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MEASUREMENTS OF THERMAL STRUCTURE OFF SOUTHERN CALIFORNIA WITH THE NEL THERMISTOR CHAIN

E. C. LaFond and A. T. Moore

U.S. NAVY ELECTRONICS LABORATORY, SAN DIEGO, CALIFORNIA

A BUREAU OF SHIPS LABORATORY

THE PROBLEM

Investigate oceanographic factors pertinent to the behaviour of underwater sound and to surface and subsurface navigation. Specifically, study the thermal structure of the upper sea layers by use of the towed thermistor chain.

RESULTS

1. The average slopes, autocorrelation, and power spectra of the isotherms obtained with the NEL thermistor chain on the different "legs" of a deep-water cruise show that many internal waves are of very long period. The spectra appear to be continuous at very low frequencies and to possess minor peaks at higher frequencies (1/20 to 1/3 cycle per minute).

2. These studies further indicate a probable shoreward movement of the dominant internal waves.

3. The records of circular tows with the chain establish that the thermal structure is complex. Although the circular paths followed were too small to clearly demonstrate significant motion in any particular direction, the data obtained do reveal that wave crests and troughs of a generally similar type were crossed in all directions of tow.

RECOMMENDATIONS

1. Continue development of the thermistor chain to improve the quality, accuracy, and reliability of the data.

2. Make detailed studies of the thermocline and its associated internal waves by use of the chain. Include studies of the effects on the thermocline of islands, shoals, coastal configurations,

tides, currents, upwelling, river runoff, water mass boundaries, storms, and seasons. Particularly, acquire more data on the direction and speed of internal waves.

3. Procure electronic equipment to provide digital tape records of temperature-depth or isotherm-depth data and still retain the present analog recording system. Use the digital tape with available large-scale computers for detailed statistical analyses of the isotherm data where applicable.

ADMINISTRATIVE INFORMATION

Work was performed under S-R004 03 01, Task 0580 (NEL L4-4) (previously listed as Task 0539 (NEL L4-1)) by members of the Marine Environment Division. This report covers the period 1 July 1961 to June 1962. It was approved for publication 28 August 1962. The authors wish to express appreciation to O. S. Lee who led the cruise on which the data for this report were collected and to G. H. Curl and E. E. Gossard for reviewing this report.

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INTRODUCTION

The U. S. Navy Electronics Laboratory thermistor chain was obtained in 1961.[1] (See list of references at end of report.) With the new thermistor chain it has become possible to measure vertical sections of the temperature structure from the surface down to 800 feet. USS MARYSVILLE (EPCE(R) 857), from which the chain is operated, is capable of steaming anywhere in the oceans (fig. 1).

The first cruise with the thermistor chain was made in June 1961 in order to test the equipment over the nearby San Diego Trough. The results of this cruise have already been reported.[2]

The second cruise, the subject of the present report, was made between 10 and 14 July 1961 off Southern California. The purpose was to investigate the nature of internal waves in the deep ocean regions. The ship's course was three-directional, consisting of a run of about 12 hours directly offshore, another of 12 hours parallel to shore, and a third of 12 hours directly toward shore (fig. 2). In addition to this course, four circles of 2-mile diameter and two of 6-mile diameter were traversed in an attempt to determine the direction of internal-wave propagation from the doppler effect created through changing the direction of tow.

EQUIPMENT

The oceanographic chain hoist,[1,3] the thermistor chain, and the drum on which the chain is wound are large and rugged, weighing 37,500 pounds. The chain is composed of flat links about 1 foot long, 10 inches wide, and 1 inch thick. At the end of the chain is a 2300-pound streamlined weight, called a "fish," to hold it down.

About 100 pairs of insulated electrical leads fit through grooves inside the flat links. Every 27 feet the electrical wires connect with the temperature sensors, or thermistor beads.

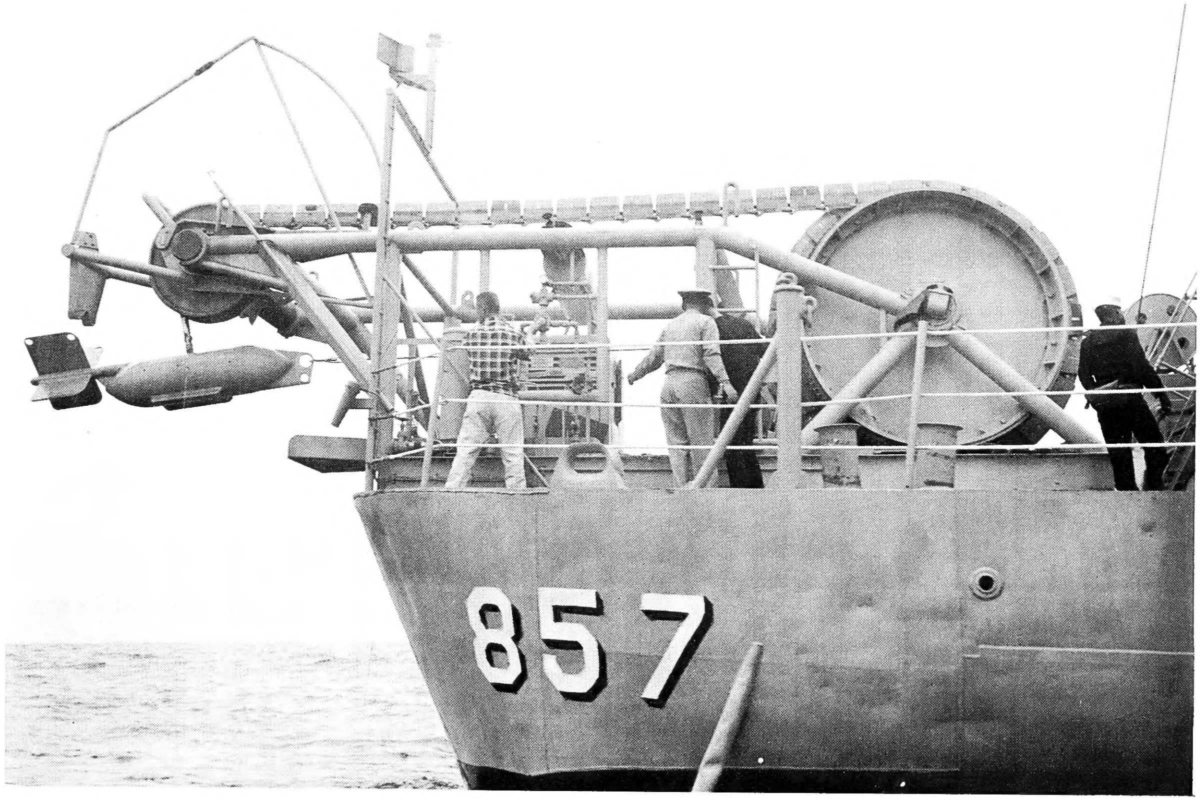


Figure 1. Thermistor chain hoist on USS MARYSVILLE.

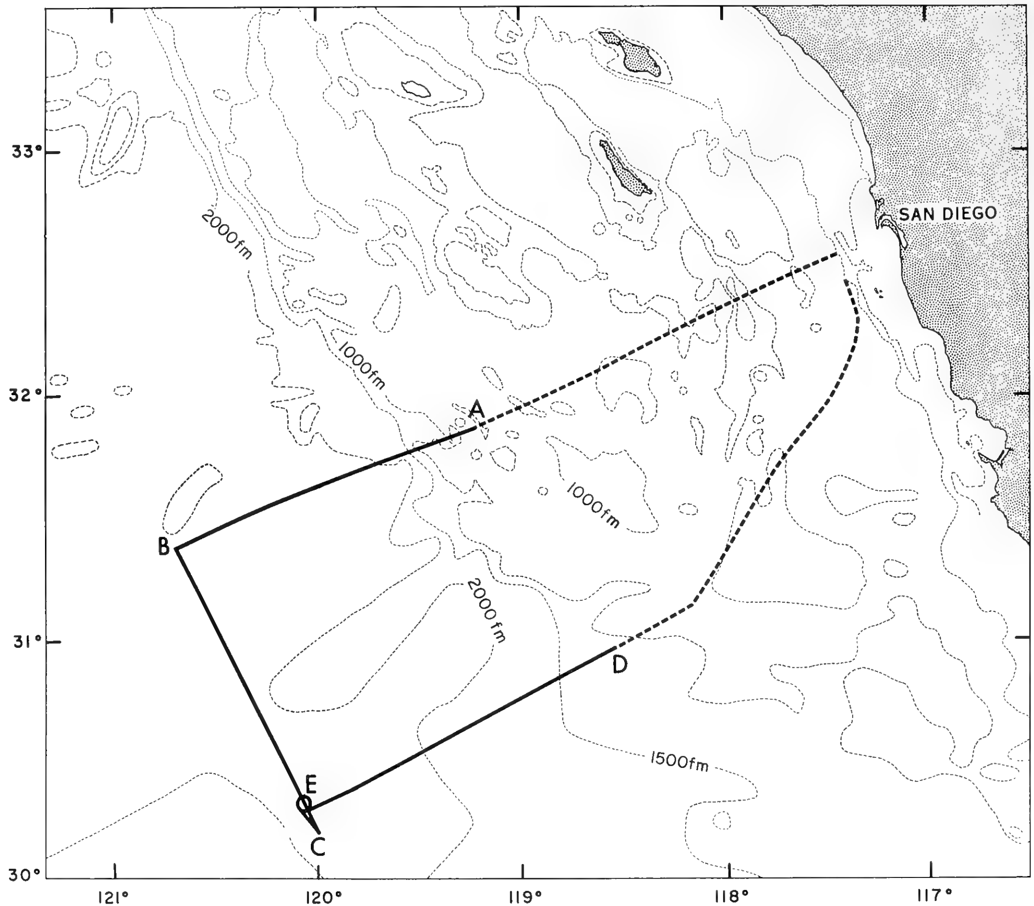


Figure 2. Track of USS MARYSVILLE on cruise 2.

The upper ends of the electrical leads connect with a recorder located in the ship's laboratory. Signals from the beads are scanned electronically every 10 to 12 seconds, and lines showing the depths of isotherms are printed on 19-inch-wide tape. This procedure is equivalent to lowering a bathythermograph every 100 to 120 feet at a ship's speed of 6 knots. Also printed on the same tape are the depth of the fish at the end of the chain, which is the maximum depth of observation, and the temperature of the sea surface.

With the new thermistor chain it is possible to lower a string of temperature sensors into the water and then cruise ahead with the string vertically suspended from the fantail. Since elements are sensing from the surface down to about 800 feet while the ship is moving through the water horizontally, two dimensions of coverage, depth and distance, are achieved.

