ACOUSTIC REMOTE SENSING OF OCEAN GYRES

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> "To understand the ocean, its dynamics, its role in climate, weather and other ocean-atmosphere phenomena, one must observe it on a basin-wide scale with adequate time and space resolution."

This quote is from a paper published by Munk and Wunsch in 1982, titled "Observing the ocean in the 1990's."[1] In that paper they described an ocean observation system consisting of two complementary components: ocean acoustic tomography and satellite observations of sea surface topography and wind stress. They noted, somewhat parenthetically, that tomography over basin-scale distances required "further engineering developments." It is now more than 20 years later. Where do we stand in the application of acoustic remote sensing methods to observing the ocean on basin scales?

Acoustic tomography, satellite altimetry and scatterometry, and a third observational component mentioned only briefly by Munk and Wunsch, freely drifting profilers, are today providing complementary basin-scale observations of the northeast Pacific Ocean. Large-scale, depth-averaged temperatures have been measured by long-range acoustic transmissions in the North Pacific Ocean for the past nine years. Acoustic sources located off central California and north of Kauai transmitted to receivers distributed throughout the North Pacific from 1996 through 1999 during the Acoustic Thermometry of Ocean Climate (ATOC) project. The Kauai transmissions resumed in early 2002 and are now continuing as part of the North Pacific Acoustic Laboratory (NPAL) project; a seven-year time series has been obtained so far. Progress has at times seemed glacial, but the engineering (and scientific) developments needed for basin-scale tomography are in fact occurring. The time series are now becoming long enough to be interesting.

Ocean acoustic tomography and thermometry

The ocean is largely transparent to sound, but opaque to electromagnetic radiation. Remote sensing of the ocean interior must therefore rely on sound. Ocean acoustic tomography measures ocean temperature and velocity *within* an ocean volume by transmitting sound *through* it.[2] Travel time is a function of temperature (and to a much lesser extent, salinity) and water velocity, and travel time measurements can provide information about the intervening ocean using inverse methods (Fig. 1). (Other less robust acoustic parameters, such as amplitude and phase, can, in principle, also be used.) The effects of temperature and velocity can be separated by using reciprocal transmissions in which sound is transmitted simultaneously in opposite directions. Sound traveling with a current travels slightly faster than sound traveling against a current. The difference in travel time is sensitive to the current parallel to the acoustic path. Reciprocal tomography is particularly

