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PAPER

Acoustic Sensing for Ocean Research

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ABSTRACT

Ocean observatories have the potential to examine the physical, chemical, biological, and geological parameters and processes of the ocean at time and space scales previously unexplored. Acoustics provides an efficient and cost-effective means by which these parameters and processes can be measured and information can be communicated. Integrated acoustics systems providing navigation and communications and conducting acoustic measurements in support of science applications are, in concept, analogous to the Global Positioning System, but rely on acoustics because the ocean is opaque to electromagnetic waves and transparent to sound. A series of nested systems is envisioned, from small- to regional- to basin-scale. A small number of acoustic sources sending coded, low power signals can service unlimited numbers of inexpensive receivers. Drifting and fixed receivers can be tracked accurately while collecting ocean circulation and heat content data (both point and integral data), as well as ambient sound data about wind, rain, marine mammals, seismic T-phases, and anthropogenic activity. The sources can also transmit control data from users to remote instruments, and if paired with receivers enable two-way acoustic communications links. Acoustic instrumentation that shares the acoustic spectrum completes the concept of integrated acoustics systems. The ocean observations presently in the planning and implementation stages will require these integrated acoustics systems.

INTRODUCTION

Recent advances in oceanography have prompted investigation of integrated acoustics systems for ocean observatories (*IASOO*, 2002) that include navigation, communications, and acoustical oceanography. Such an integrated system may be considered a combination of Underwater GPS (UGPS), acoustic communications, and acoustic sensors that support science. The purpose of this paper is to investigate the evolving concepts, primarily within the context of science scenarios, and to describe briefly some technical aspects.

A major motivating factor is the recently created National Science Foundation (NSF) ORION (Ocean Research Interactive Observatory Networks) program and the embedded Ocean Observatories Initiative (OOI) to further the sustained study of the ocean (Clark, 2001). The three infrastructure elements of the latter consist of a coarse global array of buoys (DEOS, 2001), a regional cabled observatory such as NEPTUNE (NEPTUNE Partners, 2000), and enhanced coastal observatories (Jahnke et al., 2004). A unifying theme for the OOI infrastructure investment is the provision of seafloor junction boxes providing power and communications. The expectation is that the OOI request for major research equipment and facilities centers will be included in the 2006 U.S. federal budget. This investment (equivalent to several large ships) will, with planned increases, lead to a concomitant large science investment.

We examine first some science scenarios (not meant to be exclusive) and the integration of these ideas into the infrastructure of planned research oriented ocean observatory and operationally oriented observing system efforts. We explore applications of acoustics in the areas of ocean circulation (currents, heat content, turbulence and mixing, wind and rain), the living ocean/ocean biosphere (fisheries, marine mammals, nekton), and seafloor processes (earthquakes, plate tectonics, geodesy, hot vents, gas hydrates). Technical questions about the navigation and communications are discussed with thoughts about implementation, followed with concluding remarks.

2. Science topics

2.1 Ocean Circulation

The use of neutrally buoyant and profiling floats has been a cornerstone of oceanography for the last half-century. In the late 1950s Swallow floats misbehaved by moving at "high" speed (10 cm s^{-1}) in seemingly random directions rather than slowly in a straight line (baffling the crew on the sailboat trying to track them acoustically), thus awakening oceanography to the presence of the mesoscale "weather." A detailed description of the history of acoustically tracked floats can be found at http://www.po.gso.uri.edu/rafos/general/history/index.html.

Since then it has become abundantly clear that the ocean circulation needs to be measured on all scales, from global and basin scales that are climatically relevant down to the small scales that are important to determining elusive mixing processes. There are complementary observing technologies that are relevant—satellites and radars for the surface (not considered here), and Lagrangian platforms and fixed Eulerian sensors for *in situ* point measurements, both of which can be spanned by acoustic tomography.

Fixed small scale measurements The acoustic Doppler current profiler (ADCP) is now a ubiquitous oceanographic instrument. It can measure profiles of velocity (more precisely the velocity of scatterers following the water) at ranges up to about 1 km. Because there are no moving parts, the instrumentation is robust and reliable. More recently the acoustic travel time current meter (ACM) has been used on scales of 0.1 to 1 m. The acoustic scintillation current meter (ASCM) has been developed to produce average measurements of cross-beam velocity averaged along the path, typically about 1 km. These various acoustic current measurement devices have largely replaced mechanical current meters.

Inverted echosounders (IESs) measure the round-trip travel time from the seafloor to the ocean surface. This is a measure of the integrated, averaged sound speed (~temperature) along this path. When IESs are combined with bottom pressure and a reference absolute velocity (such as a point-ACM or an electrometer that gives barotropic velocity), much can be learned about the low mode ocean velocity and density structure (Meinen et al., 2002). These sensors provide fundamental information about the gravest vertical modes of ocean circulation, and because they are so simple and robust (and may be used also for navigation, communication, and short-range tomography), they belong in any ocean observatory "basic sensor suite."

Lagrangian platforms Autonomous profiling floats, such as Argo, typically come to the surface once every ten days to telemeter temperature and salinity data and to obtain a satellite navigation fix. During the time submerged the float is untracked. According to Davis and Zenk (2001):

> *Some studies place a high premium on using floats to represent fluid-parcel trajectories requiring the uninterrupted current following that can be achieved only with acoustic tracking. The penalty for autonomous [profiling] operation is a long time interval between known positions, which precludes resolving eddies unless cycling is rapid, and periodic surfacing that interrupts the quasi-Lagrangian trajectory. For observations of subsurface velocity, it is likely that both the continuously tracked neutrally buoyant RAFOS floats and autonomous floats will be needed. For acoustic floats a major limitation to economical sampling can be overcome by widespread deployment of high-energy sound sources. It is, for example, entirely feasible today to install enough sound sources that a float could be continuously tracked anywhere in the tropical or North Atlantic. Since sound sources, like radio stations, can serve different users, the presently rather simply structured network of moored sound sources will require greater international coordination in the future. The benefits of an organized RAFOS network will be linked with the responsibility of contributing parties to maintain such arrays of sound sources over an extended period of time on a basin-wide scale. Miniaturization of receiver electronics and production in great numbers could result in significant decline in float prices. This, and the development of new sensors, could open other fields of research…*

This statement is one motivation for the present work.

