VERTICAL AND HORIZONTAL THERMAL STRUCTURES IN THE SEA

FACTORS AFFECTING UNDERWATER SOUND TRANSMISSION ARE MEASURED BY
USE OF A TOWED THERMISTOR CHAIN

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THE PROBLEM

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

RESULTS

1. Detailed temperature structure data on the upper 800 feet of the sea south of Baja California, acquired by the U. S. Navy Electronics Laboratory (NEL) Thermistor Chain, revealed vertical and horizontal motion, large scale turbulence, and possible Doppler effects.

2. The sea temperature structure was found to vary widely and may be characterized by (1) smooth thermoclines where the isotherms had vertical oscillations with wavelengths generally greater than 2400 feet; (2) normal thermoclines of varying wavelength that averaged from 1400 to 2400 feet; (3) rough thermoclines with steep isotherms and most wavelengths of less than 1400 feet; and (4) irregular thermoclines of large vertical shifts and major turbulent-type oscillations.

3. Irregular thermoclines were found to be related to fronts in water-mass boundaries caused by intermingling of the Gulf of California Water with the California Coastal Current Water and Eastern Tropical Pacific Water.

4. The isotherm slopes, determined from over 65,000 data samplings, showed a median of absolute values of vertical slope to be $0^{\circ}25'$, and the 70th percentile of absolute values of slope to be $0^{\circ}51'$. The steepest isotherm slopes were found just south of the peninsula of Baja California.

5. The slopes were steeper during a tow to the north or south, which implied that off southern Baja California and in the mouth of the Gulf of California the wave crests in the thermocline were oriented more in an east-west direction.

6. The significant peaks in the power spectrum of isotherm depth of encounter were so distributed at different frequencies that no single frequency was dominant.

7. The slopes of the log frequency vs the log of power spectrum averaged nearly $-5/3$ or in the turbulence range. Small deviations from the $-5/3$ slope occurred around 0.15 cycle per minute (cpm) (0.66 mile) in both the deeper and shallower isotherms and around 0.30 cpm (0.33 mile) in the shallower isotherm.

RECOMMENDATIONS

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

2. Investigate the use of additional sensors (in conjunction with temperature) on the thermistor chain for measuring current, turbidity, sound velocity, and salinity.

3. Use the thermistor chain to study thermoclines and associated internal waves and investigate the effects on thermoclines of islands, shoals, coastal configurations, tides, known currents, upwelling, water-mass boundaries, storms, and seasons.

4. Examine in detail with the thermistor chain to determine the most persistent areas of smooth, normal, rough, and irregular thermoclines, and conduct sound transmission studies in, and adjacent to, such features to evaluate their effect on sound transmission.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The U.S. Navy Electronics Laboratory thermistor chain, deployed from the oceanographic research vessel USS MARYSVILLE (EPCE(R) 857) (fig. 1A) measures and records vertical sections of sea temperature structure from the surface to a depth of 800 feet. The first thermistor chain cruise by USS MARYSVILLE was made in June 1961, and the results derived from it and six succeeding, data-collecting voyages have been published.^{1, 2, 3, 4, 5} The eighth chain cruise, which covered the coastal waters from San Diego, California, to Mazatlan, Mexico, investigated the nature of vertical and horizontal variations in sea temperature structure off southern Baja California and across the entrance to the Gulf of California.

To detect the area of a possible water-mass boundary, the thermistor chain was towed in a complex, fan-like pattern extending south of Baja California. This region, probably the most favorable in the northeast Pacific Ocean for acquiring data on thermocline roughness, is characterized by three types of water impinging on each other: (1) the California coastal current, relatively cold and of low salinity; (2) the warm, high-salinity, tropical, east Pacific water; and (3) the warm, high-salinity Baja California coastal water that wedges into the California current near Cape San Lucas.⁶ Each water mass has its own definitive thermal structure as well as modifications resulting from differential advection and large-scale turbulence.

The data gathered by the thermistor chain were examined for oceanographic processes and types of thermoclines. Two selected isotherms, used to investigate depth change or slope, were subjected to autocorrelation of successive depth measurements, and the power spectrum of isotherm depth was determined.

Figure 1. (A) The oceanographic research vessel USS MARYSVILLE with thermistor chain deployed.

EQUIPMENT

The NEL thermistor-chain^{7,8} assembly of drum, hoist, links, and weight weighs 37,500 pounds. The deck units consist of the hoist, chain, generator, and the drum on which the chain is wound (fig. 1B). The chain is composed of flat links 1 foot long, 10 inches wide, and 1 inch thick. A 2,300-pound, torpedo-shaped weight at the end of the chain tends to maintain it in a more vertical position during towing, and represents the maximum depth of observation. One hundred pairs of insulated electrical leads fit through grooves inside the flat links, and the electrical wires (harness) are connected to the temperature sensors at 25-foot intervals (fig. 1C). The upper ends of the electrical leads are connected to a recorder located in the ship's laboratory, where signals from each of the 34 sensors are scanned electronically.

The scan cycle time is 12 seconds. The order of sensing is from the surface to the deepest sensor, or thermistor bead. The chain, inclined backward at an angle, moves forward with the ship, and the sensing takes place in an approximately vertical

Figure 1(B). Thermistor chain assembly suspended from the fantail of USS MARYSVILLE.

Figure 1(C). Chain link, fairing, harness, and temperature sensor.

line. The signals, interpolated electronically, are used to record only the depth of whole-degree-centigrade isotherms on 19-inch-wide tape, which equals, in data acquisition, that derived from the lowering of a bathythermograph every 120 feet at a ship's speed of 6 knots. The surface temperature, recorded by the uppermost thermistor bead, and the depth of the deep extremity of the chain, recorded by a pressure sensor, are printed on the same tape. The oceanographic research vessel, towing the thermistor chain suspended nearly vertical from the fantail, cruises forward and acquires sea temperature structure data to a depth of 800 feet. Two-dimensional coverage, depth and distance, is thus achieved (fig. 2); however, time, a third dimension, must also be considered. The small change in depth at the end of the chain, caused by the forward movement of the ship, is disregarded in the following analysis.

Figure 2. Thermistor-chain towing technique used to acquire a two-dimensional measurement of sea temperature structure.

OBSERVATIONS AND DATA

Procedure

On the eighth cruise of USS MARYSVILLE with the thermistor chain, the ship followed a course about 60-80 miles off San Diego south to near Cape San Lucas, Baja California. The vessel traced a fan-like pattern that extended 100 miles from the Cape and terminated in deep water off Mazatlan (fig. 3). The return trip traced a similar, more widely spaced pattern extending out 170 miles. Advancing at a speed of approximately 6 knots, the chain recorded temperature from the surface to a maximum depth of 750-800 feet.

Before an analysis of the isotherm recordings derived from Cruise 8 is presented, certain features of sea temperature structure should be described.

Figure 3. The pattern of thermistor-chain towing on Cruise 8 and the identification of thermal structure data sections.

Vertical Thermal Oscillations

The thermal structure off Cape San Lucas was investigated on a number of cruises ^{6,9} using bathythermographs and reversing thermometers, and the studies revealed the existence of thermal fronts.* However, the nature of the detailed vertical changes in the isotherms had not been measured with the thermistor chain.

