THE HEARD ISLAND FEASIBILITY TEST

An expedition in the southern Indian Ocean demonstrated that coded underwater acoustic signals can be received worldwide and serve as a method for measuring global ocean warming.

Arthur Baggeroer
and Walter Munk

The release of carbon dioxide and other greenhouse gases into the atmosphere is associated with temperature changes in both the atmosphere and the oceans. The oceans play a vital role in global temperature changes, storing both heat and greenhouse gases. Without the oceans the atmosphere would warm at two to three times greater a rate, other factors remaining equal. To understand and predict global warming, then, it is important to measure, rather than just speculate on, changes in the heat content of the ocean.

Measurements of ocean temperature are subject to large local variability associated with mesoscale eddies. These local variations obscure the detection of much-larger-scale warming. One therefore needs a measurement method that averages over large ocean ranges.

An "acoustic thermometer" meets this requirement. Sound speed increases by 4.6 m/sec per centigrade degree, so travel time is shorter for a warmer ocean. A feasibility test conducted off Heard Island in the southern Indian Ocean demonstrated that coded low-frequency acoustic signals transmitted underwater can be received at distances of 18 000 km, or halfway around the Earth. Year-to-year changes in acoustic travel time between distant sources and receivers can provide a measure of the warming, if any, of ocean basins.

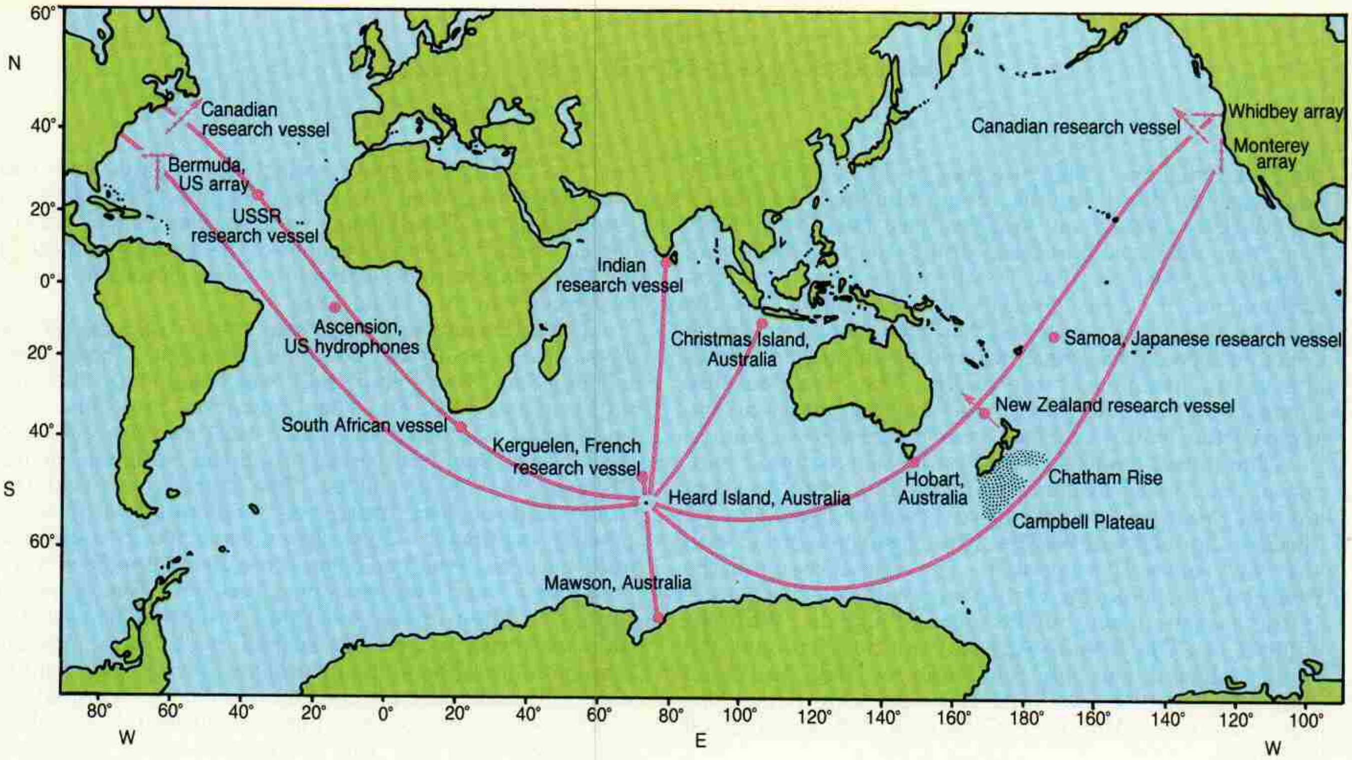
In this article we describe the Heard Island expedition, discuss the climate and acoustic propagation issues that motivated the experiment, and indicate directions of future work. The other principal members of the Heard Island experiment team are Theodore Birdsall (University of Michigan), Ann Bowles (Hubbs Sea World), Melbourne Briscoe (Office of Naval Research), Andrew Forbes (Commonwealth Scientific and Industrial Research Organization, Australia), Kurt Metzger (University of Michigan) and Robert Spindel (University of Washington).

Background

For a dozen years we have been trying to exploit two facts:
▷ the sensitive dependence of sound speed on temperature
▷ the efficiency of the oceanic acoustic waveguide, or

Arthur Baggeroer is a Ford Professor of Engineering in the department of ocean engineering and in the department of electrical engineering at Massachusetts Institute of Technology, in Cambridge, Massachusetts, and a visiting investigator at the Woods Hole Oceanographic Institution, in Woods Hole, Massachusetts. **Walter Munk** is the Secretary of the Navy Professor of Oceanography at the Institute for Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California, San Diego.

© 1992 American Institute of Physics



Paths taken by sound in the Heard Island feasibility test. The sources were suspended from the center well of the R/V Cory Chouest 50 km southeast of Heard Island. Black circles indicate receiver sites. Horizontal lines represent horizontal receiver arrays off the American west coast and off Bermuda. Vertical lines designate vertical arrays off Monterey and Bermuda. Lines with arrows off California and Newfoundland indicate Canadian towed arrays. Ray paths from the source to receivers are along refracted geodesics, which would be great circles but for the Earth's nonspherical shape and the ocean's horizontal sound speed gradients. Signals were received at all sites except the vertical array at Bermuda, which sank, and the Japanese station off Samoa. **Figure 1**

SOFAR (for sound fixing and ranging) channel.