A widely used and accurate method for studying the ocean in motion employs the deep sound or SOFAR channel to track neutrally buoyant drifters over great horizontal distances, O(10^3) km. Three or more anchored sound sources provide an acoustic navigation system whereby precisely timed acoustic signals (an 80-second long 3-Hz wide FM sweep at 260 Hz) spread out radially from each of the sources. Given the arrival times at a receiver equipped with a synchronous clock, the receiver's position can be determined to an accuracy of a few kilometers. Since the mid-1980s floats have been deployed in many different projects worldwide to study ocean currents.

The floats, also known as RAFOS floats (SOFAR spelled backwards), can be deployed to drift at any depth although greater acoustic ranges are possible if both the sound sources and the floats are not too far off the sound channel axis. The floats record the arrival times in their microprocessor memory. At the end of each float's mission underwater, it surfaces and telemeters all data back to shore. Typical missions last from months to several years. Special float designs have been developed whereby a float surfaces briefly to telemeter its data before returning to depth to continue its underwater mission. To make the floats mimic fluid motion accurately, they can be configured to drift with the waters both horizontally and vertically; these are known as isopycnal floats.

In regions of high shear, profiling floats can give erroneous estimates of velocity if they are based solely on surface fixes. Similarly, if trying to measure abyssal currents, estimates can be severely compromised if the float comes to the surface. In these cases it is advantageous to remain submerged. The same is true for other mobile instrument platforms such as gliders, autonomous undersea vehicles (AUVs), and bottom rovers. With UGPS (using low amplitude, long duration, coded, high bandwidth signals, and new low power clocks), the precision and accuracy of the tracking can be much better than with RAFOS systems (cf. LORAN and GPS) resulting in correspondingly better velocity estimates. With appropriate transmission schedules, high temporal resolution is possible, and at the limit (depending on the spatial array size), internal wave time and space scales, and perhaps even mixing scales, may be approached.

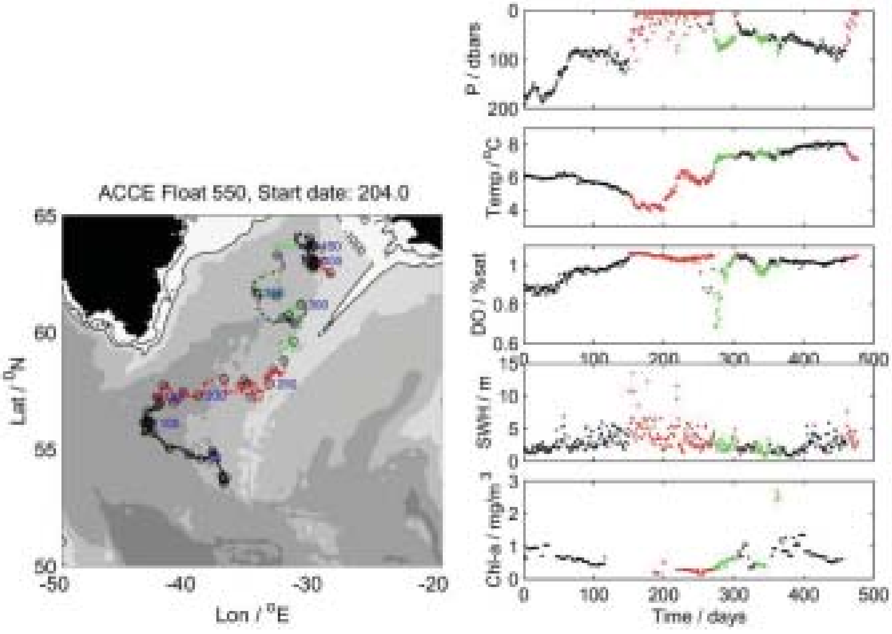
One illustrative application of use of navigated floats is in the Atlantic Climate Change Experiment (ACCE) where the float provided *in situ* observations of dissolved oxygen. All University of Rhode Island (URI) ACCE floats measured dissolved oxygen using the "pulsed" technique pioneered by Dr. Chris Langdon (Lamont Doherty Earth Observatory). Here the sensors are only briefly activated once a day, and thus can operate over the entire lifetime of the floats. From a Lagrangian viewpoint, interpreting the variability of dissolved oxygen presents the difficulty of separating the biological from the physical processes. However, there are times when the nature of the variability clearly indicates that one process dominates the other.

Figure 1 shows the track of a float (550), which outcrops in the Irminger Sea with the corresponding measurements of pressure, temperature, and dissolved oxygen, plus the satellite-derived values for significant wave height (SWH) and SeaWiFS Chl-a. The track and property plots are color-coded to indicate two distinct periods: red when the float outcrops into the wintertime mixed layer, and green when either the oxygen record indicates significant removal due to respiration or the Chl-a record indicates high rates of production. When the float outcrops, the oxygen saturation level remains at 104% ± 2%. However, at the end of the first winter the oxygen shows momentary drops as large as 30% (2 mL/L). These occur at a time when the Chl-a indicates the onset of primary production and suggests that sinking of detrital matter may be concentrated to these newly-stratified density surfaces. Around day 340, late June, the oxygen record approaches a local minimum in dissolved oxygen. This takes place after the peak of springtime production. This may be another, although less intense, indication of removal from detritus. On day 360 the summer bloom peaks simultaneously with a slight, but noticeable, 2% (0.1 mL/L) momentary drop in dissolved oxygen. However, this bloom is accompanied by a O(40 m) increase in depth, which could have also accounted for the oxygen drop.

Acoustic tomography Acoustic tomography can complement point float (Fig. 2) and moored measurements by providing spatial integrals between the navigation sources and the receivers, whether fixed or moving. Acoustic tomography is inherently averaging in space, and can sample at the speed of sound. It can very efficiently measure depth-average temperature and velocity (if reciprocal transmissions are used), with the amount of depth dependent information a function of geographic location and the sound speed profiles. A possible array showing the scale and the nesting aspects builds upon the Acoustic Thermometry of Ocean Climate (ATOC)/North Pacific Acoustic Laboratory (NPAL) array, using the future capability of seafloor junction boxes provided by NEPTUNE and other programs (Fig. 3). Note that when one source is added, data along the paths to *all* the receivers are obtained.

FIGURE 1

The track (left) of an isopycnal float (550), which outcrops in the Irminger Sea with the corresponding measurements of pressure, temperature, and dissolved oxygen (right) (from Lazarevich et al., 2004).



