Ocean Acoustics in the Rapidly Changing Arctic

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Multipurpose acoustic systems have special roles to play in providing observations year-round in ice-covered regions, complementing and supporting other observations.

Interest in Arctic acoustics began in the early years of the Cold War between the United States and the Soviet Union with the development of nuclear-powered submarines capable of operating for extended periods under the ice (Hutt, 2012). In 1958, the first operational nuclear submarine, the *USS Nautilus* (SSN 571), reached the North Pole during a submerged transit from the Bering Strait to northeast of Greenland. Beginning in the late 1950s, extensive research on Arctic acoustics was done from manned ice islands and seasonal ice camps to obtain the knowledge needed to support submarine operations and conduct antisubmarine warfare. However, military interest in Arctic acoustics waned with the end of the Cold War in the early 1990s.

As military interest was waning, there was increasing interest in the dramatic changes that the Arctic Ocean is undergoing in response to increasing atmospheric concentrations of carbon dioxide and other greenhouse gases (Jeffries et al., 2013). Surface air temperature in the Arctic has warmed at more than twice the global rate over the past 50 years (AMAP, 2017) while sea ice extent and thickness have declined dramatically (Stroeve and Notz, 2018). Moreover, ocean stratification is changing as warmer waters have entered the Arctic from the North Atlantic and North Pacific Oceans.

The ice cover presents a difficult challenge for an Arctic Ocean observing system designed to monitor the changes that are underway (**Figure 1**). Profiling floats, gliders, and autonomous underwater vehicles that measure ocean temperature,

Figure 1. *Sea ice in Fram Strait in August 2012. Photo by Peter Worcester, Scripps Institution of Oceanography, La Jolla, CA.*

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salinity, and other variables cannot surface in ice-covered regions to use the Global Navigation Satellite System (GNSS) to determine their position and to relay data back to shore, for example. Furthermore, measurements of sea surface height using satellite altimeters, which provide important constraints on the ocean circulation at lower latitudes, are not feasible when the ocean is covered with ice. Multipurpose acoustic systems can operate beneath the ice, however. Such systems provide acoustic remote sensing of ocean temperatures (ocean acoustic tomography), underwater navigation, and passive acoustic monitoring of natural and anthropogenic sounds. Thus, such systems have a special role to play in making measurements of the rapidly changing Arctic Ocean, complementing and supporting other in situ observations (Mikhalevsky et al., 2015; Howe et al., 2019).

At the same time, even as sound is used to help monitor the changes in the Arctic, the changes in the ice cover and stratification have affected acoustic propagation and ambient sound. As a consequence, what was learned about Arctic acoustics during the Cold War is now largely obsolete.

In this article, we describe a series of experiments that have been performed both to determine the effect of the changes in the Arctic on the acoustics and to use acoustic remote sensing as a tool to study the changing Arctic environment. The discussion of the experiments is preceded by a brief description of the extraordinary changes currently occurring in the Arctic and some background on Arctic acoustics. **Multipurpose Acoustic Systems in the Arctic Ocean Observing System** describes how multipurpose acoustic systems complement and support other in situ observations in ice-covered regions.

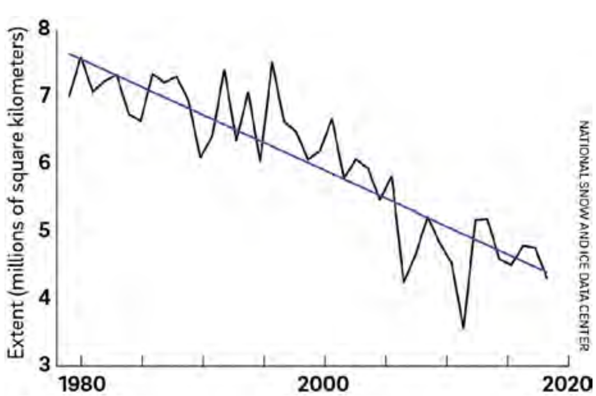


Figure 2. *Average monthly September sea ice extent from 1979 to 2019. The straight line is a linear fit showing a decline of 12.9% per decade. From the National Snow and Ice Data Center, 2019*