The SOFAR channel is a most remarkable acoustic feature of the oceans. It is created by the minimum in the sound speed, typically at 1-km depth, that is associated with a balance between the effects of temperature and those of hydrostatic pressure. Sound speed increases upward from the channel axis because the temperature increases; it increases downward because of the dominating effect of hydrostatic pressure. The SOFAR channel is typically 1–2-km thick, less than 0.03% of the Earth's radius, yet it forms a waveguide capable of guiding acoustic energy halfway around the planet. By using moored arrays of acoustic sources and receivers, we have measured the acoustic travel times, and thus the mean temperatures, along many different paths through a given ocean volume. We invert these travel time data to yield a three-dimensional map of ocean temperature. The inversion procedure is similar to that used for CAT scans in medicine, and we refer to this work as ocean acoustic tomography.[1,2]

The initial tomography experiments were carried out at separation scales of 300 km and then 1000 km between the sources and receivers. Early on we speculated on whether the method could be extended to the scale of ocean basins.[3] In 1983 John Spiesberger and his coworkers commenced measurements along a 4000-km path between Hawaii and the west coast of the continental United States.[4] They demonstrated that the measured changes in acoustic travel time were associated with seasonal temperature changes in the upper northeast Pacific.

Expedition to Heard Island

In 1989 the Heard Island feasibility test program began with the support of the Office of Naval Research, the National Oceanic and Atmospheric Administration, NSF and the Department of Energy. There were two issues for the feasibility test: Can one detect signals using currently available acoustic sources at distances on the order of 10 000 km, and if so, can one "match filter" coded signals to measure travel times to better than 0.1 sec for monitoring ocean warming? In January 1991 we actually carried out the Heard Island feasibility test—the first step of a program for measuring ocean warming on a global scale using acoustics.

We did not have the resources to develop acoustic sources with enough power and bandwidth for the feasibility test. We were fortunate to obtain permission from the US Navy, through the oceanographer of the Navy, Rear Admiral Richard Pittenger, to use some existing powerful, low-frequency sources on board the Research Vessel Cory Chouest. These sources fitted our requirements well but were limited to an operational depth of 300 m. This dictated their deployment at a high latitude, where the SOFAR channel is shallow.

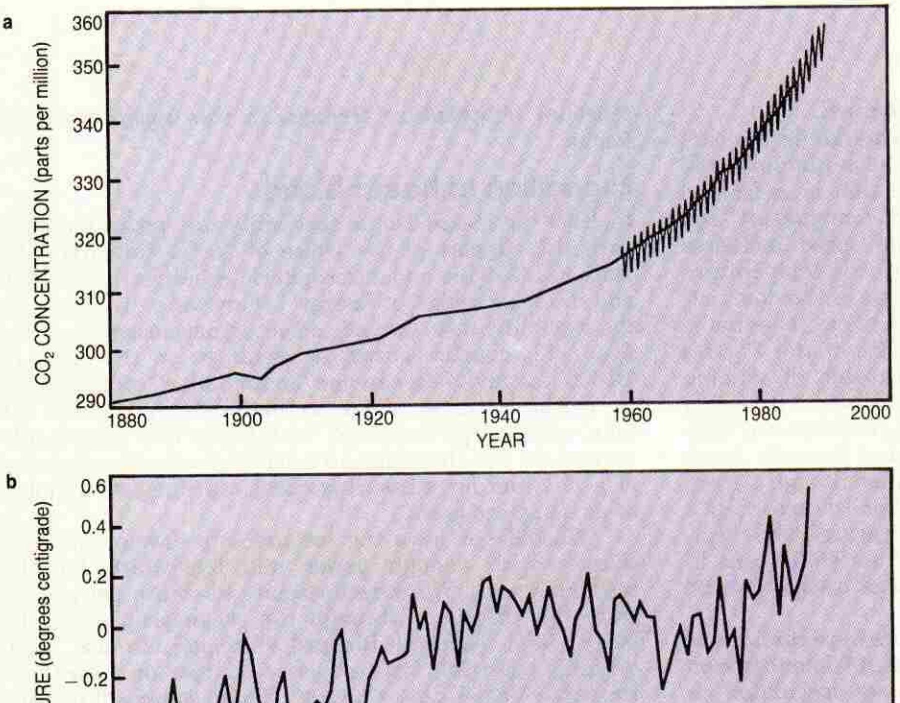
Almost by accident we discovered a site at a high latitude in the southern Indian Ocean from which one could insonify both the Atlantic and Pacific Oceans, as figure 1 indicates.[5] This site was at 54° S, 74° E, to the southeast of Heard Island, an uninhabited Australian island discovered by an American sea captain in 1853. The rays shown emanating from Heard Island are refracted geodesics; that is, the rays are, to a first approximation, great circles, but they allow for the horizontal refraction of sound by the horizontal gradients of sound speed in the SOFAR waveguide and they allow for the polar flattening of the Earth. The deviations are important when determining whether the paths encountered bottom features such as ocean ridges and seamounts.

The initial plan used existing bottom-mounted horizontal receiver arrays at Bermuda and on both coasts of the US. Metzger manned the arrays near Bermuda and Birdsall the ones near Seattle. (Our close cooperation with the Navy made this possible.) We soon recognized the desirability of deploying vertical arrays to detect separately the acoustic modes of the received signals. With the support of DOE, Science Applications International and David Packard through the Monterey Bay Aquarium Research Institute, two vertical arrays were built. One was installed off Monterey, California, and the other off Bermuda.