These ideas can be extended to under-ice operations in polar regions. One project will deploy gliders under the Labrador Sea winter ice with real-time RAFOS tracking; another will deploy profiling RAFOS floats under the Antarctic ice (C. Lee and S. Riser, personal communications, 2003). In some cases, it may be advantageous to implant a satellite/GPS-acoustic/UGPS transponder in sea ice to provide two-way communication to mobile platforms (J. Morison, personal communication, 2003).

Tomography over a 1000-km scale with a drifting hydrophone receiver has been demonstrated (AMODE Group, 1992). There are numerous simulation papers describing tomography using drifting receivers, where the position is simultaneously determined (Cornuelle, 1985; Gaillard, 1985; Duda et al., 1995) as seismologists do to determine earthquake location. This scenario of simultaneously determining float/receiver position and the sound speed field will require three or more sources to be "in view." If mobile platforms are used as receivers it is likely that a data assimilation system will be used that takes in surface fixes, travel times, Doppler velocities, depths, estimates of C(x, t), etc., to simultaneously estimate the float state (position, velocity, and acceleration as a function of time), along with the ocean state (e.g., temperature, salinity, velocity).

Turbulence Small-scale turbulence in the ocean has significant consequences for both carbon fluxes and marine biodiversity

FIGURE 2

The ATOC 0–1000-m depth-averaged temperature along a path from Kauai to the northwest (red, very small error bars), compared against Argo float data in a box surrounding the path (B. Dushaw, personal communication, 2003).

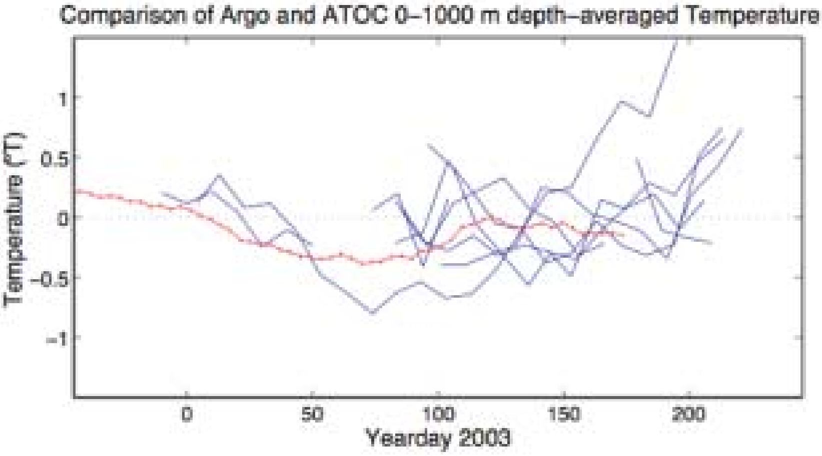
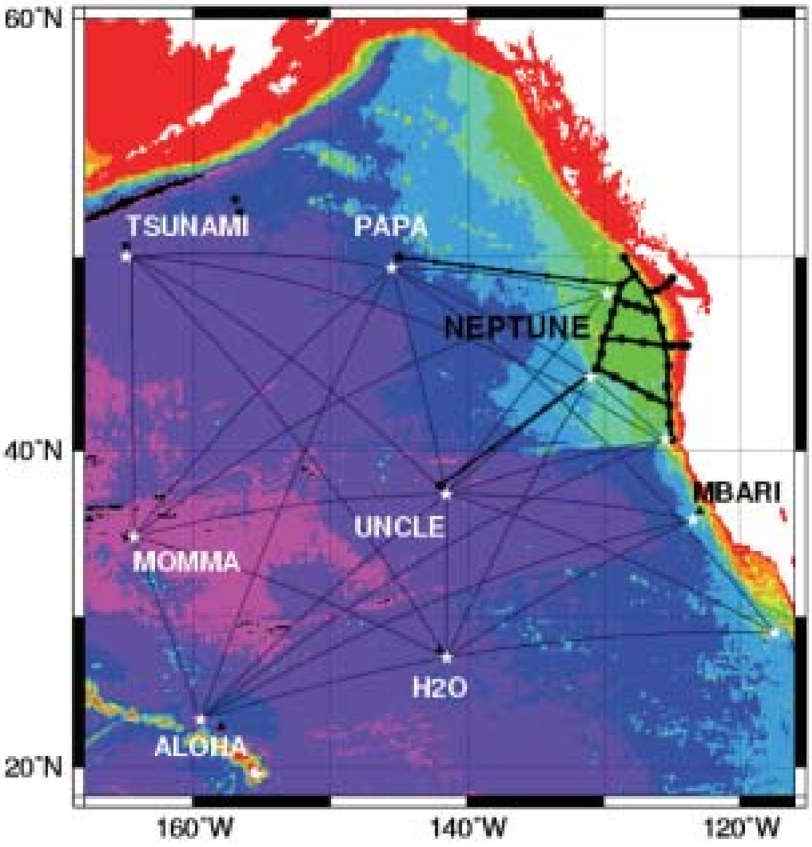


FIGURE 3

A possible acoustic array on regional and basin scale for collecting ocean circulation and heat content data while meeting navigation and communications requirement.



through direct and indirect effects on the marine ecosystem, as detailed in the SCOTS Report (Glenn and Dickey, 2003) and summarized below. In addition, turbulence has profound effects on air-sea exchanges of greenhouse gases and on the magnitude of the thermohaline circulation. Ignorance of the processes and locations of turbulent mixing in the ocean has such serious implications for global climate modeling and climate change projections that the NSF *Millennium Report* (Brewer and Moore, 2001) identifies turbulence as one of the remaining 'big questions' in ocean science. While the focus of this section in the SCOTS report was the combination of turbulent mixing and biophysical interactions, the authors felt it important to emphasize that our basic knowledge of small-scale ocean turbulence will be significantly advanced by the ability to make long time series measurements in an observatory setting, and to cover scales up to the mesoscale.