Definite density boundaries in the sea should exhibit certain frequencies and modes of oscillation. It is pointed out ^{10, 11} that a given density boundary may have its own normal oscillating frequency (the Väisälä frequency). Strong winds may create convection cells and eddies in the upper layers of the sea, and the resulting circulation will lower the thermocline more in one area than another. Vertical oscillations in the thermocline can be induced by fluctuating winds at the air-water surface, which can also generate waves on the thermocline. Tidal and other forces that impel water movement around land boundaries and topographic features can also start oscillations in the thermal structure. There is, however, reason to believe that the vertical variations in the isotherms observed with distance can be internal waves moving in one or more directions and causing reinforcement or cancellation of the individual waves (fig. 4). The progressive nature of these oscillations in shallow water has been established by studies conducted from anchored ships and from the NEL Oceanographic Research Tower.¹²

The detailed recording of isotherm depths indicates the complicated character of sea temperature structure and emphasizes the complex nature of the ocean in its temperature-related chemical properties and biological populations.

*The term thermal front is defined as the leading edge of a border separating unlike water masses. The boundary is frequently ill-defined, transient, and associated with motion causing a relative vertical displacement. Fronts are commonly observed in the region between water masses with marked gradients in temperature, salinity, and other properties. The frontal zones are important in sound transmission because of their strong horizontal and vertical gradients in sound velocity.

Figure 4. Two intersecting trains of internal waves.

THERMAL STRUCTURES

Temperature changes at either the surface or various depths may be caused by several factors, such as (1) the advection of water of a different temperature; (2) radiation from the sun; (3) mixing by the wind; (4) tidal currents; or (5) internal waves.¹³ Since such forces may occur simultaneously, it is difficult to determine their individual effects, but a detailed, two-dimensional data section, obtained by the thermistor chain, can frequently indicate the contribution of each factor to the processes taking place in the sea.

The thermal structure presented here is more properly the "structure of encounter" or "depth of encounter of isotherms." The vertical scale is depth, but the horizontal scale may be considered as either time or distance. The amplitude of the vertical

changes in isotherm depth is correct in either sense, but after 4 hours of continuous recording, changes will have occurred at the beginning of the section. The structures represent a spatial plot rather than a time shift, since the advective and vertical oscillation movements caused by internal waves in strong thermoclines occur more slowly than does the movement of the ship across the section. The detailed thermal structure data to be presented can be described as vertical sections in the sea in the same sense as oceanographic sections derived from serial station data.

The vertical scale is not entirely linear, since the thermistor chain assumes a slight curvature between the vessel and the weight at the end of the chain. For exact depths the linear depths on the analog record of thermal structure can be multiplied by the factors given in table 1.

TABLE 1. DEPTH FACTORS FOR CONVERSION
OF LINEAR SCALE TO TRUE DEPTH

Linear Recorded Scale	Depth factor * (for 100-foot intervals)
0	
100	0.930
200	0.955
300	0.980
400	1.005
500	1.030
600	1.055
700	1.080
750	1.105

The thermocline normally occurs where the ratio of linear depth to true depth is nearly unity. For practical purposes the linear scale is accurate and is used throughout this report.

*Smith, E. L., Determination of Towed Configuration and Sensor Depths of the USNEL Thermistor Chain, U.S. Navy Electronics Laboratory Report, 1966 (in preparation).

The four examples presented in the following sections describe thermal structures recorded along sections of continuous tows made off the western and southern coasts of Baja California (fig. 5). All sections in figures 6-9 represent straight-line tows of nearly 4 hours duration, or about 24 miles.

Figure 5. Locations of four measured examples of thermal structure.

Common Type

The first example (fig. 6), taken 50 miles off Baja California at Position 1, is the isotherm recording made while the thermistor chain was towed at a speed of about 6 knots. The vertical scale, magnified about 100 times compared to the horizontal scale, causes the isotherms to appear much steeper than in actuality. Only seven whole-degree isotherms, 16° to 10°C, occurred in the upper

Figure 6. A common thermal structure (Position 1, fig. 5).

800 feet. Throughout the depth was an upper mixed layer with no whole-degree isotherms from the surface down to about 200 feet. Close vertical spacing of isotherms directly under the mixed layer revealed a sharp thermocline. Below this was a gradual widening of isotherm spacing. This, the most common type of vertical temperature structure in the upper layers of all oceans, is present in 85 percent of the Pacific.¹⁴

Horizontally, the most obvious feature is large undulations of the main thermocline. These were about 12 miles long, 50-100 feet high, and probably associated with the tidal cycle. The height of the long wave decreased with depth (fig. 6). The deepest isotherm (10°C), occurring in a weak vertical gradient, fluctuated widely and showed no definite long-wavelength cycles, as do the 16°C isotherm and others in the sharper part of the thermocline.

Small vertical oscillations appeared generally at a rate of 2 to 4 per mile, but 5 or 6 per mile were noted. Such oscillations, with amplitudes from several to around 20 feet, are present in all the isotherms in the thermocline, and are largely in phase with one another throughout the strongest part. Amplitudes of the small vertical oscillations increased inversely with the strength of the

vertical temperature gradient. At greater depths (11°C and 12°C isotherms), the amplitudes were as high as 30-50 feet. Accurately observed isotherm depths in all oceans show similar vertical changes with distance and time.

Temperature Inversion

The second example (fig. 7) was recorded 90 miles south-east of the first example, where the water was warmer and the thermocline details changed. The deeper isotherms showed a radically different pattern. The surface layer in the southern part (left) was 150 feet thick, shallower than the previous sample, and mixed. In the northern part (right), a weak gradient containing one isotherm was above the main thermocline, and the temperature inversion below the thermocline was unusual. Since the surface current and surface layer were moving from north to south, it can be assumed that some of the water in the thermocline was also

SEA SURFACE

Figure 7. Temperature inversions below the main thermocline (Position 2, fig. 5).

moving southward and overrode the deep water (arrows, fig. 7). The deep water was either moving at a slower speed or in a northerly direction. The difference in speed was measured to be 0.7-1.2 knot, and the motion could create a weak shear or temperature inversion as shown by the "S" shape of the 11°C and 12°C isotherms (fig. 7). These inversions were 150-200 feet high, fairly weak (about 1°C), and probably transient. The "S" shape implies that the flow in the higher level of the inversion was counter to the ship's motion.

The main thermocline, between 150 and 300 feet, contained smaller waves. The spectrum of their wave lengths was broad; some were only 600-900-feet long whereas others (upper right) were nearly 4 miles long, and averaged 2-4 per mile. The 12-mile wave on the thermocline was less distinct than in the first example, and the thermocline less sharp. It became weaker with depth, as in the previous section, but was more uniform before transforming abruptly into the large inversions.

Cold Water Intrusion

The third example (fig. 8), recorded on a southerly tow 180 miles southeast of the second example, featured in its surface layer a 6-mile region about 1°C colder than the adjacent water. Below the surface layer a sharp thermocline changed with increasing depth into a more gradual one. The upward bending of the 13°C isotherm indicated an intrusion of colder water that did not extend into the strongest part of the thermocline. The cold area appeared to be an intrusion lying at an angle to the section rather than an up-bending of the thermocline.

The thermocline was made up of small, wave-like oscillations, particularly between the colder areas, numbering 3 per mile as compared with an average of 2 per mile on either side in the preceding sections. This may be due to a Doppler shift in frequency that corresponds to an apparent change in wavelength caused by the relative motion of the ship, current, and wave propagation. If a Doppler effect is assumed, then wave propagation in the cold region would have a more northerly component than waves in the regions on either side. The cold area at a depth of 500 feet where the isotherm curved up appeared to be characteristic of this level.

Figure 8. Colder thermal area above and below the thermocline (Position 3; fig. 5).

Here the "Z"-shaped temperature inversion implied that the upper part was moving to the right or in the same direction as the tow, whereas the "S"-shaped inversion of the second example implied that the upper of the two layers was moving in a direction opposite to the tow.