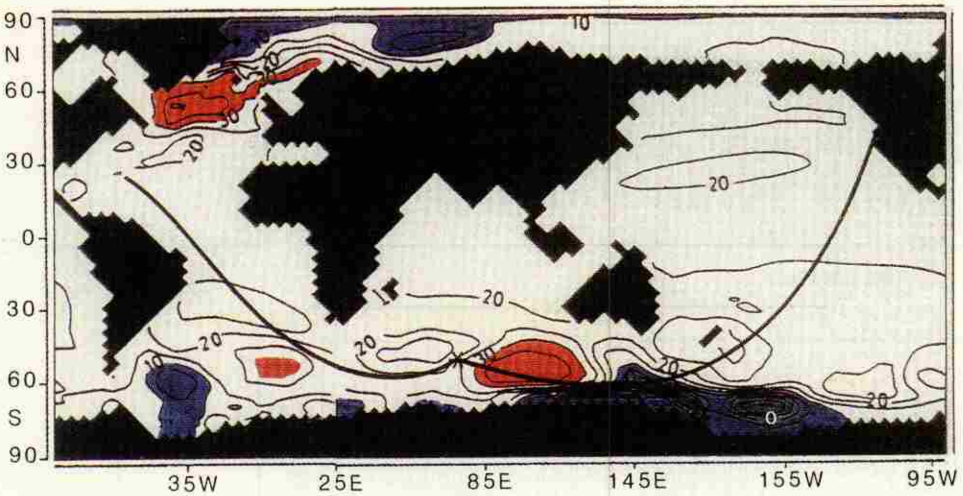
While the planning was under way we received word from oceanographic colleagues in many countries that they would welcome the opportunity to participate in the feasibility test by listening to the transmitted signals. The final result was that oceanographers from nine countries collaborated informally but very effectively (see figure 1). The signals were in fact detected at all the recording sites but two. The Bermuda vertical array sank and was eventually recovered by grappling, but there were no recorded data. The Japanese station near Samoa did not detect a signal, and we now believe the sound was blocked by the islands and seamounts and generally rough bathymetry in the Tasman Sea.

Permits required. Our plan was to transmit for ten days, commencing on 26 January 1991. Ships were scheduled; receiving equipment was being shipped to our international partners; communication protocols were established. However, in August 1990 we were informed that the test required permits from the National Marine Fisheries Service of NOAA. The concern was that the levels of the acoustic sources were potentially a threat to marine mammals. This was unexpected because the question of a permit had never come up in 12 years of work in ocean acoustic tomogaphy, albeit with less powerful sources. Moreover, oceanographers have long used far more powerful sources for seabed exploration. Marine mammals are often found near boats that are in fact quite noisy. To make matters even more difficult, Heard Island and the waters where the transmissions would take place are Australian, and the authorities there, who had previously supported the test plan without raising the issue of a permit, now decided one would be required.

We had to charter a second ship, the R/V Amy Chouest, for the necessary *in situ* biological observations. Bowles assembled in record time a team of three Australian and six American observers. We worked out a protocol with the permitting authorities whereby, should



CO_2 and temperature over the last century. **a:** Carbon dioxide concentration in the atmosphere as determined from ice cores (smooth curve) and as measured at Mauna Loa, Hawaii (annual oscillations).[7] **b:** Global average surface temperature plotted as a deviation from the mean.[8] **Figure 2**



Spatial structure of anticipated greenhouse warming in the upper ocean in 50 years, following CO_2 doubling, as indicated by calculated rise in sea level. Units are centimeters. Note the "hot spots" with rises up to 50 cm and the regions of sea level fall (within contours marked 0, as at the lower right). The plot is based on a coupled atmosphere–ocean model developed at the Max Planck Institute in Hamburg.[10] **Figure 3**

there be any evidence of or the potential for harmful effects on marine mammals, the experiment would be delayed or canceled. As it turned out there was no indication of any harmful disturbances, and in some instances the animals even swam toward the Cory while signals were being transmitted.[6] The "biological add-on" certainly added to the expense and the excitement of the feasibility test, yet it provided a welcome partnership with a devoted group of observers who worked under some very severe weather conditions.

The R/V Cory Chouest, with Munk and Forbes as chief scientists, and the R/V Amy Chouest, with Bowles as chief scientist, sailed from Freemantle, Australia, on 9 January 1991 without permits. Delay would have been tantamount to cancellation because of the logistics of using the US Navy sources and coordinating the efforts of our international colleagues. The US permit arrived by fax aboard the Cory one week before the 26 January scheduled start. The Australian permit arrived just 24 hours prior to the start time, and then under some very lucky circumstances. The Australian permit came with a message from the environment minister: "Good luck and calm seas." The latter were not to be.

The first transmissions. Heard Island came into sight five days prior to the starting time, so we could perform a rapid survey of the marine population before the onset of the acoustic transmissions. It is difficult to convey the experience of viewing Big Ben, a 3000-meter-high volcano, after seeing nothing but waves, some very high, for more than two weeks. Ten acoustic sources were deployed vertically through a center well on the Cory. We used five at a time during a transmission that provided a source level of 221 dB re 1 μPa at 1 m. (The reference unit of pressure in underwater acoustics is the micropascal, and source levels are referenced to a distance of 1 meter.) The 221-dB source generates approximately 100 kilowatts and is equivalent to a 146-dB level in air at a distance of 100 m—similar to the level near a thrusting jet engine.