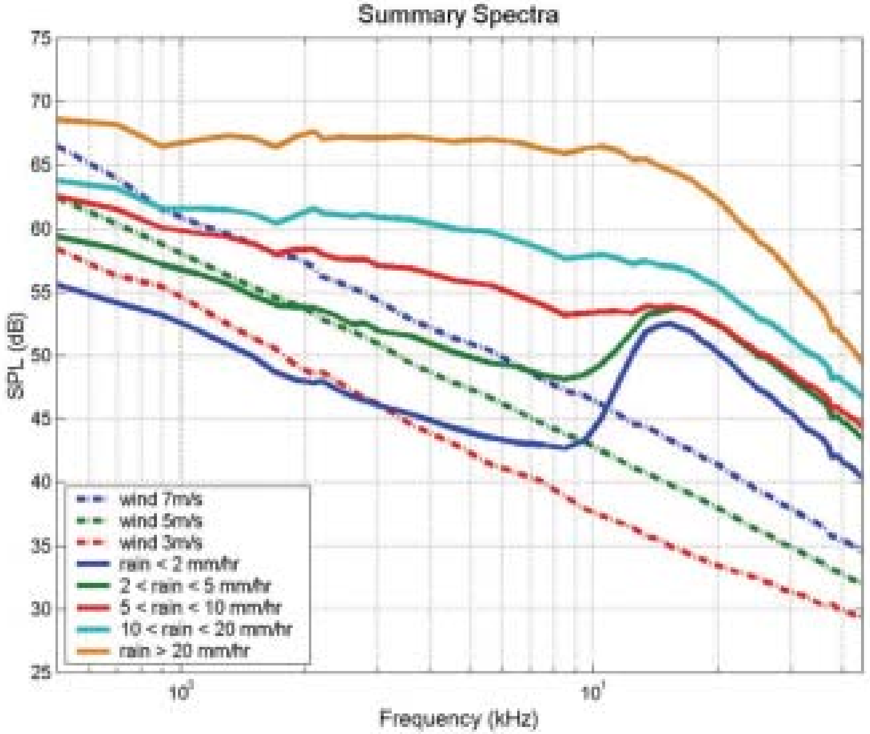
Cabled systems are essential for tackling problems in small-scale turbulence and its interactions with all levels of the marine ecosystem. Both the ample power and, especially, the broad bandwidth that will be provided by cabled systems are required by present methods for measuring turbulence quantities (dissipation scales with microscale sensors or large-eddy scales with acoustics), and for those biological techniques (such as multi-frequency acoustics, multi-wavelength and sheet light optics, holography, and video/still photography) that can provide detail sufficient to adequately delineate ecosystem responses. A regional-scale cabled system with an adequate footprint is necessary for the investigation and comparison of turbulent mixing regimes with very different characters—deep-sea mixing driven by tidal flow over steep topography, upper mixed layers subject to very different combinations of wind and buoyancy forcing, and shelf regimes strongly influenced by tidal bottom boundary mixing. The character of embedded ecosystems also varies dramatically: the challenge is to discover how much of the bio-geographical variability arises through the direct and indirect effects of small-scale turbulence.

Holbrook (2003) recently showed that one can image water column density (sound speed) gradients on vertical scales of ~10–100 m using seismic airgun data. In the past the water column data was ignored; by adjusting the gain one can look for "layers" in the ocean just as one does beneath the seafloor. Images of eddy interactions and internal waves breaking on the continental slope are possible. Equivalent cabled systems will be able to observe the time dependence of these structures.

Rainfall and wind In the frequency range from 500 Hz to 50 kHz, the dominant sources of underwater ambient sound in the ocean are bubbles generated by breaking waves and raindrop splashes (Nystuen, 2001; Medwin, 1992). Figure 4 shows the mean spectral shapes of rain- and wind-generated underwater sound gathered from over 100 months of ambient sound measurements on deep-sea moorings. The spectral shapes associated with wind and rainfall are distinctive, allowing quantitative measurements of wind speed and rainfall rate. The signal from wind has a characteristic shape that rises and falls in amplitude with wind speed. The signal from rain is much louder, containing relatively more high frequency sound. In particular, there is a unique bubble entrapment mechanism associated with small raindrops that produces sound at 13–25 kHz. This is a surprisingly loud sound that allows the acoustic detection of light drizzle at sea. While biological and anthropogenic noises can also occur in this frequency band, these noises are generally local or intermittent and usually do not interfere with acoustic wind speed and rainfall rate measurements. The measurement of wind and rain at sea is notoriously difficult, especially under storm conditions (when air-sea fluxes are highest), and the acoustic method provides one of the few ways, if not the only, to do so reliably with exceptionally robust instrumentation—a simple hydrophone. It can be a cornerstone of widespread verification of satellite-derived wind and rainfall estimates.

FIGURE 4

Wind- and rain-generated underwater sound has unique characteristics that allow acoustic measurements of wind speed and rainfall rate (courtesy of J. Nystuen).



2.2 The Living Ocean/ The Ocean Biosphere

The fundamental difference between conventional acoustic sampling platforms and ocean observing systems is the potential for broad-scale spatial and temporal sampling from a suite of sensors in real time. This unprecedented combination provides both opportunities and logistic challenges to the fisheries and marine mammal science communities. A combination of Eulerian (i.e., fixed grid) and Lagrangian (i.e., mobile) sampling strategies are required to adequately sample fish and marine mammals through the range of ecologic scales encompassed by an ocean observatory. Detection ranges of most active and passive sensors limits the feasibility of relying solely on a grid sampling design. Strategic choice and placement of sensors should enable a suite of organisms to be continuously monitored over a broad range of spatial and temporal scales. Commercial fisheries (i.e., fishes and invertebrates) research opportunities include: (1) examining spatial and temporal fluxes of biomass, (2) resource assessment with extended temporal sampling, (3) quantifying distribution variability in space and time, and (4) species-specific habitat use. Marine mammal research opportunities include: (1) quantifying spatiotemporal distributions of animals, (2) investigating biological responses to oceanographic variability, and (3) monitoring behavioral responses to anthropogenic noise sources. A common element to both groups is the opportunity to monitor changes in densities and distributions of aquatic organisms in response to variability in the marine ecosystem. Many life history characteristics (e.g., timing and path of annual migrations) are not known for fish and mammal species. A continuous suite of sensors provides a networked platform to quantify and understand aquatic life cycles.

Underwater sound is produced by marine mammals over a very wide frequency range, from a few Hz to more than 100 kHz. These sounds are used for communication, navigation, and hunting. The signals are generally unique to animal species and can therefore be used to monitor animal behaviors, including migration patterns, feeding behaviors, and communication between animals; an example of blue and fin whale spectra is shown in Figure 5. Because sound travels through water more easily than light, acoustic rather than visual investigations of marine animal populations is usually more effective. By listening to the animals' signals on multiple hydrophones, they can be tracked. A possible scenario for studying large numbers of marine mammals is to use arrays of mobile receivers (serving multiple users, such as Argo floats) positioned using a combination of UGPS and/or GPS to track the animal vocalizations. This assumes that future *in situ* recording/processing and communications capabilities increase, as is expected with time.

