BASIN-SCALE OCEAN MONITORING WITH ACOUSTIC THERMOMETERS*

By John L. Spiesberger and Kurt Metzger

. . . the first acoustic measurements of travel time . . . to measure temperature at basin scales . . .

WE HAVE DEVELOPED an acoustic thermometer capable of rapidly sensing changes in the spatially averaged temperature over long distances in the ocean, i.e., at basin scales of 1,000 to 4,000 km (Fig. 1). This thermometer is based on measurements of the travel times of acoustic pulses that travel through the interior of the ocean. In one experiment, we were able to recognize changes in the spatially averaged temperature exceeding ±0.02°C in the upper kilometer (Fig. 2). In another experiment, we were able to sense spatially averaged changes of temperature from month to month in the upper 100 m (Fig. 3A) that were not detected with available XBT (expendable bathythermograph), AXBT (airborne XBT), or CTD (Conductivity, Temperature, Depth), observations (Fig. 3B). These are the first acoustic measurements of travel time which have been shown to measure temperature at basin scales (Spiesberger and Metzger, 1991a; Spiesberger *et al.*, 1992).

These acoustic measurements of temperature variability at basin scales complement satellite and point measurements of temperature variability. Satellites give us global coverage of sea-surface temperatures, but most of the heat in the ocean and atmosphere is beneath the surface. Indeed, a few meters of ocean thickness have more thermal capacity than the entire atmosphere. Available point measurements are generally insufficient for mapping temperature evolution at basin scales. These measurements are taken too far apart and too infrequently to resolve the energetic space-time structure of internal waves, eddies, and other waves at smaller scales (Talley and White, 1987).

* Dedicated to the life of Henry Stommel.

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† Aliasing: mapping errors at long space or time scales originating from oscillations whose wavelengths or periods are less than twice the sampling interval (Oppenheim and Schafer, 1975).

‡ 440 Hz, the pitch of the A above middle C on the piano.

Because of aliasing,† this unresolved variability maps into basin scales. Aliasing confounds our ability to map, e.g., month-to-month changes in the spatially averaged heat content in the upper 100 meters of the northeast Pacific (Fig. 3B) (Wyrtki and Uhrich, 1982). We need a rapid way to average out small spatial scales in the ocean with little aliasing. Sound provides a way to do this.

Why Sound?

Sound has very special properties in seawater. At frequencies below the concertmaster's A440,‡ sound travels thousands of kilometers in the ocean. One reason sound can be heard at such great distances in sea water is because there is little damping. To understand the magnitude of this effect consider a church bell. Once struck, a church bell ringing at 200 Hz (cycles per second) resonates for about half a minute. At the same frequency, sound in seawater lasts ~40 minutes.

If sound bounced from the top and bottom of the ocean, it would die out after a few reflections like a billiard ball ricocheting from soft rails. However, sound waves bend away from the top and bottom of the ocean because of refraction, which follows Snell's law (Fig. 4). Sound in sea water travels slowest near a depth of ~1 kilometer (Fig. 4, bottom). The speed of sound becomes increasingly faster both above and below this depth. A vertical slice of sound energy in the ocean shows these acoustic waves to have a spatial cycle distance of ~50 km (Fig. 5, left). Sound travels to a distant receiver along many paths, called multipaths. The time of travel along each multipath in the sea is different, so many pulses are heard although only one has been transmitted (Fig. 5, right).

Sound Bending Discovered by Lichte after World War I

Lichte (1919) may have been the first person to recognize that sound bends in the ocean. Lichte was interested in using acoustics to clear mines from German shipping lanes after World War I.