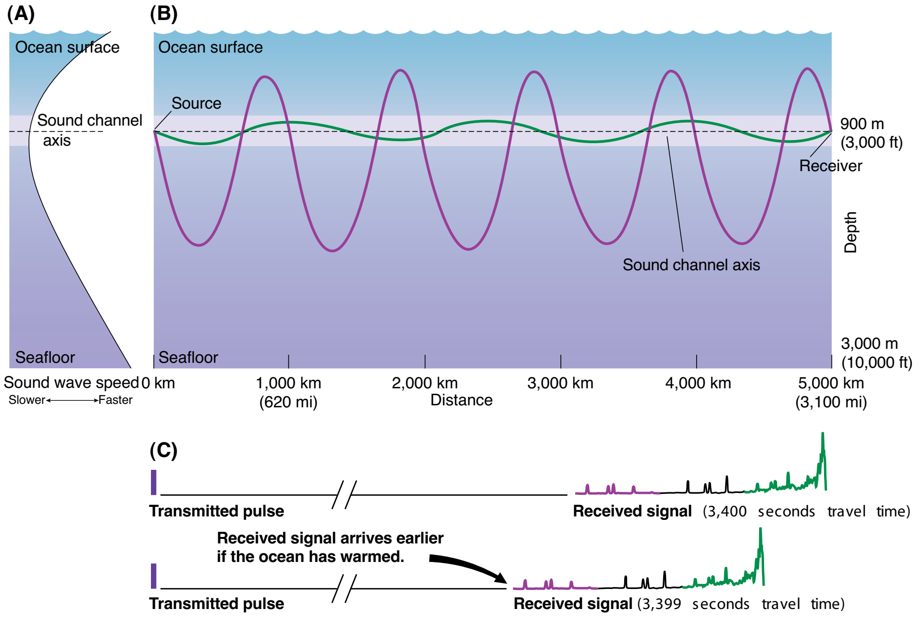

Fig. 1. (A) Sound speed as a function of depth. Sound speed increases with increasing temperature, salinity, and pressure. Near the surface temperature dominates, and sound speed decreases as the temperature decreases. At deeper depths temperature becomes nearly constant. Pressure then dominates, and sound speed increases as pressure increases. The result is a sound-speed minimum at about 1000 m depth in mid-latitudes, called the sound channel axis. (B) Low-frequency sound can propagate to long distances in the sound channel without interacting with the surface or seafloor. (C) If the ocean warms up between the source and receiver, travel time decreases because sound speed increases with increasing temperature. (From J. Howard, "Listening to the Ocean's Temperature," Scripps Institution of Oceanography Explorations **5**, *Fall 1998.)*

well suited for measuring barotropic (depth-independent) currents, such as those associated with the ocean tides, because the steep acoustic ray paths naturally provide vertical averages.

Acoustic tomography was originally envisaged as a tool to map ocean mesoscale variability (the oceanic equivalent of atmospheric weather, with spatial scales of order 100 km and time scales of order 100 days) using many crossing acoustic paths. The analogy is to CAT scans. Acoustic thermometry can be considered to be a subset of acoustic tomography, in which a much sparser set of acoustic paths is used to obtain the average temperature of the intervening ocean.

Energetic ocean mesoscale eddies dominate measurements made at a point, making it difficult to measure variability on the scale of the great wind-driven ocean gyres, which have spatial scales of thousands of kilometers. The advantage to using acoustic methods to measure gyre-scale variability is the inherent integrating nature of the acoustic transmissions. The acoustic travel time along a path from a transmitter to a receiver is determined by the *average* sound speed along the path. (Conversely, acoustic methods are not well suited to obtaining precise *local* information.) Ocean basin-scale transmissions provide horizontal and vertical averages that reduce noise due to ocean mesoscale variability, providing precise measurements of gyre-scale heat content. Further, the heat content in a vertical section across an ocean basin can be rapidly and repeatedly measured at low cost using acoustic methods, once an acoustic measurement system has been installed.

A brief history

It all started with a discussion titled “Monitoring the Ocean Acoustically” by Munk and Worcester at a celebration of the thirtieth anniversary (1946–1976) of the Office of Naval Research[3]:

> “The classical Physical Oceanographers cast their Nansen bottles and contoured dynamic heights, so that these would be available for computing geostrophic currents which are then published on permanent charts. The acoustician found it difficult to relate this delightfully simple view of a steady ocean interior to the complex and time-variable transmission of acoustic signals…”

At that meeting Munk described the results of reciprocal transmissions between the *R/V Alexander Agassiz* and the *R/V Ellen B. Scripps* at 25-km range. There was a clear distinction between the simplicity of the early deep arrivals and the subsequent complex multi-paths through the ocean’s upper layers.

Starting with the 25-km reciprocal transmission, the experiments moved in the direction of longer transmission ranges. For some years the emphasis was on mesoscale processes. The discovery in the 1960’s of a very active mesoscale was responsible in the first place for proposing *Ocean Acoustic Tomography* to meet some of the shortcomings of the traditional *Expedition Mode*. Much of the earliest work took place in the northwest Atlantic with battery-powered sources on autonomous moorings. Ranges were a few hundred kilometers, although even then receptions were recorded at longer ranges using bottom-mounted receivers that were part of the SOund SUrveillance System (SOSUS) belonging to the U.S. Navy. Between 1983 and 1989 Spiesberger and Metzger made intermittent long-range transmissions from a shallow source off Kaneohe, Oahu, to SOSUS receivers in the North Pacific, in the first systematic effort to acoustically monitor an ocean basin. In 1987 new HLF-5 hydroacoustic sources transmitting broadband signals at 250 Hz allowed the first megameter transmissions between autonomous moored instruments. In 1991 the global Heard Island Feasibility Test (HIFT) demonstrated that acoustic sources can be detected at antipodal ranges (20,000 km), but the arrival pattern is too garbled to permit precise determination of travel time.[4] From a climate point of view the very large ranges in HIFT are counter-productive, since they average across very distinct climatic provinces. Following HIFT, we have emphasized shorter ranges, generally up to 5000 km.