Ridge (or Dome)

The fourth example (fig. 9), located just south of Baja California, is marked as Position 4 (fig. 5). This thermal structure was characterized by a general ridge (or dome), and colder water was found at the surface where the isotherms curved up to intersect it. Maximum bowing occurred on the uppermost isotherms, but some doming was detectable to a depth of 500 feet. The sloping isotherms of the ridge imply a geostrophic current, which probably means the presence of a current boundary at the ridge. A net-divergency-type transport away from the ridge, as well as parallel to it, is evident.

Figure 9(A). A thermocline or dome, indicative of divergence (Position 4, fig. 5).

A detailed examination of recorded thermal structure furnished information on other oceanographic processes (figs. 9A and 9B).

The detail of long waves of encounter (fig. 9A) averaging 0.44 mile in length can reflect a natural geographical phenomenon or a Doppler effect. The smooth, 20-foot-high waves may be shorter than recorded if traveling in the same direction as the ship. If surface waves were influencing the depth of the sensors, the internal waves would appear as irregular marks, since each recorded scan would give an irregular outline to the curve (the scan would fall at all phases of the surface wave). Surface waves, because of ship stability and bead lagging, have little or no effect on the recording of smooth, sine-shaped internal waves.

In a second enlargement (fig. 9B), the recorded isotherms are much different from those of only 1-1/2 hours earlier although the speed and direction of towing were the same. The fluctuation and rough appearance of the isotherms are attributed to short-length internal waves, or waves propagating in an opposite direction to the ship. The waves of encounter are so short that

Figure 9(B). Recording of smooth (long wave) thermocline (vertical scale: 160 feet; horizontal scale: 2.6 miles).

Figure 9(C). Recording of rough (short wave) thermocline (vertical scale: 160 feet; horizontal scale: 2.6 miles).

the 12-second interval scan falls on all wave phases. If one scan falls on the wave crest and the next off it, 120 feet away, an abrupt change in the normally smooth isotherm is recorded. Other wave phases are also recorded on successive scans, and thus a rough appearance is created when short waves are encountered.

Since the isotherms in the northern part of the section are more irregular and reflect higher-frequency internal waves than those in the southern part, the ship may have been alternately moving in the same and opposite direction as the internal wave propagation, thus producing a Doppler effect.

The ridge may be considered a front, or boundary, with a sloping density structure rising toward the crest. Small internal waves propagating at an angle with the boundary may be refracted as they are on the continental slope and be propagated toward the crest from both sides. A Doppler effect can therefore be experienced when towing toward and away from the crest (left to right, fig. 9). Waves propagating toward each other can create mixing and result in isothermal water near the surface, as was measured over the crest. This may cause the large difference in wavelength measured on either side of the rise, and the mixed structure over the crest.

Other causes for differences in thermocline roughness are the variability and patchiness of the ocean. Since wave frequency on the thermocline may vary widely over a short distance, additional examples are presented in order to demonstrate the types of thermocline and their distribution.

THERMOCLINE CLASSIFICATION

Thermoclines may be categorized either by their oceanographic processes or (somewhat subjectively) by the wavelengths of their smaller oscillations. To identify types of thermoclines, a total of 30 2-hour (12-mile) two-dimensional data sections were selected from the ship's track (fig. 10) and classified in four categories: smooth, normal, rough, and irregular (Appendix A). The variability of oceanic thermal structure is confirmed by the fact that each type of thermocline is found near the other.

Figure 10. Locations of sample sections of smooth, normal, rough, and irregular thermoclines.

Smooth Thermocline

Smooth thermoclines are isotherm undulations of a more regular form than average. At a ship speed of 6 knots, the 12-second scan falls several times on a crest and several times in the trough. The wavelengths of the smaller oscillations extend more than 2400 feet, or fewer than 2-1/2 oscillations per mile.

Two examples of smooth thermoclines are identified as S-1 and S-2 (fig. 10). The first is from the central part of the area (fig. 11A). The second (fig. 11B) comes from an easterly tow directly south of Cape San Lucas. Smooth waves vary considerably in wavelength of encounter, but average more than 2400 feet in length.

SEA SURFACE

S-1

Figure 11(A). Smooth thermal structure (Section S-1, fig. 10).

SEA SURFACE

S-2

Figure 11(B). Smooth thermal structure (Section S-2, fig. 10).

REVERSE SIDE BLANK

Normal Thermocline

Normal thermoclines reflect an average condition, and their wavelength, although irregular, varies from 1400 to 2400 feet. Examples from the areas marked N-1 and N-2 (fig. 10) are presented (figs. 12A and 12B), and are derived from the general area where smooth examples S-1 and S-2 were found.

SEA SURFACE

Figure 12(A). Normal thermal structure (Section N-1, fig. 10).

SEA SURFACE

Figure 12(B). Normal thermal structure (Section N-2, fig. 10).

Rough Thermocline

Rough thermoclines are the vertical oscillations that occur more rapidly than the 12-second scan can follow and yet produce a wave-like form. Scans of 120 feet apart may fall at different internal-wave phases and thus show an irregular wave structure. The wavelengths average less than 1400 feet or about 4 cycles per mile. Two selected examples, identified as R-1 and R-2 (fig. 10) and presented in figures 13A and 13B, come from the extreme northern and southern parts of the area. To reconstruct the internal-wave forms, a few of the scattered points have been connected with a fine line.

SEA SURFACE

Figure 13(A). Rough thermal structure (Section R-1, fig. 10).

SEA SURFACE

Figure 13(B). Rough thermal structure (Section R-2, fig. 10).

Irregular Thermocline

Displaced thermoclines are found in frontal areas where the entire thermocline has shifted or buckled and inversions have usually occurred. The vertical changes are larger than the usual 2-4 cycles per mile. Examples of irregular thermoclines, marked D-1 and D-2 (fig. 10), are presented in figures 14A and 14B. Both irregular thermoclines are characteristic of regions where two water masses impinge on each other. These frontal features do not remain in a fixed position, but shift, dissipate, and reform.

Although Doppler effects can apparently cause differences in the wavelength method of characterizing thermocline roughness, a natural geographic or time difference in thermocline roughness can also be a factor. The average roughness of 1400-2400 feet is equivalent to $2\frac{1}{2}$ -4 minutes, or near the Väisälä frequency.

SEA SURFACE

D-1

Figure 14(A). Irregular thermal structure, or front (Section D-1, fig. 10).

SEA SURFACE

Figure 14(B). Irregular thermal structure, or front (Section D-2, fig. 10).

TEMPERATURE STRUCTURE VARIABILITY

In addition to the general classification of sea temperature structure by degree of roughness, a statistical analysis was conducted to determine isotherm depth variation and thus identify oceanic regions by their statistical differences. The analysis included isotherm steepness, which can be considered a measure of roughness.

Each section of the continuous towing track was alphabetically identified by 27 sections (A to Z, AA) (fig. 15), and the time and geographical position recorded (table 2). The selection of sample sections for analysis was made to obtain geographical coverage of an area during a period when the tow was continuous in one direction. The length and quality of the sample towing were planned to be adequate for reliability in statistical results. For geographical considerations, the midpoint of the sections is treated as a unit or data point.

Prior investigations studied the variability of surface and subsurface sea temperatures; others developed procedures for the statistical analysis of physical properties applicable to temperature variability.^{15, 16, 17, 18, 19, 20} In this report, three methods of studying isotherm depth variability are employed: (1) differences in depth values — isotherm slopes; (2) autocorrelation of depth values; and (3) power spectrum of depth values.

Figure 15. Alphabetically identified sample sections used in the data analysis of isotherm characteristics. Geographic centers of sample sections are marked.

