustic signals with a center

FIGURE 4. (a) THE MAP SHOWS THE ARCTIC OCEAN TRANSECTS of several acoustic remote-sensing initiatives, including the Transarctic Acoustic Propagation (TAP) experiment, the Arctic Climate Observations Using Underwater Sound (ACOUS) project, and the Coordinated Arctic Acoustic Thermometry Experiment (CAATEX, yellow dots). **(b)** The maximum temperature data of the Atlantic layer were obtained from historical climatology data, the 1994 TAP mode-2 acoustic travel times, the 1999 ACOUS mode-2 travel times, and the SCICEX 1995, 1998, and 1999 submarine transects. The uncertainties in the TAP and ACOUS temperatures are $\pm 0.2^\circ\text{C}$ and $\pm 0.25^\circ\text{C}$, respectively. The change in maximum temperature (arrows) is inferred from the changes in acoustic travel times. (Adapted from B. D. Dushaw et al., in *Observing the Oceans in the 21st Century*, C. J. Koblenz, N. R. Smith, eds., GODAE Project Office and Bureau of Meteorology, 2001, p. 391.)

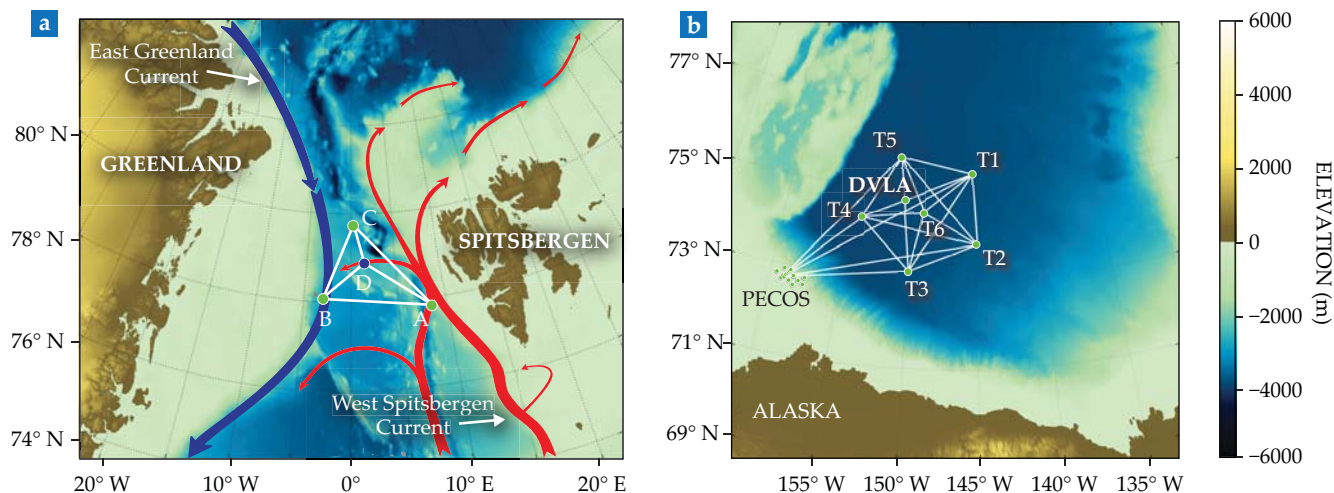


FIGURE 5. (a) THE ACOUSTIC TECHNOLOGY FOR OBSERVING THE INTERIOR OF THE ARCTIC OCEAN (ACOBAR) experiment ran from 2010 to 2012 to gather improved estimates of heat and freshwater transport in Fram Strait. Acoustic transceiver moorings (green) were located at A, B, and C. (Mooring C failed prematurely.) An acoustic receiver mooring (blue) was located at D. (Adapted from ref. 13.) **(b)** The geometry of the 2016–17 Canada Basin Acoustic Propagation Experiment included six acoustic transceiver moorings (T1 through T6) and a vertical line array receiver mooring (DVLA). The sound transmissions were also recorded by acoustic receivers located on the continental shelf and upper slope to the southwest of the array (PECOS). Some of the acoustic paths connecting the sources and receivers are shown in white. (Image by P. F. Worcester and M. S. Ballard.)

frequency of 19.6 Hz were transmitted by a source located at ice camp Turpan north of Svalbard. The signals traveled across the Arctic basin to receiving arrays at ice camps Narwhal in the Lincoln Sea and SIMI in the Beaufort Sea.¹² The distance from Turpan to SIMI was 2630 km, and the measured travel time of the acoustic normal mode that sampled the Atlantic layer was 2.3 ± 1.2 s shorter than that computed from long-term climate data. The result, summarized in figure 4, indicates a warming of 0.4 ± 0.2 °C across the basin. The warming was subsequently confirmed by measurements made from submarines during various efforts by the Science Ice Exercises Program and from icebreakers.

