On Monitoring Depth Variations of the Main Thermocline Acoustically

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It is shown that depth variations over weeks and months of the main thermocline may be resolved effectively by means of an inverted echo sounder that measures precisely the time for an acoustic signal to travel from the sea bottom to the surface and back. Calculations with hydrographic data show that depth changes as small as 10 meters may be resolved. Preliminary experiments off Bermuda show that apart from a variation due to the surface and internal semidiurnal tides, the travel time is stable for more than a week, which is consistent with the observation that the thermocline depth does not change substantially on this short a time scale.

INTRODUCTION

This is a preliminary report on the possible use of inverted echo sounders on the ocean bottom to record variations in the thermal structure of subtropical oceans, specifically the depth of the main thermocline, which separates the warm surface water from the deep cold water. The principle is based on the simple fact that the speed of sound in water is a function of temperature in addition to pressure and salinity. Thus, if one has a sound source on the ocean bottom and carefully measures the travel time for a signal transmitted to the surface and reflected back, one should expect the travel time to depend on the ratio of warm to cold water, i.e. the depth of the thermocline.

Should this hypothesis of remotely sensing the thermocline depth prove to be valid, then a number of applications suggest themselves. An array of echo sounders could examine the nature and extent of coupling of vertical perturbations of the thermocline at different locations in the Sargasso Sea. Suitably located echo sounders along (and across) the mean path of the Gulf Stream, which is a region in which the thermocline changes depth rapidly, could continuously monitor the position of the stream as well as the growth and propagation of meanders. Such information could, of course, be obtained with vertical arrays of temperature sensors. This acoustical method may, however, prove to be more satisfactory in applications for which reliability over extended periods of time is mandatory.

The following section uses hydrographic data from the Sargasso Sea (Bermuda) and the Gulf Stream area to illustrate the high correlation one may expect between the depth of the thermocline and the travel time of a signal. A preliminary experiment of in situ travel-time measurements during an 8-day period off Bermuda is reported. It demonstrates that the travel time can be measured unambiguously and will remain stable at least during low sea states.

TRAVEL-TIME ESTIMATES FROM HYDROGRAPHIC DATA

Existing hydrographic data are used to examine the correlation between the depth of the thermocline and the vertical travel time for an acoustic signal. The vertical travel time is obtained by first calculating the sound velocity profile from the depth, temperature, and salinity data by the use of *Wilson*'s [1960] formula and then calculating the integral

$$\tau = 2 \int_0^H \frac{dZ}{C(Z)} \tag{1}$$

where the factor 2 is for the round trip travel time. The depth of the main thermocline is defined as the depth of a certain isotherm. One simplification is introduced in that, when the sound velocity profile is calculated, the variable warm surface waters are ignored so that they cannot alias the travel-time estimates. This is arranged by setting all temperatures greater than 18°C to this value when calculating the profile for the sound velocity. This simplification is not serious partly because, as will be shown, its effect on the travel time is limited and partly because in a real experiment one could use synoptic bathythermometric information to correct for the seasonal thermocline variations.

Data from two different regions are used in these calculations. One set of data is the 'Panulirus' hydrographic stations, which are a continuing series of stations taken 30 miles SSE of Bermuda by the R.V. *Panulirus* of the Bermuda biological station. The second set, which represents the Gulf Stream region, was obtained during the Gulf Stream '60 survey [*Fuglister*, 1963].

Panulirus data. The Panulirus stations have been taken roughly every 2 weeks since 1954. This set of data is used to calculate the travel time as well as the depth at which $T = 10°C$, Z_{10}. The round-trip travel time is given by

$$\tau = 2 \sum_{i=1}^{N} \frac{(Z_{i+1} - Z_i)}{\frac{1}{2}(C_{i+1} + C_i)} \qquad (2)$$

where $Z_1 = 0$ and $Z_{N+1} = 2000$ meters.