TABLE 2. TIME AND LOCATION OF THERMISTOR CHAIN DATA SAMPLES
USED FOR ANALYSIS (Continued on page 35)

Data Sample (Section)	Date (1962)	Time	SECTION		Duration (hr)	Average Direction (true)	Isotherm Used (°C) and Total Data Points	
			Central Position	°W			Deep	Shallow
A	27 Jan	0800-2000	22°44.8'	111°24.9'	12.0	141°	12°	1440 19° 1440
B	27-28 Jan	2000-0600	22°27.5'	110°31.0'	10.0	064°	12°	1200 19° 1200
C	28 Jan	0700-2400	21°50.4'	110°02.2'	17.0	186°	13°	2160 19° 2040
D	29 Jan	0000-1000	21°09.9'	109°35.5'	10.0	076°	12°	1200 20° 1200
E	29 Jan	1000-2200	21°46.3'	109°16.4'	12.0	336°	12°	1400 20° 1400
F	30 Jan	1000-2200	22°20.2'	108°42.1'	12.0	131°	13°	1440 19° 1440
G	30-31 Jan	2200-0800	22°22.2'	107°57.9'	10.0	033°	13°	1200 20° 1200
H	31 Jan	0800-2000	22°54.1'	108°16.5'	12.0	284°	13°	1440 20° 1440
I	1 Feb	0300-1000	23°35.7'	108°49.9'	7.0	063°	12°	840 17° 840
J	1 Feb	1000-1500	23°36.7'	108°25.4'	5.0	143°		18° 600
K	1 Feb	1500-1700	23°29.2'	108°13.5'	2.0	089°	12°	240 19° 240
L	1 Feb	1700-2100	23°20.4'	108°01.6'	4.0	146°		19° 480
M	1-2 Feb	2100-0355	23°12.4'	107°33.8'	6.9	088°	12°	831 19° 830
N	7 Feb	1100-2032	22°30.6'	106°52.3'	9.5	187°	13°	1146 20° 1165
O	7-8 Feb	2040-0740	22°17.0'	107°30.7'	11.0	302°	12°	1326 20° 1322
P	8 Feb	0740-1945	22°52.3'	108°38.2'	12.1	297°	12°	1455 20° 1442

TABLE 2 (Continued).

Data Sample (Section)	Date (1962)	Time	SECTION		Duration (hr)	Average Direction (true)	Isotherm Used (°C) and Total Data Points		
			Central Position °N	°W			Deep		Shallow
Q	9 Feb	0100-1300	22°19.3'	109°00.9'	12.0	133°	12°	1440	19° 1440
R	9 Feb	1300-2400	21°25.3'	108°04.4'	11.0	138°	13°	1320	20° 1320
S	10 Feb	0000-1049	20°37.8'	108°08.9'	10.8	234°	13°	1300	20° 1296
T	10 Feb	1050-2250	20°56.0'	108°53.7'	12.0	341°	13°	1451	20° 1442
U	10-11 Feb	2250-0800	22°03.1'	109°17.8'	9.2	342°	13°	1110	20° 1100
V	11 Feb	1310-2400	22°10.7'	109°53.8'	10.8	183°	13°	1305	20° 1300
W	12 Feb	0000-1110	20°58.8'	109°58.4'	11.2	184°	13°	1341	20° 1342
X	12 Feb	1110-2330	20°37.7'	110°28.9'	12.5	302°	13°	1485	20° 1500
Y	12-13 Feb	2330-1130	21°31.3'	110°37.8'	12.0	025°	13°	1440	20° 1440
Z	13-14 Feb	1515-0117	22°28.1'	110°41.6'	10.0	261°	13°	1206	20° 1236
AA	14 Feb	0130-1330	22°49.6'	111°39.5'	12.0	322°	12°	1440	20° 1440

Differences of Depth Values (Isotherm Slopes)

The first method of presenting isotherm variability is by depth differences from point to point along selected isotherms. The isotherm depths were scaled from the original record at half-minute intervals.

SELECTION OF SLOPE INTERVALS

From each section shown in table 2 (except J and L), two isotherms were chosen for analysis. One of the selected isotherms was located in the main thermocline and the other below it. Of two isotherms analyzed in part of section Q (fig. 16), the temperature of the shallower one in the main thermocline was 19°C and in the deeper one below the main thermocline, 12°C.

The depth differences from point to point along the isotherms were determined from the formula

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

$$1 \leq k \leq N$$

X_i and X_{i+1} are depths (in 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 (in feet). When the isotherm is falling, the difference is negative.

From ship speed and depth difference, approximate slopes can be calculated. At a speed of 6 knots, the ship traveled 304 feet in each half-minute interval; therefore dividing the depth differences by 304 feet gave the slope of the isothermal surface in the direction of the ship's motion. The slope could also be expressed by the angle having this slope for a tangent.

From 240 to 2040 consecutive observations of isotherm depths were taken from each sample section. The distribution of depth changes and the slopes for each selected isotherm on each 2-17 hour section were diagrammed as a cumulative frequency curve of depth changes and slope angle (Appendix B).

SEA SURFACE

Figure 16. Original data from which 1/2-minute depth readings of the 19°C and 12°C isotherms were obtained (Section Q, fig. 15).

The graphs show that, in several of the isotherms, half-minute depth changes as large as plus or minus 30 feet were observed within 304 feet, which correspond to a slope angle of $5^{\circ}40'$. However, 24.3 percent of the adjacent half-minute readings showed changes of less than one-half foot for the shallower isotherm; 16.6 percent showed changes of less than one-half foot for the deeper isotherm.

An example of a single cumulative frequency curve of depth differences (fig. 17) represents data derived from section Q (fig. 16). The change in depth of the 19°C isotherm may be plus or minus with distance. To derive a meaningful value for a large sample of slopes, the 50th and 70th percentiles were chosen. The frequency distribution shows that for the shallower isotherm the

Figure 17. Cumulative percentage distribution of differences in depth between half-minute or 304-foot-spaced readings of the 19°C isotherm (Section Q). The 25th and 75th percentiles delineate the central 50 percent of data; the 15th and 85th percentiles delineate the central 70 percent.

25th and 75th percentile depth changes are -2.3 and +2.5 feet; thus in 50 percent of the cases the change is less than 2.4 feet (in absolute value) in a horizontal distance of 304 feet. The 15th and 85th percentile changes occur at -4.7 and +4.8 feet, with 70 percent of the data in this range. The corresponding vertical angles are less than $0^{\circ}27'$ (in absolute value) for the central 50 percent of the cases and less than $0^{\circ}54'$ for the central 70 percent of the data. The example is a nearly typical case because the median of the absolute values of the slope of more than 65,000 data samplings is $0^{\circ}25'$, and the 70th percentile of the absolute values of the slope is $0^{\circ}51'$.

As a measure of depth-change variability in the entire area, the values of depth changes per 304 feet, which corresponded to the 25th and 75th percentile, were scaled from each of the cumulative percentage distributions (Appendix B). The absolute values were averaged as was done in the single example (fig. 17). The 15th and 85th percentiles were also determined and averaged. This is analogous to the "significant wave" method whereby the upper 30 percent is "average." However, these values represent a depth change greater in absolute value than 70 percent of the observations.

As an alternate treatment, a cumulative percentage distribution curve could be plotted for the absolute values of depth differences. The new 70th percentile change would agree almost exactly with the average of the absolute values of the 15th and 85th percentiles. Hence the average will be designated 70th percentile of absolute value of depth change (absolute-value 70th percentile — depth change). Likewise, the 50th percentile in an alternate treatment would agree with the average of the absolute values of the 25th and 75th percentiles, and that average will be designated absolute-value 50th percentile — depth change.