Both marine mammals and fish can be tracked using acoustic tags, either passive (in the RAFOS mode) or active (in the SOFAR mode) depending on the situation. There have been significant developments in tagging technology for marine mammals and fish. For example, G. Fisher, C. Recksiek, and T. Rossby at University of Rhode Island are developing a "fish chip" RAFOS receiver that can operate 2–3 years with a 100-mA-hr battery. The entire tag is 2.5 cm long and 1 cm in diameter. In addition to position, the tag provides temperature and pressure that is be stored in non-volatile memory. The small size and long lifetime would allow individual fish to be tagged and potentially tracked in an appropriately instrumented ocean basin. When the fish are caught, data in the tag can be downloaded. In the active mode several groups are working with small salmon tags which allow the fish to be counted as they go by a bottom-mounted hydrophone array. The range of the system is several hundred meters at best (Fig. 6).

Modern imaging sonar can reveal critical information about the behavior and habits of marine animals. Figure 7 shows a sonar image of two fin whales foraging on a school of herring. Concepts for autonomous vehicles that can image krill with 3D arrays are under development for large volume biomass assessment (P. Chandler, personal communication, 2003).

2.3 Seafloor Processes

Integrated acoustics systems can support a broad range of scientific objectives in marine geology and geophysics including crustal hydrology/geochemistry/biology, clathrates and subduction zone fluids, continental margin sedimentation, ridge crest processes, and seismology/geodynamics.

Hydrologic systems in the ocean crust and sediments at ridge crests, ridge flanks, and subduction zones play key roles in influencing rock alteration, mineral formation, and hydrocarbon migration. Hydrologic processes and their consequences are strongly linked, and therefore to understand any single one requires an integrated knowledge of the others. For example, rock alteration, mineral precipitation, and the formation of gas hydrate (methane "ice") caused by fluid flow change the mechanical and hydrologic properties of the structure. Marine gas hydrates represent an untapped hydrocarbon resource of great magnitude, and at the same time, a possible source of greenhouse gas that could lead to global climate change if the gas were released in large quantity. A primary goal over the next few decades will be to understand the factors in the hydrological system that affect hydrate stability.

Sites with acoustic instrumentation can provide long-term monitoring of seafloor hydrocarbon vents and the associated structural changes with hydrate formation. These surface sites should be linked to borehole experiment sites where the presence and/or absence of structural controls for fluid flow (e.g., faults, high permeability layers, cracked rock) have been adequately mapped by geophysical surveys and/or deep sea drilling.

A generic suite of acoustic sensors should include the following: broadband seismometer/sea floor hydrophone; broadband seafloor moored hydrophone arrays, both vertical and horizontal; associated hydrophone and geophone arrays in boreholes drilled near the hydrate sites. A suitably instrumented borehole array in a gas hydrate province would provide a tomographic image to monitor the hydrological system over time.

Observatories will be used to study the temporal variability of ridge crest processes (tectonic/physical/chemical/biological). It is often stated that we know the topography of Mars and Venus better than we do Earth, largely because of the masking nature of the oceans. Mapping is one of the natural first tasks of exploring a new environment, and its importance in understanding and developing the oceans over the next century should not be underestimated.

While near-autonomous mapping is just beginning it is expected that long duration missions will be possible in the future, making use of seafloor charging and communications stations/docks. This is one possible way to cover relatively large areas at a reasonable cost. AUVs can also be used in a

FIGURE 5

Multi-year ambient sound spectra from Point Sur, California. Daily average spectra are plotted so signals from earthquakes, ships, and other sources are not shown. Marine mammals at ~17 Hz are the loudest signals here.

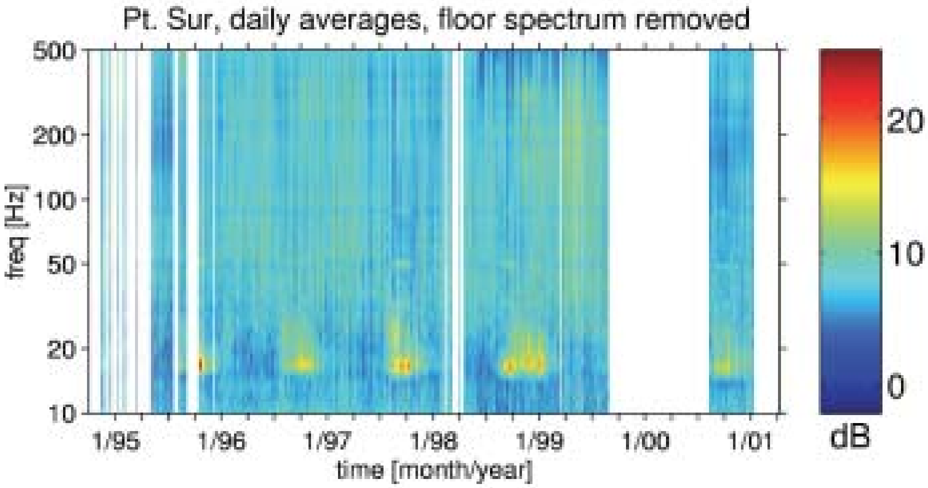


FIGURE 6

Proposed hydrophone array locations of the Pacific Ocean Salmon Tracking Project (POST). Additional information can be found at *www.coml.org/descrip/post.htm*.