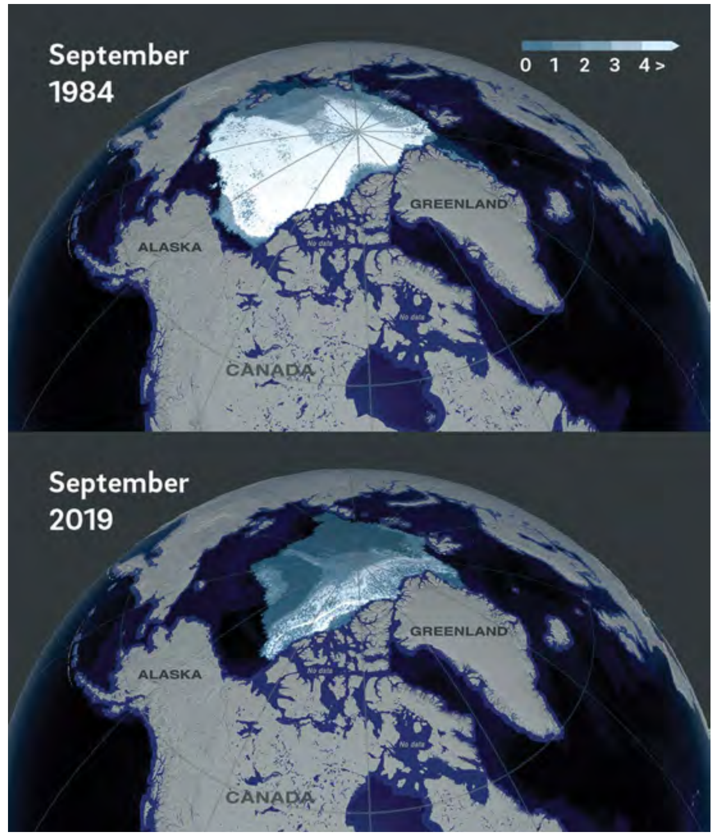


Figure 3. *Arctic sea ice age in September 1984 (**top**) and September 2019 (**bottom**). **Dark blue,** younger sea ice, or first-year ice; **white,** ice that is four years old or older. From the National Aeronautics and Space Administration (NASA) Scientific Visualization Studio, 2019.*

The Rapidly Changing Arctic Ocean

Ice

Satellites with passive microwave sensors have made accurate measurements of the areal extent of sea ice (defined as the area of ocean with at least 15% sea ice) since 1979. The monthly average extent of ice in September, when it is at a minimum, declined from 7.5 million square kilometers in 1980 to 4.4 million square kilometers in 2019 (**Figure 2**). The minimum extent in the satellite record occurred on September 16, 2012, when there were 3.4 million square kilometers of ice. Although there is considerable year-to-year variability, a linear fit yields a decline of 12.9% per decade in the September monthly average from 1979 to 2019 (National Snow and Ice Data Center, 2019). The ice extent in winter is also declining, although more slowly.

The decrease in the observed Arctic sea ice area is directly correlated with anthropogenic CO_2 emissions (Stroeve and Notz, 2018). The ice loss per ton of anthropogenic CO_2 emission is about 3 square meters during summer and slightly above 1 square meter during winter. Extrapolating these relationships into the future, the Arctic will become ice free in the months of August and September when an additional roughly 800 ± 300 gigatons of anthropogenic CO_2 have been released. The emission rate today is about 40 gigatons of CO_2 per year. If this emission rate continues unchanged into the future, an additional 800 gigatons of CO_2 will have been released in about 20 years.

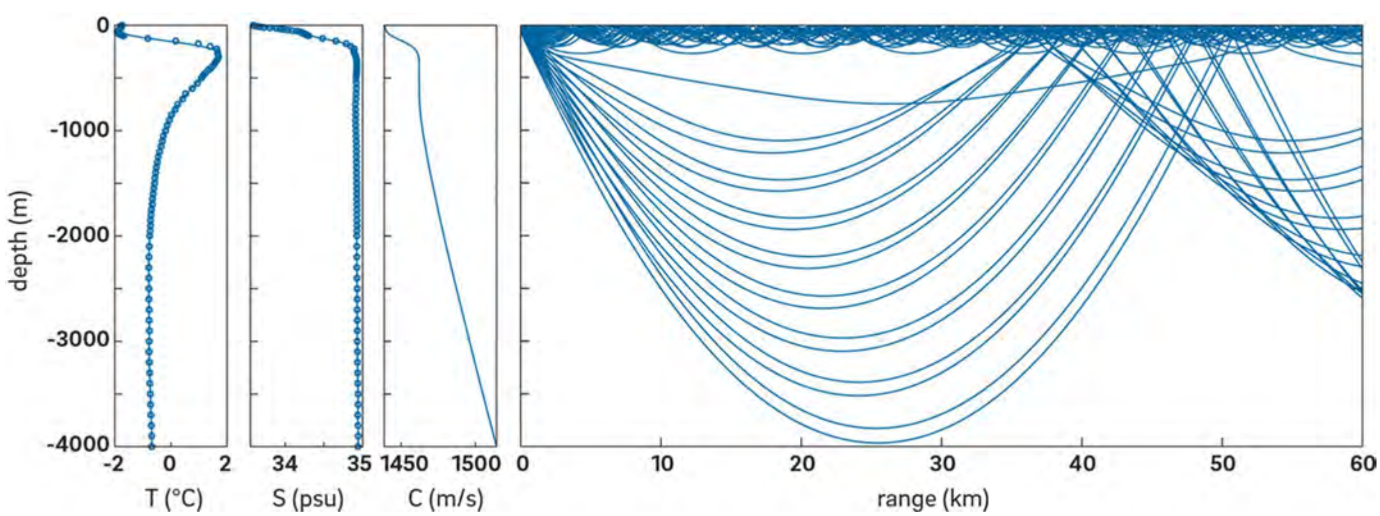
Ice thickness is more difficult to measure than ice extent (Kwok and Untersteiner, 2011). Thickness estimates are available from upward-looking sonars that measure ice draft (the distance from the ocean surface to the bottom of the ice) installed on submarines and moorings and from satellite altimeters (ICESat and CryoSat-2) that measure ice freeboard (the distance from the top of the ice to the ocean surface). Between the early submarine measurements (1958 to 1976) and the CryoSat-2 period (2011 to 2018), the average thickness over most of the deep-water portions of the Arctic at the end of the melt season decreased by 2.0 meters, or about 66% (Kwok, 2018). The most dramatic decrease has been at the North Pole where the average ice thickness at the end of the melt period decreased by about 2.9 meters, from 3.8 meters to 0.9 meter (Kwok, 2018).

