Ocean-scale acoustics

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Abstract

The world's oceans present many fascinating weather patterns. The Gulf Stream winds it way along the U.S. coast, spinning off enormous lenses of water (eddies) some 100 km across, bringing a hint of Florida to Cornwall, and even delivering warm saline water to the farthest reaches of the Arctic Ocean. Along the world's continental shelves the Sun and the Moon draw the oceans twice daily between the continental shelf and slope. As a result, at the Portuguese shelf-break, internal tides 25 m in height are generated while scarcely causing a ripple at the surface. At the mouth to the Mediterranean, these same tidal forces generate a solibore, travelling tens of kilometres east into the Mediterranean while strong winter winds in the Greenland Sea stir the ocean to several hundred meters forming a thick surface duct. This paper will look at such oceanographic features in terms of how they affect the sound propagation and what we have learned about how sound can be used to observe the features themselves.

1. Introduction

As discussed by Urick [1] the role of the ocean's weather on sound propagation had been predicted theoretically and demonstrated experimentally by 1919 [2]. The importance of this connection between acoustics and oceanography was gradually appreciated, as early sonar systems were found to be highly variable in their performance. In the U.S., a milestone was passed in 1940 when the U.S. Navy brought the problem to the attention of the Scripps Institution of Oceanography and Woods Hole Oceanographic Institution leading to an extensive research program. The results are summarized in the final report of the U.S. National Defense Research Committee published as Physics of Sound in the Sea [3] .

Half a century later, much is still unknown and this has generated a great deal of naval research into the forward problem of how the ocean features affect sound. As one might expect, the same features that affect sound significantly are also often the most amenable to being measured and observed acoustically [4-6]. This is the inverse problem of acoustical oceanography that in recent years has emerged as a discipline of its own.

In the remainder of this paper, we will take a brief tour of a few of the key oceanographic features that both affect and can be observed by acoustic systems. We organize the material into three categories: shallow water, deep water, and Arctic propagation, and use these themes to talk about typical oceanographic features that have a big impact on the acoustics.

2. Shallow water and internal tides

Modelling sound propagation in shallow water is notoriously difficult. Since the surface is heated, the water often gets cooler with depth, causing the sound to bend towards the ocean bottom. The reflectivity of the bottom may be highly variable since the ocean bottom — like the coastal landmasses — may vary over short spatial scales. In addition, the fresh rivers, sometimes warm and sometimes cold, pour into the ocean, while the tides generate complicated swirling patterns of cold and warm, fresh and salty water.

Despite this apparent complexity, there are many common characteristics of shallow-water environments and often one can do an excellent job of modelling the key features. As an example, we consider INTIMATE96 (Internal Tide Monitoring by Acoustic Tomography Experiment) [7, 8]. A source was deployed on the continental slope and the sound was recorded by a 4-phone vertical line array on the continental shelf. A ray trace from the source gives an impression of the propagation conditions as shown in Figure 1. The features seen here are typical of shallow water conditions during the summer. Note how the warmer surface layer tends to refract the rays down towards the ocean bottom. As a result, the paths in Figure 1 divide in two groups depending on whether they miss the surface (solid lines) or not (dotted lines). The former are obviously not directly sensitive to the surface effects (bubbles, waves, surface tide). Both groups of rays are sensitive to the reflectivity of the bottom so that knowing whether the bottom is silt or sand can have a huge effect on the energy levels (but not so much the arrival times).