OBSERVATIONS AND DATA

Offshore Section

On 11 July 1961 USS MARYSVILLE towed the chain from near San Diego in a southwesterly direction (247°). Some of the temperature data collected on this line from point A on figure 2, 31°52'N, 119°13'W (0500 on 11 July), to the end of this leg of the cruise, point B, 31°22'N, 120°41'W (1830 on 11 July), are presented in figure 3. The incompleteness of the shallow part of the record is due to malfunction of some of the shallow thermal sensors. However, the 9°C isotherm was correctly recorded for the whole of this traverse. In the figure, the vertical temperature record between 250 and 550 feet is divided into three connecting parts (WX, XY, and YZ). The nearshore point is W (corresponding to A in fig. 2) and the farthest offshore point is Z (corresponding to B in fig. 2). The horizontal scale may be considered as either time or distance, and these scales are marked between the sections.

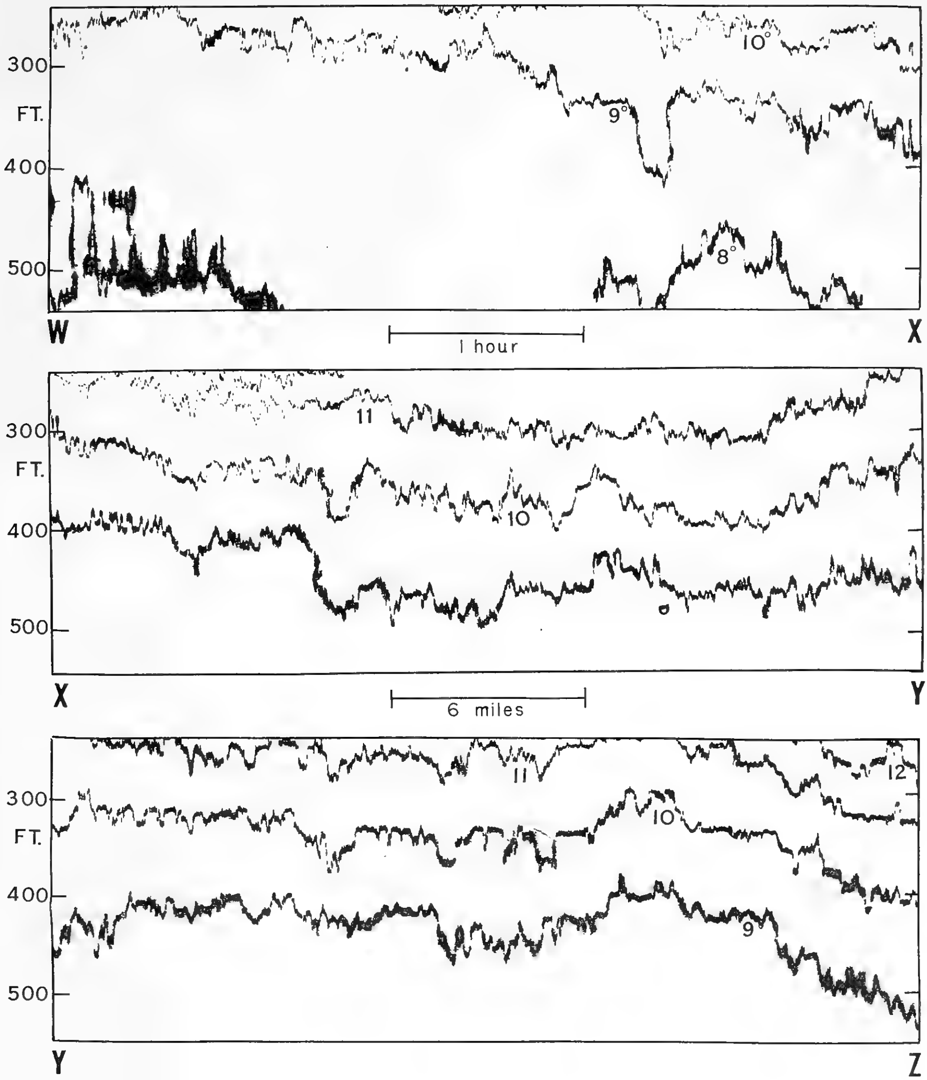


Figure 3. Isotherm data from leg one of cruise 2 (250-550 feet).

Because of the rapid scanning rate, the isotherms are nearly continuous. The part of this record nearest shore (WX) contains the 8°, 9°, and 10°C isotherms and shows the descending or deepening trend of the isotherms in an offshore direction. The other two parts (XY and YZ) also contain three to four isotherms. These isotherms dip to the right.

It is apparent that none of the isotherms is horizontal, and that they fluctuate up and down in a short distance or interval of time. The thermocline or thermal structure, in general, is rough. The detail shown in figure 3 cannot be obtained by bathythermograph lowerings or with other instruments.

Alongshore Section

From point B, 31°22'N, 120°41'W, the chain was towed in a southeasterly direction (154°) parallel to the continental shelf. This traverse started at 1830 on 11 July and ended at 0700 on 12 July at point C, 30°10'N, 120°00'W. Some of the temperature data collected on this leg are presented in figures 4 and 5. In both figures the record is broken into three connecting parts, as in figure 3, with WX the farthest north and YZ the most southerly.

Figure 4 covers the depth range from 100 to 300 feet with isotherms from 12° to 17°C, and includes the main thermocline. The isotherms are more nearly horizontal than for the offshore leg, and the surface becomes warmer in the more southerly sections. Figure 5 covers the depth range 400 to 600 feet, where only the 9° and 10°C isotherms were found. In both figures it is again evident that the depths of isotherms change over short distances.

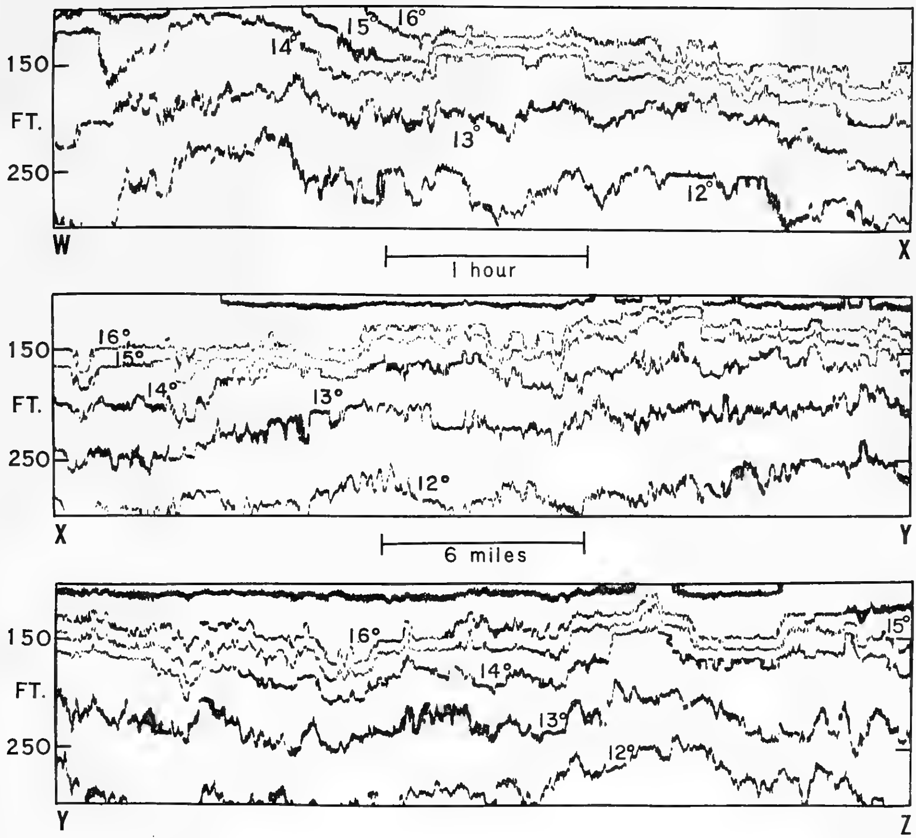


Figure 4. Isotherm data from leg two of cruise 2 (100–300 feet).

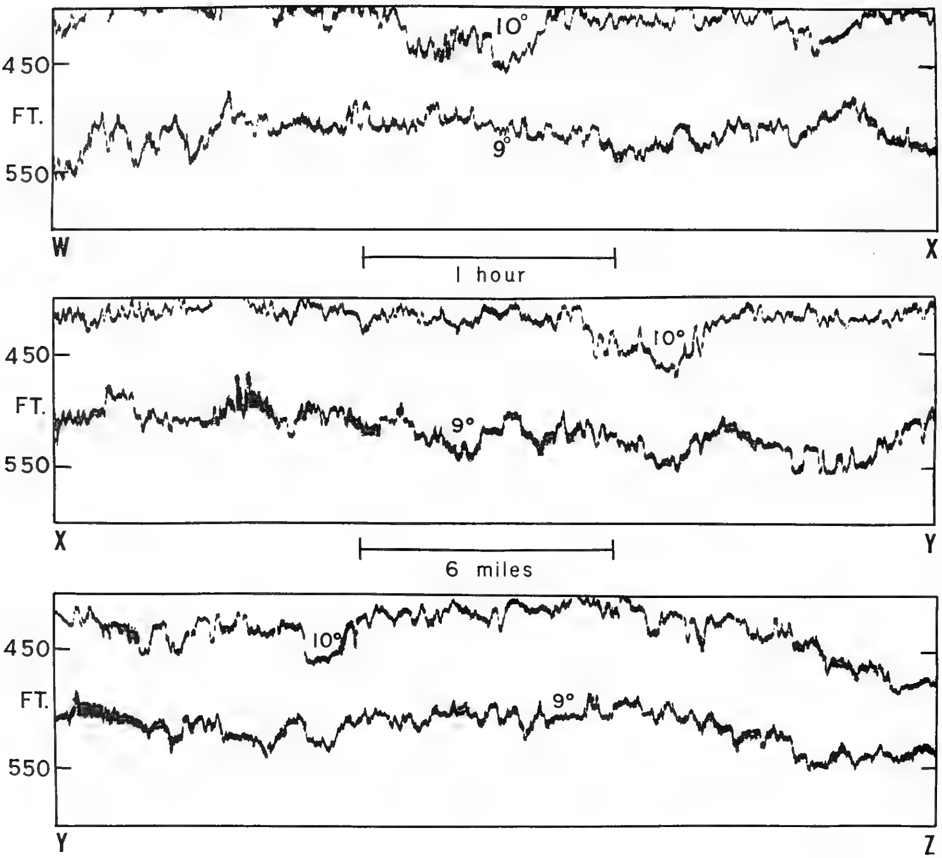


Figure 5. Isotherm data from leg two of cruise 2 (400-600 feet).