The presence of multiyear ice (i.e., ice that survives the summer melt season) is closely related to ice thickness and volume. Sea ice age can be estimated using a combination of satellite passive-microwave data and drifting buoys to derive the formation, movement, persistence, and disappearance of sea ice (Maslanik et al., 2011). The area covered by sea ice that was four years of age or older declined from 2,687,000 square kilometers in September 1984 (week 38) to 53,000 square kilometers in September 2019 (week 38; **Figure 3**; National Snow and Ice Data Center, 2019). The disappearance of multiyear ice has affected not only the average ice thickness but also the pressure ridges and associated ice keels formed when ice floes collide. Old multiyear ice has larger pressure ridges than first-year ice, with ice keels that can extend down tens of meters. These deep keels are disappearing together with the multiyear ice.

Ocean Stratification

Warm, salty water from the Atlantic Ocean enters the Arctic through Fram Strait between Greenland and Svalbard and through the Barents Sea. This water sinks and forms the relatively warm Atlantic layer at depths of approximately 150-900 meters (**Figure 4**). (The density of sea water, and therefore the ocean stratification, is largely controlled by the salinity at the near-freezing temperatures in the Arctic Ocean.) The Atlantic water travels in a counterclockwise sense along the deep

Figure 4. Left three: *temperature (T), salinity (S), and sound speed (C) profiles at 84°N, 28°E in the eastern Arctic Ocean from the 2013 World Ocean Atlas. The temperature maximum at about 300 meters is associated with the Atlantic layer.* ***Right:*** *geometric ray paths for an acoustic source at a 60-meter depth. Rays with positive (**upward**) and negative (**downward**) launch angles of the same magnitude give rise to the closely spaced ray pairs. The ray with a positive launch angle reflects from the surface before starting downward.*



Arctic basin margins and ridges, guided by the bathymetry and becoming deeper as it travels. It is present throughout the Arctic Ocean. Data from 1950 to 2010 show that the Atlantic water core (maximum) temperature steadily warmed beginning in the 1970s (Polyakov et al., 2012).

In addition to the changes associated with the warming Atlantic layer, the western Arctic is also influenced by waters entering from the Pacific Ocean through the shallow Bering Strait between Russia and Alaska. These Pacific-origin waters take two forms in the Canada Basin north of Alaska: the fresher Pacific Summer Water (PSW) between approximately 40 and 100 meters in depth characterized by a local temperature (and sound speed) maximum and the more saline Pacific Winter Water (PWW) characterized by a local temperature (and sound speed) minimum (McLaughlin et al., 2011). The PSW warmed and thickened starting in about 2000 (Timmermans et al., 2014) while the depth of the PWW increased from 150 to 200 meters.