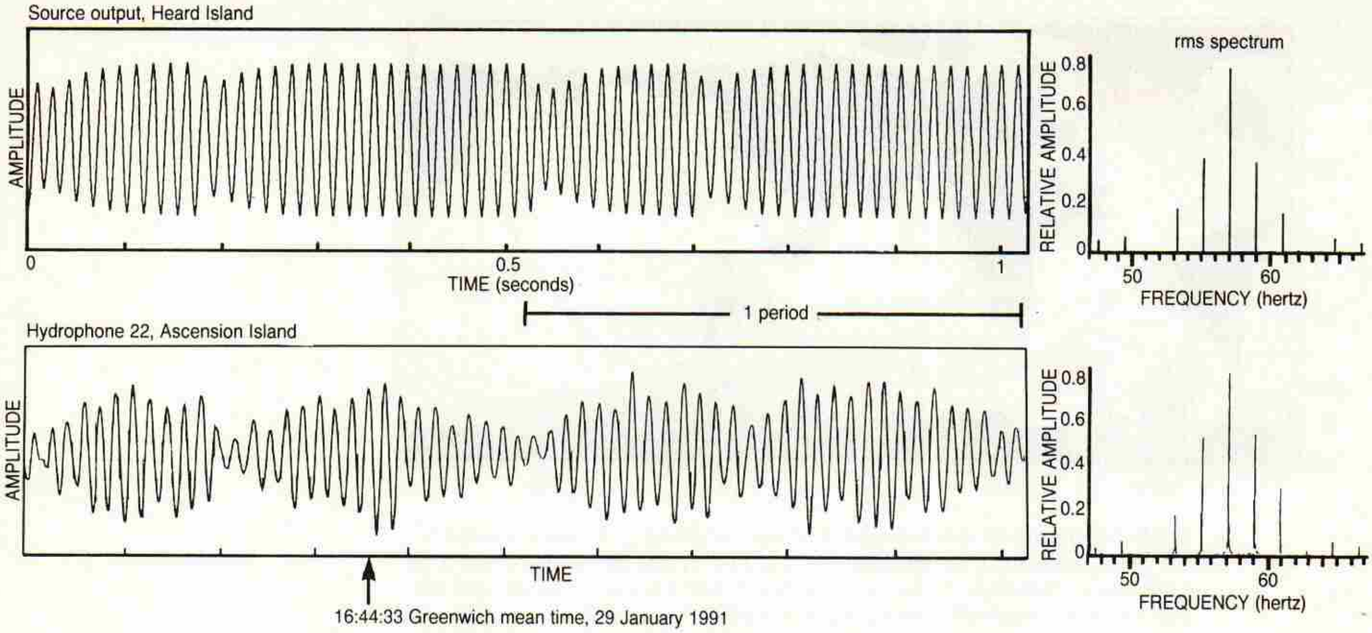
Our plan was to transmit for one hour out of three hours commencing at 0000 Greenwich mean time, 26 January. Twelve ships were standing by to receive signals in all the world's oceans except the Arctic. Communication was coordinated through the Applied Physics Laboratory of the University of Washington under Spindel. Everyone was anxious about who would be among the fortunate to have "heard from Heard." The first responses were expected to be from Bermuda and from Whidbey Island near Seattle. Those sites had arrays to reduce the ambient noise and used "real time" signal processors for spectral analysis and detection. The sound to Bermuda and Whidbey traveled eastward and westward, respectively, for $3\frac{1}{2}$ hours over approximately 18 000 km, almost halfway around the planet. The question was, Could it be detected? The answer was by no means certain *a priori*, as estimates of transmission losses differed by more than 60 dB!

On the day prior to the scheduled start, the technicians aboard the Cory requested a five-minute checkout test of the sources. Three and one-half hours later the ship received a fax from an annoyed Metzger on Bermuda, demanding to know what was going on! Fifteen minutes after that a similar message arrived from Birdsall at Whidbey Island. The first question for the feasibility test, about the adequacy of the source level, was answered, and the test had not yet begun.

The scheduled transmissions commenced on time, and other stations soon began to report reception. On 31 January the Cory encountered a gale with 10-meter seas. One suspended source was torn loose and went to the bottom, and the others were severely damaged. Fortunately there had been 28 successful runs before this untimely termination.

Ocean warming and climate

C. David Keeling's three decades of painstaking CO_2 measurements at Mauna Loa Observatory (figure 2a) have played a major role in the ongoing debate on global energy policy.[7] The monotonic increase in mean annual CO_2 does not resemble the wavy increase in global surface temperature compiled by James Hansen (figure 2b).[8] The interpretation most friendly to the greenhouse interpretation is that the measured temperature record consists of two components: a monotonic increase by 0.5 °C per century associated with the greenhouse effect, and an ambient



Transmitted and received signals and their spectra. Top: Transmitted signal and its spectrum as recorded at the source near Heard Island. Bottom: Signal received at Ascension Island, about 9000 km away, and its spectrum. The spectrum consists of the five strong lines of the pentaline code; half the power is in the 57-Hz carrier. (Figure courtesy of David Palmer, Atlantic Oceanographic Marine Laboratory, National Oceanic and Atmospheric Administration.) **Figure 4**

variability of ± 0.4 °C with a decadal time scale. The most greenhouse-unfriendly interpretation is that all the variation is due to natural ambient variability.

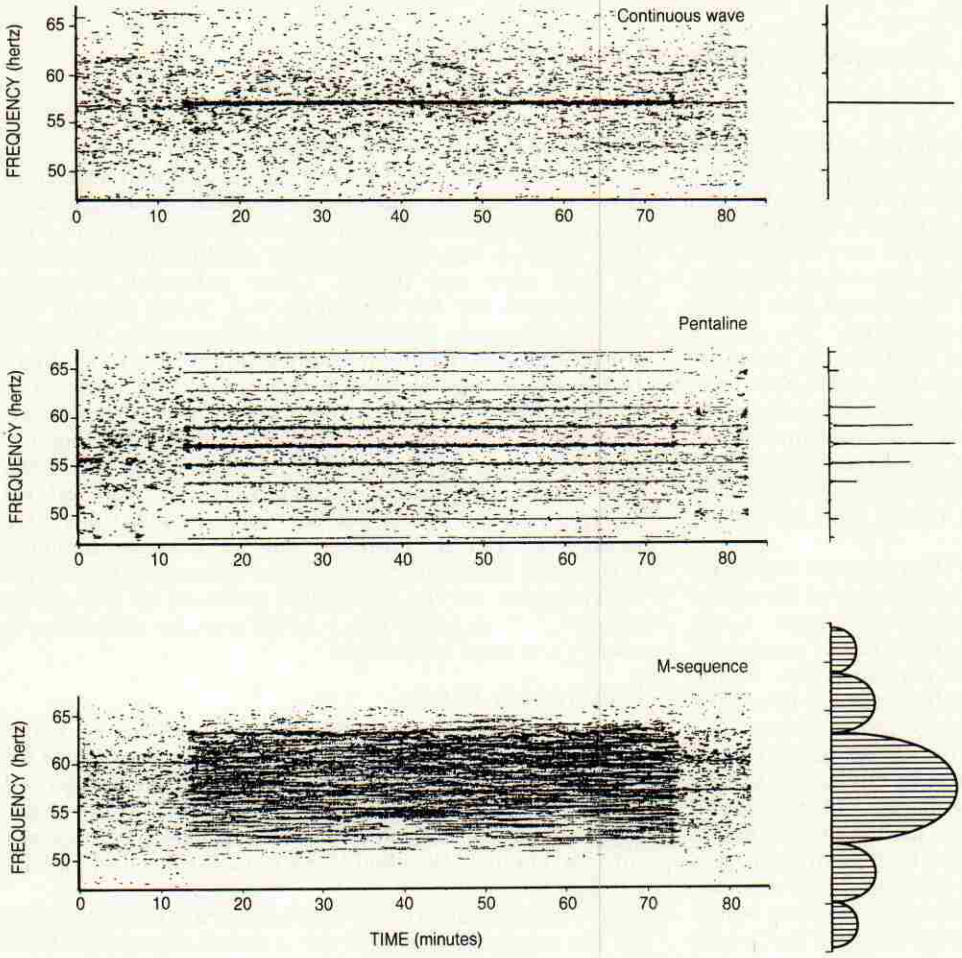
Let us summarize some of the quantitative considerations favorable to the greenhouse interpretation.[9] Taking as the starting point the beginning of the industrial revolution, around 1860, there is no question that the CO_2 content of the atmosphere has increased from about 280 to 355 ppm. As a result the surface heat flux has increased by 2 W/m^2. To be in equilibrium with this increased heat flux, Earth's surface temperature should rise by 1 °C. The Hansen curve suggests a rise by half that amount. If this is correct, the simplest explanation is that the other half is going to ocean heating.