Acoustic Thermometry of Ocean Climate (ATOC)

The completion of HIFT found us in an up-beat mood. We had transitioned from the earliest 25-km reciprocal transmissions to the documentation of a time-variable mesoscale to basin scale and now to a global scale. (The next step would be more difficult.) We were ready to tackle the problem of measuring the changing ocean heat content (central to the ongoing debate on climate change). Our first goal was to monitor the subtropical gyre of the northeast Pacific.

There were two problems: money and permits. At the behest of Senators Gore[5] and Nunn, the Defense Department had initiated the “Strategic Environmental Research and Development Program” (SERDP). In late 1992, after prolonged negotiations, we secured a 30-month, $35-million grant for the Acoustic Thermometry of Ocean Climate (ATOC) project. The goals were (i) to determine the precision with which acoustic methods can measure large-scale changes in ocean temperature and (ii) to determine what effects, if any, the acoustic transmissions would have on marine mammals and other marine life. The hope was that ATOC would lead to a long-term, global program for measuring the changing ocean heat content. At Heard Island we had used a vertical array of powerful HLF-4LL transducers suspended from shipboard transmitting at 57 Hz; now we could backtrack to less powerful and less expensive projectors. ATOC featured cable-connected, bottom-mounted HX-554 bender-bar sources on Pioneer Seamount off central California and off the north coast of Kauai (Fig. 2). The cable-connected sources allowed for the long time series needed.

The permit issue proved to be much more difficult. HIFT had been widely publicized under the unfortunate slogan “The Shot Heard Around the World.” It caught the imagination of the public, but also the attention of the environmental community. As a result, operation of the ATOC sources could not begin until approvals were granted and permits were issued. When the approvals were finally issued, the permits placed control of the sources under the

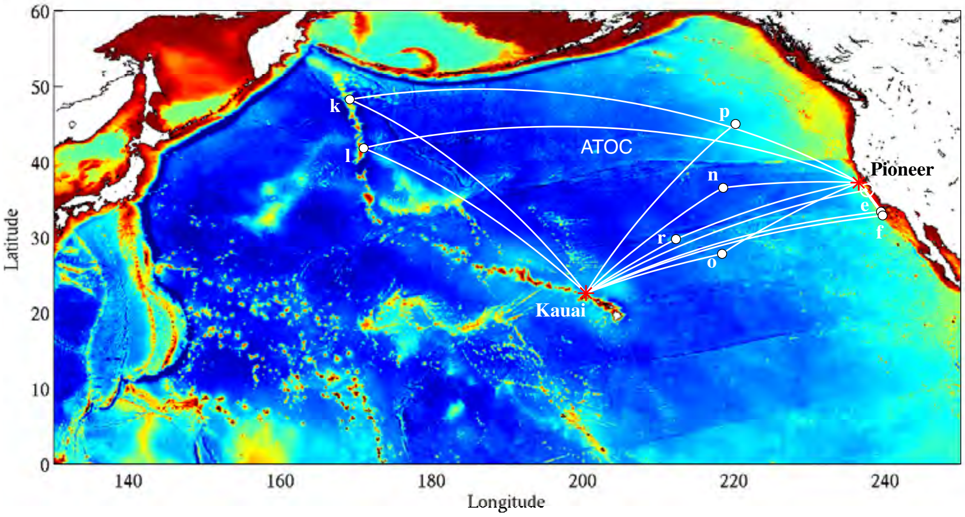

Fig. 2. The ATOC array. (From Ref. 7 © 2005 Acoustical Society of America.)