Onshore Section

The temperature records for the shoreward tow from 1900 on 12 July to 0730 on 13 July are similarly presented in figures 6 and 7. This leg of the cruise started at point C, 30°15'N, 120°01'W, and ended at point D, 30°58'N, 118°31'W. Isotherms 12° to 16°C are present in the 100-to-300 foot record, which is also broken up into three connecting parts. The apparent temperature inversion in the 14°C isotherm that results in closed isotherms around 200 feet in the XY and YZ sections appeared to be caused by malfunction of a thermistor. In the deeper section, running from 450 to 650 feet, the 9° and sometimes the 10°C isotherms are present.

Isotherms and Internal Waves

The nature of the vertical changes in the isotherms in deep water has not been investigated in such detail before. Likewise, the cause of vertical oscillations has not been established. It is possible, but not likely, that these changes in temperature are balanced by changes in salinity, and thus that the density surfaces are level. Another possibility is that the vertical temperature changes are merely the result of standing waves in the thermocline. Eckart,[4] referring to Väisälä,[5] points out that a given density boundary may have its own normal oscillating frequency, the Väisälä frequency. Still another possibility is that strong winds may create convection cells in the upper layers of the sea, the circulation of which causes the thermocline to be lowered more in one area than another. There is, however, reason to believe that the vertical variations observed with distance in the isotherms are caused by internal waves moving in one or more directions. Evidence to support the latter explanation lies in the fact that, at all anchor stations where repeated measurements have been made, the isotherms show vertical fluctuations with reference to time. The progressive nature of these oscillations in shallow water has been proved by results obtained off anchored ships and at the NEL Oceanographic Research Tower.[6] In this report, therefore, the oscillations are assumed to move as progressive internal waves.

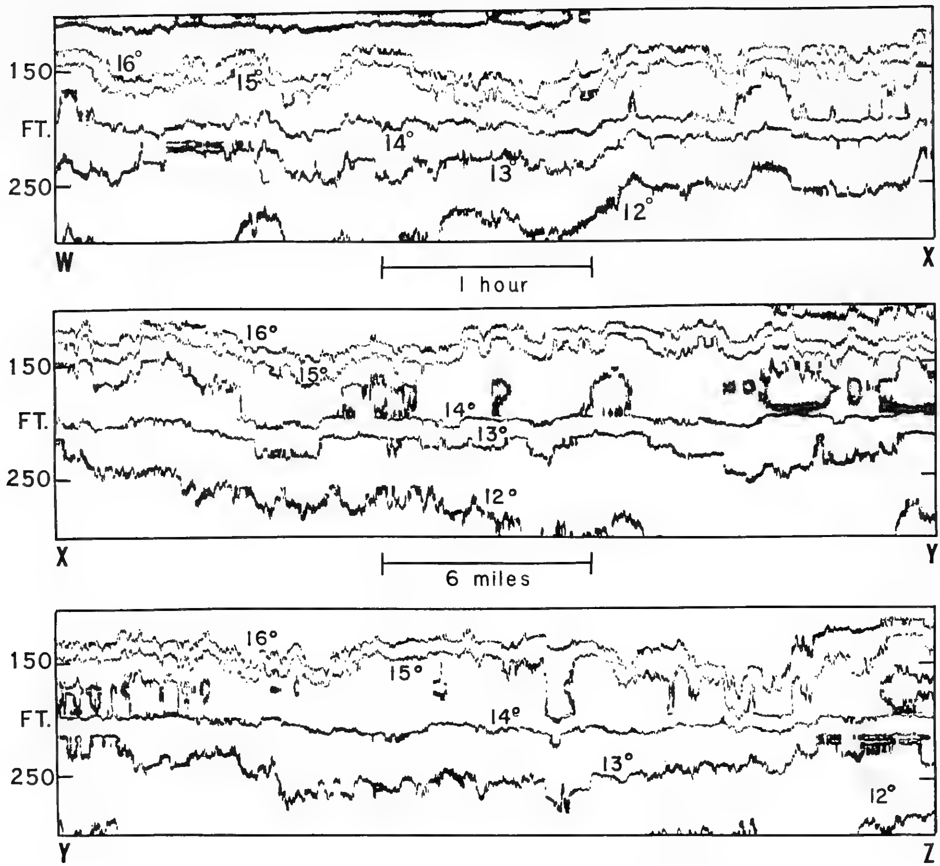


Figure 6. Isotherm data from leg three of cruise 2 (100-300 feet).

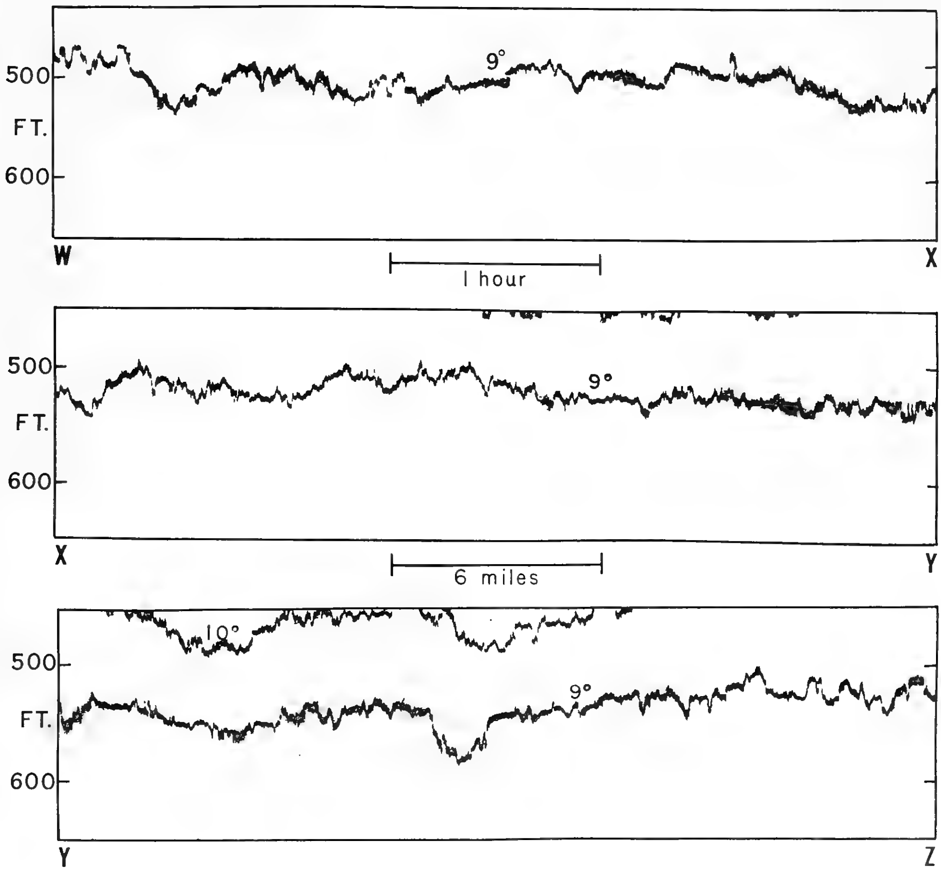


Figure 7. Isotherm data from leg three of cruise 2 (450 and 650 feet).

The detailed recording of isotherm depths indicates the complicated character of the thermal structure of the seas. It also emphasizes that the ocean is probably a complex body, not only as regards temperature, but also as regards chemical, biological, and other aspects.

ISOTHERM DEPTH VARIABILITY

Changes in sea temperature at the surface and at various depths may be attributed to any of several factors, among which are the advection of water of different temperature into an area, radiation from the sun, mixing by the wind, tidal currents, internal waves, and others.[7] Since all the factors simultaneously exert influence, it is difficult to sort out their individual effects. It is equally difficult to adequately describe the structure and variability of the sea temperature.

Several investigators have made studies of the variability of surface and internal temperatures.[8, 9, 10, 11] Others have developed methods for the statistical analysis of physical properties applicable to sea temperature variability.[12, 13, 14, 15, 16] In this report three approaches to the study of isotherm depth variability are used: (1) differences in depth values; (2) autocorrelation of depth values; and (3) power spectrum of depth values.

Differences in Depth Values

The depths of isotherms were scaled from the original record (figs. 3 - 7) at half-minute intervals. The isotherms chosen were 9°C for all legs, 14°C for the alongshore leg, and 16°C for the onshore leg. The depth differences from point to point along the isotherms were determined from the formula

$$X_i - X_{i+1} = Y_k$$

where

$$1 \leq k \leq N$$

The quantities X_i and X_{i+1} are depths (feet) of a given isotherm at the beginning and end of the i^{th} distance (or time interval) along the track, Y_k is the depth difference (feet), and N is the total number of readings in a given series. When the isotherm becomes deeper with distance run, the difference is negative.

From the speed of the ship and depth differences, approximate slopes can be obtained. At a speed of 6 knots, the ship traveled 304 feet in each half-minute interval; therefore, dividing the depth differences by 304 feet gives the slope of the isothermal surface in the direction of the ship's motion. This slope can also be expressed by the angle of which the slope is the tangent. However, it must be pointed out that the slopes measured by this method are influenced by the wave motion, that is, the vertical change of isotherm depth caused by wave motion that takes place in half a minute. Thus, exact slopes cannot be acquired; however, this method yields the best approximation yet obtained of the slopes of isothermal surfaces in the deep ocean.

At least 1500 observations of isotherm depth were made on each leg of the cruise. The frequency distributions of depth changes and slopes for each selected isotherm on each leg of the cruise are shown in figures 8, 9, and 10. Half-minute depth changes as great as plus or minus 30 feet were observed in the 9°C isotherm on the offshore run (fig. 8), corresponding to an angle of 5°38'. Twenty-six per cent of adjacent half-minute readings showed depth changes less than 1 foot. However, 50 per cent of the slopes observed on this leg were less than 25 minutes from the horizontal, as indicated by the vertical lines in the figure.

On the alongshore leg (figs. 9A and 9B) nearly all half-minute depth changes were less than 15 feet. For the 14°C isotherm, 50 per cent of the depth changes in 304 feet were less than 1.2 feet, corresponding to a slope of 14 minutes from the horizontal. The 9°C isotherm had a somewhat broader distribution of slopes, but the distribution was narrower than for the same isotherm on the offshore leg. Here 50 per cent of the slopes fell within 21 minutes (fig. 9B).