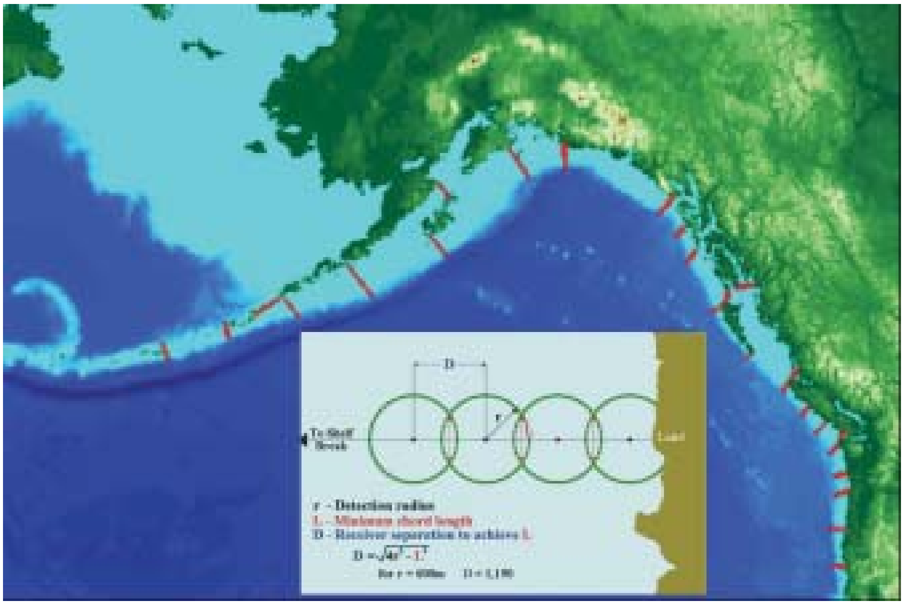
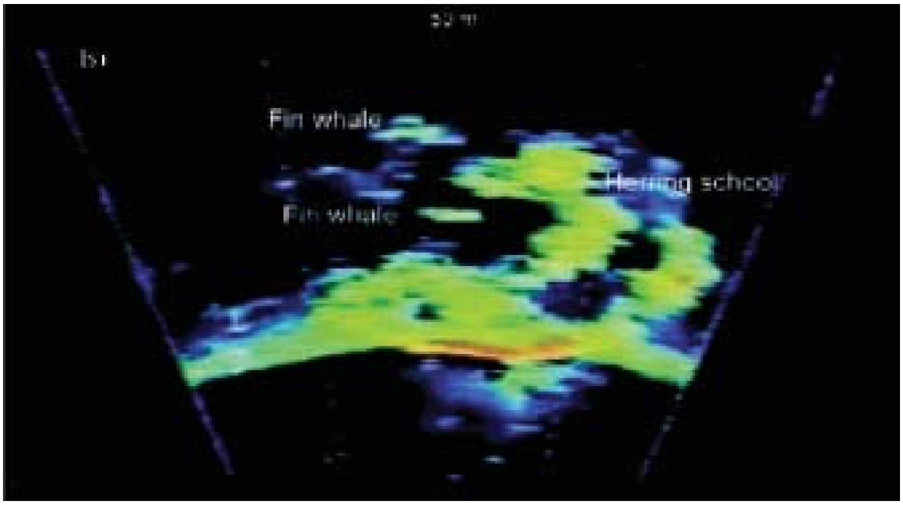


FIGURE 7

Two fin whales foraging in a school of herring off the coast of Norway (courtesy of O. Misund, IMR, Norway)



survey mode to locate hydrothermal vents in remote locations. In many situations precision repeat surveys over large areas (100s of kilometers) are desired as in, for example, studies of seafloor deformation near subduction zones (with centimeter accuracy) and deep sea ecology. Sensor networks for ocean observatories should include navigation and communication with AUVs and bottom rovers. The latter might be controlled in real time using two-way acoustic communications to make routine surveys, and then during an eruption, to concentrate activity around lava flows. In the past temporary local transponder nets have been set up at significant expense for a particular operation; future work will require permanent navigation and communications capability.

Most of the earthquakes in the world occur either under the oceans or involve at least one oceanic plate. Seafloor seismic observatories will be a valuable tool to extend the global distribution of seismic stations to the seafloor (Stephen et al., 2003), to study earthquake processes at active margins such as ridges, transform faults, and subduction zones and to study intraplate earthquake activity. Any and all acoustic receivers can play a role in the detection of earthquakes because they will observe seismic T-phases (water borne signals). When signals from even a sparse array of receivers are combined, even small earthquakes can be observed and earthquake locations can be determined relatively precisely (Fig. 8). This has been applied with success in monitoring the Juan de Fuca plate, East Pacific Rise, and mid-Atlantic Ridge for volcanism and seismicity. Recently, these water borne signals have been used to infer information on the state of icebergs and ice sheets in Antarctica. Deep “shadow zone” arrivals (Dushaw, 1999; Butler, 2002) have been detected below the sound channel. While the theoretical explanation for these is lacking (it is thought some scattering process is responsible), this means that navigation in parts of the deep ocean that were previously thought to be excluded should be possible at some level. These T-phase data can be used for CTBT monitoring purposes, and could contribute to tsunami early warning systems.

The combination of IASOO and AUVs will provide a unique opportunity to obtain complementary long-term measurements of crustal deformation for the entire life cycle of a plate from creation to subduction. Geodetic instruments will be concentrated near the plate boundaries, but it is also important to incorporate techniques to measure plate scale deformation. Compared to land-based observations, seafloor geodesy is in its infancy. However, several techniques are emerging to measure both the vertical and horizontal deformation (Chadwell et al., 1999; Chadwick et al., 1999, Spiess, et al., 1998). It should be feasible to use AUVs as the intermediate vehicle for acoustic geodesy, and acoustic “beacons” will be required to navigate the AUVs. Just as the GPS satellites are used for both navigation and geodesy on land, a network of acoustic transponders could serve a dual purpose in the oceans.

Deep ocean hydrothermal systems are notoriously difficult to study. Our ability to study these systems and their relation to tec-

FIGURE 8

A relatively few single hydrophones in the sound channel can be used to detect and locate many earthquakes in an ocean basin that would be undetectable from land arrays. In this example six hydrophones (white stars) can be used to locate earthquakes (red dots) throughout the North Atlantic (courtesy of D. K. Smith).