ATOC Marine Mammal Research Program (MMRP). Thus, permission for climate-oriented research was to be subsequent to studies relating to the possible effects of sound on marine life.

Nonetheless, analyses of data from the ATOC project demonstrated that acoustic thermometry is a powerful tool for making routine measurements of large-scale ocean temperature variability and heat content, as originally hypothesized.[6] We found that acoustic travel times could be measured with a precision of about 20–30 msec at 3000–5000 km ranges. For comparison, the total travel time for an underwater acoustic signal over 5000 km is nearly an hour. ATOC measurements proved to be more precise than originally thought possible. The initial concern that acoustic scattering from small-scale ocean structure, such as internal waves, might make accurate measurements of acoustic travel times impossible at 3000–5000 km ranges proved to be unfounded. The travel times can then be used to estimate the range- and depth-averaged temperature with a precision of about 0.010°C.

The ATOC Marine Mammal Research Program was significantly expanded during the process of obtaining the necessary authorizations. In the end the California and Hawaii ATOC MMRPs consisted of multiple components, including (i) aerial surveys to determine any changes in the abundance and distribution of marine mammals, (ii) elephant seal tagging studies to determine any changes in elephant seal migratory or diving behavior, (iii) playback studies to humpback whales off the Kona-Kohala coast of Hawaii designed to look for behavioral changes in response to ATOC-like sounds, (iv) visual observations of humpback whale abundance, distribution, and behavior north of Kauai, (v) undersea acoustic recordings made with seafloor data recorders north of Kauai to determine any changes in humpback vocalizations, (vi) auditory measurements on small toothed whales (odontocetes) to determine their sensitivity to the frequencies transmitted by the ATOC sources, and (vii) playback studies to fish at the Bodega Bay Marine Laboratory designed to look for behavioral changes in response to ATOC-like sounds. None of the studies found any overt or obvious short-term changes in abundance, distribution, behavior, or vocalizations! Statistical analysis of the aerial survey data showed some small shifts in the distribution of humpback (and possibly sperm) whales away from the sources during transmission periods. Statistical analyses of the behavioral data revealed some small changes in the behavior of humpback whales in response to the playback of ATOC-like sounds and to the transmissions of the ATOC Kauai source. The conclusion was that the minor effects that were observed would not adversely impact either the survival of an individual whale or the status of the North Pacific humpback whale population.

North Pacific Acoustic Laboratory (NPAL)

Encouraged by the ATOC results, we decided to undertake the effort needed to obtain the approvals and permits required to resume transmissions from the Kauai source. The ATOC permits allowed for two years of transmissions from each source. The Kauai transmissions had begun on 30 October 1997 and been terminated on 3 October 1999. We began the arduous process of obtaining the required authorizations in 1999 (Fig. 3). Transmissions from the Kauai source finally resumed on 24 January 2002 as one component of the North Pacific Acoustic Laboratory program.[7] The Kauai time series are therefore now over seven years long, albeit with a substantial gap while we were obtaining the authorizations needed to resume transmissions.

Even at long time and large spatial scales the ocean is highly variable. A path from Kauai to California (receiver f) shows a modest cooling trend (longer travel times) until the present time (Fig. 4). A path to the northwest (receiver k)