Central Arctic Acoustics

Acoustic Propagation

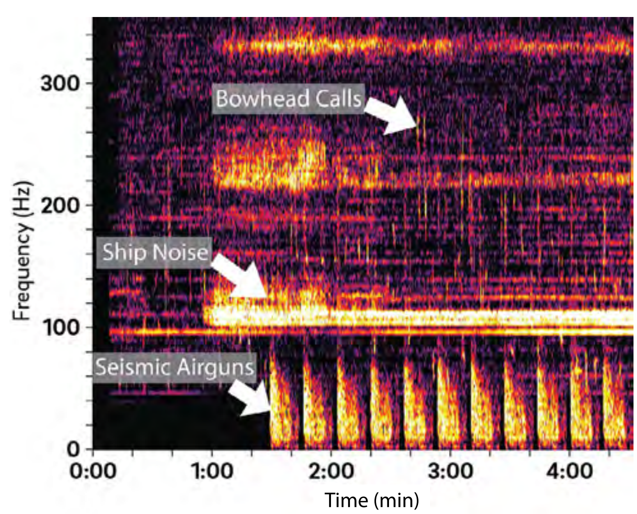
In general, sound speed increases monotonically with depth in the eastern central Arctic (**Figure 4**). The sound speed profile is, therefore, everywhere, upward refracting, and sound interacts repeatedly with the ice as it propagates. Some of the acoustic energy is reflected with each interaction, but some is scattered by the rough ice and some is converted to compressional and shear waves within the ice. The resulting losses increase with increasing frequency; the Arctic waveguide is effectively a low-pass filter. During the Cold War, propagation to ranges in excess of a few hundred kilometers was limited to frequencies below about 30 Hz or wavelengths greater than 50 meters (Mikhalevsky, 2001). The strong ice interactions mean that the changes in the ice cover that are occurring have important implications for acoustic propagation. As the frequency becomes even lower, however, the vertical extent of the acoustic normal modes increases and they begin to interact with the seafloor and lose energy to it. The resulting losses increase with decreasing frequency, leading to a lower frequency bound of 5-10 Hz for long-range propagation.

Acoustic propagation in the western Arctic differs from that in the eastern Arctic because of the presence of the Pacific-origin waters. Sound speed increases with depth, except for the sound speed minimum at the depth of the PWW, which forms an acoustic duct. As the PSW has warmed and thickened in recent years, the sound speed duct, sometimes referred to as the Beaufort duct, has become stronger (i.e., the difference in sound speed between the maximum in the PSW and the minimum in the PWW has increased). Signals transmitted from sources within the duct can be trapped and propagate to long ranges without interacting with the ice cover or the seafloor. An acoustic navigation and communications system deployed in the Beaufort Sea achieved ranges in excess of 400 kilometers using 900-Hz sources deployed at 100-meter depth in the Beaufort duct, for example (Freitag et al., 2015). The duct is sufficiently weak, however, that signals at frequencies below a few hundred hertz are not fully trapped.

Ambient Sound

The sources and propagation of ambient sound in the Arctic differ substantially from those at midlatitudes. The prevailing sound in ice-covered regions of the Arctic is largely generated when the ice cover deforms and fractures in response to forcing from wind, swell, currents, and thermal stresses (e.g., Mikhalevsky, 2001; Johannessen et al., 2003). In contrast, low-frequency (~20- to 500-Hz) sound at lower latitudes is predominately caused by distant shipping, whereas higher frequency (~500- to 100,000-Hz) sound is mostly due to spray and bubbles associated with breaking waves. More episodic sources of sound in the Arctic include marine life (especially in the marginal ice zone that separates pack ice from open water), earthquakes, and anthropogenic sound due to seismic surveys and ice breakers (**Figure 5**). There is a broad peak in the spectrum at 15-20 Hz in the central Arctic due to the band-pass nature of propagation from distant

Figure 5. *Spectrogram from a hydrophone in Fram Strait showing bowhead whale calls, a ship transiting, and airgun pulses from a seismic survey. Reproduced from Moore et al., 2012, with permission of Oxford University Press.*



sources of sound. The level and character of ambient sound in the Arctic can be expected to change as the ice coverage and thickness decrease and anthropogenic activities, such as seismic exploration, fishing, and shipping, increase. Ambient sound in the Arctic is highly variable in space and time, however, and no trends are yet evident (Ozanich et al., 2017).

Arctic Ocean Acoustic Tomography

Ocean acoustic tomography is a method for remote sensing of the ocean interior by transmitting sound through it (Munk et al., 1995; Worcester et al., 2005). The speed at which sound travels through the ocean depends on the temperature and velocity fields, and precise measurements of acoustic travel times therefore provide information on ocean temperature and current. Inverse methods are used to infer the state of the ocean traversed by the signals from the measured travel times. The effects of ocean currents on travel times are typically one to two orders of magnitude less than the effects of sound speed perturbations, but they can still be measured by transmitting sound in opposite directions (reciprocal transmissions). Sound traveling with a current travels faster than sound traveling against it.

Travel times are inherently spatially integrating, providing horizontal and vertical averages over long ranges and suppressing 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," usually in the context of geometries for which there are few or no crossing acoustic paths.

Basin Scales

During the 1994 Transarctic Acoustic Propagation (TAP) experiment, phase-modulated acoustic signals with a center frequency of 19.6 Hz transmitted by a source located at ice camp Turpan north of Svalbard traveled across the Arctic basin to receiving arrays located at ice camp Narwhal in the Lincoln Sea and ice camp SIMI in the Beaufort Sea (Mikhalevsky and Gavrilov, 2001). The range from Turpan to SIMI was about 2,630 kilometers, and the measured travel time of the acoustic normal mode that primarily sampled the Atlantic layer (mode 2) was shorter by 2.3 ± 1.2 seconds than that computed from climatology, indicating a basin-scale warming of almost 0.4° ± 0.2°C (**Figure 6**). This result was subsequently confirmed by measurements made from icebreakers and submarines (Science Ice Exercise [SCICEX]; also known as the Submarine Arctic Science Program).