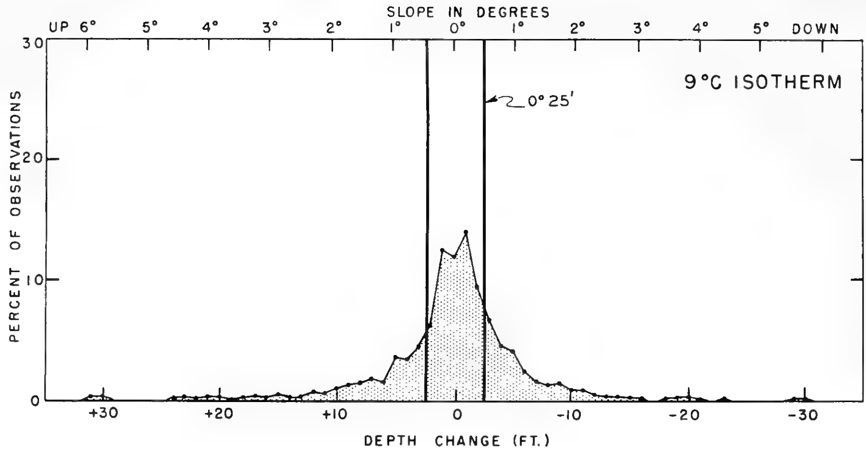
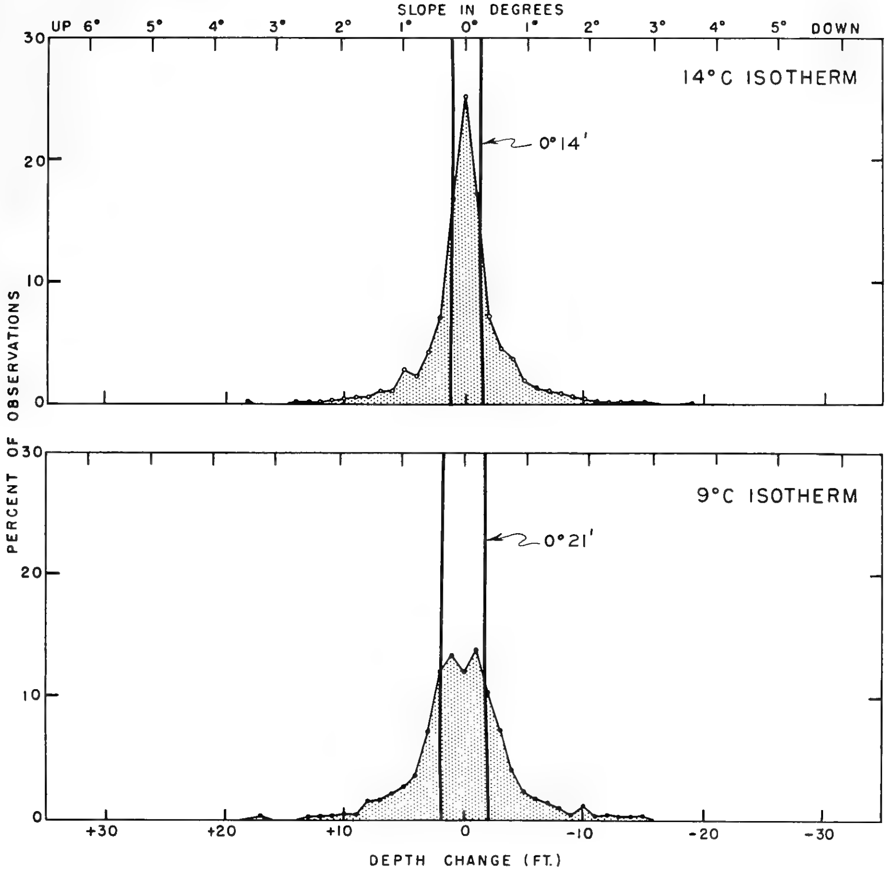


Figure 8. Frequency distribution of differences in depth between half-minute or 304 ft spaced readings of 9 °C isotherm, leg one, cruise 2.

The vertical depth and slope changes of the two chosen isotherms on the shoreward leg are shown in figure 10. The frequency distribution for the 16 °C isotherm is sharply peaked and narrower than for any other record. The 9 °C isotherm also has a narrower slope distribution than in the two previous directions of tow, with 50 per cent of observations falling within 15 minutes.

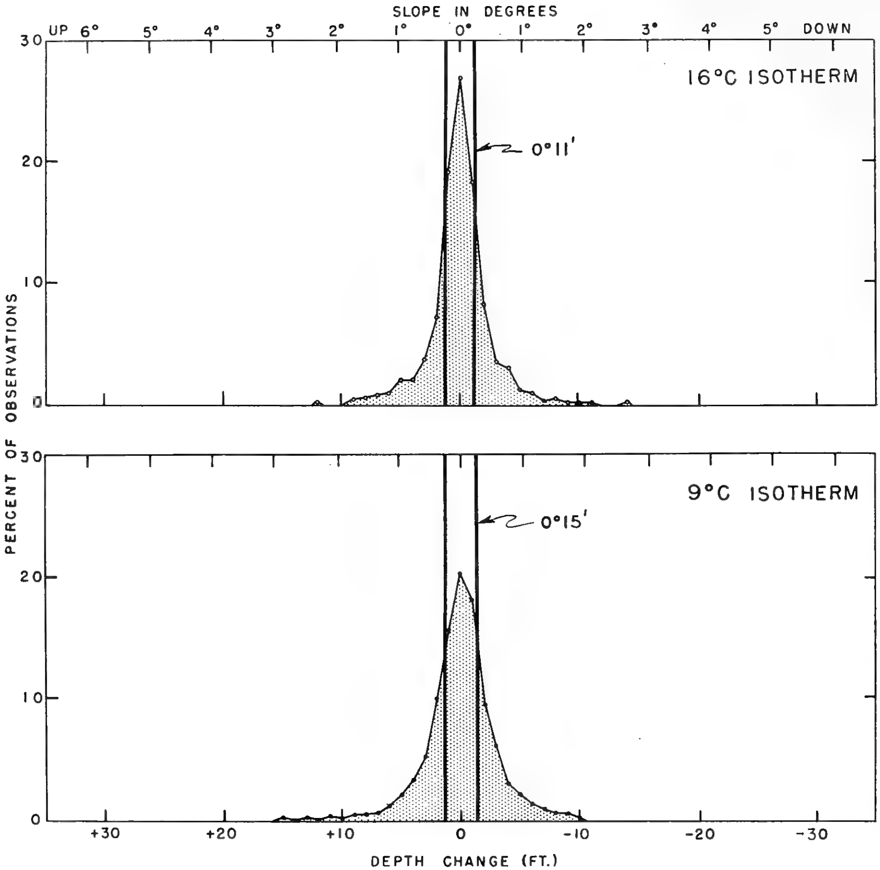
The distribution of isothermal slopes may be useful in determining the propagation direction of the dominant internal waves. When the ship is running counter to the waves the slopes should be steeper, and when the waves are running in other directions the slopes should be less. The diagrams show that the slopes were more gentle on the last two legs of the cruise (figs. 9B and 10B) than on the first leg, for similar isotherms (9 °C). Thus, it may be inferred that the waves were moving more in the shoreward direction than the other two directions sampled (see later discussion under Direction of Propagation). However, it must again be pointed out that not all the isotherm depth readings were simultaneous. The depths are actually depths of encounter and thus these slopes may not necessarily be the true ones.



(A)

(B)

Figure 9. Frequency distribution of differences in depth between half-minute or 304 ft spaced readings of 14°C and 9°C isotherm, leg two, cruise 2.



(A)

(B)

Figure 10. - Frequency distribution of differences in depth between half-minute or 304 ft spaced readings of 16°C and 9°C isotherm, leg three, cruise 2.

A similar study was made of the approximate slope of isothermal surfaces from the NEL Oceanographic Research Tower off Mission Beach, California.[17] Here, the approximate slope was obtained by means of a continuous depth recording of a single isotherm in the thermocline made with an isotherm follower.[18] The computation of slopes with the isotherm-follower record, as the internal waves pass the fixed point (tower) in 60 feet of water, is based on an average wave speed of 0.31 knot. Waves moving faster than 0.31 knot would give steeper slopes than actually exist, and slower moving waves more gentle slopes. This effect has a tendency to give a little wider distribution of slopes, but the average should be close to the true value. The slopes (accumulative frequencies) detected by this method are shown in figure 11 together with similar curves for the 14° and 16°C isotherm slopes obtained from the data of figures 9A and 10A.[19]

Although the two methods of obtaining slopes are not the same, nor the results wholly accurate, a comparison of the curves based on large samples (10,000 at the tower, 3000 in deep water)

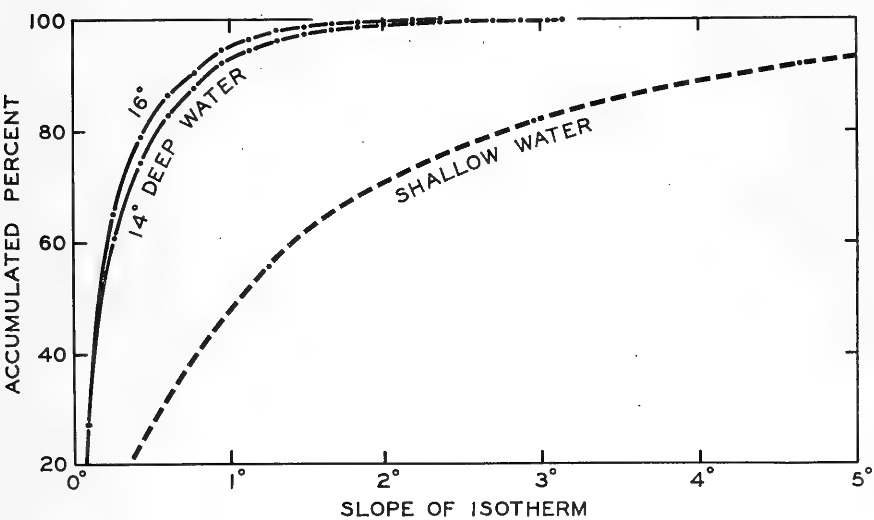


Figure 11. Approximate slopes of isothermal surfaces measured in deep and shallow water.

shows that the accumulative per cent of small angles of the deep water isotherms (from the traverses at right angles) is significantly greater than for similar isotherms in shallow water. It is therefore reasonable to assume that the shallow water internal waves in the thermocline are considerably steeper than those 180 miles farther out to sea. This difference indicates that the internal waves peak as they move into shallow water.