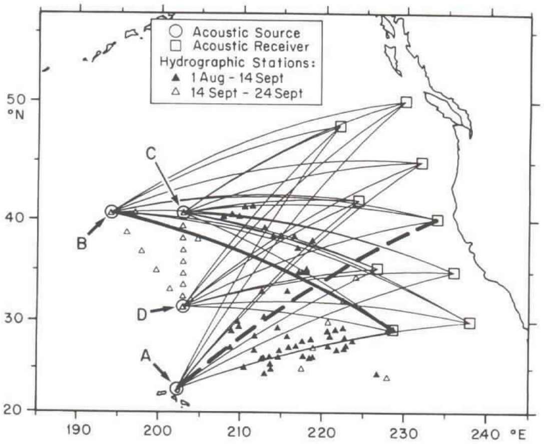

Fig. 1: Plan view of acoustic monitoring experiments with the approximate positions of four acoustic sources and nine receivers indicated. The dashed line between Kaneohe Bay, Oahu (source A) and northern California indicates a 4,000-km section occupied since 1983. The thick solid line indicates a 3,000-km section between a tautly moored source (B) at about 900 m depth (Worcester et al., 1990) and a bottom-mounted receiver. The triangles give the positions of XBTs, AXBTs, and CTDs taken when acoustic travel times were measured along the thick solid line. The stations arranged along the perimeter of the right triangle with vertices at sources B, C and D are part of this experiment (courtesy D. Behringer); the others are coincidental (Adapted from Spiesberger and Metzger, 1991a).

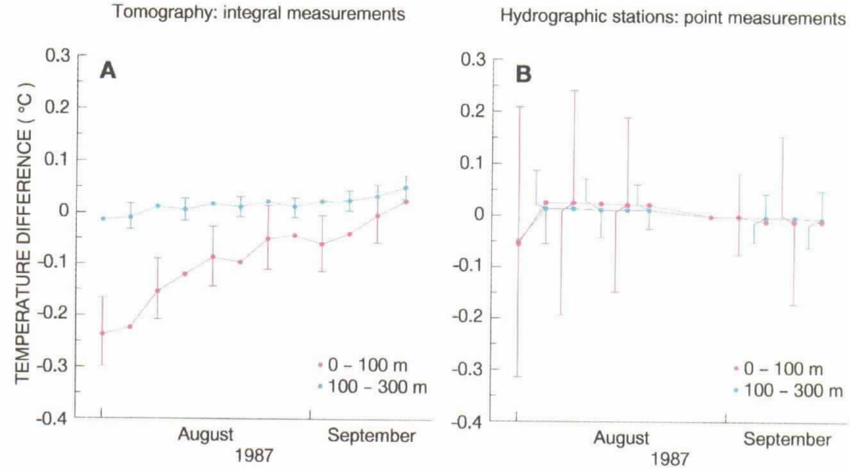

*Fig. 3: Estimates of the average temperature difference, compared with 29 August, along the 3,000-km section indicated by the thick solid line in Fig. 1. (**A**) From acoustic tomography data and (**B**) from all hydrographic stations shown in Fig. 1. Tomographic estimates exhibit a significant trend in the upper 100 m (the seasonal thermocline), indicative of the characteristic warming expected between August and September. Available hydrographic stations are insufficient for detecting warming over this period. An error bar is indicated for every other point and each represents one standard deviation. Tic marks on the horizontal axis denote month boundaries (Adapted from Spiesberger and Metzger, 1991a).*

He theorized that sound bends near the ocean surface. Deducing that the speed of sound increases with temperature, pressure, and salinity, he predicted that sound would bend away from the surface because, with cooling, the speed of sound would decrease with depth. Lichte validated his theory with acoustic data collected from frigates before the war. Ahead of his time, he also hypothesized that sound would bend upwards in the deep ocean because the speed of sound would increase due to a steady rise in pressure.

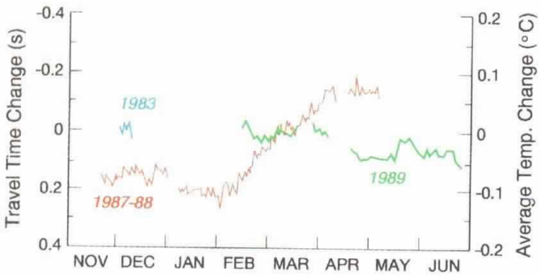

Fig. 2: Changes in acoustic travel time (left-hand scale) measured between Kaneohe Bay, Oahu and the coast of northern California (Fig. 1, dashed line) compared with the first travel times measured in 1983. Months are indicated on the horizontal axis. The right-hand axis provides an approximate guide (to within ~30%) for the change in average temperature in the upper kilometer that is required to yield observed changes in travel time (Adapted from Spiesberger et al., 1992).

More than two decades later, these principles of wave bending were appreciated by American scientists (Ewing *et al.*, 1941; Mathisson and Hickley, 1942; Vine *et al.*, 1947; Ewing and Worzel, 1948). Working without knowledge of Lichte's results published in German, they went one step further and graphed the speed of sound as a function of depth. They showed that the minimum speed occurs at ~1 km depth in middle and equatorial latitudes. The trade-off between temperature and pressure gives what Ewing and Worzel called the sound channel (Fig. 6), so named because sound is channeled away from the top and bottom of the ocean by refraction. Salinity variations usually have little effect on the speed of sound in seawater (Fig. 6).