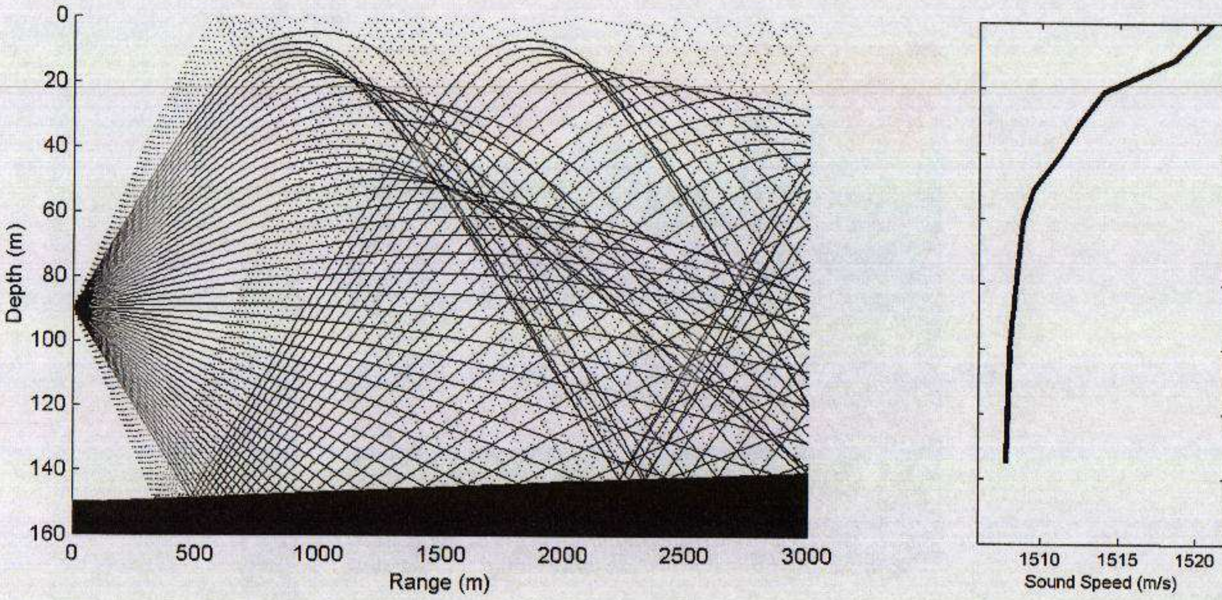

Figure 1. Ray trace for the INTIMATE96 experiment revealing typical shallow-water propagation characteristics. Weaker, surface- and bottom-reflected paths are shown as a dotted line.

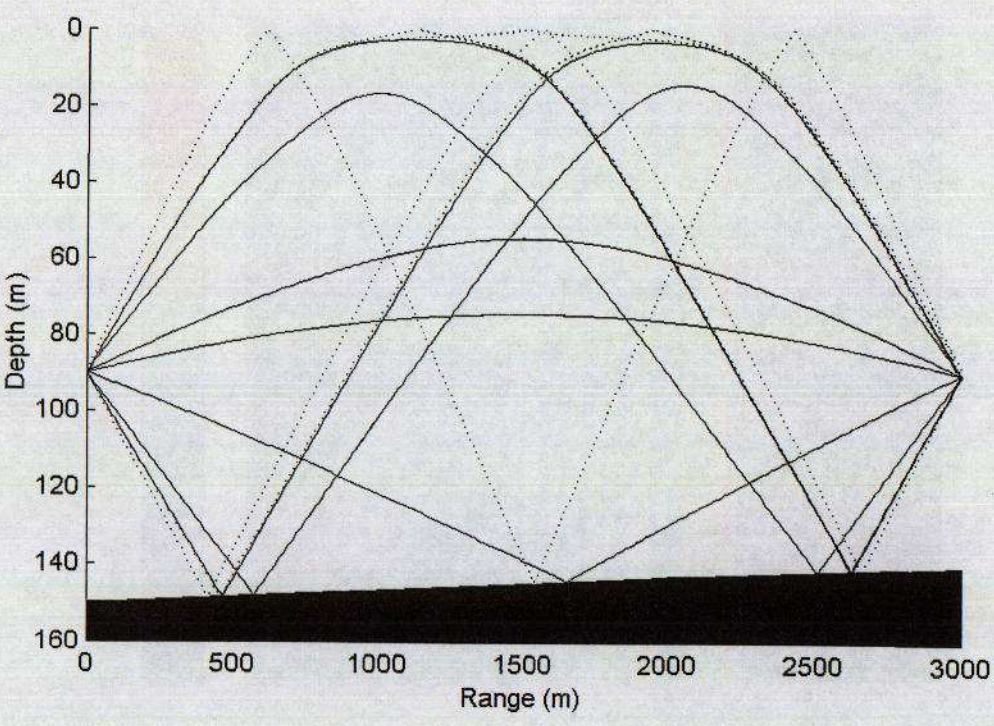

Figure 2. Eigenrays connecting source and receiver for the INTIMATE96 experiment showing paths interacting with bottom, surface, or neither boundary.

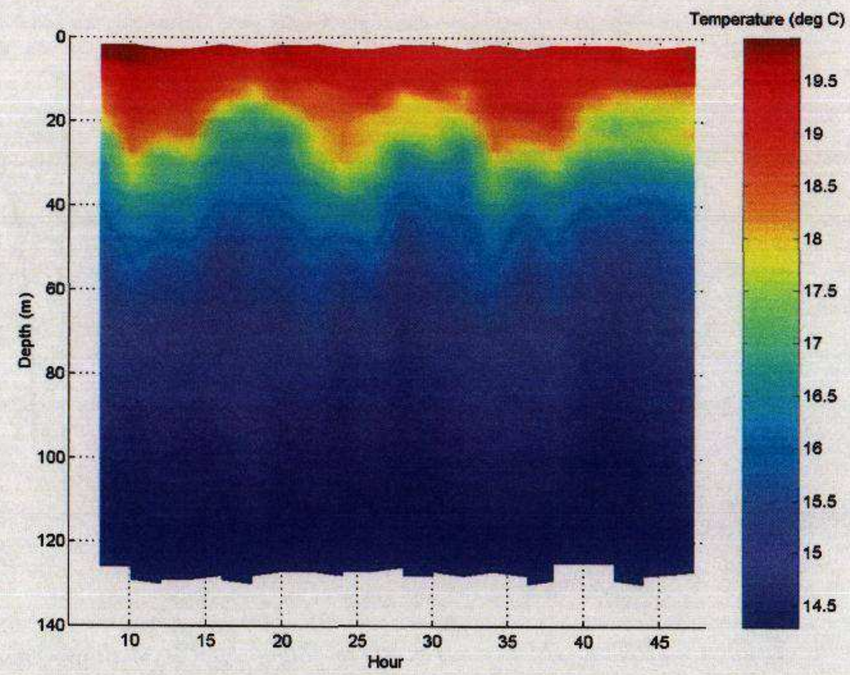

Figure 3. Thermal structure of an internal tide measured off the coast of Portugal during INTIMATE96.