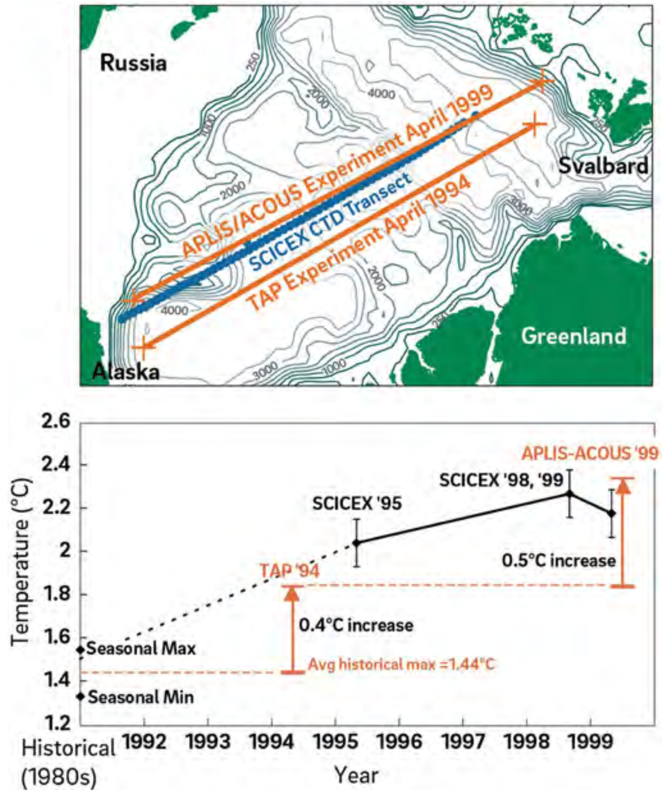


Figure 6. *Top: Transarctic Acoustic Propagation (TAP), Arctic Climate Observations using Underwater Sound (ACOUS), and Science Ice Exercise (SCICEX) trans-Arctic sections (see text for descriptions). Bottom: maximum temperatures of the Atlantic Layer obtained from historical climatology, the 1994 TAP and 1999 ACOUS mode-2 travel times, and the SCICEX 1995, 1998, and 1999 submarine transects. The uncertainties in the TAP and ACOUS temperatures are ±0.2°C and ±0.25°C, respectively. Arrows, change in maximum temperature inferred from the acoustic travel time changes. Reproduced from Dushaw et al., 2001, with permission.*

In October 1998, as part of the joint US-Russian Arctic Climate Observations using Underwater Sound (ACOUS) project, another ultralow-frequency source (20.5 Hz) was moored in Franz Victoria Strait (Mikhalevsky and Gavrilov, 2001). The transmissions were recorded from October 1998 to December 1999 on a vertical array moored in the Lincoln Sea and in April 1999, on a vertical array at ice camp APLIS in the Chukchi Sea. The acoustic path to APLIS from the moored source was close to that from Turpan to SIMI during the TAP experiment. It gave mode-2 travel times that were 2.7 ± 1.3 seconds shorter than the TAP measurements (corrected for the different path lengths), indicating a further warming of 0.5°C ± 0.25°C of the Atlantic layer (**Figure 6**).

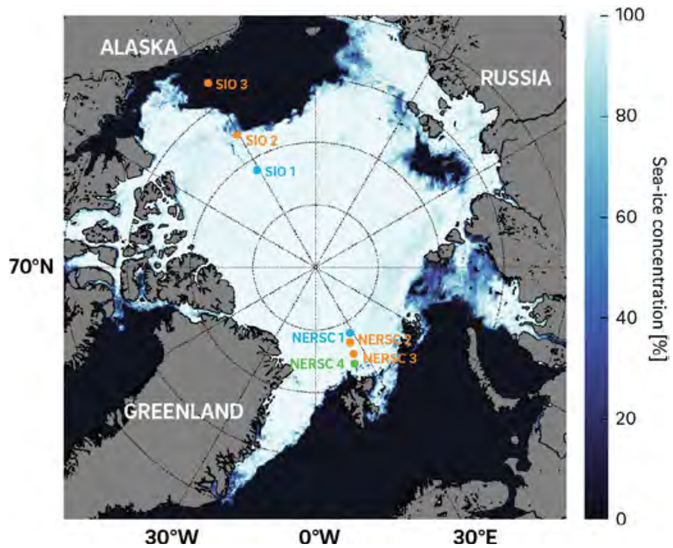


Figure 7. *The geometry of the 2019–2020 Coordinated Arctic Acoustic Thermometry Experiment (CAATEX). The acoustic transceivers are located at SIO1 and NERSC1 (**blue**). There are four vertical receiving arrays: SIO2, SIO3, NERSC2, and NERSC3 (**orange**). The mooring at NERSC4 (**green**) has conventional oceanographic instrumentation to measure temperature, salinity, and currents. All of the NERSC moorings are in the Nansen Basin south of the Gakkel Ridge; ice conditions prevented deployment further north. The sea ice concentration on October 31, 2019 is from the Advanced Microwave Scanning Radiometer 2 (AMSR2) dataset provided by the University of Bremen (Spreen et al., 2008). Available at acousticstoday.org/sea-ice.*