The trade-off between temperature and pressure gives . . . the sound channel . . .

Recognizing Change in the Ocean's Temperature with Sound

Had global warming been as topical an issue in the 1960s as it is today, scientists likely would have attempted to use their measurements of acoustic travel times to derive changes in average temperature in the ocean. Working with different scientific agendas, they were interested instead in

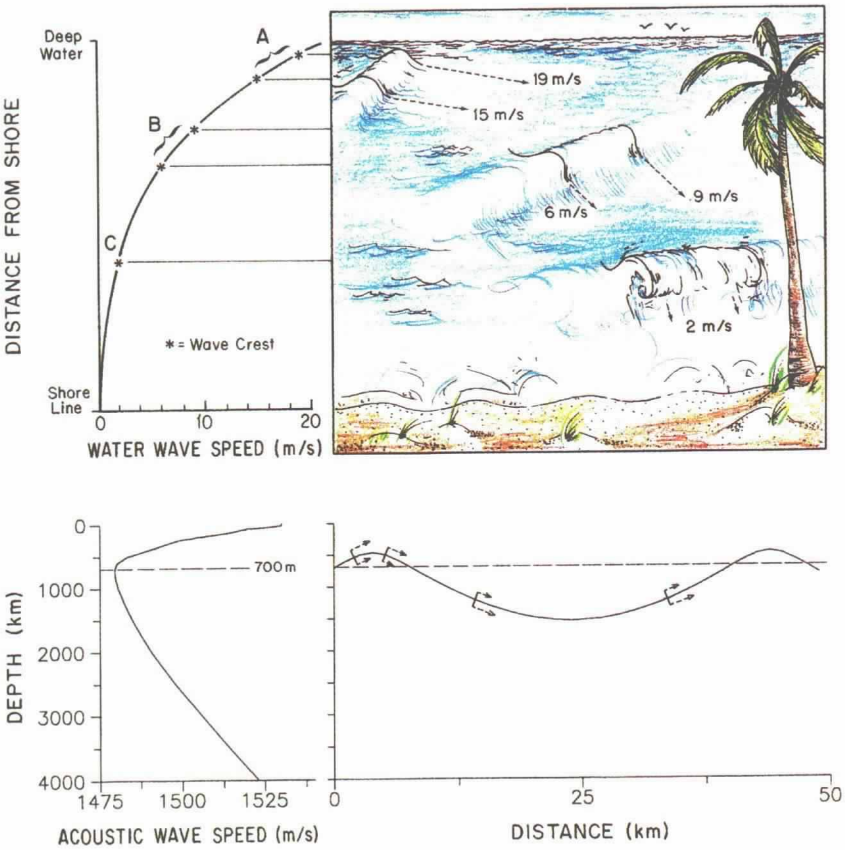

Fig. 4: Refractive principles applied to water waves and acoustic waves. ***Top:*** *Water waves break nearly parallel to beaches because of refraction. They travel faster in deep water (left). An offshore wave (A) starts to bend (refract) toward shore because the offshore part of its crest moves faster than its inshore part. As the wave bends toward the beach (B), the offshore part of the wave crest still moves faster than its inshore part until the wave bends nearly parallel to shore and breaks (C).* ***Bottom:*** *Acoustic waves bend away from regions where they travel faster. In the northeast Pacific the minimum speed of sound is at ~700 m depth (left). Unlike water waves, acoustic waves do not break because the acoustic wave speed does not go to zero. The acoustic waves keep turning back toward 700 m depth, the depth of minimum speed (right).*