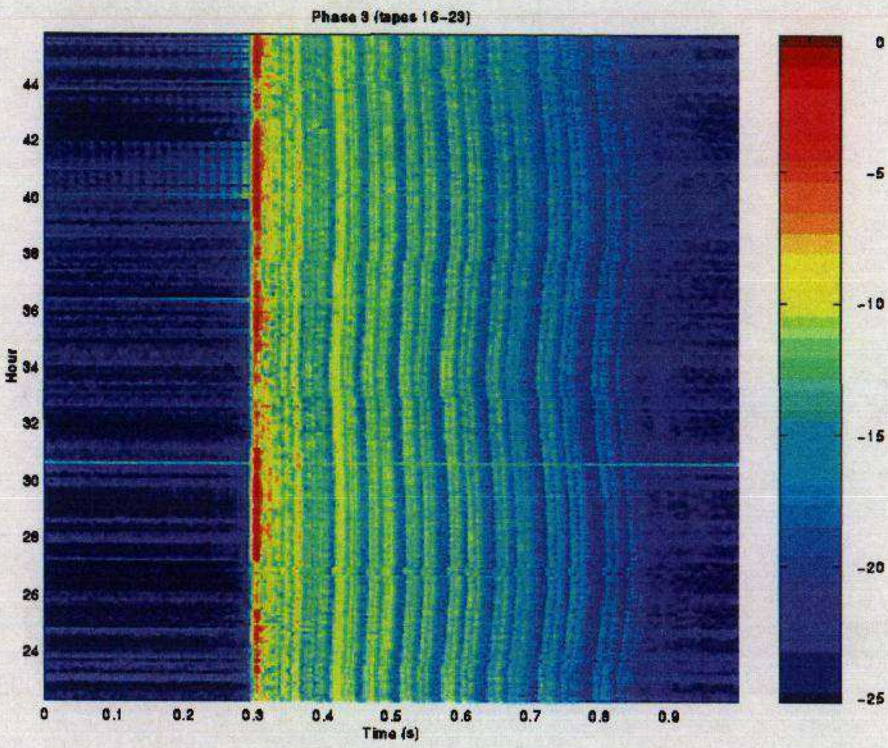

Figure 4. Variation of the echo pattern over an entire day during INTIMATE96, showing the effect of the tides. The colour scale shows intensity in dB relative to an arbitrary reference. The arrivals correspond to the ray paths shown in Figure 3.

If we focus our attention on a receiver located at a depth of 90 m and a range of 3 km, and extract only the rays from Figure 1 that pass through (or near) this receiver, we obtain the eigenray plot shown in Figure 2. Here we can more clearly see the paths associated with echoes heard at the receiver. The steeper-angle paths are only slightly affected by the thermal structure and form a regular pattern of arrivals.

One of the key physical features effecting shallow water propagation is the tide. As is well known, it raises and lowers the ocean surface by a meter or so. As a proportion of the water depth that difference is often significant in shallow water, allowing the tides to easily be observed using acoustics. However, besides the usual surface tide, there is an internal tide whose physics is perhaps best understood by reviewing the ordinary waves one sees breaking on the beach. In sterile, scientific terms these are simply interfacial waves that exists between two media (air and water) of different densities. They can be excited by anything that disturbs the surface; however, the energetic waves are frequently associated with distant storms. Indeed, from where one of us writes in California, the waves that fiercely pound our coast can originate from storms as far away as Australia [9] . As the waves move towards the beach, they are refracted by the ocean bottom, but tend to break parallel to the shore. Their amplitude is initially small and their shape sinusoidal; however, as they advance, they become steeper. Finally, as nonlinear effects become important, they lose their sinusoidal shape and eventually break. This final release is often quite violent; all frequent beach-goers know the hazards of 'going over the falls'.

We can now easily relate the familiar waves seen at the beach to internal waves. The surface waves travel along the interface between two layers of different density; the internal waves do the same, except the two media involved are a warm layer of water over a colder one (or more generally, a medium with continuous density variations). All of the previously described features apply to the internal waves. When the dominant excitation is tidal, the internal waves are termed internal tides. We have captured a picture of one (Figure 3) during INTIMATE96 using its thermal signature measured on a vertical line over 2 days [7]. This particular internal wave was excited by the tides drawing water over the shelf edge, which separates the continental slope from the continental shelf. The particular site was off the coast of Portugal near Lisbon, but similar characteristics could be found in coastal sites all over the world. Notice that their amplitude is about 20 m and their period is about 12.4 hours, which corresponds to the lunar tide.