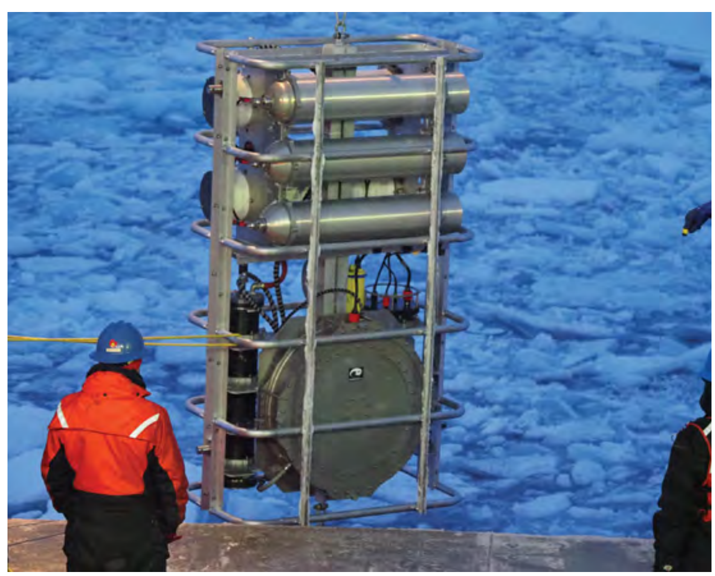
Twenty years later, the joint US-Norwegian Coordinated Arctic Acoustic Thermometry Experiment (CAATEX) was deployed in late summer 2019 to repeat the basin-scale measurements made during the TAP and ACOUS experiments, allowing present-day basin-scale heat content to be compared with that in the 1990s. Six moorings were installed, providing both basin-scale and shorter range measurements (**Figure 7**). Two moorings (one each in the eastern and western Arctic) are transceivers. Each has a 35-Hz acoustic source at 60-meter depth (**Figure 8**) and a vertical receiving array extending down below the source. Four moorings have only vertical receiving arrays. The sources are programmed to transmit every three days. The moorings are scheduled to be recovered in late summer 2020.

Fram Strait

Fram Strait, with a width of nearly 400 kilometers and a sill depth of ~2,600 meters, is the only deepwater connection between the Arctic and the rest of the oceans in the world (**Figure 9**). The northbound West Spitzbergen Current on the east side of the Strait transports relatively warm and salty Atlantic water into the Arctic, forming the Atlantic Layer. The southbound East Greenland Current on the west side of the Strait transports sea ice and relatively cold and fresh polar water out of the Arctic. Significant recirculation of the Atlantic water and intense mesoscale variability in the center of the Strait make it difficult to accurately measure ocean transports through the Strait.

A series of tomographic experiments have been conducted in Fram Strait to determine whether or not integral acoustic measurements, when combined with other data and ocean models, can provide improved estimates of the transports of the inflowing and outflowing water masses. A preliminary engineering test in 2008–2009 as part of the Developing Arctic Modeling and Observing Capabilities

Figure 8. *An ultralow-frequency source assembly (f_0 = 35 Hz; Δf = 4 Hz) on the US Coast Guard Cutter (CGC)* Healy *during deployment in the Canada Basin during September 2019. The source transducer, developed by GeoSpectrum Technology, Inc., is mounted at the bottom of the frame. It is approximately 1 meter in diameter and 0.2 meter thick. Above it are high-pressure gas bottles for the pressure-compensation system needed to keep the internal gas pressure equal to the external water pressure. The pressure compensation system itself as well as the source controller, power amplifier, and batteries are on the opposite side of the frame. Photo by Lee Freitag, Woods Hole Oceanographic Institution, Woods Hole, MA.*