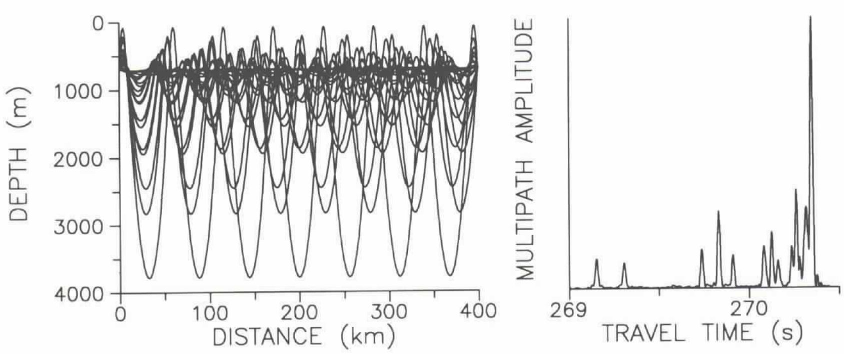

Fig. 5: ***Left:*** *The paths of acoustic waves emitted from an acoustic source at 700 m depth to an acoustic receiver at the same depth and at a distance of 400 km. Only paths that leave the source in an upgoing direction are shown. These paths are called multipaths.* ***Right:*** *The travel times of the multipaths. The steepest multipaths arrive first, and the flattest arrive last.*

using underwater sounds to measure the locations of underwater volcanoes and earthquakes (Johnson, 1969) and the locations of missiles that struck the sea surface (Hamilton, 1977). These localizations were accomplished by measuring the arrival time differences of sound at distant hydrophones. Accurate localizations depended on knowing the average sound speed. So Johnson and Hamilton calculated the average speed by measuring acoustic travel times over thousands of kilometers between explosive charges and underwater receivers.

In 1983, our scientific agenda was to measure the travel times of sound across the ocean for the next 50–100 years to detect changes in the spatially averaged temperature due to hypothetical changes in climate (Spiesberger *et al.,* 1983, 1992). We reasoned that if the average temperature increased, the average speed of sound would increase, and the travel time would decrease. To date, our data are not of sufficient length to discern any long-term change in the ocean's temperature. We have shown that changes in travel time are sensitive measures of changes in the spatially averaged temperature in sea water.

Earlier work had shown that acoustic multipaths scintillate because of aberrations introduced by internal waves. The probability of detecting acoustic multipaths increased significantly if many repeatable signals were transmitted during a day and suitably averaged at the receiver (Spiesberger *et al.,* 1980; Spindel and Spiesberger, 1981). Multipath scintillation may have been an important reason that early investigators measured the travel times of only the very last acoustic arrivals (Hamilton, 1977). It may have been difficult to generate repeatable signals from explosive charges.

Our first goal was to locate an acoustic source that could transmit repeatable acoustic signals. An unused source was sitting at 200 m depth on the ocean bottom five miles north of Kaneohe on Oahu. It was cabled to shore where the energy and timing of the signals were controlled. The pulses were ~0.06 s wide and were composed of frequencies near 133 Hz. The electronic source was as loud as the mating call from a male finback whale (*Balaenoptera physalus*), ~183 dB, and so was much quieter than the explosive charges used in the 1960s.

We listened to the signal 4,000 km away on a bottom-mounted receiver cabled to shore near northern California (Fig. 1, dashed line). The experiment started after a phone call was placed from our station in California to Roger Buecher at Kaneohe Bay, who turned on the source. The signal took ~40 min to go 4,000 km. We were able to detect the sound after averaging the signal and using pulse compression techniques. The first five multipaths arrived far enough apart from each other so that their travel times could be separately measured. The remaining multipaths arrived so