A 300-800 Hz chirp was transmitted repeatedly during INTIMATE96. Using standard pulse compression methods (which involve nothing more than correlating the received signal with a replica of what was transmitted), the chirps are converted to the equivalent of a series of short-duration explosions. Plotted over the course of a day and using a log scale (Figure 4), we get a picture of how the echo pattern in the channel varies over time. A single horizontal slice on this plot is the response due to a single chirp after pulse compression. Here in the time domain, we can see the echoes corresponding to the eigenrays shown earlier.

As is fairly typical for shallow water, the first arriving pulses are the refracted paths that do not hit the surface. These are not resolved in the time-domain and appear as a sort of clump. The later paths are the steeply travelling ones that reflect off both boundaries and are not heavily influenced by the ocean thermal structure. On these plots we can clearly see the effects of the tides. The sinusoidal meander of the late arrivals is the direct effect of the raising and lowering of the ocean surface. We also see changes in the early arrivals that involve changes in the intensity and duration of the first cluster of arrivals. Those changes are directly related to the internal tides. In fact, a few simple measurements on the parameters of the echo pattern are sufficient to resolve the first three tidal modes [7] .

Internal waves are of particular interest at the moment. They have been fingered as a key suspect in a cascading process that robs the moon of its orbital energy. As discussed by Munk and Wunsch [7] laser reflections from a lunar mirror show that the total power dissipation is 3.7 terawatts. The energy is lost to the familiar surface tide, which in turn couples to internal tides with substantial coupling at the shelf edge. The energy for internal tides is in turn dissipated on a smaller scale in an aggregate process described loosely as turbulence. Interestingly, estimates of the coupling from surface to internal tides at the world's shelf edges are a couple of orders of magnitude too small to account for the expansion of the lunar orbit. However, it has recently become clear that internal waves can just as easily be generated at offshore ridges. In particular, internal tide fields radiating from the Hawaiian Islands have been detected using both acoustic tomography and satellite altimetry. Much however, remains to be learned about the role of tidal dissipation.

3. Deep-water propagation in temperate environments

Studies conducted during World War II demonstrated the nearly ubiquitous presence of a significant minimum (see Figure 5) in the sound speed, forming the so-called Deep Sound Channel (a.k.a. SOFAR or Underwater Sound Channel) [11] . While the acoustic propagation is significantly more complicated because of the resulting refractive effects, the channel is in another sense greatly improved for it: acoustic energy is trapped within the bowl, so that modest sources can be heard at great ranges, even around the entire globe. The trapping effect is illustrated in the ray trace in Figure 5, showing the well-known convergence zone (CZ) pattern in which energy refocuses near the surface at periodic intervals of around 50 km. This particular plot is taken from a deep-water Mediterranean case. Typically, the CZ period is in the range of 40-70 km.

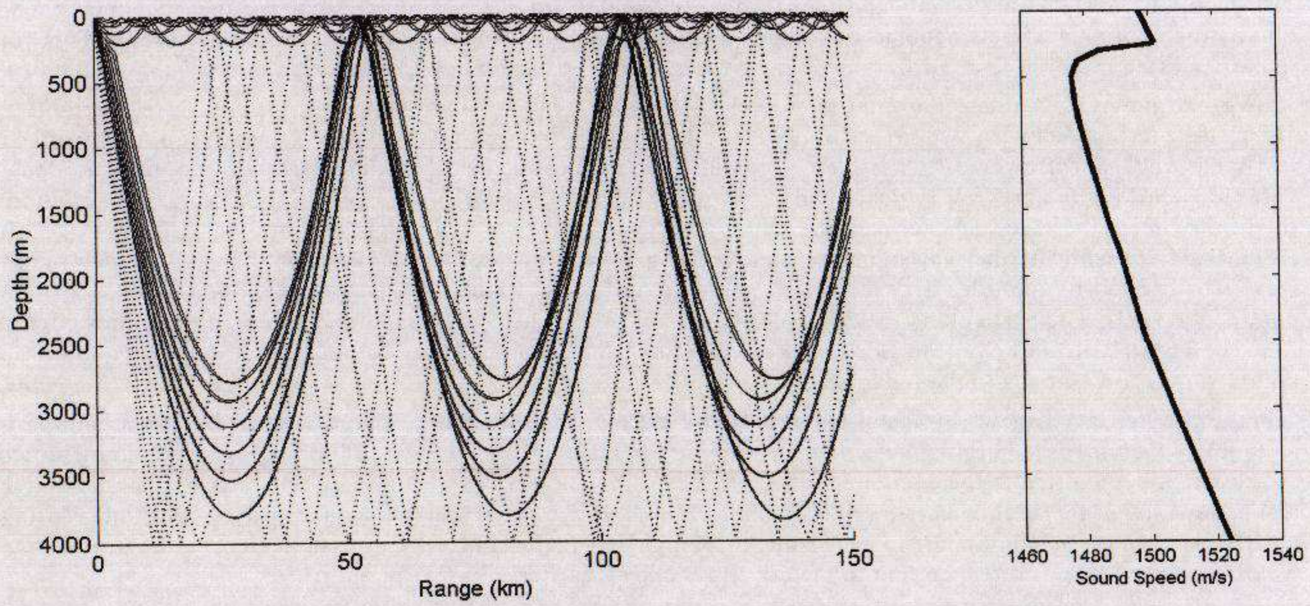

Figure 5. Sound-speed and ray trace for a Mediterranean profile (on a common depth axis) showing typical deep-water characteristics.