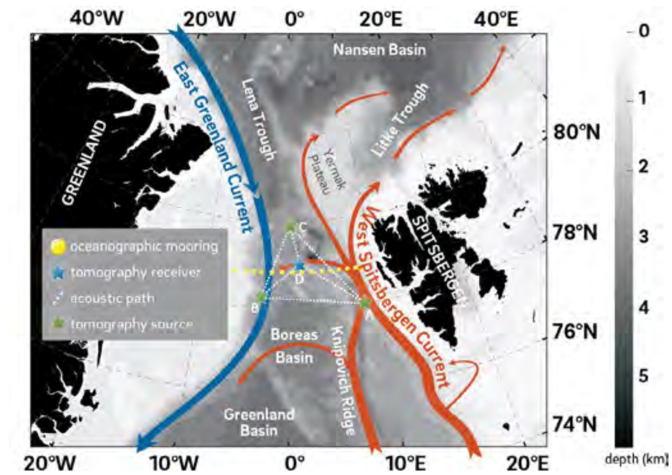


Figure 9. *Geometry of the 2010–2012 Acoustic Technology for Observing the Interior of the Arctic Ocean (ACOBAR) experiment in Fram Strait. Acoustic transceiver moorings (**green**) were located at A, B, and C. (Mooring C failed prematurely.) An acoustic receiver mooring (**blue**) was located at D. Oceanographic moorings were maintained at about 78°50′N by the Norwegian Polar Institute (NPI) and the Alfred Wegener Institute (AWI; **yellow**). The principal currents in Fram Strait are also shown. The bathymetry is from the International Bathymetric Chart of the Arctic Ocean (IBCAO). Reproduced from Sagen et al., 2017, with permission of the Acoustical Society of America.*

for Long-term Environmental Studies (DAMOCLES) project was followed by acoustic measurements made as part of the 2010–2012 Acoustic Technology for Observing the Interior of the Arctic Ocean (ACOBAR; **Figure 9**) and the 2014–2016 Arctic Ocean UNDER melting ICE (UNDER-ICE) projects. All of the experiments employed Teledyne Webb Research swept-frequency 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 result in complex acoustic arrival patterns (Sagen et al., 2017). Nonetheless, it has proved possible to obtain robust estimates of range and depth average temperature along the acoustic paths (Sagen et al., 2016).

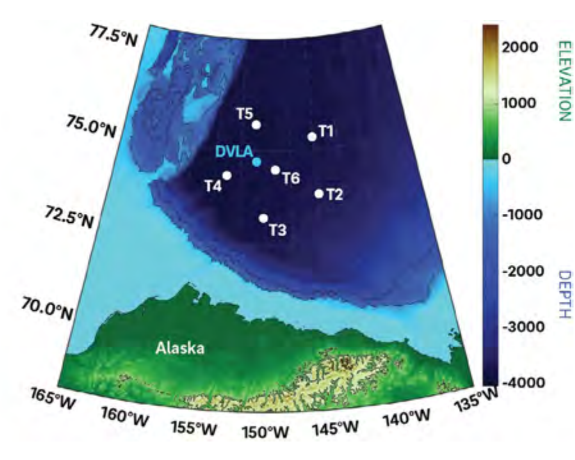
As a first step toward using the travel times to constrain ocean models, a high-resolution regional ocean model has been used to interpret the structure and variability of the acoustic arrivals (Geyer et al., 2020). Acoustic signals that overlap in time but arrive at the receiver from different vertical angles can be resolved using the acoustic arrival patterns computed from the ocean model fields, providing insight into the arrival structure and the seasonable variability of the propagation.

Canada Basin

The dramatic changes in the ice cover and ocean stratification that are occurring in the central Arctic motivated the Canada Basin Acoustic Propagation Experiment (CANAPE). Six acoustic transceiver moorings were deployed during late summer 2016 in the Canada Basin in an array with a radius of 150 kilometers (**Figure 10**). A distributed vertical line array (DVLA) receiver was located slightly to the northwest of the center of the array. All of the moorings were recovered in late summer 2017. The transmissions were also recorded on acoustic Seagliders deployed in summer 2016 and summer 2017 in the Canada Basin Acoustic Glider Experiment (CABAGE; L. Van Uffelen, personal communication, 2019).

The goals were to understand the effects of the changes in the ice and ocean on acoustic propagation and ambient sound. In addition, the tomographic array would provide information on the spatial and temporal variability in the upper ocean throughout the annual cycle and make it possible to assess whether acoustic methods, together with other data and ocean modeling, can yield estimates of the time-evolving ocean state useful for understanding the local ocean dynamics and for making improved acoustic predictions.