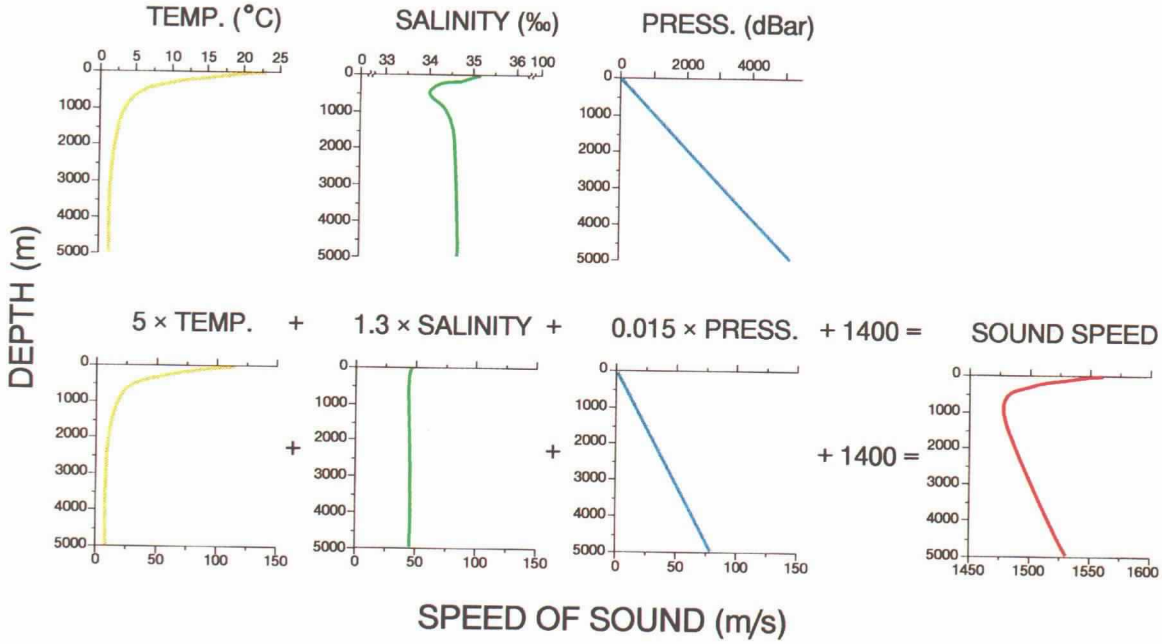

Fig. 6: Why does the speed of sound have a minimum near 1 kilometer depth? ***Top:*** *Vertical profiles of temperature, salinity, and pressure from summertime in the northeast Pacific (Levitus, 1982). A pressure of 1 dBar is ~1 meter depth.* ***Middle:*** *The equation gives an approximation for the speed of sound (m s^{-1}) as a function of temperature (°C), salinity (ppt), and pressure (dBar). Units are omitted from the coefficients in the equation for simplicity.* ***Bottom:*** *The top profiles are converted to sound speed. The speed of sound initially decreases away from surface because of cooling. The speed of sound increases in deep water because of the rise in pressure. Salinity variations are so small they have little influence on the shape of the speed of sound with depth.*

close to each other that their travel times could not be discerned (see cover).

Transmissions were made for one week in November–December 1983, for 5 months between November 1987 and May 1988, and for 5 months between February and June 1989. As changes in travel time were nearly identical for all five multipaths, we show only their average changes.

Travel times changed by up to 0.4 s over periods of many months (Fig. 2). Given that travel times were measured to a precision of ~0.03 s on a daily basis, the observed change was significant. Our research shows that temperature is the only variable that could account for the change in travel times (see box). Variations of pressure, currents, and salinity are so small that they only affect travel times by ~0.04 s. Therefore, we have an acoustic thermometer that is simple to read. If travel times decrease by 0.2 s, the average temperature rises by the equivalent of ~0.1°C in the upper kilometer. The error of the acoustic thermometer is only 0.02°C, as set by fluctuations of pressure, currents, and salinity.

Why did the average temperature change from year-to-year (Fig. 2)? Our experiment gives no evidence of any long-term change in temperature that could be ascribed to global warming. Temperatures were actually cooler in June 1989 than in December 1983, but this is probably coincidental given the large variability from year to year. A tantalizing but unproven hypothesis for the sudden rise of temperature between February and May 1988 is that the interior northeast Pacific started to warm ~14 months after the El Niño in November 1986 via oceanic teleconnections similar to those that occurred following the 1982 El Niño (Shriver *et al.*, 1991).

The error of the acoustic thermometer is only 0.02°C . . .

Mapping Change in the Ocean's Temperature with Depth

Up to this point, we have used acoustic travel times to recognize changes in the spatially averaged temperature of the ocean. The next step is to calculate temperature change as a function of depth. The diversity of multipaths is an asset, because each multipath samples ocean depths differently. If we can trace out the multipath (Fig. 5, middle) for each received pulse (Fig. 5, right), then, using the Munk and Wunsch (1979) tomographic technique, we can construct a vertical profile of temperature change from travel times. We have not estimated multipaths between Oahu and California, because the state of the art in acoustic computing is not ready to model the transition between the shallow source, at 200 m depth, to the deep sound channel with the steep volcanic slope in between.

However, using signals from another source moored at ~900 m depth, and well away from any bottom features (Worcester *et al.*, 1990), we have estimated multipaths over a 3,000-km section in the northeast Pacific (Fig. 1, thick solid line). The source transmitted pulse-like signals ~0.02 s wide near 250 Hz. A half hour after each transmission, the receiver picked up sixteen distinct pulses (Fig. 7, bottom).