Surface and bottom reflected paths are still important, particularly for quiet sources (implying short ranges), and indeed detection in the so-called shadow zone between the convergence zones relies completely on such boundary interacting paths. However, at long ranges, the cumulative effects of reflection loss eventually overwhelm the signal, leaving only the purely refracted paths. The principal losses for these paths are volume attenuation and scattering due to internal waves. The former is sufficiently low that direct measurements are quite difficult. The latter is a subject of current research and generally not well understood.

Another interesting feature in this case is the surface duct formed in the upper 200 m of this profile and normally understood in terms of wind mixing. Interestingly, the mixing has a fairly sharp cut-off at a depth determined by the buoyancy profile of the ocean. In the simplest models, this layer is perfectly mixed (and therefore isothermal) so that the sound speed gradient is simply determined by the increase in pressure, i.e. 0.016/s. In this view, the effectiveness of the duct is a simple function of its thickness. In practice, the mixing is generally incomplete and the sound-speed profile becomes a more complicated function of depth. So called upper-ocean models predict this evolution taking into account changes in the surface heating (as the cloud cover itself changes) and variations in the wind speed. The resulting gradients within the duct are critically important [12] (and harder to predict than depth). These, upper-ocean models are perhaps one of the most visible successes of research on oceanographic modelling.

Amongst the many interesting oceanographic phenomena, fronts, eddies, internal waves/tides and surface ducts are the disturbances most often cited. From a submarine viewpoint these are parts of the oceanscape that may alternately conceal or reveal a target of interest. An interesting example is provided by the Gulf Stream, whose warm, meandering jet pinches off warm and cold core eddies. A simulated Gulf Stream environment is shown in Figure 6.

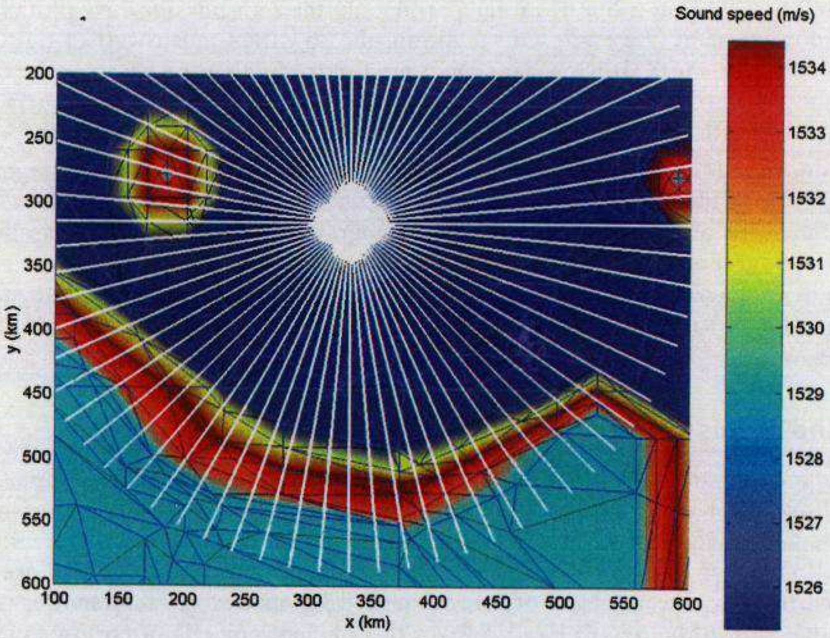

Figure 6. Plan view of the environment for a source north of the Gulf Stream radiating energy south into the Sargasso Sea. Radials in white show paths along which the acoustic field is calculated. The patchwork of triangles is used to dicretize the environment. The surficial sound speed is indicated by the colormap.