Figure 10. *Geometry of the 2016–2017 Canada Basin Acoustic Propagation Experiment (CANAPE). Six acoustic transceiver moorings (**white**) and a distributed vertical line array (DVLA) receiver mooring (**blue**) were deployed in the Canada Basin. The transmissions were also recorded by acoustic receivers located on the continental shelf and upper slope to the southwest of the array (not shown). The bathymetry is from the International Bathymetric Chart of the Arctic Ocean (IBCAO).*



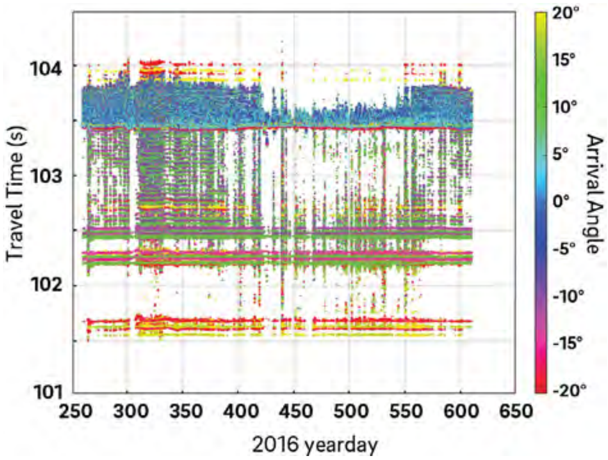


Figure 11. Travel times as a function of yearday (yearday 1 is defined to be January 1, 2016. The yeardays continue into 2017 for transmissions from mooring T5 to mooring T6 during the 2016–2017 CANAPE experiment (see ***Figure 10****). The range is approximately 149 kilometers. Each peak in the acoustic receptions that exceeds a specified threshold is plotted as a dot. The size of the dots is proportional to the signal-to-noise ratio, and the color indicates the vertical arrival angle at the receiver. See text for a further explanation.*

The acoustic transceivers were similar to those used in Fram Strait. Each source transmitted every four hours. The resulting arrival structures can be conveniently summarized in "dot plots" constructed for each source-receiver pair in which the travel times of the peaks in each reception are plotted versus yearday (Munk et al., 1995). The receptions at mooring T6 (in the center of the array) for transmissions from mooring T5 are shown in **Figure 11**. There are multiple ray paths along which the transmitted signal travels from the source to the receiver (eigenrays). Each approximately horizontal line in the plot corresponds to arrivals from a specific ray path. For example, the arrivals at ~102.2 seconds are from a ray path that has a lower turning depth close to 2,000 meters. The color indicates that the vertical arrival angle at the receiver is about +12° (traveling upward). The closely spaced arrivals between approximately 102.6 and 103.4 seconds have much shallower lower turning depths and interact more frequently with the surface than the deeper turning rays. The disappearance of the arrivals clearly shows the effects of the increased losses that occur as the ice cover reaches a maximum thickness of about 1.5 meters in late winter. The unresolved, low-angle arrivals occurring after about 103.4 seconds are from energy largely trapped in the Beaufort Duct.

The dot plots show that that the measured travel times are remarkably stable, with peak-to-peak variability of only about 20 milliseconds over the entire year. In comparison, travel times in midlatitudes at similar ranges vary by something like an order of magnitude more (~200 milliseconds peak to peak) due to the effects of ocean mesoscale variability, with spatial scales of roughly 100 kilometers and timescales of about 1 month.

Multipurpose Acoustic Systems in the Arctic Ocean Observing System

Monitoring and understanding the rapid changes underway in the Arctic Ocean are of crucial importance in assessing its role in climate variability and change. In addition, as the Arctic converts from a largely perennial ice cover to a seasonal ice cover, oil and gas exploration, fisheries, mineral extraction, shipping, and tourism will increase the pressure on the vulnerable Arctic environment, requiring improved ocean-ice-atmosphere data to inform and enable sustainable development while protecting this fragile environment.

Multipurpose acoustic systems can make important contributions to an integrated Arctic Ocean observing system designed to observe the rapid changes underway in the Arctic, taking advantage of the fact that acoustic signals can travel long distances beneath the ice (Mikhalevsky et al., 2015; Howe et al., 2019). Acoustic networks can provide under-ice navigation for floats, gliders, and autonomous underwater vehicles. They can measure large-scale temperatures and currents (ocean acoustic tomography). Passive acoustic monitoring of natural sounds can provide information on marine life, ice, and seismic events, whereas monitoring of anthropogenic sounds can help assess the potential for impacts on marine animals. In an integrated multipurpose acoustic system, the same sources generate signals for both underwater navigation and ocean acoustic tomography. The receivers used for ocean acoustic tomography are also used for passive acoustic monitoring. The spatially averaged temperature fields provided with high temporal resolution by ocean acoustic tomography and the high spatial resolution data provided by floats, gliders, and autonomous underwater vehicles are naturally complementary. Both data types provide constraints for ocean general circulation models. Pilot multipurpose acoustic networks were successfully implemented on a regional scale in the 2010–2012 ACOBAR and 2014–2016 UNDER-ICE projects in Fram Strait and the 2016–2017 CANAPE experiment in the Canada Basin using autonomous sources and receivers. The CAATEX experiment is a first step toward developing a basin-scale multipurpose acoustic network using modern instrumentation. It will provide the data on low-frequency acoustic propagation in today's Arctic needed to design basin-scale acoustic networks to help monitor the Arctic as it continues to change.

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