When Roger Revelle and Hans Suess first proposed, in 1957, that a measurable increase in atmospheric CO_2 was taking place even then as a consequence of burning fossil fuel, they attempted to close the CO_2 budget. The present view, very roughly, is that 6 gigatons of carbon per year is produced from fossil fuels and another 2 gtc/year from the clearing of forests. This is balanced by 4 gtc/year of incremental storage in the atmosphere, 2 gtc/year in the biosphere and 2 gtc/year in the oceans. The rate for ocean storage is obtained not by measurement but by subtracting large and uncertain numbers pertaining to the atmosphere and biosphere. This uncertainty is intolerable; all we know for sure is that the oceans are an important sink of heat and CO_2, and of ignorance.

What kind of ocean warming could we expect from an increased heat flux of 2 W/m^2? (The 0.5 °C/century atmospheric warming requires only 0.03 W/m^2.) For orientation we take 0.02 °C/year at the ocean's surface (consistent with the Hansen curve), decreasing exponentially to 0.005 °C/year at 1-km depth. This requires a heat input of approximately 2 W/m^2 and leads to a rise in sea level of 1.8 mm/year due to thermal expansion. These are acceptable values and are consistent with models of the greenhouse effect.

Ocean warming should not be thought of as a uniform global process. The interior warming is not the result of a diffusive downward flux; rather, the heat is carried downward selectively in regions of downwelling associated with a convergence of horizontal flow. Figure 3 shows the change in sea level by the year 2050 due to greenhouse warming, as computed from the Hamburg coupled atmosphere–ocean model.[10] We can regard sea level as a surrogate for upper ocean temperature. The average rise is 20 cm, but there are regions of twice this rise and regions where sea level falls. So greenhouse ocean warming has a very structured spatial signature with strong contributions on the scale of the ocean's general circulation (the "gyre") and the ocean basins. Moreover, different atmosphere–ocean models lead to different spatial signatures.[11] Similarly, the ambient ocean variability has a spatial structure with gyre- and basin-scale contributions; however, the greenhouse and spatial variabilities are not the same. Knowing the characteristics of these structures, or at least estimating them, leads to a well-defined detection problem.[9] Very preliminary analysis suggests that ten years of observations with a reasonable global network of sources and receivers could lead to an estimate of greenhouse warming of the oceans with a modest measure of confidence. The work on estimating atmospheric greenhouse warming has dealt largely with interpreting the time history of the global mean surface temperature. The corresponding ocean problem can be approached in the space and time domains by a network that suppresses the ambient mesoscale spatial variability of the oceans.

What is the expected greenhouse signature for an acoustic system? A warming by 0.005 °C/year produces a decrease in travel time of approximately 0.2 sec/year for a 10 000-km path. In our ocean acoustic tomography work we have achieved a precision of 0.001 sec in measuring travel times over 1000 km. Over the longer ranges we expect to achieve a precision of 0.01 sec, which is adequate for detecting the expected yearly trends. The problem of finding the greenhouse signal, therefore, is not the precision of the measurements of travel time. Rather, the



Three signal modulations and their spectra as recorded at Ascension Island. Top: 57-Hz continuous-wave tone. Middle: Pentaline code. Bottom: M-sequence pseudorandom code. These are sonograms, or time–frequency plots. Some 60-Hz noise is evident before and after the transmissions. The persistence of the lines for several minutes after the one-hour transmission stopped must be attributed to scattering and multiple horizontal paths. **Figure 5**

problem is ambient variability and the multiple paths of acoustic propagation in the SOFAR channel.

Any greenhouse signal is embedded in the natural ambient variability of the oceans, and this variability is on time and space scales at which we have little data. We need to look to the acoustic modelers for guidance. The fact that the models may be flawed is, in our opinion, a reason for doing the measurements, not a reason against it. From the perspective of many oceanographers, learning something about large-scale ocean variability is of as much interest as greenhouse warming.

Acoustic channels

A separate issue from ocean warming and climate is the complexity of acoustic propagation at low frequencies over paths on the scale of 10 000 km. The refraction that produces the SOFAR waveguide leads not to one path between a source and receiver, but to many paths. Each of these paths potentially contains information about the temperature of the section of the ocean through which the signal has propagated. At low frequencies the multipath arrivals are closely spaced and difficult to resolve. They fluctuate in response to mesoscale eddies and other processes that change the structure of the SOFAR channel. Consequently it is important to identify these paths and to track them consistently over long times.

The SOFAR channel was discovered at the end of World War II by Maurice Ewing and Joseph Worzel in the US and independently a few months later by Leonid Brekhovskikh in the USSR. In the temperate oceans the sound speed profile has a minimum at depths between 600 and 1200 m that forms the axis of the SOFAR acoustic waveguide. Well beneath the axis the temperature of the oceans is fairly uniform and the sound speed increases with depth at a rate of 0.017 m/sec per meter. Above the axis the sound speed increases with higher temperatures. There is considerable variability, especially as one nears the mixed layers below the ocean surface. In the temperate oceans the sound is ducted by refraction both above and below the SOFAR axis, never reflecting off the surface; such paths are often termed RR, for "refracted–refracted." With increasing latitude, both to the north and to the south, the SOFAR axis rises and eventually reaches the surface, forming a waveguide where the sound is refracted beneath the shallow SOFAR axis and reflected by the ocean surface above; these paths are often called RSR, for "refracted–surface reflected."