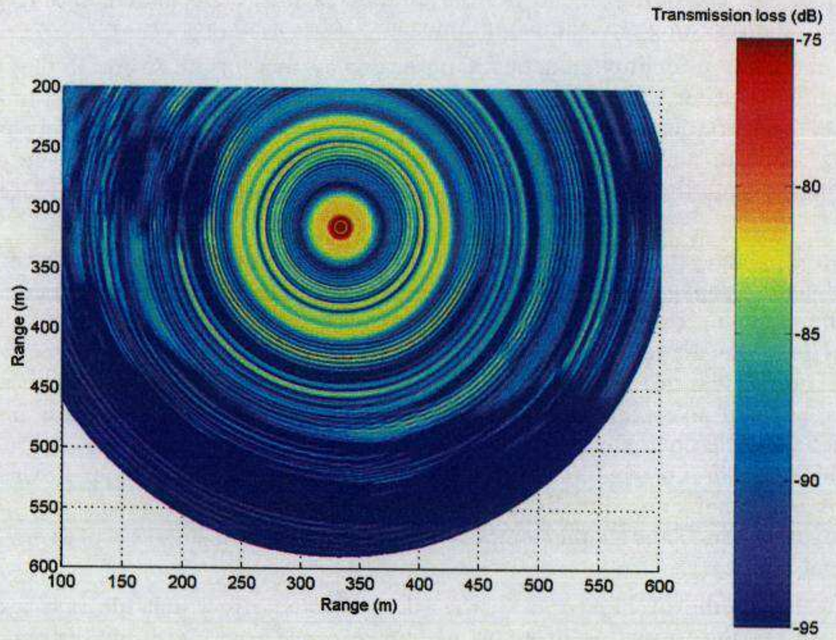

Figure 7. Transmission loss across the Gulf Stream environment shown in Figure 6.

From a numerical point of view, this sort of problem is conveniently treated by dividing the area into a patchwork of triangles [13] . At the nodes of the triangles, we compute the normal modes, which provide a sort of local characterization of the propagation conditions. We can then readily drop a source into the simulation area and compute transmission loss on a fan of radials, producing the transmission loss plot shown in Figure 7. Here we can see the shadows cast by the eddies. In addition, the so-called north wall of the Gulf Stream blocks the sound travelling towards the south. It is perhaps more precise to say that the warm surface waters in the Sargasso Sea (the water to the south of the Gulf Stream), refract the energy away from the surface causing an apparent blockage. However, the North 'wall' of the Gulf Stream is acoustically more like a veil.

Here we have considered the acoustics in a forward sense, looking at the acoustic signature of oceanographic features. Obviously, the shadow cast by these features can also be used to infer their shape and tremendous progress has been made in recent years in acoustic tomography. The most encompassing of these efforts was ATOC (Acoustic Tomography of the Ocean Climate) and the associated Heard Island Feasibility Test [5, 15]. This program sought to monitor the oceans on a global scale, using a global scale network of sources and receivers to measure the mean temperature. Collaterally, ATOC has also taught us an enormous amount about ocean acoustics.

4. Arctic and the Trans-Arctic Propagation Experiment

There are several characteristics of Arctic waters that are of interest. First, the environment has sometimes been compared to a shallow-water environment turned upside down. This is a good comparison in the sense that the sound speed profile is typically upward refracting; however, an inverted Arctic profile would not be easily mistaken for a shallow-water one. A second aspect of interest is the ice canopy whose roughness can scatter acoustic energy significantly. Over ranges of a few hundred kilometres the scatter loss is typically sufficient to restrict useable frequencies to below 50 Hz. However the ambient noise is often low compared to other oceans, despite the persistent cracking of the ice, in part because shipping traffic is typically limited.

While the weather and climate of all the world's oceans are intrinsically interesting, there are a couple of issues that make the Arctic stand out. First, climate models suggest that the Arctic may manifest global warming sooner and with greater strength [15] . Indeed human industry is believed by some already to be having a significant, observable effect on Arctic circulation. However, in general we do not understand precisely these processes and significant changes may also be the result of 'natural' cycles. Finally, 18 nuclear reactors in discarded submarines are corroding at the bottom of the sea [16] . An understanding of Arctic circulation is important to gauging the resulting environmental impact.

Plans are well underway to deploy an acoustic observing system for the Arctic in the ACOUS (Arctic Climate Observations using Underwater Sound) program. The notional configuration is shown in Figure 8 and involves 3 sources and 6 receivers forming an acoustic web with 18 paths. Acoustic tomography is particularly appealing here since sending ships to make direct measurements is difficult because of the ice canopy. Similarly other remote sensing methods (satellite sea-surface temperature measurements) are also less effective because of the ice canopy.

Before deploying such a system one obviously would like a pilot demonstration. The first demonstration (TAP for Transarctic Acoustic Propagation experiment) of ocean acoustic tomography was conducted in April of 1994 [17] . Following the great success of TAP, the first phase of ACOUS was begun in 1998. To understand how such a system works, it is useful to review the oceanography. Figure 9 shows a measured sound-speed profile that shows features that are typical of the Arctic [18] . The top layer (upper 100 m) is the so-called *polar water* and is also referred to as a mixed layer, since the water has a roughly constant temperature and salinity. This forms a sort of surface duct with the characteristic upward-refraction caused by the pressure gradient. The middle layer (100-1000 m) is the *Atlantic Intermediate Water*. As the name suggests, this water flows into the Arctic from the Atlantic and forms a warmer core. Finally the bottom layer is the cooler *deep Arctic layer*, which is a fairly homogeneous slab of water. Though the temperature is roughly constant, the pressure increases significantly driving up the sound speed.

The ray plot in the middle of Figure 9, verifies the expected effect that the rays are all refracted up to the surface. We can also see the formation of a sort of 'convergence zone' with the deeper rays refocusing near the surface every 40 km or so. Note that the rays launched with a very shallow angle and trapped near the surface tend to have short loop lengths. On the other hand, scatter loss tends to be lower at lower grazing angles. The total reflection loss for a ray is the loss per bounce times the number of bounces. As the range increases the latter effect dominates and shallow ray take-off angles end up having the largest loss.