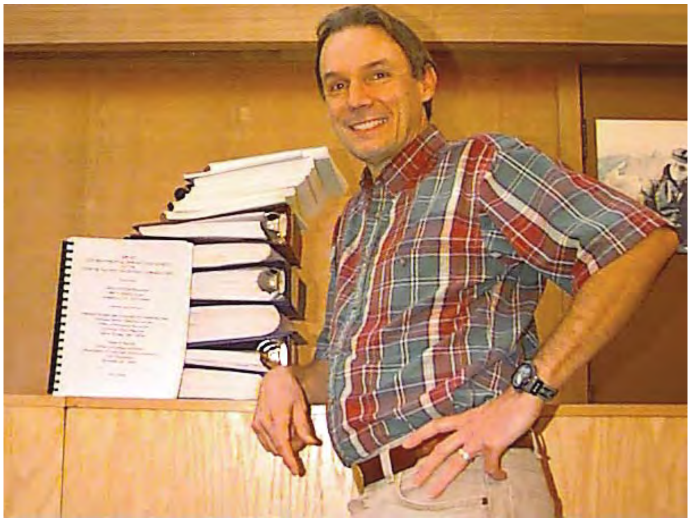

Fig. 3. Peter Worcester, North Pacific Acoustic Laboratory (NPAL) principal investigator, with the environmental documentation prepared in the course of obtaining the authorizations needed to operate a low-frequency sound source off the north shore of Kauai to do a second phase of research on the feasibility and value of large-scale acoustic thermometry. Obtaining the required authorizations took nearly three years and cost in excess of half a million dollars.

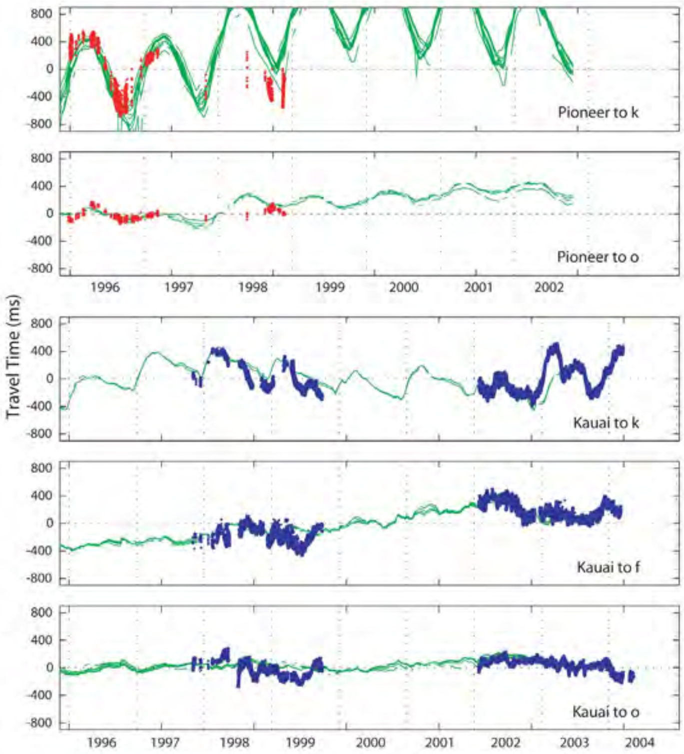

Fig. 4. Travel times measured on the 1–5 Mm-long acoustic paths (red and blue) compared to travel times predicted using the JPL-ECCO ocean model (green). See Fig. 2 for path identification. Six to twelve rays are resolved and identified on each acoustic path. (From Ref. 8 © 2004 Institute of Electrical and Electronics Engineers.)

showed modest warming and a weak annual cycle from late 1997, when the transmissions started, until early 2003, when the path cooled abruptly and a strong annual cycle returned. In retrospect, these changes stemmed from the warming of the central Pacific that occurred in this interval.

Acoustic thermometry and ocean models

From the very start we envisioned a close coordination between acoustic thermometry and satellite altimetry to provide complementary constraints on ocean circulation models. This strategy combines the good horizontal resolution of altimetry and the depth resolution and good time resolution of tomography. In order to use acoustic path integral data as constraints on ocean models, one must first be able to use the model output to construct realistic sound-speed fields for use in acoustic propagation calculations (the *forward* problem). Until quite recently the vertical resolution of ocean general circulation models was too coarse to allow construction of realistic sound-speed profiles. Modern models, however, such as that implemented by the ECCO Consortium (Estimating the Circulation and Climate of the Ocean), finally have the vertical resolution needed for acoustic propagation calculations, allowing for straightforward comparison of measured and predicted travel times.