Variations in τ were tested against variations in Z_{10} by a least-squares fit of the function

$$\tau = a + bZ_{10} \qquad (3)$$

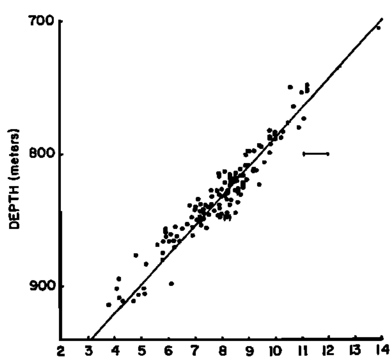

Fig. 1. The depth of the 10°C isotherm is plotted against the round-trip travel time in milliseconds (relative to 2.650 seconds after transmission) for each Panulirus hydrographic station (158 were used). The straight line is the least-squares fit according to equation 3 and has a slope equal to −22.2 m/msec. The horizontal bar measures the standard deviation ×2.

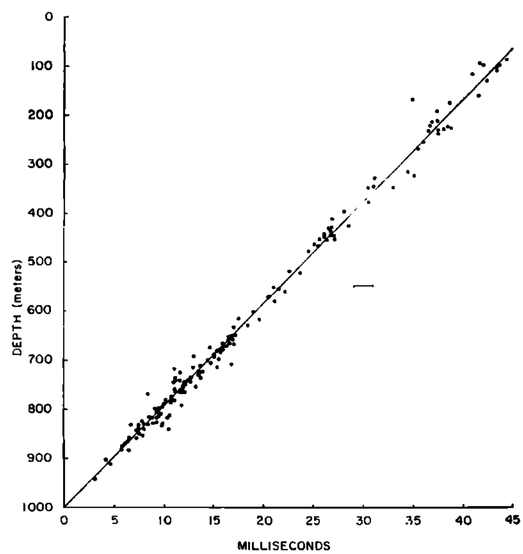

Fig. 2. The depth of the 12°C isotherm is plotted against the round-trip travel time in milliseconds (relative to 5.290 seconds after transmission) for each Gulf Stream '60 hydrographic station (~150 stations were used). The straight line is the least-squares fit and has a slope equal to −20.9 m/msec. The horizontal bar measures the standard deviation ×2.

and by computing the resulting standard deviation. Figure 1 shows the depths plotted against the corresponding travel times and the linear least-squares fit is also shown. The maximum variation in depth is 200 meters, although most observations fall within a 100-meter interval. When compared with this variation, a standard deviation of 0.45 msec, which is equivalent to ±10 meters, seems reasonably small. If the seasonal thermocline is included in the travel-time calculation, the standard deviation increases to 0.61 msec, which corresponds to ±13 meters. The reason that the resolution is not worse in this case must lie in the fact that, although the seasonal thermocline is extremely variable, it cannot move in the vertical. In addition, the warm surface waters in the summer are quite shallow so that their contribution to the travel-time integral is limited.

Gulf Stream data. The Gulf Stream '60 data [*Fuglister*, 1963] were taken during a 10-week period in the spring of 1960 by the R.V. *Chain*, R.V. *Crawford*, R.V. *Atlantis*, and the U.S.C.G.C. *Evergreen*. The calculations with these data are essentially the same as with the

Panulirus data, except that the integral (equation 2) is calculated to 4000 meters. The stations at which there is no water warmer than 12°C, which is assumed to represent the main thermocline, are not included in these calculations. All temperatures greater than 18°C are set to 18°C. Stations with missing salinities are ignored. The resulting standard deviation is 0.99 msec, which corresponds to ±21 meters. Figure 2 shows the data for this case with the linear least-squares fit as well. When compared with the total depth range for Z_{12}, it is clear that ±21 meters is very small, particularly when it is remembered that the stations used in these calculations extend from 33°N to 43°N and from 55°W to 67°W. It is interesting to note that, since the main thermocline changes depth by nearly 700 meters in 50 km across the Gulf Stream, one should be able to detect lateral changes in position of less than 2 km.