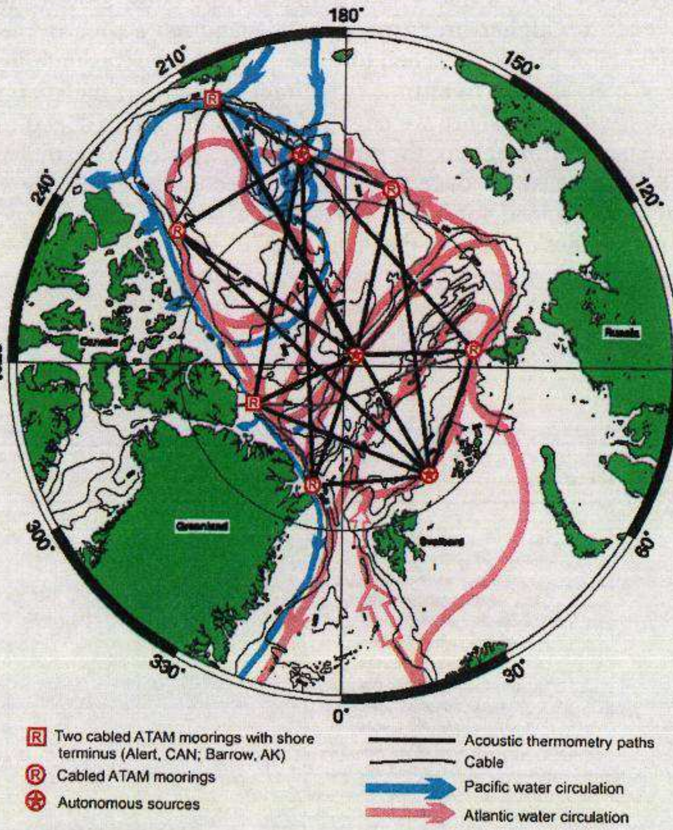

Figure 8. Proposed climate-observing system for the Arctic [4]

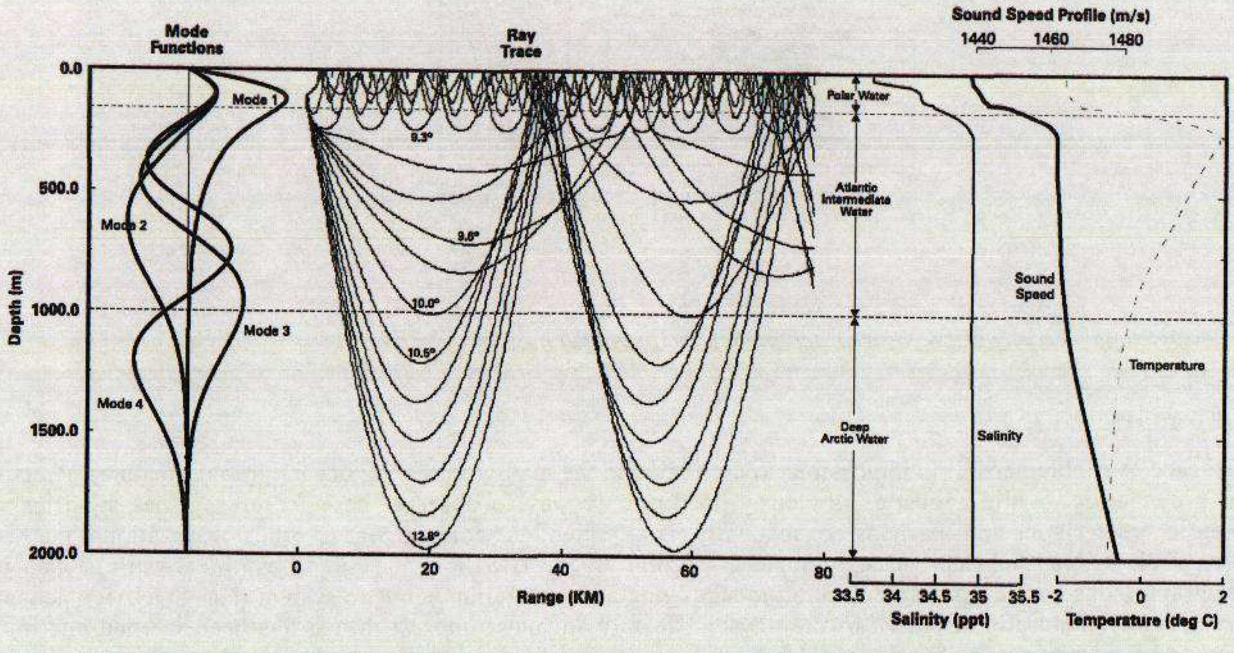

Figure 9. Modes, rays, and their relation to the oceanography in the Arctic [Ref 18, © Academic Press]