In October 1998, as part of the joint US–Russia Arctic Climate Observations Using Underwater Sound (ACOUS) project, another ultralow-frequency source (20.5 Hz) was moored in Franz Victoria Strait.¹² The transmissions were recorded on a moored receiver in the Lincoln Sea and by a receiver at ice camp APLIS in the Chukchi Sea in April 1999. The acoustic path to APLIS from the moored source was similar to that from Turpan to SIMI during the TAP experiment. ACOUS reported travel times 2.7 ± 1.3 s shorter than the TAP measurements: Scientists concluded that the Atlantic layer further warmed by 0.5 ± 0.25 °C.

Twenty years later, the 2019–20 US–Norway Coordinated Arctic Acoustic Thermometry Experiment (CAATEX) was conducted to repeat the basin-scale measurements made during the TAP and ACOUS experiments, as shown in figure 4a. Six moorings were installed, providing both basin-scale and shorter-range measurements. One mooring in the eastern Arctic and another in the western are acoustic transceivers, each composed of a 35 Hz acoustic source and a vertical receiving array. The remaining four moorings have only vertical receiving arrays.

Regional-scale tomographic experiments have been conducted in Fram Strait since 2008 and are shown in figure 5a. With a width of nearly 400 km and a sill depth of about 2600 m, Fram Strait is the only deep-water connection between the Arctic and the rest of the world's oceans. The West Spitsbergen Current transports relatively warm and salty Atlantic water into the Arctic to form the Atlantic layer. The East Greenland Current

transports sea ice and relatively cold and fresh polar water out of the Arctic. Significant recirculation of the Atlantic water and intense variability in the center of the strait make it difficult to accurately measure ocean transport through the strait.

The primary goal of the experiments in Fram Strait is to determine whether acoustic measurements, when combined with other data and ocean models, provide improved transport estimates of the inflowing and outflowing water masses. All the experiments employed acoustic sources that transmitted linear, frequency-modulated signals with bandwidths of 100 Hz and center frequencies of approximately 250 Hz. The oceanographic conditions in Fram Strait produce complex acoustic arrival patterns.¹³ Nonetheless, researchers succeeded in obtaining robust estimates of range and depth-averaged temperature along the acoustic paths using the measured travel times.¹⁴ As a first step toward using the travel times to constrain ocean models, researchers have interpreted the structure and variability of the measured acoustic arrivals by comparing them to arrivals computed using sound-speed fields obtained from a high-resolution regional ocean model.¹⁵

The Canada Basin has experienced some of the greatest decreases in ice cover and the most significant changes in ocean stratification in the Arctic.¹⁶ Six acoustic transceiver moorings similar to those used in Fram Strait and a vertical line array receiver mooring were deployed for the 2016–17 Canada Basin Acoustic Propagation Experiment (CANAPE), shown in figure 5b. The transmissions were also recorded by receivers on the continental shelf north of Alaska¹⁷ and by acoustic Seagliders, autonomous underwater vehicles.

The goals of CANAPE were to understand how the changes in the ice and ocean stratification affected acoustic propagation and ambient sound. In addition, the data from the tomographic array provide information on the spatial and temporal variability of the upper ocean throughout the annual cycle and make it possible to assess whether acoustic methods, with other data and ocean modeling, can yield improved estimates of the time-evolving ocean state. The amplitudes of the receptions de-

crease in wintertime, likely a consequence of the increasing ice thickness, which reached a maximum of about 1.5 m in late winter, and of the changes in the structure of the Beaufort Duct. Whereas the transmission loss is highly variable over the year, the travel-time variability was roughly an order of magnitude smaller than is typical in midlatitudes at similar ranges. Compared with other oceans, the Arctic is a remarkably stable acoustic environment.

Multipurpose acoustic systems

Monitoring and understanding the rapid changes underway in the Arctic Ocean are of crucial importance for researchers assessing its role in climate variability and change. As the Arctic converts from largely perennial to seasonal ice cover, oil and gas exploration, fisheries, mineral extraction, shipping, and tourism will increase the pressure on the vulnerable environment. To inform and enable sustainable development and protect that fragile environment, scientists will need improved ocean, ice, and atmosphere data.

Gliders, profiling floats, and autonomous underwater vehicles that measure ocean temperature, salinity, and other variables cannot surface in ice-covered regions to use the Global Navigation Satellite System and relay data back to shore. Furthermore, measurements of sea-surface height using satellite altimeters, which provide important constraints on the ocean circulation at lower latitudes, cannot be obtained when the ocean is covered with ice.

Multipurpose acoustic systems, however, can operate beneath the ice. Such systems provide acoustic remote sensing of temperatures via ocean acoustic tomography, underwater navigation, and passive acoustic monitoring of natural and anthro-

pogenic sounds. Such systems have a special role in making measurements of the rapidly changing Arctic Ocean and complementing and supporting other *in situ* observations.¹⁸

This article is based on the paper "Ocean acoustics in the rapidly changing Arctic" by one of us (Worcester), Matthew Dzieciuch, and Hanne Sagen, *Acoustics Today*, volume 16 (2020), page 55.

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