The multipath followed by each of these 16 pulses could be estimated with wave bending principles. First, vertical profiles of temperature and salinity were obtained between the source and receiver by averaging historical measurements (Levitus, 1982). Second, each vertical profile of temperature and salinity was converted to a vertical profile of sound speed using the international standard algorithm (Fofonoff and Millard, 1984; Chen and Millero, 1977). The time required for each pulse to follow its multipath is called the reference travel time. Reference travel times are never equal to measured travel times, because the sound channels are built from historical measurements. But when reference travel times are close to those measured, as for our 3,000 km section (Fig. 7), one can make a one-to-one correspondence between the computed multipaths and the set of observed arrival times.

Determining the multipaths followed by the received pulses was a significant advance in the field of underwater acoustics. There was no physical law or previous experimental evidence that acoustic propagation could be so well understood after sound crossed a fluctuating ocean. Because multipaths could be estimated, it was possible for the first time to use tomographic techniques to map temperature over whole oceans in an economical manner.

One of the multipaths reflected from the surface ~60 times before reaching the receiver. The other multipaths never reached the surface but turned away at depths between 20 and 200 meters. This small difference in vertical sampling allowed us

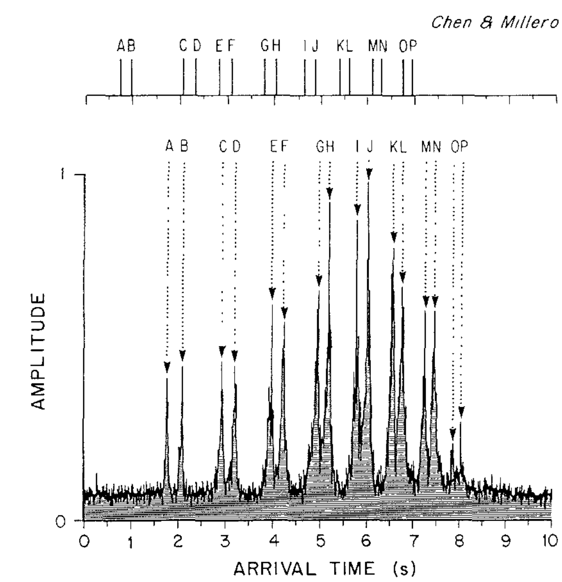

*Fig. 7: Comparison of the arrival times of acoustic multipaths on 10 September 1987 (**bottom**) with theory (**top**) along the 3,000-km section shown by the thick solid line in Fig. 1. Theoretical arrival times are computed from the international standard algorithm for the sound speed in seawater based on Chen and Millero (1977). All arrival times are compared with the same travel time (~30 min). (Adapted from Spiesberger and Metzger 1991b).*

Acoustic Thermometer?

What causes acoustic travel times to change by up to 0.4 s (Fig. 2)? This is a controversial issue among physical oceanographers. Some argue that the travel times might change because the acoustic multipaths (the numerous paths between the source and the receiver) change positions due to fluctuations in the ocean. This is unlikely. If any one multipath was sensitive to small changes in the ocean, it would be unlikely that its travel time would change by the same amount as another multipath. The fact is that all five multipaths change travel time by the same amount and at the same time. According to another argument, travel times might change because acoustic multipaths bend sideways away from the original transmission path. Sideways bending is caused by variations in currents and sound speeds perpendicular the acoustic section. Horizontal bending does occur, but the associated change in travel time is only 0.01 s (Spiesberger *et al.*, 1992).

We find that only temperature changes can account for the change in acoustic travel times. If the speed of sound changes by δc over a distance R, the travel time changes by, $\delta t = R/(c + \delta c) - R/c$, where the mean speed of sound is c (Munk and Wunsch, 1979). For $\delta t = 0.4$ s, R = 4,000 km, c = 1.5 km s^{-1}, we require that the speed change by -0.23 m s^{-1}. Using the relationships of temperature, salinity, and pressure to sound speed (Fig. 6), we find that a change of -0.23 m s^{-1} is equivalent to changes in temperature, salinity, and pressure of -0.045°C, -0.17 ppt, and 14 dBar, respectively.