Preliminary Experiments

The analysis of the hydrographic stations suggests that there is an excellent correlation between the depth of the thermocline and the travel time. It must, however, still be shown that this correlation is experimentally realizable and is not aliased by other factors, which have not been appreciated in the preceding analysis. Experimentally, one would place the sound source on the ocean bottom and have it receive its own transmission after reflection at the sea surface. The distance will be nearly constant, but even a 1-meter tide will alter the travel time 1.3 msec since the speed of sound is ~1500 m/sec. This effect is not serious if the information sought is well below the tidal frequency, since it can be filtered.

We have been able to conduct a study of the stability of the travel time for only a short period of time. This was done in September 1968 off Bermuda with an underwater sound source that could be operated from a shore laboratory either as a transmitter or as a receiver. The transducer was run for 8 days with the travel time measured and recorded photographically. The experiment consisted of a precise timing circuit, which provided 2-msec-long cw pulses at 2 kHz. As soon as each pulse was transmitted, the transducer was switched to receive. A separate countdown circuit initiated a 10-msec oscilloscope sweep at such a time that the received signal appeared in the center of the field intensity modulated. A camera with slowly moving film recorded each event. The 8 successive days of data are shown from noon to noon in Figure 3, in which the tide at St. George's West, Bermuda, is also shown.

The tidal travel-time variation is about 2 msec, which would correspond to a 1.5-meter tide. This value is 60% larger than the tide observed on Bermuda. The discrepancy could be due to the difference in location, since the transducer is in 2500-meter-deep water 9 miles south of the island. It is more likely, particularly in view of the 1- to 2-hour time difference between the two, that the discrepancy is due to an internal tide. If indeed this is the case, then, assuming that the surface tides at sea and on the island are coincident, one can show that the internal tide should have an amplitude of 30 meters and a phase in advance of the surface tide of ~3 hours, which is not unreasonable. For example, the recordings by *Haurwitz et al.* [1959] show, on several occasions, tidal fluctuations of 0.5°C, which at 500-meter depth (where these observations were made) would correspond to a 50-meter internal tide.

Except for the first 2 days, the average time of arrival for each day remains nearly constant, being only slightly later toward the end of the record, which suggests that the thermocline is rising somewhat. Although this interpretation cannot be compared directly with hydrographic data, it at least is consistent with the observation (from the Panulirus data) that the thermocline does not move vertically from one week to another more than perhaps 20–30 meters, although exceptions are known in the vicinity of Bermuda. The earlier arrivals for the first 2 days are due to a lower threshold setting in the intensity display of the oscilloscope, which means the weaker, earlier arrivals are also displayed. These earlier arrivals are due to the finite rise time of the transmitted pulse and the temporal dispersion of the reflected pulse.

Throughout this experiment the sea was nearly calm. The winds were usually 5–15 knots and the wave height was 1–2 meters, corresponding to sea states ≤3. There is no observable deterioration of the quality of the reflected signals or change in time of arrival that could be attributed to the higher sea states. It is not clear whether this form of measurement