Autocorrelation of Depth Values

Another approach to the problem of subsurface temperature variability is by means of autocorrelation coefficients.[16] By using the same half-minute isotherm-depth data, autocorrelations were computed for each leg of the cruise and each selected isotherm. Elements of successive pairs of points (depth of an isotherm) at equal but overlapping time intervals were correlated with each other, and the process repeated for each time interval, increasing by half-minute steps from a half-minute to 250 minutes. Autocorrelation, R_λ, was computed for increasing intervals, λ, of 304 feet (half-minute), using the expression:

$$R_\lambda = \frac{(N-\lambda)\sum_{i=1}^{N-\lambda} X_i X_{i+\lambda} - \sum_{i=1}^{N-\lambda} X_i \sum_{i=1}^{N-\lambda} X_{i+\lambda}}{\left\{(N-\lambda)\sum_{i=1}^{N-\lambda} X_i^2 - \left[\sum_{i=1}^{N-\lambda} X_i\right]^2\right\}^{\frac{1}{2}} \left\{(N-\lambda)\sum_{i=1}^{N-\lambda} X_{i+\lambda}^2 - \left[\sum_{i=1}^{N-\lambda} X_{i+\lambda}\right]^2\right\}^{\frac{1}{2}}}$$

where $\lambda = 0, 1, 2, \ldots.$ 500 lag intervals and N is the total number of depth readings in each leg. The computed autocorrelations based on about 1500 depth readings (sample length, 750 minutes) and lag length variable from 0 to 500 steps (0 to 250 minutes) are shown in figures 12 through 16.

Figure 12 gives the results of the autocorrelation of the half-minute sampling rate for the depth of the 9°C isotherm of offshore traverse, leg 1. The correlation is positive throughout.

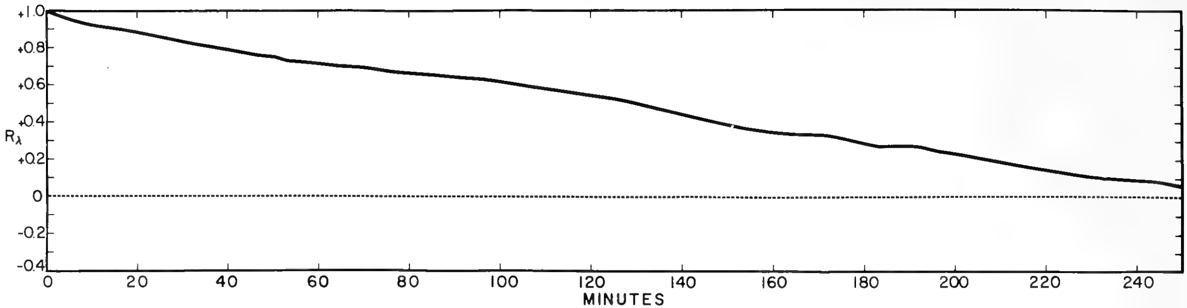


Figure 12. Autocorrelation computed from successive half-minute interval readings of the depth of 9°C isotherm, leg one, cruise 2.

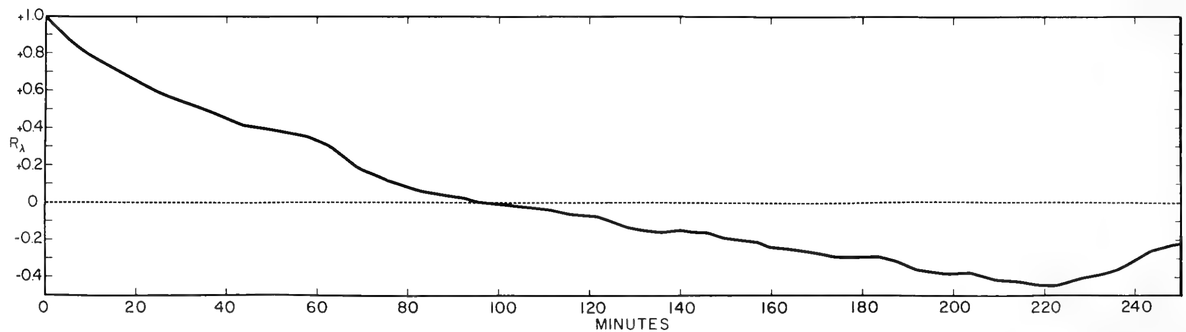


Figure 13. Autocorrelation computed from successive half-minute interval readings of the depth of 14°C isotherm, leg two, cruise 2.

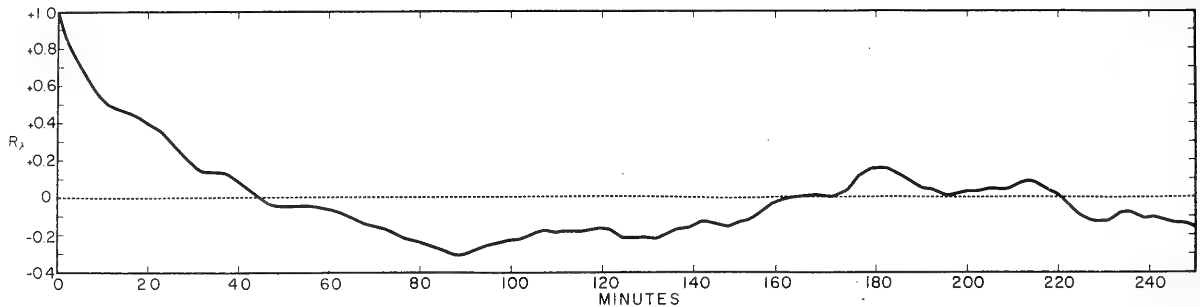


Figure 14. Autocorrelation computed from successive half-minute interval readings of the depth of 9°C isotherm, leg two, cruise 2.

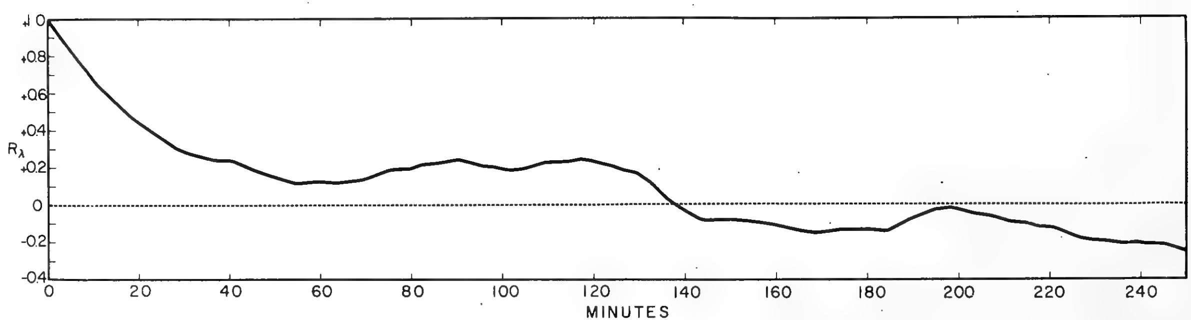


Figure 15. Autocorrelation computed from successive half-minute interval readings of depth of 16°C isotherm, leg three, cruise 2.

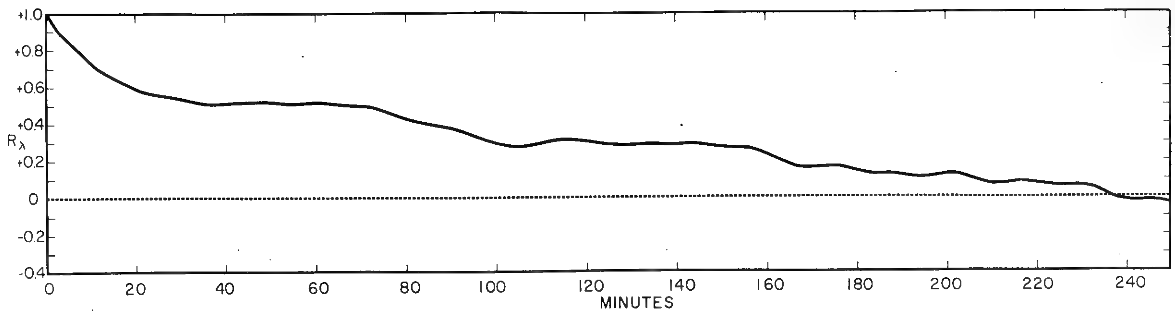


Figure 16. Autocorrelation computed from successive half-minute interval readings of the depth of 9°C isotherm, leg three, cruise 2.

Autocorrelation of depth of the 14°C isotherm in the alongshore traverse, leg two (fig. 13), showed a positive correlation for lag intervals of a half-minute up to about 90 minutes (9 miles). After 100-minute intervals, the correlation remained negative for over 6-hour intervals. By comparison, the deeper 9°C isotherm (fig. 14) gave a positive correlation for only 45 minutes, followed by a negative correlation for about 2 hours, after which the correlation again became slightly positive. This comparison indicates that any dominant cycles in the 14°C isotherm are of longer period than those in the 9°C isotherm.

The results of the same correlation for the depths of the 16° and 9°C isotherms, measured on the shoreward traverse, leg three of the cruise, are given in figures 15 and 16. The depth correlation for the 16°C isotherm remained positive for over 2 hours whereas that for the 9°C isotherm remained positive for 6 hours. Here the dominant cycles are much longer than the period of computation.

If the values of R remain positive, the long periods dominate the spectrum which may be broad or narrow. In all cases the major waves are of long period because the correlation does not reach a maximum negative value for 220 and 90 minutes (figs. 13 and 14) and greater than 250 minutes for the data shown (figs. 12 and 16). The time interval to maximum negative value is half a wave period. The minimum wave periods, then, for the most significant correlations are for the 9°C alongshore waves and amount to 180 minutes or 18 miles. The wave periods for the onshore and offshore data runs are greater than 500 minutes or 50 miles. In all cases the short-period waves are not consistent enough to outweigh the long-period ones, by this comparison.

Power Spectrum of Depth Values

The third method of representing variability is by the power spectrum.[10, 13, 15] The power spectrum $U(h)$ is given by the Fourier transform of the autocorrelation, R . It is the energy per unit bandwidth and thus designed to emphasize the dominant frequencies, since the amplitudes are squared. The smoothed power spectrum values were obtained as follows:

$$U(h) = \frac{1}{n}\left[R(o) + \sum_{\lambda=1}^{\lambda=n-1} R(\lambda)\ (1 + \cos\frac{\pi\lambda}{n})\ \cos\frac{\pi\lambda h}{n}\right]$$

where $h = 0, 1, 2, 3 \ldots. n$ index number of frequency (actual frequencies are given by $h/(2\Delta t)$ cycles/min, $\Delta t = 1/2$ min), and

$\lambda = 0, 1, 2, 3 \ldots. n$ is the lag number

The power spectrum $U(h)$ was converted to units of variance per cycle per minute by multiplying by $2n\Delta t$ where Δt is the time interval between depth samples and is equal to 0.5 minute.