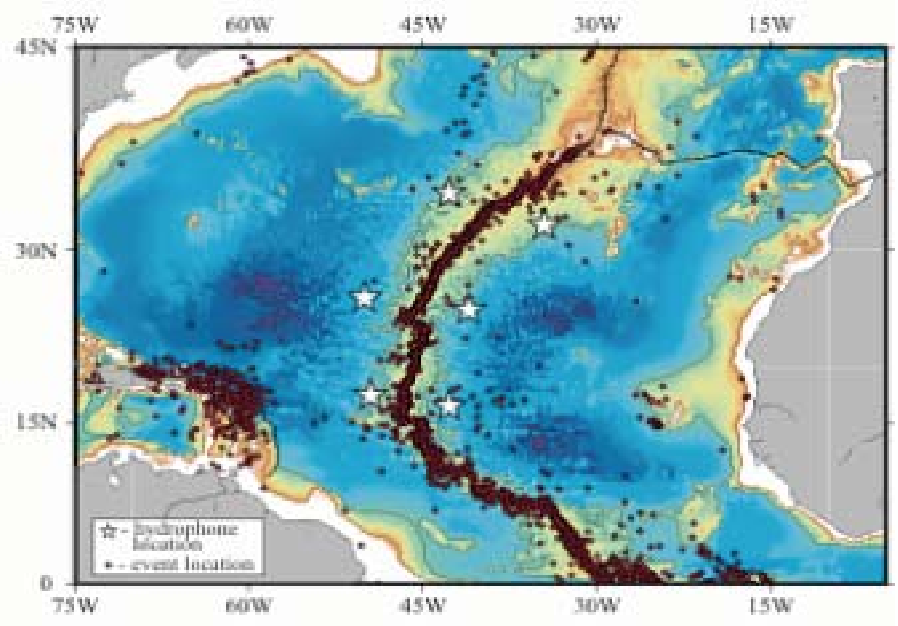
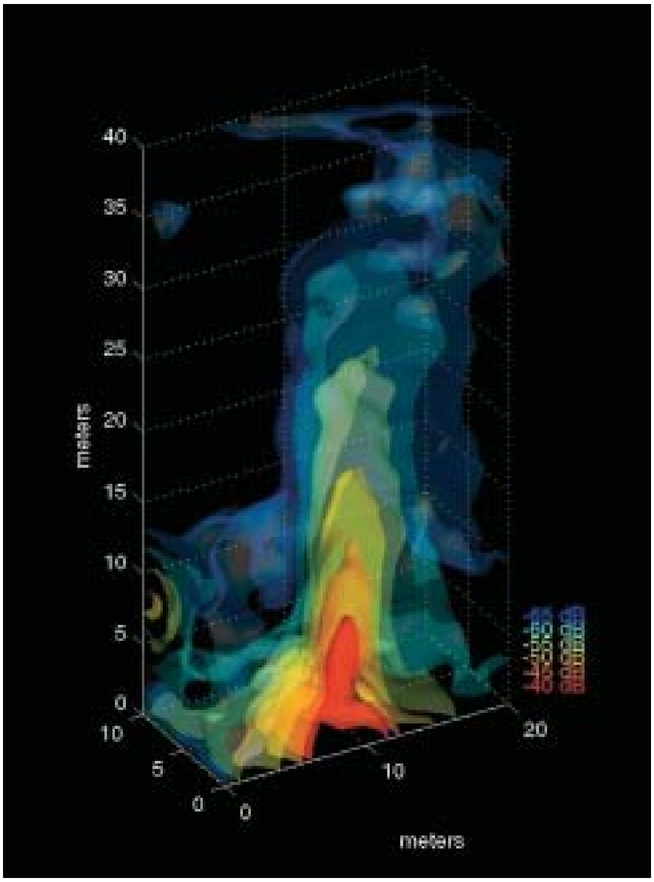


FIGURE 9

An acoustic volume backscatter image of a buoyant plume from which estimates of plume geometry as a function of time, particle mass concentration, flow velocity, and mass flux can be derived (courtesy of C. Jones).



tonic, magmatic, oceanographic, and biological processes is limited by the lack of tools for resolving critical spatial and temporal scales of flow that are characteristic of ridge tectonic processes. Observing the temporal/spatial variability and partitioning of energy between different types of flow is critical for understanding fluid circulation in the crust, its interaction with crustal alterations, and its interaction with biological habitat. The ability to model hydrothermal fluid circulation after it has left the seafloor and the entrainment of surrounding water into hydrothermally induced flow is limited by our inability to characterize flow at the scale of the entire plume within sub-tidal time scales. Point measurements made from a moving ROV or AUV, for example, are often subject to variability associated with tidal cycles. Interpretation of such aliased measurements requires well defined forward models of tidal flow and its interaction with complicated topography.

Acoustic systems are a primary technology for probing and monitoring hydrothermal flow in the context of observatory science. In coordination with point measurements from both stationary and mobile seafloor systems (AUVs), acoustic remote sensing can offer access to new scales of hydrothermal processes and their interactions with the wider seafloor and ocean. Figure 9 illustrates an acoustic volume backscatter image of a plume from which estimates of plume geometry as a function of time, particle mass concentration, flow velocity, and mass flux can be derived.

3. Integrated acoustics systems

3.1. Navigation

Acoustic navigation has taken two forms: fixed and floating ranges. Typical fixed ranges, e.g., Navy tracking ranges, use simple pings or relatively simple coded signals and are deployed over limited areas. Floating ranges emulate fixed ranges since the positioning of their fiduciaries are accurately known with GPS (Howe et al., 1989), and there are several commercial products offered. There is at least one commercial product that has a bottom mounted system directly analogous to GPS, with continuous transmissions of broadband pseudo-random noise (PRN) signals. Float tracking for oceanography first used the SOFAR mode (drifting sources, fixed receivers) and later the RAFOS mode (fixed sources and drifting receivers). Tomography instrumentation immediately used PRN signals. Because prerequisites for tomography are accurate timing and accurate navigation of the instruments, tomography arrays can be used immediately for navigation purposes and vice versa (cf. atmospheric and ionospheric tomography).

Because of bathymetry and the nature of the sound speed field throughout the oceans, we do not have an ideal geometry, and cannot have the coverage that GPS does. There will be areas and depths not covered. It will be necessary to treat special cases (e.g., shallow seas, deep trenches, double ducts, polar seas, stripping of steeper angles by bathymetry) with creativity, understanding there may not be just one solution.