DISTRIBUTION OF SLOPE

The frequency distribution and cumulative frequency of all slope data on isotherms, both shallow and deep, are presented (fig. 18). The cumulative frequency is based on 65,000 data points and summarizes the isotherm slope in the entire area around the tip of Baja California. The cumulative frequency curve shows that

Figure 18. Frequency distribution of all slopes in foot drop per 304-foot travel for both shallow and deep isotherms separately, and cumulative percentage distribution of both shallow and deep isotherms together (65,132 data points).

the isotherm waves are nearly symmetrical, with the absolute-value 50th percentile being the average of absolute values down slope, 2.17 feet, and up slope, 2.22 feet per 304 feet of travel. This corresponds to an absolute-value average median slope of $0^{\circ}25'$. The absolute-value 70th percentile comes from a 4.52-foot down-slope and a 4.57-foot up-slope change over the same distance, and corresponds to an average absolute-value median slope of $0^{\circ}51'$. The Baja California waters thus contain much steeper isotherms than does the open Pacific, where the 50th percentile of absolute values of slope was $0^{\circ}16'$ and the 70th absolute-value percentile, where the value is $0^{\circ}30'$.³

Some difference exists in the frequency distribution curves of depth changes for the shallower and deeper isotherms. The deeper isotherms show a flatter curve with fewer zero values and more high slope values than do the shallow ones, which means

that the deeper isotherms undergo greater vertical oscillations per unit distance.

Since the distribution of values is not skewed, the oscillations can be approximated by a sine curve of the form $Z = Z_0 + A \sin(kx + wt)$. The second term for the shallower isotherm is approximately equal to $1/119 \sin(kx + wt)$, whereas the deep isotherm is $1/84 \sin(kx + wt)$. The total of the 65,000 observations (fig. 17) is about $1/100 \sin(kx + wt)$.

DIRECTION OF SLOPE

If there is a dominant direction to internal-wave propagation in the thermocline, the absolute-value 50th percentile of slope should be greater when (1) the tow is opposite to the direction of propagation, or (2) in the same direction as the waves if the ship speed is much greater than that of the waves. The slope values would be expected to be relatively small when the ship is running parallel with the crests or troughs.

Although the data samplings are not distributed equally in all directions of tow, there is considerable spread around the compass and in different areas. The steepness of the thermocline may be related to the direction of tow. To show this relationship, the computed absolute-value 50th percentile of slope for each section of isotherm depth is plotted with reference to the direction of tow (fig. 19, open points). The individual values are marked A to AA corresponding to the sections shown (fig. 15). A wide fluctuation of median slopes is present in all directions of tow. The absolute-value median slopes range from less than 10 minutes (0.9 foot change per 304 feet of travel) to over 52 minutes (4.7 foot change per 304 feet of travel). The average slope value of all data was 25 minutes, which is higher than the average of 16 minutes measured on a previous cruise between San Diego and Honolulu.³

A similar presentation of the absolute-value 70th percentile slope values for the shallow isotherm of each section is also given (fig. 19, solid points). The results show that this percentile angle varies from $0^{\circ}17'$ to $1^{\circ}37'$.

To smooth the values and demonstrate any dependence on the towing direction, data were averaged by 45-degree increments of direction of tow and the averages were connected by a solid line for

Figure 19. Direction of tow vs overage median vertical isotherm angle derived from differences in depth between the half-minute or 304-foot-spaced depth readings. Curve represents isotherm slopes overaged by 45-degree groupings.
 (A) Upper: 70th percentile of absolute value of isotherm slope in the main thermocline. Sample values in solid points.
 (B) Lower: 50th percentile of absolute value of isotherm slope in the main thermocline. Sample values in open points.

the 50th percentile and for the 70th percentile (fig. 19). Although considerable variability in the changes in the vertical angle was shown in both the 50th and 70th absolute-value percentile slope, the 50th absolute-value percentile values in the shallow isotherm have a higher average when the towing is to the north or southwest. This would imply that the vertical wave crest structures in shallower parts of the thermocline were oriented more to the east and west.

A scatter plot showing the relationship between the average direction of tow (degrees) on the x-axis and the percentage of hauls with a certain number of fish on the y-axis. The x-axis ranges from 45 to 360 degrees. The y-axis ranges from 0 to 100 percent. Two lines represent the 50th and 70th percentiles. Data points are labeled with letters A through Z. The 50th percentile line starts at approximately 45 degrees (0%), rises to a peak of about 65% at 135 degrees, then falls to a minimum of about 10% at 315 degrees, and rises again to about 30% at 360 degrees. The 70th percentile line starts at approximately 45 degrees (0%), rises to a peak of about 85% at 225 degrees, then falls to a minimum of about 20% at 315 degrees, and rises again to about 50% at 360 degrees. Data points are scattered around these lines, with some points (like A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z) falling above the 70th percentile line and others (like A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P, Q, R, S, T, U, V, W, X, Y, Z) falling below the 50th percentile line.

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towing direction. The resulting slope curve with reference to direction of tow is shown (fig. 21). The similarity of orientation implies that the vertical wave-like structures, or internal waves, are oriented more to the east and west because the slopes are steeper when they are crossed during towing normal to their crests. Since the steeper values occur towing to the south and southwest, it would seem that the propagation of dominant internal waves was northward and into the Gulf of California.

Figure 21. Average 50th percentile slope of deep and shallow isotherms; 45-degree grouping vs direction of tow.

GEOGRAPHIC DISTRIBUTION

To be comparable with other sample sections, and to give a geographic distribution of the measure of isotherm slope, the absolute-value 50th and 70th percentiles of vertical change per 304 feet for the selected isotherms in the main thermocline were spatially plotted (figs. 22A and 22B). These median changes in depth are located at a geographic position corresponding to the center of the line of tow (fig. 15). The distribution of slopes is contoured.

When widely spaced values are contoured, an option may exist of where the contour could be drawn. In such event, the contour can be made to cross itself, indicating both options. The areas of steepest isotherms, however, were clearly defined and the choice was not necessary. The contoured values for the

A

Figure 22. Geographical distribution of difference in depth between the half-minute or 304-foot-spaced depth readings of the shallower isotherms.
(A) Upper: 50th percentile of absolute value of isotherm slope in the main thermocline.
(B) Lower: 70th percentile of absolute value of isotherm slope in the main thermocline.

shallower isotherm vary from 1 to 4 feet (per 304 feet of travel) for the 50th percentile and from 2 to 8 feet for the 70th percentile. The relation of vertical change to angle is given in table 3.

TABLE 3. CUMULATIVE DISTRIBUTION OF SLOPES OF ISOTHERMS (DEEP AND SHALLOW ISOTHERMS)

Depth Change Per 304 Feet	Angle From Horizontal	Percent of Observations
>5	> 0°56'	11.6
5	0°56'	3.5
4	0°45'	3.5
3	0°34'	4.4
2	0°23'	6.3
1	0°11'	10.2
0	0°0'	20.5
-1	-0°11'	10.5
-2	-0°23'	6.4
-3	-0°34'	4.4
-4	-0°45'	3.5
-5	-0°56'	3.5
<-5	< -0°56'	11.7

The plots show that the isotherm in the main thermocline has higher values, or a rougher thermocline, in the region extending south and southeast from Baja California. About 100 miles off the point, a wide band of water, running northeast-southwest, showed a smoother thermal structure. Farther off-shore, the roughness increased slightly.

A similar presentation was made of the deeper-isotherm slope. The geographic distribution of the absolute-value 50th percentile is shown (fig. 23A) with contours ranging from 2 to 3.5 feet (per 304 feet of travel). The absolute-value 70th percentile values range from 3 to 6.5 feet (fig. 23B). Both contours show

Figure 23. Geographical distribution of differences in depth between the half-minute or 304-foot-spaced depth readings of the deeper isotherms.