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Nonetheless, sound speeds derived from the ECCO model initially gave unphysical results when used for acoustic calculations. The time mean state of the model was therefore replaced by fields from the World Ocean Atlas. Once this was done, measured travel times and travel times computed from the model are similar, although significant differences remain (Fig. 4).[8] The ocean state estimate used here is based on an integration of the MIT General Circulation Model in a global configuration that spans 75° S to 75° N, with latitudinal grid spacing ranging from 1/3° at the equator to 1° at the poles and longitudinal grid spacing of 1°. The model assimilates a variety of satellite and *in situ* data and data products, including TOPEX/POSEIDON altimetric data, World Ocean Circulation Experiment (WOCE) hydrography, eXpendable BathyThermograph (XBT) sections, and Argo float data.

The next step is to use the travel times as integral constraints on the model variability. If the data estimated by the model do not match the observations, then the ocean model state is adjusted to bring the model into better agreement with the data. Using modern ocean state estimation methods, the acoustic data can be compared to and ultimately combined with upper-ocean data from Argo and sea-surface height data from satellite altimeters to detect changes in abyssal ocean temperature and to test the complementarity of the various data types.

Acoustic thermometry and Argo float data

The Argo program is deploying autonomous floats that drift with the ocean currents at a depth of about 2000 m. Approximately every 10 days the floats surface, measuring temperature and salinity as they rise. The temperature and salinity profiles are transmitted to shore via satellite link, and the float then returns to depth. The goal is to have about 3000 floats deployed globally at all times, with a nominal spacing of about 300 km. Although the Argo profiling floats and acoustic thermometry sample the ocean in quite different ways, the Argo data can be used to construct line averages for comparison with the acoustic data.

All float profiles within 300 km of the acoustic path from the Kauai source to receiver k were first extracted. Figures 5 and 6 show the horizontal and vertical sampling in a 10-day snapshot. The annual mean World Ocean Atlas temperatures were then subtracted to remove most of the geographical variations in temperature and to focus on the "anomalies." The resulting temperature profile anomalies were depth-averaged, and these in turn were averaged together on 10-day intervals—insofar as this was possible (many of the floats early in the time series are shallow). The acoustic travel time measurements were inverted using a simple statistical ocean model consisting of six vertical modes, including a mixed layer, to represent vertical variability and a red spectrum with 20 wave numbers to represent horizontal variability; the variance in the main thermocline was ~ 1°C.

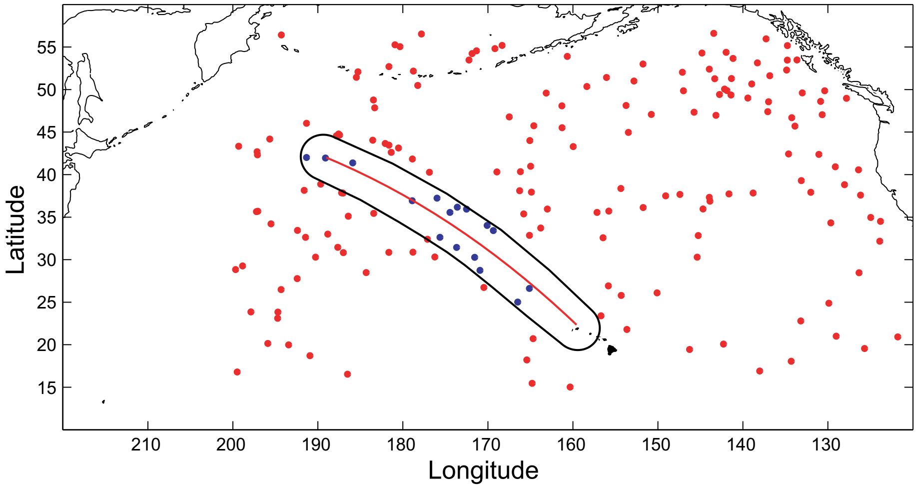

Fig. 5. Acoustic path from the Kauai source to receiver k with positions of the available Argo floats during a 10-day period in fall 2003. (From Ref. 8 © 2004 Institute of Electrical and Electronics Engineers.)