The results of the computation are shown in figures 17 through 21. The power spectrum of the 9°C-isotherm depth on the offshore leg is plotted in figure 17. The importance of the power spectrum lies in the peaks in the curve which indicate frequencies (or periods) in the original data which may have been obscured by "background noise." Significant is the fact that this power spectrum has a large number of peaks ranging in periods from 3.2 to 13.5 minutes which corresponds to 0.3 and 1.3 miles, but none of these is especially dominant. The greatest power is in the low frequencies which show no peaks. There are, however, several high frequency peaks but there is no dominant one.

Similar computations of power spectrum of the 9°C-isotherm depth (fig. 18) on the alongshore leg show a number of peaks with periods of 3.0 to 21.3 minutes (0.3 to 2.1 miles).

The power spectrum for 9°C of the onshore traverse (fig. 19) shows only a low frequency peak at 14.7 minutes (1.5 miles) and quite weak higher frequency peaks. In comparison, the offshore 9° spectrum has higher power in all frequencies (by a factor of 10 or more) than that for the alongshore or onshore examples.

A similar comparison can be made between the alongshore 14°C isotherm power spectrum and that for the onshore 16°C isotherm. The power spectrum for the 14°C isotherm in the

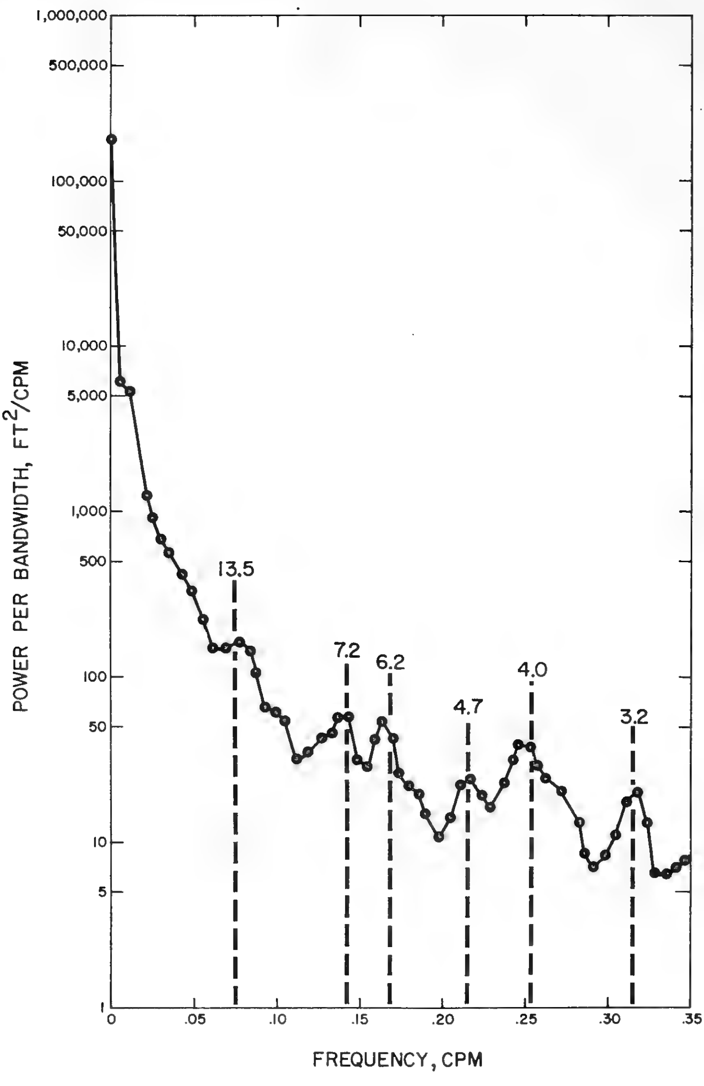


Figure 17. Power spectrum computed from successive half-minute interval readings of depth of 9°C isotherm, leg one, cruise 2.

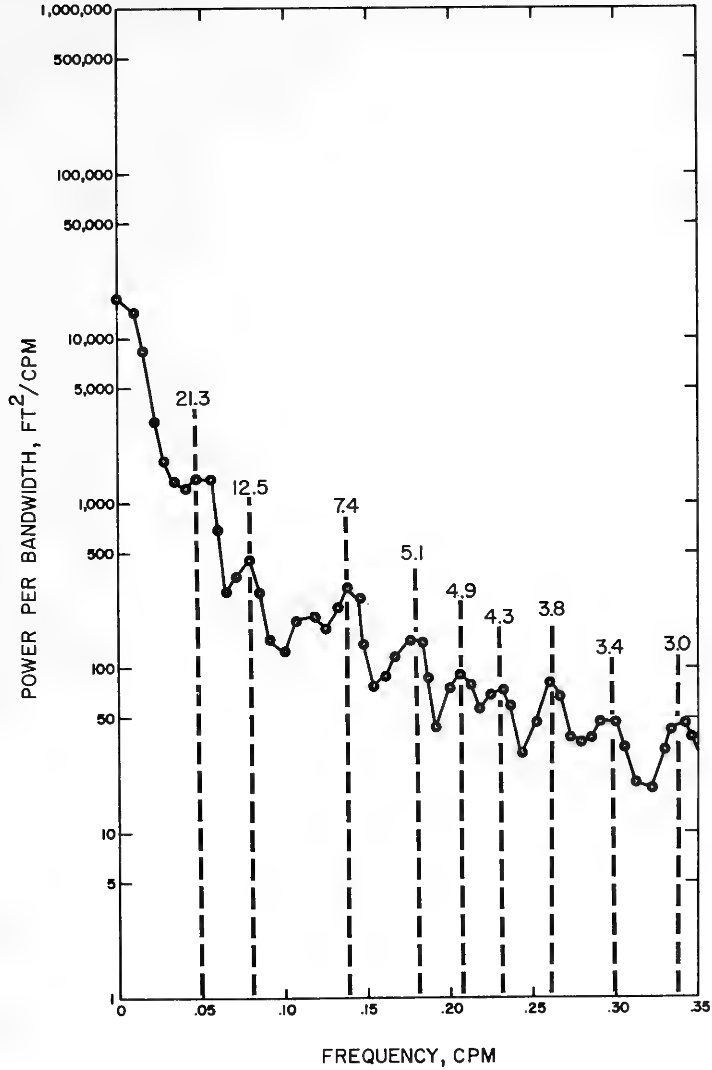


Figure 18. Power spectrum computed from successive half-minute interval readings of depth of 9°C isotherm, leg two, cruise 2.

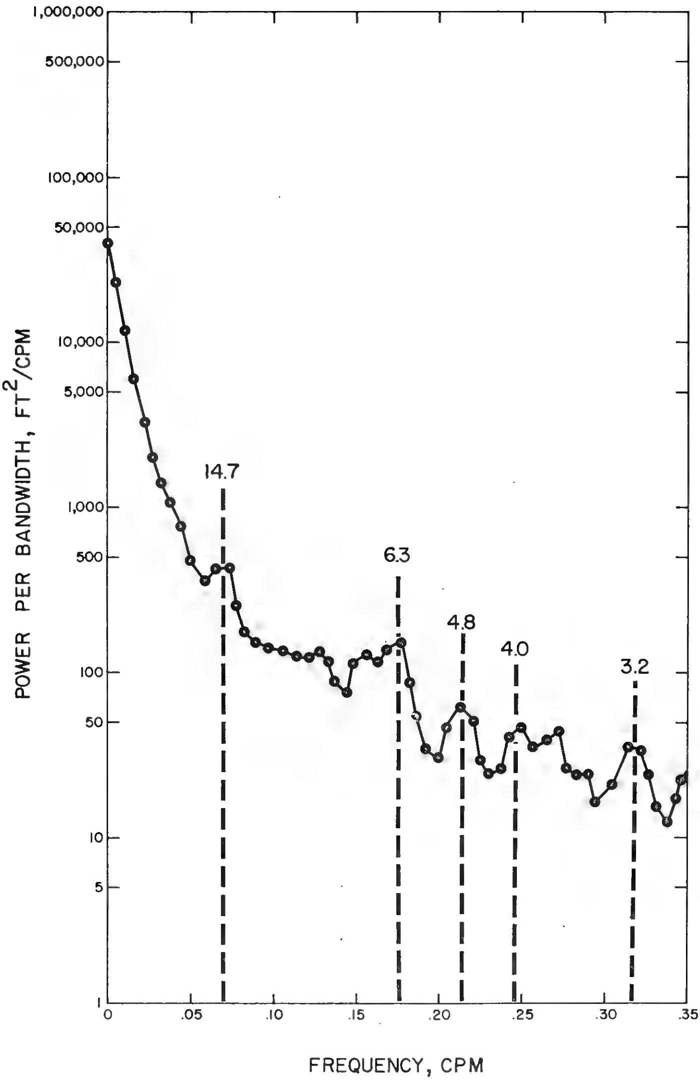


Figure 19. Power spectrum computed from successive half-minute interval readings of depth of 9°C isotherm, leg three, cruise 2.