(A) Upper: 50th percentile of absolute value of isotherm slope below the main thermocline.

(B) Lower: 70th percentile of absolute value of isotherm slope below the main thermocline.

that the higher values form a zone directly off southern Baja California. The low-value contours occurring in the northeast-southwest zone lie in the same position. Of all isotherms considered, those recorded from the region 60 miles to the south-southeast from the extremity of the peninsula are generally steeper and show more variability than those elsewhere in the area.

Autocorrelation of Depth Values

Another method of measuring subsurface temperature variability is by means of autocorrelation coefficients.¹⁸ By using the same half-minute isotherm depth data, autocorrelations were computed for each selected isotherm and section of Cruise 8. Successive pairs of points at equal but overlapping time intervals were tested for correlation with each other, and the process was repeated for each time interval, increasing by half-minute steps from one-half minute to 72 minutes (144 lags) or 10 percent of the number of data points. Autocorrelation, R_λ , was computed for increasing intervals of λ , each interval increased by 304 feet (half minute), using the expression:

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

where, in general, $\lambda = 0, 1, 2, \dots, 144$ lag intervals and N = total number of depth recordings in a run. N is usually 1440 and the maximum value of λ is $N/10$. The computed autocorrelations of the selected isotherms on each sample section were plotted for comparison (Appendix C).

One example of the 52 autocorrelations (fig. 24) is from data derived from section Q (fig. 15). Starting with zero lags (zero minutes) the autocorrelation R_λ is 1.0, but as the lags increase, the correlation becomes less. In some cases the

Figure 24. Autocorrelation of successive half-minute readings of the depth of the 19°C isotherm (Section Q). The 60-lag (30-minute) and 120-lag (60-minute) values are indicated ($\lambda = 60$ and 120, respectively).

values are negative. In the example, the value of R_λ after 60 lags is reduced to 0.66; after 120 lags R_λ , 0.33; and after 144 lags R_λ , 0.22. There are no dominant peaks in the curve.

To summarize the autocorrelation of successive depth changes with time and distance, two points were scaled off the individual plots of autocorrelation, one at 60 lags (30 minutes) and another at 120 lags (60 minutes) (table 4).

TABLE 4. AUTOCORRELATION R_λ OF SUCCESSIVE HALF-MINUTE READINGS OF ISOTHERM DEPTH IN MAIN THERMOCLINE (SHALLOW) AND ISOTHERM BELOW MAIN THERMOCLINE (DEEP) (Continued on page 50)

Section	$\lambda = 60$ Lags (30 minutes)		$\lambda = 120$ Lags (60 minutes)	
	Shallow	Deep	Shallow	Deep
A	0.59	-0.02	0.31	-0.12
B	0.70	0.45	0.43	0.30

TABLE 4 (Continued)

Section	$\lambda = 60$ Lags (30 minutes)		$\lambda = 120$ Lags (60 minutes)	
	Shallow	Deep	Shallow	Deep
C	0.76	0.80	0.61	0.69
D	0.15	0.19	-0.03	0.04
E	0.66	0.27	0.49	0.09
F	0.76	0.68	0.69	0.58
G	0.63	0.86	0.35	0.78
H	0.28	0.56	0.08	0.37
I	0.44	0.17	---	---
J	---	---	---	---
K	---	---	---	---
L	---	---	---	---
M	0.74	0.67	---	---
N	0.45	0.33	---	---
O	0.79	0.37	0.60	0.06
P	0.78	0.48	0.68	0.24
Q	0.66	0.63	0.33	0.53
R	0.73	0.48	0.39	0.41
S	0.53	0.34	0.15	0.10
T	0.65	0.84	0.55	0.65
U	0.58	0.53	---	---
V	0.58	0.24	0.33	-0.21
W	0.16	0.83	-0.18	0.80
X	0.50	0.47	0.33	0.32
Y	0.87	0.72	0.77	0.59
Z	0.39	0.57	---	0.45
AA	0.65	0.47	0.53	0.22

GEOGRAPHIC DISTRIBUTION

To be comparable with other sample sections, and to give a geographic distribution of autocorrelation values of successive measured isotherm depths, the 60-lag and 120-lag R_λ values for the shallower isotherm were plotted at a geographic position corresponding to the tow center line (figs. 25A and 25B). These values are contoured with R_λ values ranging from 0.3 to 0.7 for 60 lags (30-minute) of the shallower isotherm. The 120 lags (60-minute) of the same isotherm vary from -0.1 to 0.8. Both geographical distributions are similar, but no clearly significant geographic distribution of values exist as in the grouping of slope values. There is, however, a tendency for low values to fall near the southern end of Baja California and extend to the south-east.

In the corresponding R_λ for deep isotherms, no definite areas of high and low correlation of the 60 and 120 lags (figs. 26A and 26B) are outstanding. The strikingly low correlation area is caused by only one or two values.

A

B

Figure 25. Geographic distribution of autocorrelation of successive half-minute readings of isotherm depth in the main thermocline.

(A) $\lambda = 60$ lags (30 minutes).

(B) $\lambda = 120$ lags (60 minutes).

A

B

Figure 26. Geographic distribution of autocorrelation of successive half-minute readings of isotherm depth below the main thermocline.

(A) $\lambda = 60$ lags (30 minutes).

(B) $\lambda = 120$ lags (60 minutes).

Power Spectrum of Depth Values

The third method of representing variability is by the power spectrum.^{13, 14, 15, 16} The power spectrum $U(h)$ is given by the Fourier transform of the autocorrelation, R_λ . It is the energy (1/2 amplitude squared) per unit bandwidth* and thus emphasizes the bandwidths in which the dominant frequencies occur. The smoothed power spectrum values were obtained as follows:

$$U(h) = \frac{1}{n} \left[R(0) + \sum_{\lambda=1}^{\lambda=n-1} R(\lambda) \left(1 + \cos \frac{\pi \lambda}{n} \right) \cos \frac{\pi \lambda h}{n} \right]$$

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

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

The power spectra computed from half-minute readings of isotherm depth are given (Appendix D). Each plot is a spectrum of the variations in depth of single isotherms listed (table 2).

One example of the computed power spectrum (fig. 27) is based on the depth of the 19°C isotherm of section Q (fig. 15). The importance of the power spectrum lies in the curve peaks that indicate frequencies (or periods) in the original data which may have been obscured by background noise. It is significant that this example of power spectrum has several peaks or peak

*The units for $U(h)$ used here are feet²/cycles per min. and $U(h)$ might better be designated as variance.

Figure 27. Power spectrum from successive half-minute readings of the depth of the 19°C isotherm (Section Q, fig. 15). The peaks and zones of higher power are indicated.

zones ranging in frequency* from 0.049 to 0.270 cycle per minute, which is equivalent to a period of 20.4 to 3.7 minutes or a wavelength of 2.04 to 0.37 nautical mile. When the peaks are wide they are considered zones; for example, 0.090 to 0.110 cycle per minute (or 1.11- to 0.91-mile wavelengths) and 0.182 to 0.200 cycle per minute (or 0.55- to 0.50-mile wavelengths) are considered zones or wide bandwidths.

The power spectrum curve shows that the greatest power is in the low frequencies without peaks. The number of degrees of freedom is given by $\nu = \frac{2N}{n} - \frac{1}{2}$. When 1440 consecutive depth sample values and 144 lags are used, $\nu = 19.5$. The corresponding ratio of computed to true value¹⁷ falls between 0.54 and 1.60 for 90-percent confidence limits.

The ratio of background to peak height was determined by constructing a base line and vertical height (fig. 27). For example, the 3.7-minute-period peak of the 19° isotherm depth has a peak-to-background ratio of 82 to 50, or 1.64, which is significant, whereas the 9.1-minute-period peak in the peak zone (fig. 27) has a ratio of 1.38, which is not significant.