However, for the ranges of interest, only the low-frequency components can be received and even the sharp crack of a probing pulse would become a long-duration thump. As a result, the individual ray arrivals overlap in time forming a standing-wave pattern that is best understood in terms of the channel modes as shown on the left of Figure 9 (for a frequency of 20 Hz). Mode 1 is confined to the cool, slow water in the surface duct and is invariably a late arrival. Indeed, the higher-order modes that spend more time in the deeper, faster waters arrive first, as is shown in Figure 10 [17] . Since the speed of these modes increases monotonically with the temperature of the Atlantic Intermediate Water, their arrival time is a direct measure of the averaged Artic water temperature. This is shown more clearly in Figure 11, where we have calculated the group speed of the second and third modes using hundreds of profiles measured throughout the Arctic [19] If we plot the group speed against the temperature of the Atlantic Intermediate Water that produced that group speed, we obtain the simple progression shown in Figure 11. The inversion of group speed for water temperature is obviously immediate and provides a simple, practical means of monitoring climate change in the Artic.

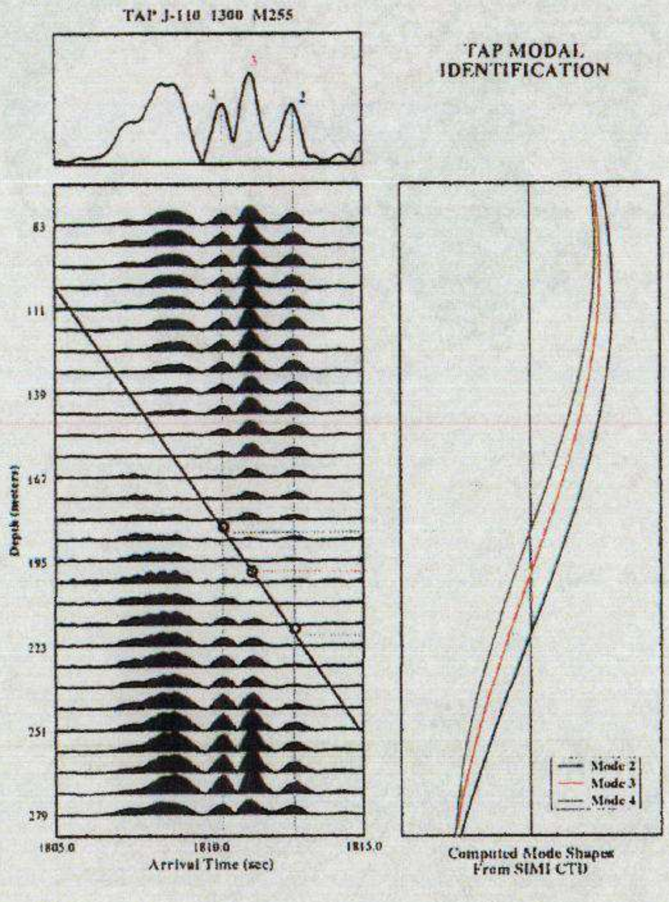

Figure 10. Modes, rays, and their relation to the oceanography in the Arctic [17] . The circles show the correspondence between measured (left panel) and predicted nulls of the modes.

5. Summary

In the space available here, it is impossible to do justice to the many interesting oceanographic features affecting sound propagation. While acoustics is clearly not the only way to observe these features, it has significantly different characteristics and, perhaps consequently, is a tremendous complement to other observational methods such as CTD's, Nansen casts, Ocean Surface Current Radar (OSCR), and satellites. Meanwhile, since the oceanographic observation is often directed to supplying an input for an acoustic system (e.g. SONAR), acoustic observations are naturally sensitive to the physical features of most interest. Much has been learned and much remains to be learned.

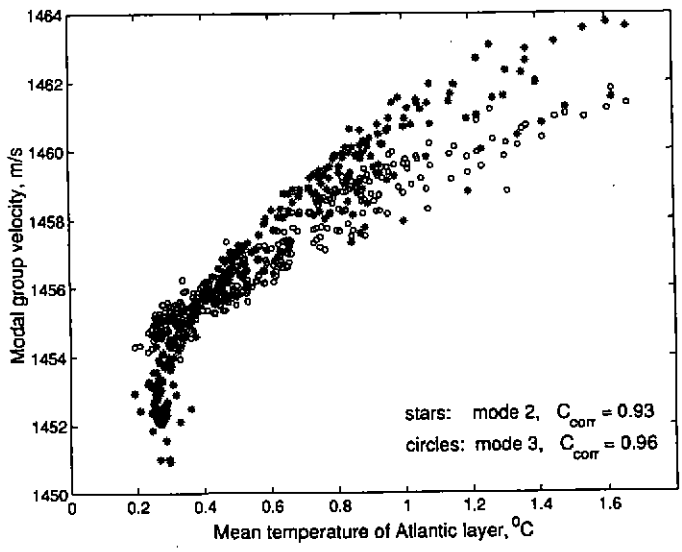

Figure 11. Mode group-velocity derived from an ensemble of sound-speed profiles in different parts of the Arctic shows the direct relation to mean temperature of the Atlantic layer [19]. The correlation coefficient of group velocity and temperature for each mode is designated by C_{corr} in the inset.

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