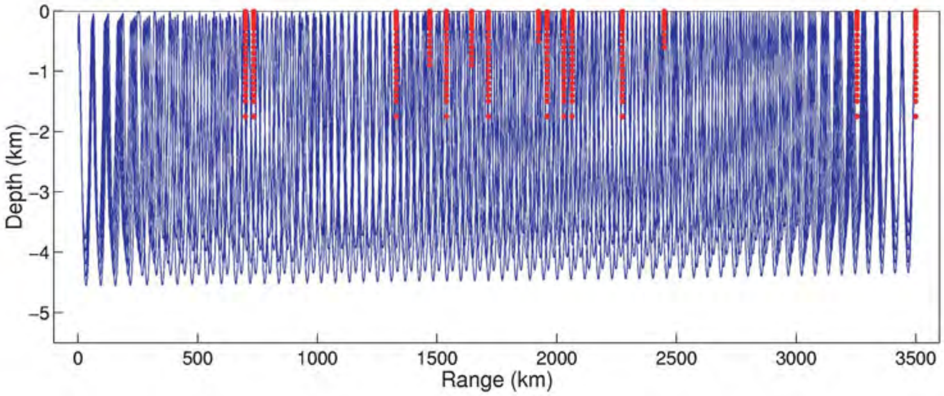

Fig. 6. Sixteen Argo float profiles within 300 km of the acoustic path during a 10-day period superimposed on the ray trajectories from the Kauai source to receiver k. (From Ref. 8 © 2004 Institute of Electrical and Electronics Engineers.)

The direct comparison between the float "path averaged" temperatures and the ATOC derived temperature measurement is shown in Fig. 7. Here, the thin vertical magenta bar gives the standard deviation of the vertical averages of the float profile data within the area in a 10-day interval, ±0.6°C. An estimated uncertainty for the Argo volume mean is this standard deviation divided by the square root of the number of samples in the 10-day interval (~20); this is shown by the heavy magenta bar, ±0.15°C. The corresponding uncertainty in the ATOC-derived temperature from the inversion process is ±0.02°C. This substantially lower uncertainty is a direct result of the path averaging inherent in the acoustic measurement. The difference between the Argo- and ATOC-determined average temperatures is ~30–50 percent of the annual cycle, within the uncertainty estimates and consistent with both measurements.

The substantial variability found in the Argo temperature profiles is consistent with internal wave and mesoscale variability of order 1°C. This variability makes detection of oceanic climate change from measurements of local profiles difficult, requiring extensive averaging of the profiles in space and time. The acoustic time series are *a priori* spatially smoothed.

Observing ocean climate

At the International Conference on the Ocean Observing System for Climate: OCEANOBS 99 in St. Raphael, France (18–22 October 1999), Dushaw *et al.*[9] summarized the appropriate role for acoustic tomography in observing ocean climate. Some preliminary planning had previously been done for thermometry systems in the Atlantic, Arctic, and Indian Oceans. More recently, planning for the National Science Foundation ORION global network of moored-buoy observatories and the ORION cabled regional observatory has included provision for the data telemetry, power, and precision timing needs of acoustic thermometry, which would supplement the spot measurements at the moorings with measurements of ocean temperature *between* the moorings.[10] One particularly intriguing possibility is that acoustic transmissions between the global moored-buoy observatories might provide measurements of the variable ocean heat content in the abyssal ocean. Systematic measurements of deep-ocean temperature currently exist at only a few locations in the world ocean, and these few time series do not show any consistent pattern. We need to understand the processes that bring heat into the abyssal depths if we are to understand the role of the ocean in storing heat and the impact of