Low-frequency sound travels extraordinary distances in the ocean SOFAR channel. In 1960, a detonation of 150 kg of TNT in the sound channel off Perth, Australia, was clearly recorded on hydrophones located at the SOFAR axis off Bermuda—at a distance of nearly 20 000 km and nearly antipodal (179.2° away).[12] Seismic exploration for oil and geophysical research both use low-frequency signals to penetrate deep into the Earth's crust. These signals are generated explosively and are routinely detected without any signal processing enhancement at distances of more than 3000 km. Numerous experiments with explosives ranging in size from a few kilograms of TNT to nuclear bombs have produced echoes from bathymetric features many thousands of kilometers away.[13]

Explosive sources, while both wideband and powerful, are not well suited to the measurement of travel time. The signals are not repeatable and have poor "matched filtering" (pulse compression) characteristics due to large frequency sidelobes caused by bubble pulse oscillations in which the cavity created by the explosion collapses and reopens a few times. Such sidelobes are very undesirable when one is trying to identify paths. One needs wideband sources that generate repeatable signals and that can be modulated appropriately for low sidelobes. The signals from such sources can be matched filtered, this being the basic processing procedure for almost all radar and sonar systems.[14] Matched filtering compresses the coded energy transmitted over a long time into a single resolution cell whose width is the reciprocal of the signal bandwidth. Such coded sources are less powerful than explosives, and estimates of their detection and travel time depend on phase-coherent processing.

Real-ocean processes. The Heard Island feasibility test was designed to test the characteristics of the SOFAR waveguide over very long propagation distances. Long-range, low-frequency propagation in the SOFAR waveguide can be described in terms of either rays or modes. In the ray path description, the signals refract toward the SOFAR axis, forming "cycles" with a typical length of 60 km. The steeper rays, or higher modes, have higher group speeds and arrive first. These are followed by the axial rays, or low modes, which are very densely spaced. Our past ocean acoustic tomography experiments exploited the steep, early arriving ray paths for purposes of inverting the data to obtain the temperature. For the feasibility test we expected the propagation primarily to be axial, in which case the signal can be well represented by just the lowest few eigenmodes.

The feasibility test signals propagated in two acoustic environments: polar and temperate. Signals were launched near Heard Island into a polar sound channel, but most of the propagation took place in a temperate sound channel. These environments govern the structure of the rays and modes.

In a real ocean several processes modify the ray and mode model:

▷ absorptive losses within the ocean

▷ attenuation and scattering at the ocean's surface and bottom boundaries

▷ scattering in both the vertical and horizontal directions within the ocean.

Because the feasibility test involved such great ranges, it magnified effects that one usually ignores at shorter ranges. The absorptive losses were kept small by the choice of the 57-Hz carrier frequency.[15] At this frequency absorption is very low—in fact so low that it is difficult to measure. A current estimate is 0.5×10^{-3} dB/km, or a Q of 5×10^4; this leads to a total of 9 dB over the 18 000-km paths of the Heard Island test.

Because we purposely sited the sources in a high latitude to couple efficiently to the SOFAR channel, the first 5000 km of most paths were subject to surface interactions. The high seas at 50° S latitude led to large surface scattering losses. A preliminary examination of the feasibility test results suggests that the surface attenuation was less than expected. Bottom interaction leads to large losses because the attenuation of sound is much greater in the seabed than in the ocean, even at 57 Hz. Typical Q values for the seabed run from 100 to 600; clearly any significant bottom interaction would attenuate the signal to unacceptably low levels. We believe this did in fact occur in the Tasman Sea.

Interior scattering in both the vertical and horizontal directions leads to multipath, or modal, structures that can be difficult to identify. Oceanographers have long been aware of internal waves that scatter energy vertically from rays and modes. Other potential scattering mechanisms for the feasibility test paths include the abrupt changes in the sound channel across the Antarctic convergence, which is an oceanographic feature that can be traced around the globe, and in the eddy-rich region at the tip of South Africa. The concern is that significant coupling to such features complicates path identification and introduces ambiguity into the interpretation of the travel time. Horizontal refraction results from lateral changes in the ocean or seabed. Ocean acousticians have mostly ignored it; however, the very large distances involved in global propagation lead to some very sensitive dependencies on the horizontal structure of the SOFAR channel.[12,16] It takes but a small angular deflection to modify a path of 18 000 km!

Preliminary results

We transmitted on a schedule of "one hour on, two hours off." By choosing the exact carrier frequency of 57 Hz we avoided the 60-Hz and 50-Hz power-line frequencies used at the various receiver sites. The signals were phase modulated by ± 45°, which put at least 50% of the power into the carrier. We used three modulations designed by Birdsall and Metzger:

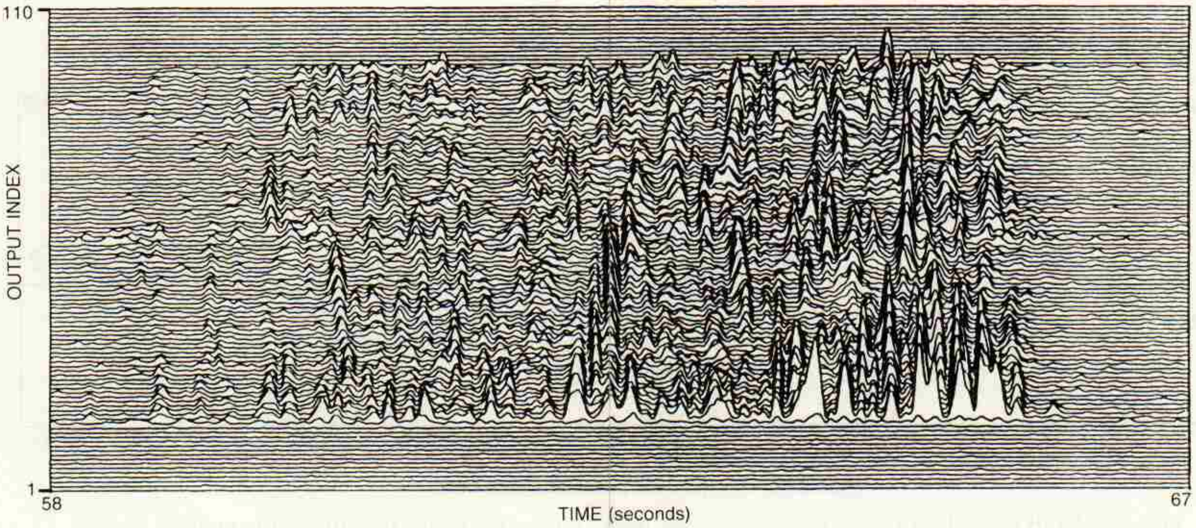
▷ 57 Hz, continuous tone. This provided the simplest way for the receivers to search for a signal—by narrowband spectral analysis.