Temperature changes little below a kilometer depth in the northeast Pacific. The fractional length of a multipath above a depth of one kilometer is ~0.2. So, if temperature decreases by ~0.045/0.2 (i.e., ~ -0.2°C) in the upper kilometer, travel times would increase by 0.4 s. The historical record contains abundant evidence that the upper kilometer changes by 0.2°C in the northeast Pacific.

Seasonal changes in average salinity are ~0.005 ppt or less below 100 m depth in the northeast Pacific (Levitus, 1982). This is 30 times less than required to give 0.4 s changes. A pressure change of 14 dBar implies sea level rises by 14 m. This did not happen. A change of 0.4 s could also be caused by sound going with or against a uniform current of 0.23 m s^{-1}. This is much larger than observed in the northeast Pacific. Effects from realistic currents in shallow and deep water amount to only ~0.03 s (Spiesberger *et al.*, 1992). A combination of all nontemperature effects could account for ~0.04 s. Changes in travel time exceeding ~0.04 s are thus due to changes in temperature.

to map the change in temperature in vertical layers near the surface. In both the upper 100 m and in the layer between 100 and 300 m depth, tomographic maps showed a significant increase of about 0.25°C and 0.06°C, respectively, from August to September (Fig. 3A). Conventional data sets that happened to be available were insufficient to detect any significant warming from month-to-month (Fig. 3B).

Sound Arrived 1 Second Late

A curious result of our study was that the 16 pulses arrived at our receiver ~1 second later than predicted after travelling 3,000 km distance (Fig. 7). Long thought to be a settled issue, this 1-second discrepancy called into question the validity of the international algorithm for the speed of sound in seawater (Fofonoff and Millard, 1984). The Pacific would have to be 1°C colder than we believed to delay the multipaths by 1 second. Because point measurements indicated this was not so, the only other conclusion was that the algorithm for the speed of sound was too fast (Spiesberger and Metzger, 1990, 1991b,c). The speed of sound is closely related to the compressibility of water; therefore, a question also exists regarding the accuracy of the equation of state of seawater, which contains a compressibility term. Worcester *et al.* (1991) and O. Diachok (personal communication) measured acoustic signals over 1,000 km and also found the international algorithm yielded sound speeds that were too fast.

One of the first estimates for the speed of sound in water was made in 1826 by Colladon (1893) in Lake Geneva. He measured the acoustic time of travel between two boats separated by ~16 km. Modern algorithms for the speed of sound in sea water are based on measurements of acoustic signals taken over a few inches in controlled laboratory environments (Del Grosso, 1974; Chen and Millero, 1977). The pendulum has now swung back to 1826, because the speed of sound is once again measured from the travel times of acoustic signals over long distances in water.

Future Possibilities

An international group recently transmitted sound from a source near Heard Island in the Indian Ocean to receivers located half-way around the world (Munk, 1989; Munk and Forbes, 1989). This was an exciting experiment because it confirmed that electronically generated sound could be detected at semi-global distances. However, according to the results presented to date, the multipaths were not repeatable from hour-to-hour over semi-global distances. This is necessary to develop a multi-year geophysical time series of acoustic travel time for temperature estimates (see session results in *J. Acoust. Soc. Am.*, 1991, Vol 90, No. 4, Pt. 2, 2328–2331 and 2346–2348). There are still many mysteries to resolve about ocean acoustics, including why these multipaths were not repeatable.

Monitoring the average temperature of an ocean basin is important, but not enough; to understand climate, we must map ocean temperatures at scales between eddies and basins. Many of the physical processes involving climate change occur at these intermediate scales (Gill, 1982). However, the ocean's interior is rarely measured at intermediate scales because the task has proved technically difficult. The Ocean-Climate Acoustic Thermometry (OCAT) group is developing new technology capable of real-time acoustic mapping at intermediate scales in the global ocean. Instead of cabling acoustic sources to shore, we propose to attach sources to subsurface moorings deployed and maintained by research vessels. The system's receivers, which are drifters with surface floats, are designed to move quickly. They are propelled through the ocean by eddies and wind, thus providing many more tomographic sections than stationary receivers. Data from these receivers can be telemetered to shore by satellite. This new system offers a way of acquiring an unprecedented data set (orders of magnitude more tomographic data than present systems). With this amount of data we may begin to achieve the resolution needed to understand climate change. We estimate that the system will provide six to nine times the resolution possible with monitoring systems that use sources and receivers cabled to shore (Spiesberger, 1992).

. . . orders of magnitude more tomographic data . . . [are] needed to understand climate change.

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