3.2. Communications

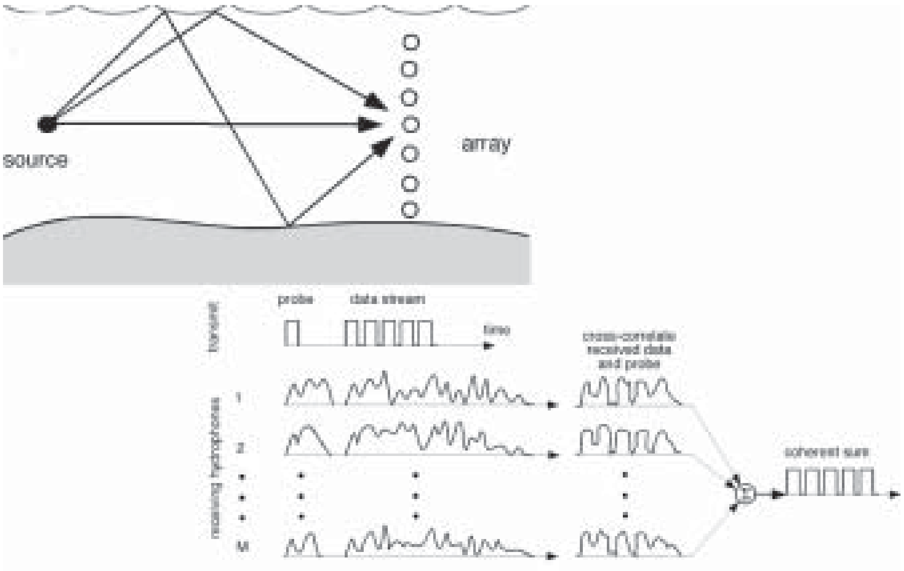
Simultaneously satisfying all the science, navigation, and communications requirements of an integrated system will be challenging. Acoustic communications have proven to be difficult. While basin-scale communications have been shown to be feasible (Freitag and Stojanic, 2001), most effort has been devoted to short-range (kilometers) applications either in shallow water (with relay stations, for instance) or with vertical paths in deep water (bottom to a surface mooring). Signal processing has included both coherent (Fig. 10) and incoherent methods. Clearly more research and development is necessary, and the community needs to converge to a common set of standards that will accommodate the limitations of the medium and instrumentation while spanning the wide range of desired space scales, frequencies, noise conditions, data and error rates.

3.3. Implementation

Some uses of acoustics have been described briefly here. There are clearly many more including volume imaging, side-scan sonars, fish and bio-acoustic backscatter, turbulence and internal wave sensing, and sediment transport. In an observatory setting, a basic science/infrastructure element could be a single (in principle) bottom-mounted acoustic transducer that could serve multiple purposes: an inverted echosounder (depth-averaged temperature), tomography, geodesy, ambient sound (wind, rain, marine mammals, T-phases, etc.), and navigation and communications. Together, all these applications will require management of the acoustic spectrum.

FIGURE 10

Coherent signal processing for communications using spatial diversity (Rouseff et al., 2001)



Following are some of the questions the community will need to address accompanied by brief comments.

- What are the optimal frequencies and bandwidth to use? ATOC at 75 Hz has shown that adequate signal-to-noise (SNR) ratio can be obtained at ranges of 5 Mm. Are there advantages to transmitting two frequencies? Recent work by the NPAL Group (Worcester et al., 1999) has shown that signals at lower frequencies appear to suffer fewer detrimental effects from internal wave induced fluctuations (28 vs. 84 Hz).
- What are achievable integration times? Experience shows that at 75 Hz coherent averaging times are about 14 minutes. In the Arctic coherence at 20 Hz is sufficient that phase can be tracked over long time periods.
- What data must be broadcast on top of the navigation signal? If a source is on a mooring should the source position be sent (or model parameters describing the motion), much as ephemeris data is transmitted as part of the GPS signal?
- What are the optimal types of acoustic sources to use under various circumstances? Should they incorporate directionality?
- What type(s) of signals should be used? PRN signals are optimal in one sense (and are "orthogonal" to marine mammal vocalizations), but their use might exclude some types of sources. Code, time, and frequency division multiplexing are all possible.
- What should the duty cycle be? If the source is deep, with a horizontally-oriented beam pattern, and relatively low level (all measures to mitigate possible effects on marine mammals), is it practical to consider continuous transmission?

- While ambient sound variability is not well characterized, estimates are still required to determine SNR budgets.
- Should receivers be arrays with vertical or horizontal directionality? It would seem reasonable to use two hydrophones on a float (top and bottom) to get an extra 3 dB of gain, for example.
- For a given geometry of sources, a noise scenario, and the sound speed field, it will be necessary to estimate the signal level, SNR, and position error estimates as a function of position. The estimated signal levels and SNR for a single receiver will be necessary to evaluate the ocean volumes in which marine mammals might hear the raw signal above the noise.
- How do we resolve conflicts between active and passive users?

As even this sample of questions indicates, there is much work required to mature this concept, let alone implement it. The development effort will include: establishing essential standards to unify the field (such as signal protocols), working on more efficient broadband and directional sources and miniature acoustic receivers, investigating coherence times and lengths as functions of frequency and range, understanding ambient sound variability, to name but a few.

Over the last decade, much research has been done on the effects of anthropogenic sound on marine mammals. Concerns about possible effects will have to be taken into account in designing an integrated system. Some mitigations measures have already been suggested, e.g., deep, directional, low-level sources (less than 250 W, 195 db re 1 mPa at 1 m) using PRN codes. Much work is on-going in this area and it can benefit from an integrated system.

Actual fielding and operation of systems on various space scales might fall within the ocean observatories and ocean observing systems that are being planned. On a regional scale NEPTUNE will provide a relatively dense array of seafloor nodes that can support the acoustics sensor networks. On a global scale significant acoustic coverage can be obtained with fixed instruments using ocean observatory and ocean observing system assets; and augmenting this fixed array with receivers on floats will further extend the spatial coverage.

4. Concluding Remarks

A navigation and communications infrastructure is a prerequisite to sustained human endeavors in the ocean. Many applications require or are enabled by this infrastructure. Autonomous undersea vehicles (powered and gliding) can navigate themselves over the ocean bottom and through the water column without coming to the surface. They can navigate and communicate their data and status to users via acoustic modems to cabled or surface satellite telemetry systems without breaking away from their underwater missions. Profiling and drifting floats can more accurately measure the ocean's velocity structure, tagged fish and marine animals can be tracked with high precision, and bottom-fixed instruments can measure seafloor motion.

The acoustic sources and receivers of such a system can serve multiple functions: sources as navigation and communications components as well as multi-static active transmitters, and receivers as communications components as well as passive listening devices. With signal standards and protocols for managing the acoustic spectrum, the system will be an extensive, multipurpose acoustics infrastructure, capable of supporting applications even beyond our present vision. Analogous to the GPS and its use for tomography of the atmosphere and ionosphere, the various acoustic sources and multitude of receivers can function similarly in the ocean. This has significant implications for observing the ocean's interior in real time and measuring long-term climate variability. Receivers on globally distributed floats can also listen to ambient sound: wind and rainfall, seismic T-phases, marine mammals, and ships. Some of these natural sources of sound can in turn be used as sources of opportunity for other purposes.

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