▷ pentaline code. This was generated by phase modulating the carrier to generate five dominant subcarriers at 1.9-Hz separations. Each digit consisted of nine carrier cycles, so each three-digit word was about 0.5-sec long. Figure 4 illustrates the signal and spectra at the source and at a receiver at Ascension Island, at a range of 9000 km.

▷ pseudorandom M, or maximal length shift register, codes densely covering a 10-Hz bandwidth. (Reference 14 and references therein describe maximal length shift register codes.) We repeated the code for one full hour to test the stability of the channel. We used M codes of length 255 (22.5 sec), 511 (45 sec), 1023 (90 sec) and 2047 (180 sec). One of the big unknowns prior to the test was how long one could integrate the signals coherently; as it turned out, the 2047-length sequences lasting three minutes were very effective.

Figure 4 indicates the remarkable signal-to-noise ratio and stability of a signal that has propagated over 9000 km. One can hear the signal on analog recordings without any signal processing enhancement. The modulation is discernible in the time domain, but with some distortion resulting from the interference of the multiple paths described earlier. Figure 5 shows a sonogram and spectra for each of the three signal types as received at Ascension Island. One can clearly discern the tonal components of the continuous and pentaline signals as well as of the broadband M code. Note also the persistence for several minutes of the tonal components in the continuous and pentaline signals and the 57-Hz carrier of the M code. This large a duration can only be attributed to scattered arrivals of horizontal multipath signals.

A crucial test for acoustic monitoring of ocean



Christmas Island data. Plotted are 90 successive outputs of the matched filter for an M-sequence code 255 digits long repeated every 45 seconds. A dozen or so output sequences before and after the transmissions are also included. Peaks mark arrivals via multiple paths. **Figure 6**

temperature is the ability to resolve and identify stable transmission paths. Figure 6 shows the linear magnitude of the matched filter output at Christmas Island. The "output index" axis labels responses for 90 repeated transmissions of an M code over an hour. The horizontal axis shows the signal intensity to be spread over an interval of 8 sec, which is consistent with the expected dispersion of the lowest eight acoustic modes. Higher modes interact with the sea bottom and are presumably attenuated. The arrival of so many modes was unexpected; we had predicted that only the very lowest modes would survive the scattering along the 5000-km path. The survival of relatively higher modes is also suggested by the data from the vertical array off Monterey, more than 17 000 km away. If the higher modes are stable, they can give important information about temperature well away from the SOFAR axis.

One of the most remarkable aspects of the data has been the high phase stability of the channel. During the one-hour transmission the Cory headed into the wind and swell at about 3 knots to assure the stability and safety of the ship in high seas. The course and speed were kept as steady as possible and a Global Positioning System fix was logged every ten seconds. The fixes were exceptionally accurate because the usual intentional degradation of the GPS was suspended during the Persian Gulf war. The Doppler shift for 3 knots is roughly 10^{-3} of the carrier. The phase of the tonal data, including the carrier of the M sequences, was exceptionally stable and could be tracked very well. Figure 7 illustrates the detected phase of a continuous signal at Ascension after removal of a linear phase ramp for the mean Doppler shift. Also illustrated is the phase predicted by projecting the GPS navigation along the geodesic to Ascension. The agreement is to within 10 meters!

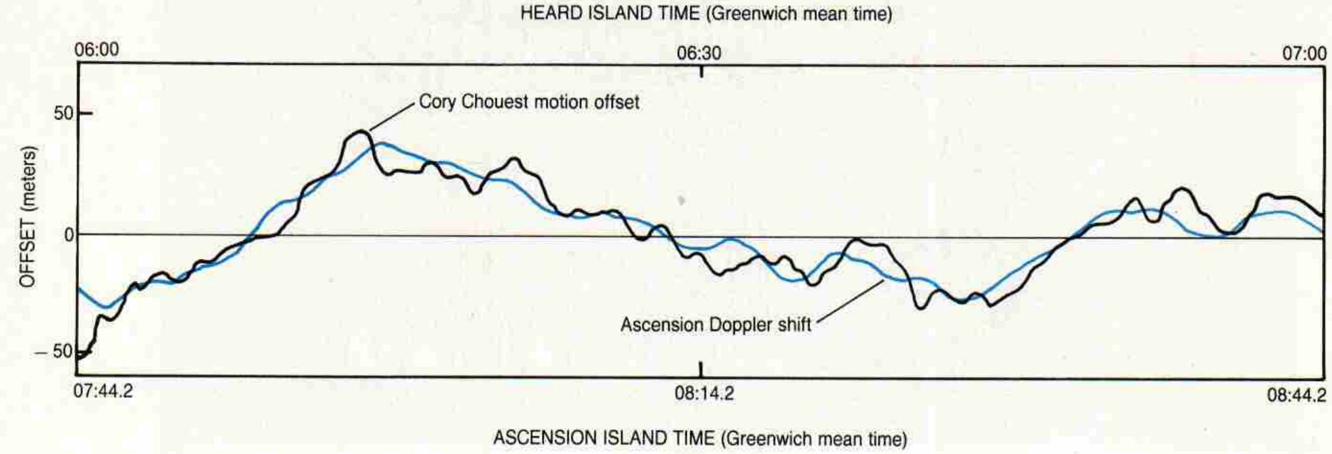
The Doppler measurements have also proven useful in identifying the paths taken by the sound. The geodesic to Oregon and Washington goes through the Tasman Sea passing west of New Zealand; the geodesic to California passes east of New Zealand over the Chatham Rise. The Canadian towed array off California measured an arrival azimuth angle consistent with the computed geodesic (see figure 1). However, the horizontal arrays off Washington showed arrival angles 20° to the left of the geodesic through the Tasman Sea, consistent with a passage *east* of New Zealand. The measured Doppler shift at the Washington station, together with the precise GPS measurements of the speed of the Cory Chouest, also indicates that the transmission to Washington passed east of New Zealand. We must conclude that the Tasman passage is blocked by the rough and relatively shallow bottom terrain beyond New Zealand. This is consistent with the lack of reception by the Japanese vessel off Samoa.