DIRECTIONAL POWER SPECTRUM

To summarize the power spectrum, the peaks and peak zones were read from the individual power spectrum graphs, and the peak-to-background ratio was computed and listed (fig. 28) for the data sections with the isotherm in the thermocline and (fig. 29) for data sections with the isotherm below the thermocline.

*Here the sampling chain is moving through a quasi-stationary field of internal waves and the frequencies discussed are frequencies of encounter. The wavelengths are nominal and computed from the ship speed of 6 knots, assuming that the internal waves are essentially stationary, i.e. moving much slower than 6 knots. Broad peaks (or peak zones) should be expected as often as narrow peaks if the internal waves are traveling in all directions; e.g. if internal waves of only a very narrow band of frequencies arrived from all directions, the straight track of the ship would intercept apparent wavelengths corresponding to a broad band of frequencies.

Figure 28. Summary of direction of tow distributions of power spectrum from successive half-minute readings of isotherm depth in the main thermocline (shallower isotherm). Circled are the more significant ratios.

In both graphs, the values were arranged with reference to direction of tow and frequency.

The ordinate is frequency (cycles per minute) and the abscissa is direction of tow. If the tow direction creates a Doppler effect, the dominant frequencies would shift with the direction of tow. All the peak-to-background power spectrum values of the shallow isotherm (fig. 28) that were derived from the power spectrum plots are entered. Each peak ratio is numerically identified, and peak zones of high values are connected with a dashed line. Some sample sections have nearly the same direction of tow and are thus plotted near each other. The highest values (over 1.6) are circled to emphasize the most important and to more easily relate them to direction and frequency. Values greater than 1.6 are considered significant in

Figure 29. Summary of direction of tow distributions of power spectrum from successive half-minute readings of isotherm depth below the main thermocline (deeper isotherm). Circled are the more significant ratios.

accordance with the 90-percent confidence limits. The important circled points fall at all frequencies and all directions of tow.

The values show that the zones of significant frequencies of vertical changes in isotherm depths vary widely from sample to sample. No power spectrum peak ratio to background value exceeds 2.5. The higher values appear to be distributed in patches.

A similar presentation of the deeper isotherm power spectrum (fig. 28) shows the circled higher peak values again occurring at all directions of tow. However, slightly more values over 1.6 at the higher frequencies are apparent, especially when towing to the east or south. This contrasts with the omnidirectional distribution of the shallow-isotherm power spectrum.

GEOGRAPHIC RELATIONSHIP OF POWER SPECTRUM

To show a general relation of the power-spectrum peak values over the background to geographic location, the values were plotted with reference to longitude. The purpose was to determine if the internal waves in the Gulf of California (along lower longitudes) had specific frequencies different from those in the open Pacific (along higher longitudes). Peak to background values of 1.6 and greater are circled (fig. 29).

For the shallow isotherms (fig. 30), no shift in significant

Figure 30. Summary of longitudinal distribution of power spectrum from successive half-minute readings of isotherm depth in the main thermocline (shallower isotherm). Circled are the more significant ratios.

frequency with longitude is apparent. A slightly greater concentration of high ratios falls between 108°W and 109°W in the area where a water-mass boundary is expected (south-southeast of Cape San Lucas).

The power spectrum for the deep isotherm (fig. 31) contains more high ratios in the central part of the area 108°-110°W. There is only a slight relationship of significant power spectrum values to longitude in these data.

Figure 31. Summary of longitudinal distribution of power spectrum from successive half-minute readings of isotherm depth below the main thermocline (deeper isotherm). Circled are the more significant ratios.

TOTAL POWER SPECTRUM

The relative power in the power spectrum was determined approximately by integrating under the curve of the power spectrum for the frequency band between 0.05 to 0.30 cpm.

$$U_B = \int_{0.05}^{0.30} U(h) df$$

An example of the power in this band at section Q (fig. 15) is shown (fig. 32). The integrated values in the band 0.05 to 0.30 cpm are plotted with reference to their geographic position (figs. 33 and 34) and the values are contoured. In the shallow isotherm the values for the integrated power in the band, U_B , that fall between 0.05 and 0.30 cpm vary from 104.5 to 19.2 ft².

The geographic distribution of U_B (fig. 33) shows the values decreasing with increasing distance. The inverse relationship of U_B to distance finds the highest values of U_B nearest the southern end of Baja California. In the deep isotherm, the values U_B for the integrated curve are between 136.6 and 16.8 cpm. The higher values also fall near the end of Baja California and to the south. The distribution may be interpreted as a measure of thermal structure roughness similar to that for wave lengths and the slope.

Figure 32. Total power spectrum in the band between 0.05 to 0.30 cpm. Data are from half-minute readings of depth of 19°C isotherm (Section Q, fig. 15).

Figure 33. Geographic distribution of the integrated power spectrum of frequencies between 0.05 and 0.30 cpm from successive half-minute readings of isotherm depth in the main thermocline (shallower isotherms).

Figure 34. Geographic distribution of the integrated power spectrum of frequencies between 0.05 and 0.30 cpm from successive half-minute readings of isotherm depth below the main thermocline (deeper isotherm).

Turbulence

Variation in isotherm depth may be a turbulence phenomenon.¹⁵ This supposition is based on evidence that energy is transferred from one spectrum component to another through its transfer from large to small turbulent eddies. In larger eddies, energy is received from an external driving force; in the smallest eddies the same energy is transformed into heat. But a subrange of eddy motion, which participates neither in energy loss nor gain, passes the energy of large eddies to small eddies where it is finally transformed. Within such a subrange, the spectrum function must theoretically have the form:²¹

$$E(k) = B\epsilon^{3/2}k^{-5/3}$$

where (k) = the wave number
 $E(k)$ = the power spectrum function
 ϵ = the rate of conversion of turbulent energy to heat
 B = a constant

If a constant value of ϵ is assumed to lie in this subrange, the spectrum $E(k)$ plotted as a function of k on a log-log scale must have a slope of $-5/3$. A curve of this slope (in the appropriate units of fig. 35) has been superimposed on the power spectrum results of the 19° isotherm depths of section Q (fig. 15).

This was done by using the following substitution to change the units of the plot from wave number to frequency: $k = f/c$, where c is the ship's speed. Then the above equation may be rewritten as

$$\frac{1}{c} E(f) = B\epsilon^{2/3} \left(\frac{1}{c}\right)^{-5/3} f^{-5/3}$$

And assuming B , ϵ , and c are constants; the frequency spectrum would have the form

$$E(f) = Mf^{-5/3}$$

where M is a constant in the inertial subrange.

The Kolmogorov spectrum deals with three dimensions whereas the above data have been measured in only one dimension. The vertical stability of the ocean and reduced horizontal stability indicate anisotropic turbulence. However, if horizontal

Figure 35. Power spectrum from successive half-minute readings of the depth of 19°C isotherm (Section Q). The slope $-5/3$ in the log-log plot is indicated as well as the slope (-1.356) estimated from the power spectrum.

isostropy is assumed, then the spectral densities in one horizontal direction would represent the spectrum in any horizontal direction; thus the numerical value of slope is the same as for the log-log plot of $U(h)$ vs frequency.

The slopes were found by visually fitting a straight line through the central part of the log-log points of the power spectrum. The visually fitted curve for section Q data (fig. 35) has a slope of -1.36, which lies close to the -1.67 curve. The data from section Q are approximately average for the area under consideration. The slope values for all the data sections are listed (table 5).

To obtain an overall plot of power spectrum, 25 sets of data for the shallower isotherm are averaged together and plotted (fig. 36). A similar average power spectrum for the deeper isotherm is also included. Since these data are for a wide range of towing directions and cover different areas, they may be considered representative power spectrum curves.