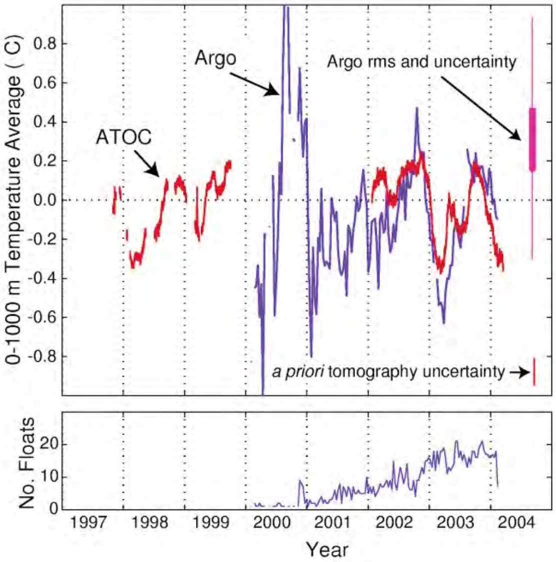

Fig. 7. Time series of range- and depth-averaged temperature along the acoustic path from the Kauai source to receiver k derived from acoustic thermometry and from Argo float data. (From Ref. 8 © 2004 Institute of Electrical and Electronics Engineers.)

increasing greenhouse gases on climate. The travel times of acoustic rays that cycle deep into the ocean, when combined with other measurements of the upper ocean, may make it possible to detect climate signals in the abyssal depths with the required precision of a few m°C.

It is inconceivable to us that oceanographers (and other marine mammals) should not take advantage of the fact that the ocean is transparent to sound.**AT**

Acknowledgments

As is the case for many large research projects, the authors of this short summary are no more than reporters of the work of many. The results presented here represent the efforts of our colleagues in the ATOC Consortium (A.B. Baggeroer, T.G. Birdsall, C. Clark, J.A. Colosi, B.D. Cornuelle, D. Costa, B.D. Dushaw, M.A. Dzieciuch, A.M.G. Forbes, C. Hill, B.M. Howe, J. Marshall, D. Menemenlis, J.A. Mercer, K. Metzger, W.H. Munk, R.C. Spindel, D. Stammer, P.F. Worcester, and C. Wunsch) and the NPAL Group (J.A. Colosi, B.D. Cornuelle, B.D. Dushaw, M.A. Dzieciuch, B.M. Howe, J.A. Mercer, W.H. Munk, R.C. Spindel, and P.F. Worcester). Our research on acoustic tomography and thermometry has been supported over the years by the Office of Naval Research, the National Science Foundation, the Defense Advanced Research Projects Agency, and the National Ocean Partnership Program.

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[5] Munk subsequently briefed Vice President Gore on ATOC. When Munk encountered the Vice President on a number of occasions following the briefing, the Vice President referred to Munk as the "Whale Killer."

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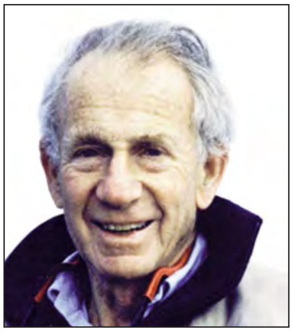
Walter Munk received his doctorate at the Scripps Institution of Oceanography, University of California, in 1947. He then became professor of geophysics at Scripps Institution of Oceanography, where he has continued to work to this day. His principal research interests are ocean acoustics, tides, waves, tsunamis, and the Earth's rotation. Dr. Munk has received many awards and honors for his work including the National Medal of Science (1985); William Bowie Medal, American Geophysical Union (1989); Vetlesen Prize, Columbia University (1993); Kyoto Prize, Japan (1999); Doctor Philosophiae Honoris Causa, University of Bergen, Norway (1975), University of Cambridge, England (1986), and University of Crete, Greece (1996). He is a member of the National Academy of Sciences (1956), The Royal Society, London (1976), American Philosophical Society (1976), Russian Academy of Sciences (1994), and an Honorary Fellow of the Acoustical Society of America (2004).



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