Future plans

We have not demonstrated that the complex arrival structure can be tracked from day to day. We attribute the variability to movement of the source and the differing headings for each transmission. An extrapolation of our measurements and those of others at shorter ranges suggests there is remarkable phase stability at these low frequencies and that we can expect stable and identifiable features for transmissions between fixed sources and receivers. Our first priority now is to transmit over a path from California to New Zealand for one year. We plan to compare seasonal variation in travel time with that inferred from oceanographic measurements taken along the same path.

Given successful transmissions to New Zealand, the problem before us will then be to establish an affordable global network of acoustic sources and receivers that can resolve the spatial modes of greenhouse warming and of natural ambient variability. To do this, the acoustic system must be able to identify and track the propagation paths over very long periods. The criteria for the source and receiver sites include steep bottom slopes at accessible coastal locations so that the SOFAR channel is not too far away. Current plans include 5000- and 10 000-km paths. The experiment will differ from the Heard Island feasibility test in two important ways: Sources and receivers will be fixed, so that we do not confuse ambient variability with that induced by a changing path geometry, and they will run for years.

Heard Island will not be among the stations. It is remote, and the logistics of operating there, not to mention the harsh weather, are formidable. It was a unique site that served us well as a benchmark for global transmissions into the world's ocean basins. We exploited the shallow polar sound channel because of the depth limitation of available sources, but this necessitated injecting



Observed and GPS phases. The black line shows the R/V Cory Chouest's departure from uniform motion along a course of 267° toward Ascension Island on 26 January 1991, as determined by the Global Positioning System. The colored line is the detected phase of the signal at Ascension Island. The source–receiver separation is approximately 9000 km, yet the relative distance between them is tracked to within 10 m. **Figure 7**

the sound into the biologically important upper ocean layers. North of the Antarctic convergence, the sound channel is deep. With a source at the channel axis the sound levels at the surface are reduced significantly. We expect that the potential impact upon marine mammals can be reduced to an acceptable level for the permanent system.

The criteria for the source technology are challenging:

▷ low center frequency (70 Hz or less) with a 20-Hz bandwidth
▷ moderately high intensity: 195–205 dB re 1 μPa at 1 m
▷ depth capability to 1500 m
▷ reliable performance for ten years.

The last is especially important because source deployment and recovery are expensive.

The receivers also pose challenges. Ultimately we want to make them as simple as possible but still meet the objective of unambiguous path identification. The conventional wisdom is that it is easier to obtain gain at the receiver than at the source because increasing the number of hydrophones is less expensive than increasing source power. This is a bit misleading, because the transmission of the data back to shore dominates the cost of a receiver. We are considering both horizontal and vertical arrays. Horizontal arrays are useful because they provide more gain per element. They perform better in environments of low signal-to-noise ratio, but they cannot identify vertical structure. Initially we will probably deploy vertical arrays to provide mode resolution and processing gain. The mode resolution is highly desirable because it gives some measure of the vertical structure of the greenhouse warming and of the ambient variability.

The most intellectually challenging problem is to understand what it takes to separate greenhouse trends from natural ambient variability. Our knowledge about processes in the ocean with extremely long time scales is very limited. We now have to depend upon model studies to estimate the magnitude and spatial structure of both the greenhouse signal and ambient variability (see figure 3). There is considerable skepticism within the oceanographic community about the validity of the existing computer models. Assimilating the acoustic measurements into the climate models could enhance their validity and their role in the interpretation of such measurements.

Countries other than the US participating in the feasibility test (and the principal scientists) were Canada (N. R. Chapman), France (B. Olivier), South Africa (G. Bundritt), the USSR (N. Dubrovsky), India (B. N. Desai and W. Morawitz), Australia (A. Forbes), New Zealand (G. Bold) and Japan (I. Nakamo).

The principal members of the Heard Island experiment team acknowledge the support and encouragement of Fred Saalfeld (ONR), John Knauss and Ned Ostenso (NOAA), Ari Patrinos (DOE), Craig Dorman (Woods Hole Oceanographic Institution), Rear Admiral (retired) Richard Pittenger (Woods Hole) and others mentioned in the text.

References

1. W. Munk, C. Wunsch, Deep Sea Res. **26A**, 123 (1979).
2. The Ocean Tomography Group, Nature **299**, 121 (1982).
3. W. Munk, C. Wunsch, Philos. Trans. R. Soc. London **307**, 439 (1982).
4. J. L. Spiesberger, K. Metzger, J. Geophys. Res. **96**, 4896 (1991).
5. W. Munk, A. Forbes, J. Phys. Oceanography **19**, 1765 (1989).
6. A. Bowles, *The Marine Mammal Monitoring Program for the Heard Island Feasibility Test*, National Marine Fisheries, Natl. Oceanic Atmospheric Admin., Washington, D. C. (1991).
7. C. Keeling, R. Bacastow, A. Carter, T. Whorf, M. Meinmann, W. Mook, R. Roeloffze, in *Aspects of Climate Variability in the Pacific and the Western Americas*, Geophys. Monograph 55, D. H. Peterson, ed., Am. Geophys. Union, Washington, D. C. (1991), p. 165.
8. J. Hansen, S. Lebedeff, J. Geophys. Res. **92**, 13345 (1987).
9. W. Munk, *The Heard Island Experiment*, Indian inaugural lecture of Int. Sci. Lecture Ser., organized by Natl. Acad. Sci. and Office of Naval Res., November 1990, Natl. Acad. Sci. P., Washington, D. C. (1990).
10. U. Mikolajewicz, B. Santer, E. Maier-Reimer, Nature **345**, 589 (1990).
11. P. Stone, Technology Rev., February–March 1992, p. 32.
12. W. Munk, W. O'Reilly, J. L. Reid, J. Phys. Oceanography **18**, 1876 (1988).
13. A. B. Baggeroer, I. Dyer, in *Seismo-Acoustics*, J. Berkson, T. Akal, eds., Plenum, New York (1986), p. 313.
14. A. B. Baggeroer, in *Applications of Digital Signal Processing*, A. V. Oppenheim, ed., Prentice–Hall, Englewood Cliffs, N. J. (1978), ch. 6.
15. R. J. Urick, *Principles of Underwater Sound for Engineers*, McGraw–Hill, New York (1988).
16. K. D. Heaney, W. A. Kuperman, E. McDonald, J. Acoust. Soc. Am. **90**, 2586 (1991). ■