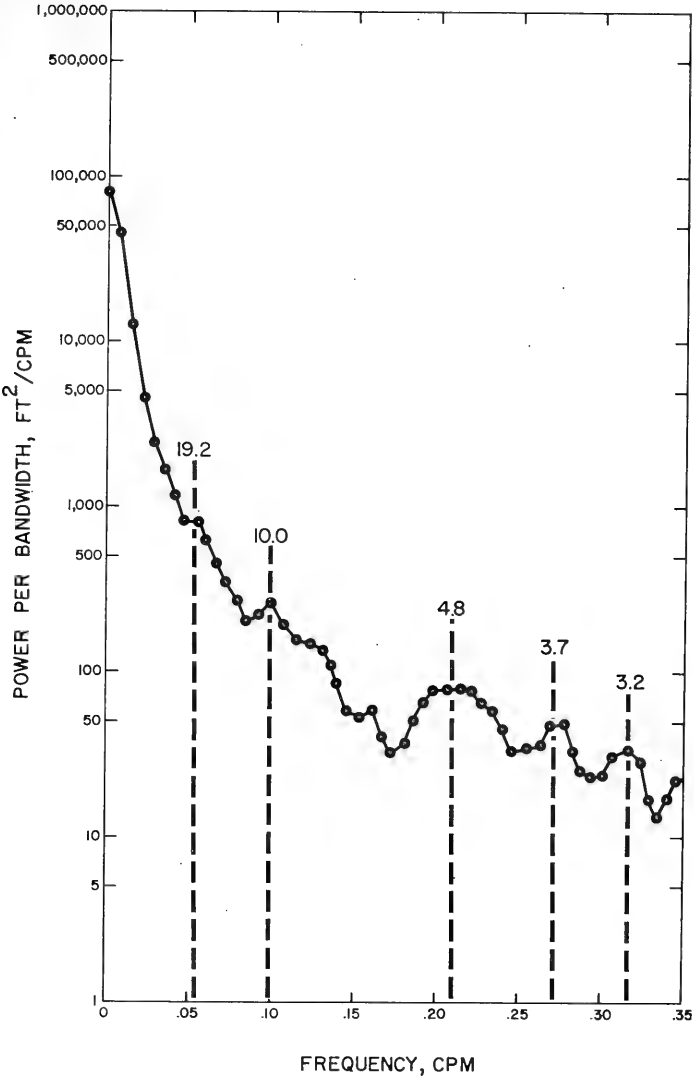


Figure 20. Power spectrum computed from successive half-minute interval readings of depth of 14°C isotherm, leg two, cruise 2.

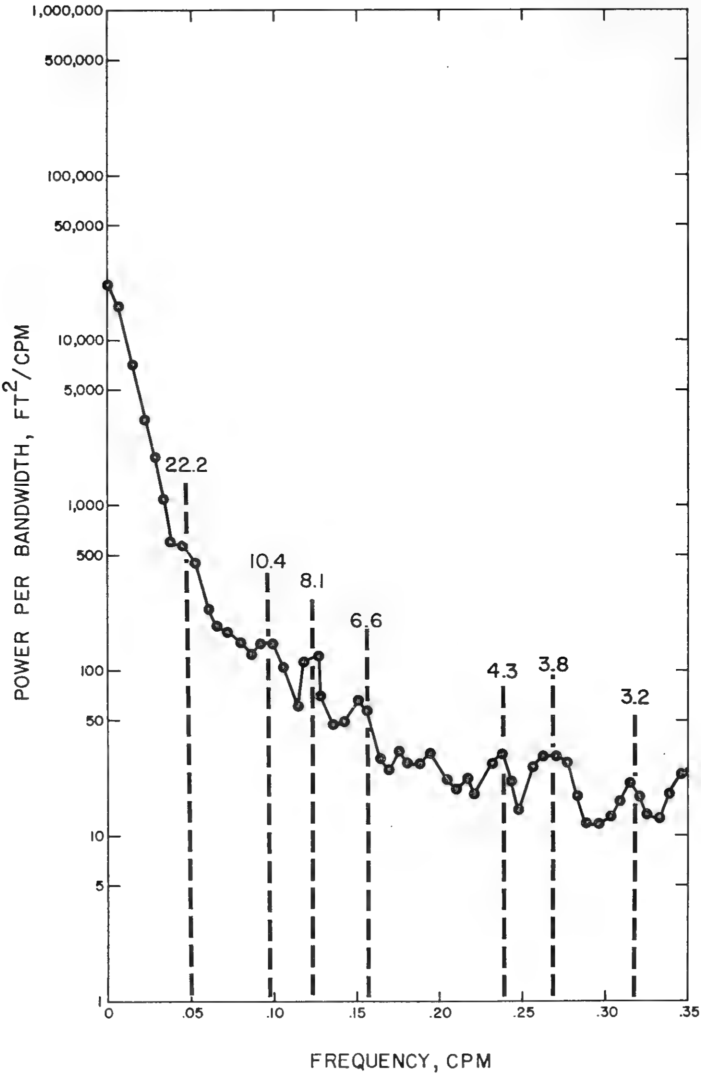


Figure 21. Power spectrum computed from successive half-minute interval readings of depth of 16°C isotherm, leg three, cruise 2.

alongshore traverse shows few peaks. The two lower frequency peaks (fig. 20) are for 10.0 and 19.2-minute periods (or 1.0 and 1.9 miles), which are relatively long periods when compared to the 9°C isotherms.

The power spectrum computed for the 16°C isotherm for the onshore leg shows low peaks which occur between 3.2 and 22.2 minutes (0.3 to 2.2 miles) (fig. 21).

The degree of freedom $v = \frac{2N}{n} - \frac{1}{2}$. When using 1500 depth sample values and 150 lags, $v = 19.5$. From reference 12, the ratio of measured to average value falls between 0.54 and 1.60 for a 90 per cent confidence limit.

Thus the 7.2 minute period peak of the offshore 9°C isotherm depth (fig. 17) has a ratio to background of 58 to 31 or 1.87 which is significant, whereas the onshore 14.7 minute period peak shown in figure 19 has a ratio of 1.65 which is barely outside the 90 per cent confidence limit.

The difference in power spectrum, if caused by a dominant internal wave moving in one direction, sheds some light on which way the waves are moving. The greatest power is concentrated in the long-period fluctuations at the beginning of the spectrum.

Comparing the power spectra with the corresponding autocorrelation curves indicates that when the autocorrelation curve is irregular the power spectrum shows a greater number of peaks. However, any possible wavelength shown on a correlation curve is at the low frequency end of the power spectrum diagram.

DIRECTION OF PROPAGATION OF INTERNAL WAVES

Little is known of the propagation direction of internal waves in deep water. It is reasonable, however, to assume that internal waves do propagate in one or, more likely, many directions. Since the ship is moving at 6 knots with reference to the sea surface, and the internal waves are moving in unknown directions, it is difficult to establish definite structures of the thermocline or its movements. However, some qualitative assessment of the dominant direction of propagation can be made.

It was indicated earlier that the slopes of the isothermal surfaces might assist in determining the direction of internal-wave motion. In addition, the autocorrelation and power spectrum indicate a shoreward direction. Furthermore, a doppler effect may be obtained by towing in different directions.

If the ship with the chain is anchored, the wave trains will move past and be recorded in accordance with their true frequencies. If the chain is towed in a direction parallel to the "crests" of long-crested waves, that is 90 or 270° to their direction of propagation, the true frequency should again be recorded. However, if the chain is towed in any other direction relative to the waves, their true frequencies will not be recorded. In other words, the recorded frequency of waves will depend on the relative directions of ship and waves and their relative speeds.

If some arbitrary speed is assumed for the waves, such as 1.5 knots, and the ship's speed is 6 knots (fig. 22), a frequency factor can be computed for all relative directions of ship and waves (fig. 23). Under these conditions the frequency factor should be three times normal when the chain is towed in a direction with waves and five times when being towed counter to the waves. When a towing is conducted in a relative direction of 75°31' and 284°29', no waves should be encountered if the fronts are long and parallel, and if the waves are of constant period. Unfortunately the waves are not so uniform, but it is believed that there may be dominant waves that would be revealed by the doppler effect. Thus, to test the directionality of internal waves, an experiment was arranged (at position E, fig. 2, near 30°19'N, 120°03'W) whereby the direction of tow was changed 6 degrees every minute. In this way the ship made a complete 2-mile-diameter circle in 1 hour. Four such circles were made; the recorded isotherms are presented in figure 24. In addition, two larger circles of 6-mile diameter were traversed in a similar fashion; the resulting data are presented in figure 25.

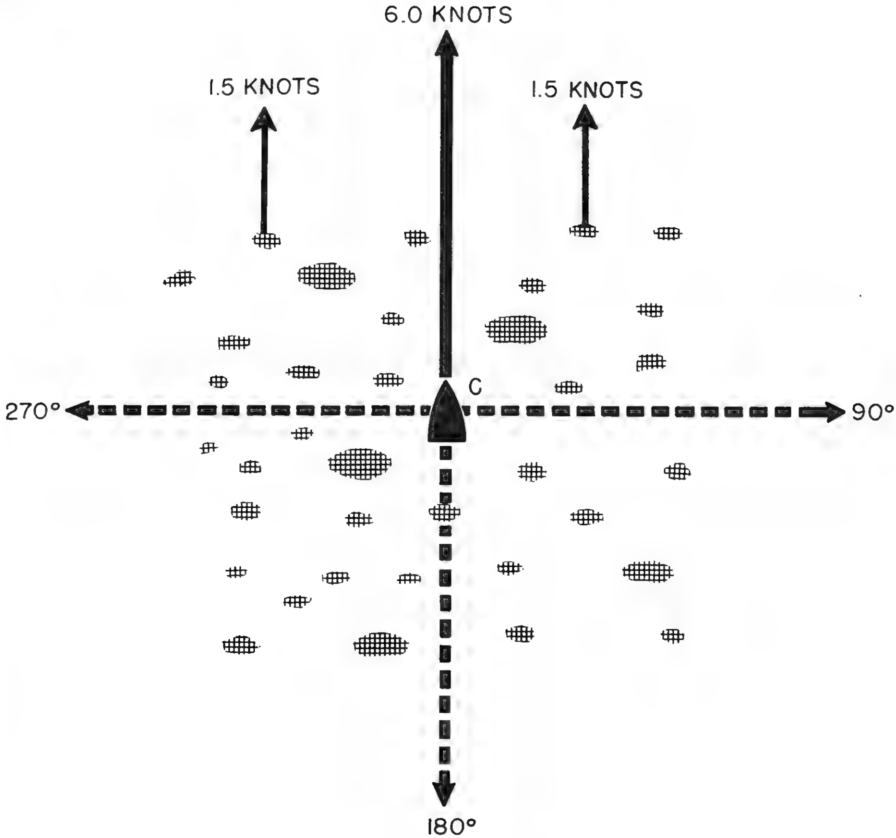


Figure 22. Schematic of the relative motions of ship with chain (C) moving at 6 knots and the dominant wave crests moving at 1.5 knots.

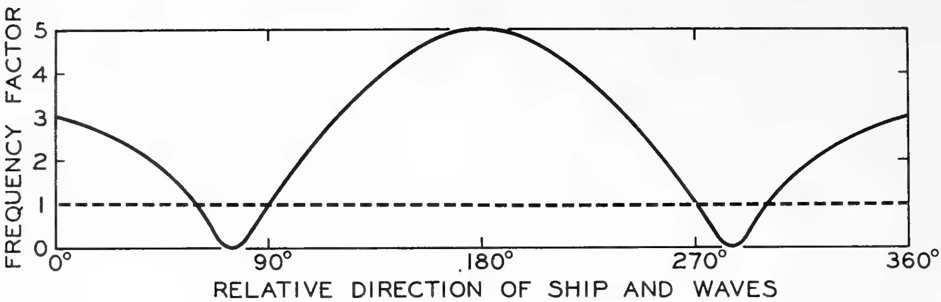


Figure 23. Frequency factor of the relative direction of ship and internal wave motion using the speed of 6 knots for ship and 1.5 knots for waves.