The averaged curves show no distinct peaks in the central part of the limited frequency range (0.05-0.30 cpm). Both curves have a slope which approximates the -5/3 reference curve, and this close relationship may be indicative of turbulent motion in accordance with the Kolmogorov theory. There are, however, small peaks in both average power spectra around 0.15 cpm (0.66 mile) and 0.3 cpm (0.33 mile) in the shallower isotherm spectrum, which indicates these to be the dominant frequencies. Individual power spectrum curves have more significant breaks in this frequency range, but at varying frequencies, which are nearly smoothed out in the average plot (fig. 36).

TABLE 5. SLOPE OF LOG-LOG RELATIONSHIP BETWEEN POWER SPECTRUM AND FREQUENCY OF DEPTH OF ISOTHERM IN MAIN THERMOCLINE (SHALLOW) AND ISOTHERM BELOW MAIN THERMOCLINE (DEEP) (Continued on page 68)

Section	Shallow Iso- therm Slope M	Deep Iso- therm Slope M
A	-1.19	-1.75
B	-1.74	-1.91

TABLE 5 (Continued).

Section	Shallow Iso- therm Slope M	Deep Iso- therm Slope M
C	-1.67	-1.83
D	-1.78	-2.09
E	-1.59	-1.77
F	-1.53	-1.71
G	-1.82	-1.89
H	-1.40	-2.09
I	-1.23	-1.83
J	-2.06	---
K	-1.94	-2.21
L	-2.59	---
M	-1.51	-2.12
N	-1.56	-1.68
O	-1.51	-1.74
P	-1.81	-2.00
Q	-1.36	-2.10
R	-1.53	-1.53
S	-1.36	-1.62
T	-1.94	-1.90
U	-1.13	-1.83
V	-1.49	-1.69
W	-1.61	-1.54
X	-0.66	-1.65
Y	-1.67	-1.81
Z	-1.64	-1.62
AA	-1.74	-1.98

Figure 36. Average power spectrum of 25 shallow and 25 deep isotherm depths. The slope of $-5/3$ in the log-log relationship is indicated.

GEOGRAPHIC DISTRIBUTION

From the power spectrum slopes of each data sample a geographic distribution of slope values for the shallower isotherm is presented (fig. 37). Values of power spectrum slopes range from -0.66 to -1.94 . The lower values are generally near the coast and describe a pattern similar to that of other variables. A similar geographic distribution of the deeper-isotherm slope values (fig. 38) is more irregular than that of the shallower one and has slightly smaller values.

Figure 37. Geographic distribution of slope of power spectrum curve from successive half-minute readings of isotherm depth in the main thermocline (shallower isotherm) (frequencies 0.05 to 0.30).

Figure 38. Geographic distribution of slope of power spectrum curve from successive half-minute readings of isotherm depth below the main thermocline (deeper isotherm) (frequencies 0.05 to 0.30).

RECOMMENDATIONS

1. Continue development of the thermistor chain to improve the quality, accuracy, and reliability of oceanographic data.
2. Investigate the use of additional sensors (in conjunction with temperature) on the thermistor chain for measuring current, turbidity, sound velocity, and salinity.
3. Study, by means of the thermistor chain, the nature of internal waves and the effects on thermoclines of islands, shoals, coastal configurations, tides, known currents, upwelling, water-mass boundaries, storms, and seasons.
4. Determine, by use of the thermistor chain and partially known sea temperature structures, the most persistent oceanic regions of smooth, normal, rough, and irregular thermoclines, and study the effects of such structures on sound transmission.

SUMMARY AND CONCLUSIONS

The two-dimensional investigation with the thermistor chain of 27 sections of temperature structure off Baja California provides new detailed data on the upper layers of the sea and makes it possible to determine the processes of differential water motion, turbulence, and apparent Doppler effect.

The isotherm slope at two levels in the 27 locations revealed that the median value generally became steeper when the towing was to the north or south, which implies an east-west orientation of wave-like fluctuations in the thermocline. Similarly, the deeper of the two isotherms, selected where the vertical temperature gradient was weak, had more larger vertical angles than did the shallower one. A wavelength between 1400-2400 feet is common for thermocline oscillations. This corresponds to a frequency of $2\frac{1}{2}$ -4 minutes, or near the Väisälä frequency.

The autocorrelation of successive depth values of given isotherms decreased more rapidly when the towing was to the east or west. The power spectrum of isotherm depth showed peaks at varying frequencies. The higher, more significant peaks appear to be most numerous in the zone marked by an

underseas extension of the extremity of Baja California. This corresponds to the water-mass boundary between the Gulf of California Water and two other bodies of water, the California Coastal Current Water and the Tropical Pacific Water.

Log-log plots of power spectra averages for each of the shallower and deeper isotherms result in nearly straight lines. A small change in slopes occurs around 0.15 cycle per minute (cpm) for both curves and 0.30 cpm for the shallower curve. The overall slopes appear to be near $-5/3$, which may mean that the thermal structure is partly a turbulence phenomenon in the frequency range between 0.05 and 0.30 cpm.

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APPENDIX A

THERMAL STRUCTURES (FIGS. A1-A30)

Smooth (long wavelengths)

A1 to A8

Normal (average wavelengths)

A9 to A14

Rough (short wavelengths)

A15 to A20

Displaced (shifted or buckled)

A21 to A30

SEA SURFACE

A-1

SEA SURFACE

A-2

Examples of smooth thermal structures.

SEA SURFACE

SECTION G

A-3

SEA SURFACE

SECTION H

A-4

SEA SURFACE

SECTION L

A-5

SEA SURFACE

SECTION O

A-6

SEA SURFACE

SECTION T

3 MI

~ 100 FT

12°

A-7

SEA SURFACE

25°

SECTION W

3 MI

~ 100 FT

12°

A-8

SEA SURFACE

A-9

SEA SURFACE

A-10

Examples of normal thermal structures.

SEA SURFACE

SEA SURFACE

SEA SURFACE

A-13

SEA SURFACE

A-14

SEA SURFACE

A-15

SEA SURFACE

A-16

Examples of rough thermal structures.

SEA SURFACE

A-17

SEA SURFACE

A-18

SEA SURFACE

A-19

SEA SURFACE

A-20

SEA SURFACE

SECTION Z

A-21

SEA SURFACE

SECTION E

A-22

Examples of displaced thermal structures.

SEA SURFACE

A-23

SEA SURFACE

A-24

SEA SURFACE

A-25

SEA SURFACE

A-26

SEA SURFACE

A-27

SEA SURFACE

A-28

SEA SURFACE

SEA SURFACE

APPENDIX B

ISOTHERM DEPTH DIFFERENCES (FIGS. B1-B52)

FREQUENCY DISTRIBUTION OF ISOTHERM SLOPES DERIVED
FROM DIFFERENCES IN DEPTH OF ISOTHERMS (SLOPES) AT
HALF-MINUTE (304-FOOT) INTERVALS

APPENDIX C

ISOTHERM DEPTH AUTOCORRELATION (FIGS. C1-C52)

AUTOCORRELATIONS, R_{λ} , FROM DIFFERENCES IN DEPTH OF
ISOTHERMS AT HALF-MINUTE (304-FOOT) INTERVALS

APPENDIX D

ISOTHERM DEPTH POWER SPECTRA (SEMI-LOG) (FIGS. D1-D52)

POWER SPECTRUM $U(h)$, FROM DIFFERENCES IN DEPTH OF
ISOTHERMS AT HALF-MINUTE (304-FOOT) INTERVALS ON
SEMI-LOG SCALES

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