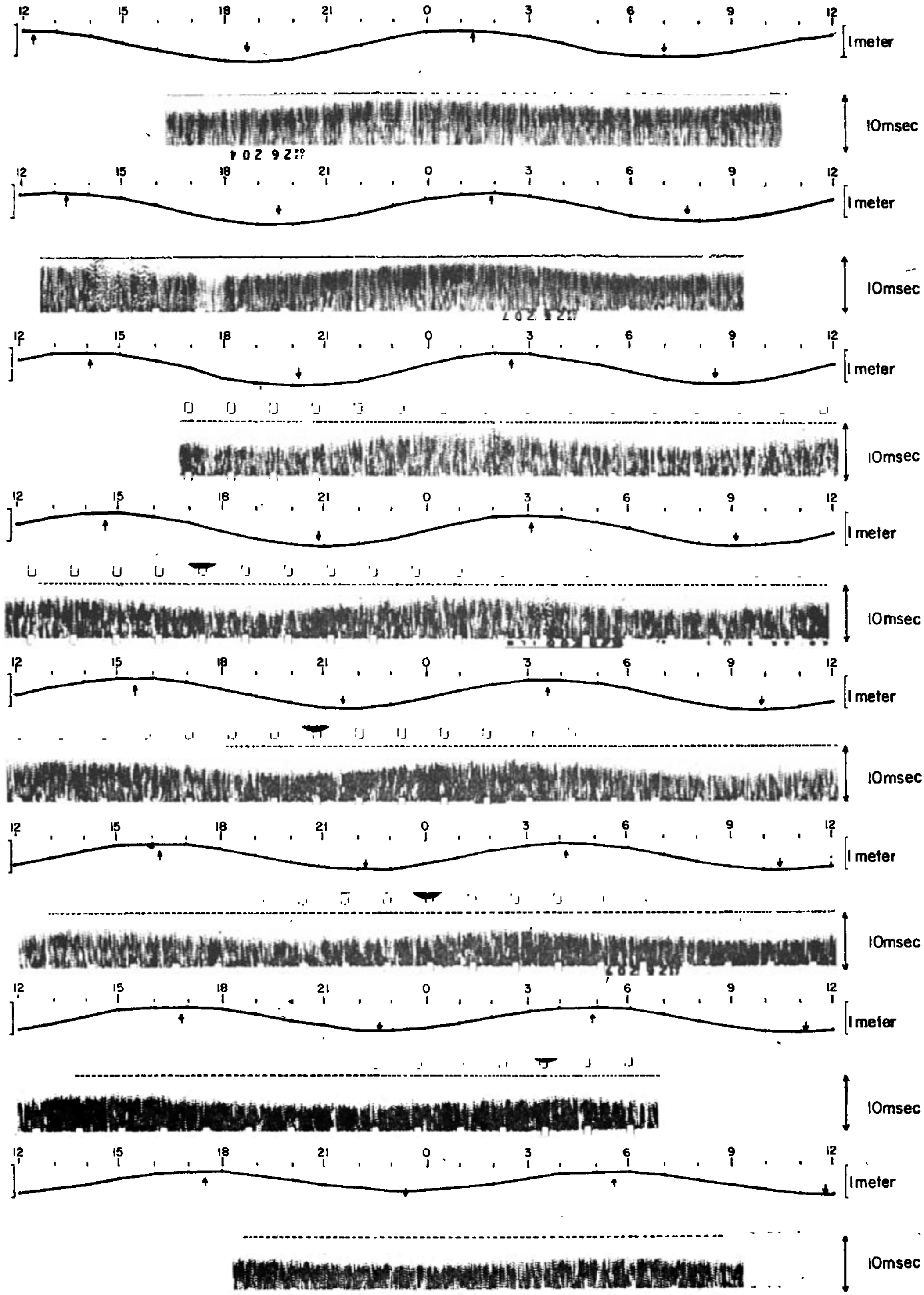

Fig. 3. Eight-day recording from noon to noon of the travel-time variations. The upper edges of the dark bands define the arrival of the transmitted signal after reflection at the surface. The vertical scale is indicated by the 10-msec arrow to the right. The dashed line represents 3.200 seconds after transmission. The surface tide in meters at St. George's West, Bermuda, is also plotted. Low tide and decreasing travel time are plotted upward. The small vertical arrows indicate the time of extreme tide. See text for discussion.

can be extended to any arbitrary sea state with a retention of its intended meaning. Exactly what happens at high sea states is now being studied.

We believe this preliminary experiment shows that the travel time is stable and is not aliased over extended periods of time, provided that the sea state is not too high. We have been so encouraged by this preliminary study that we have started a program to further evaluate directly the correlation between the travel time and the thermocline depth.

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