The records from the four 2-mile-diameter tracks (I, II, III, and IV, fig. 24) are arranged one above the other for comparison. In each case the record is broken down into four depth intervals, going from left to right in the figure. The horizontal scale is the direction of tow in each case. However, the nature of the waves at all directions of tow fails to indicate any wavelength that is specific for a particular direction of tow.

A similar depth-direction (distance) presentation of isotherms is used for the 6-mile-diameter record (fig. 25).

The significant point is that there are vertical fluctuations in all directions of tow for both the 2- and 6-mile tracks. Visual inspection reveals no dominant wave heights in any direction nor any obvious change in frequency. The duration of tow in any direction by this small circle technique is too small for reliable analysis, but the occurrence of internal waves at any direction of tow demonstrates that waves are not parallel in lines. In fact, they must be in the form of irregular bumps and depressions, so that any direction of traverse will cross a high and low thermal surface feature.

In the sharp parts of the thermocline there is a good correspondence in the vertical traverse of adjacent isotherms, but this correlation deteriorates when the vertical gradients become weak.

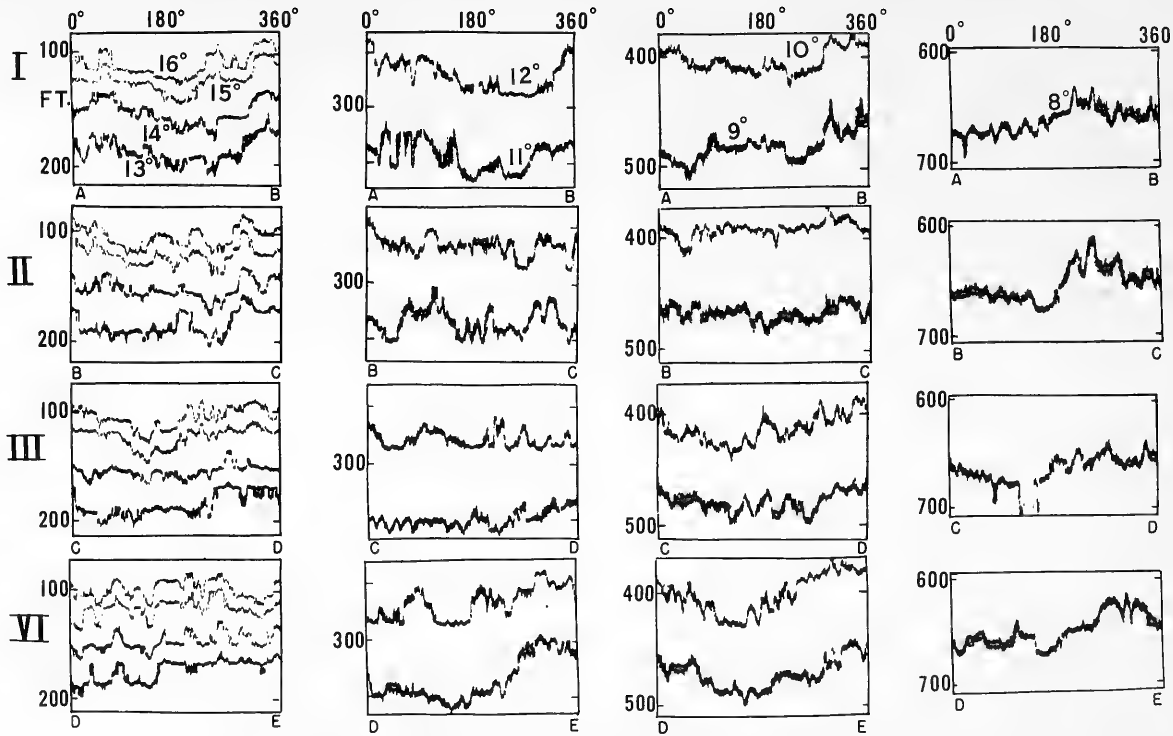


Figure 24. Vertical temperature structure resulting from four circular tows with the thermistor chain. The same depth intervals on the four 2-mile-diameter tows are arranged together for comparison.

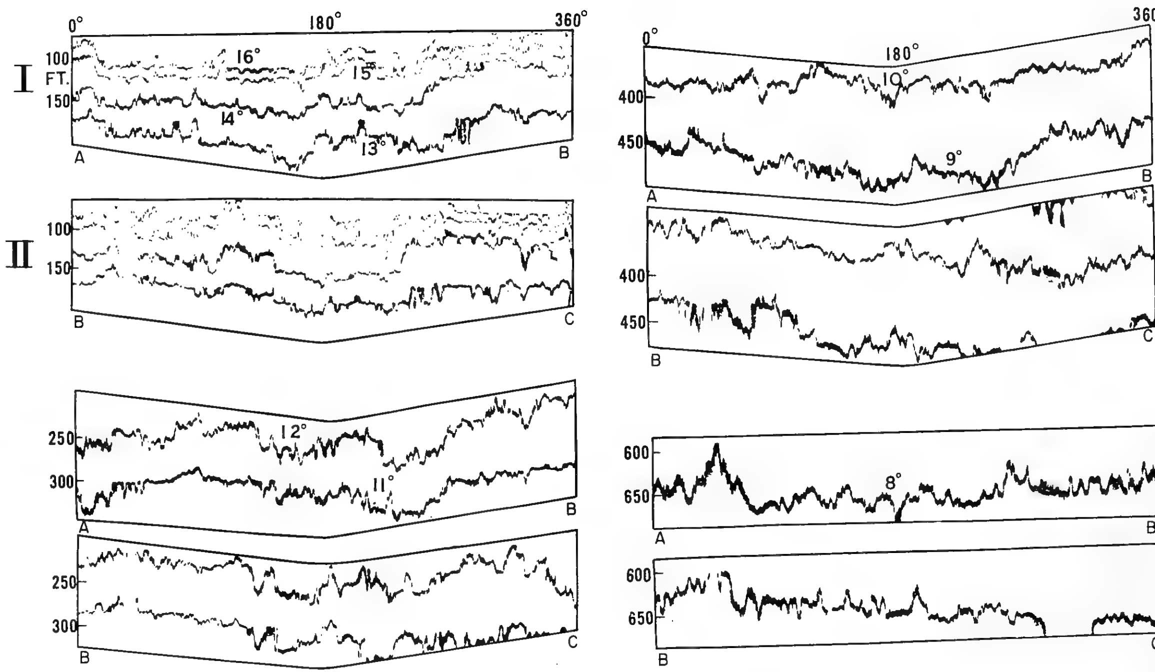


Figure 25. Vertical temperature structure resulting from two circular tows with the thermistor chain. The same depth intervals on the two 6-mile-diameter tows are arranged together for comparison.

This implies that the waves must have different modes and frequencies and are probably moving in different directions.

The establishment of the characteristics of internal waves and three-dimensional isothermal surfaces by use of the chain is not as difficult as might be supposed. If the waves are moving one-fourth as fast as the ship, the results can be treated as spatial distributions rather than as time variations. In the specific case cited above, the distortion would be in error by only 25 per cent at the most, and would become less with increased relative speeds and by towing in directions nearly normal to the directions of propagation of the dominant wave.

It is therefore possible to construct a fairly reliable representation of internal waves and isothermal surfaces by considering their space distributions at a given time.

If we consider, for example, the depth of the 9°C isotherm recorded during the two circular traverses (fig. 25) of 6-mile diameter, assume a ship drift of 0.5 knot down the coast, and disregard the wave propagation and time of traverse, an approximation of a three-dimensional representation of the 9°C isothermal surface can be constructed (fig. 26). This artist's conception, based on the isotherm depths for the two circles, appears to be a rough irregular pattern similar to the sea surface or a mountain range.

SUMMARY AND CONCLUSIONS

With the thermistor chain it has been possible to record a two-dimensional picture of the thermal structure. In addition, by towing the chain in rectangular and circular paths, an attempt has been made to gain knowledge of the spatial changes in isotherm depth and the direction of propagation of internal waves.

The record of the rectangular tow, away from, parallel to, and toward shore, was analyzed by computing the isotherm depth differences at half-minute intervals. These were used to study

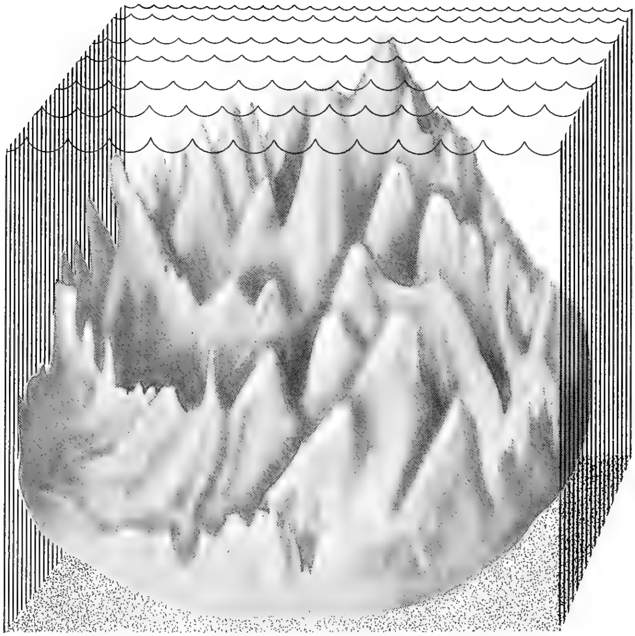


Figure 26. Three-dimensional construction of the 9°C isothermal surface based on two repeated 6-mile-diameter tows with the thermistor chain (vertical scale equals about 200 times horizontal).

isothermal surface slopes, and to compute autocorrelations and power spectra. From the results obtained it was concluded that many significant waves are of very long period. These analyses further indicated that there is probably a shoreward movement in the dominant waves.[20]

The records of circular tows showed that the thermal structure is very complex. The circles were too small to clearly demonstrate significant motion in any direction. The data did reveal that wave crests and troughs of a generally similar type were crossed in all directions of tow. Thus, the isothermal surfaces are very complex and vary in all directions.

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UNCLASSIFIED

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2. Thermistors-Applications

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