This behavior presents an interesting example of the value of Rx tests in demonstrating system characteristics unlikely to have been revealed by theoretical studies, although the elimination of cyclic pitching has now led to the virtual disappearance of cyclic rolling.

Conclusion

The Rx craft was designed originally to undertake parametric studies on a wide variety of hydrofoil systems, but her greatest use has been in exhaustive testing of the particular system developed for HMCS "Bras d'Or" and, particularly, in the development of a superventilating bow foil unit. The soundness of the original Rx design was demonstrated by her ready adaptability as a quarter-scale version of this ship, and she gave yeoman service by demonstrating in a practical way the capabilities of the system in rough water. She not only verified important design techniques and data but gave positive evidence of certain unexpected deficiencies and assisted greatly in their rectification. This experience has emphasized the value of a large-scale manned model with six degrees of freedom in the development of advanced ocean vehicles, and such open-water trials are considered an essential and integral part of the design process.

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Internal Thermal Structures in the Ocean

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Advanced equipment makes possible the acquisition of a continuous two-dimensional thermal structure of the upper 240 m of the sea. Shallow-water temperature data were recorded at the Navy Electronics Laboratory Oceanographic Research Tower from horizontally and vertically mounted arrays of thermistor beads. Deep-water temperature data were recorded by a 900-ft towed thermistor chain mounted on the USS Marysville. Detail of these structures reveals many oceanographic processes such as internal waves, turbulence, oceanographic fronts, upwelling, and other types of water motion. The internal structure of both shallow and deep water is made up of a broad spectrum of waves. One dominant oscillation is close to the Väisälä frequency. Common wavelengths fall between 500–800 m in deep water but shorten as they refract across the continental shelf. The wavelengths and direction of propagation are influenced by density and topographic boundaries. Near shore, the changes in depth and strength of the thermal structure are largely controlled by wind transport, in accordance with the Ekman effect. Some internal structures can be ascertained from sea surface slicks and recordings made with airborne infrared equipment.

Introduction

THE ocean is a composite of many relatively thin layers, each exhibiting different properties. The lightest layer is uppermost, and the more dense layers lie progressively deeper in the sea. These layers are neither flat nor still; they slope in ever-changing patterns of depth, thickness, and angle. Most layers tilt less than one-half deg, but this small shift is a significant clue to many of the internal processes of the sea. Even these small angles which change with time and space can alter the direction of sound rays passing through the boundary layers and influence the bearing and range accuracy of acoustic detection. Changes in internal temperature structures therefore become of primary interest.

The most informative feature of the ocean for acoustic studies is density; but since this is not easily determined, temperature is commonly used because it is one of the easiest properties to measure and normally controls density. Isothermal oscillations resulting from heat exchange and various water motions have therefore been studied intensively.

The U. S. Navy Electronics Laboratory (NEL), which has been investigating thermal structures in both shallow and deep water, employs separate techniques and equipment for each. For shallow-water studies, both horizontal and vertical fixed arrays are suspended into the sea from the NEL Oceanographic Research Tower. The vertical array of thermistors shows changes in the depth of isotherms, and the circular-horizontal array gives both spacial and time changes. For deep-water studies, a towed 900-ft chain is used to delineate thermal structure.

Theory

The sea temperature and its resulting thermal structure derive from the heating and cooling of the ocean by sun and sky. The heat is distributed by advective, conductive, and mixing processes through internal and external forces such as wind or tide.[1] Internal waves, which travel at different frequencies, depths, and directions, are also a dispersing factor.

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Theoretically, free internal waves exist only between the inertial and Väisälä frequencies.[2] The lower limit is a function of latitude; the upper limit, the Väisälä or stability frequency N, is a function of depth z,

$$N^2 = -(g/\rho)(d\rho/dz) - (g^2/c^2) \qquad (1)$$

where ρ is density of the medium, c is speed of sound wave in the medium, and g is gravitational acceleration.

The theory of the existence of internal plane waves, as opposed to origin or destruction, implies the perfect coherence of plane waves over space.[3] This would mean that an internal wave would travel undistorted across an ocean, but in reality the natural internal waves of the sea are not this coherent. The ocean may contain an endless number of propagating sources, the waves from which can combine randomly, sometimes reinforcing or canceling each other[4] (Fig. 1).

In deep water, an infinite number of modes is mathematically possible for any one frequency or excitation, but physically an upper limit must exist because of the inherent shear. Each higher mode at a given frequency has a higher wave number and travels at a slower phase speed.

The observed spectra of internal displacement generally decrease with increasing frequency. Minor peaks often appear in the spectra at tidal frequencies and near the stability frequency.

Cause of Internal Waves

In addition to oscillations exhibiting certain frequencies and modes related to the Väisälä frequency, other oscillations or internal waves are possible. Strong winds create convection cells and eddies in the upper layers of the sea. The resulting circulation lowers the thermocline more in one area than in another. Fluctuating winds at the air-water surface can cause vertical oscillations, or waves, in the thermocline. Tidal and other forces producing water movement around land boundaries and topographic features start oscillations in the thermal structure. However, the vertical variations in the isotherms observed with distance appear to be internal waves moving in many directions. The progressive nature of the oscillations in shallow water has been verified by studies conducted from anchored ships and the NEL tower[5] (Fig. 2).

Data Acquisition in Shallow Water

Research Tower

During the past seven years, studies of water motion, underwater acoustics, electromagnetics, chemical composition, marine biology, marine geology, and thermal structure have been successfully conducted from the NEL Oceanographic Research Tower (Fig. 3), off San Diego, Calif.

Originally built to compensate for a shortage of surface ships, the structure was designed to provide oceanographic environmental information to the Navy on shallow-water phenomena, especially those that pertain to underwater detection. In these studies from the stationary tower, the advantages of such a fixed platform have become apparent. The first asset is stability, which permits constancy in space and permanent orientation of equipment. A second advantage is suitability for long-period observations, which are especially needed for the study of cycles in thermal structure. A moving platform, such as a ship, cannot equal the stable, quiet, laboratory-like conditions of a stationary structure. The prime advantage, however, is the economy of conducting oceanographic research from the tower, which is far less expensive to operate than a ship in the same locality.

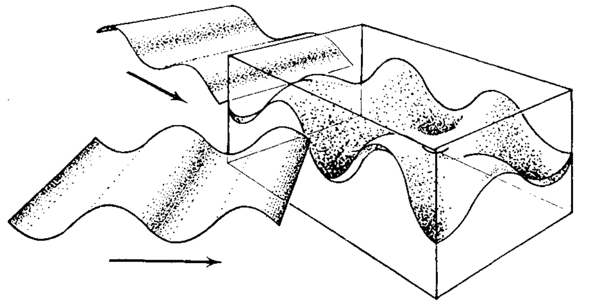

Fig. 1 Open sea deep-water thermal structure is made up of domes and depressions as a result of the coalition of internal waves moving in different directions.

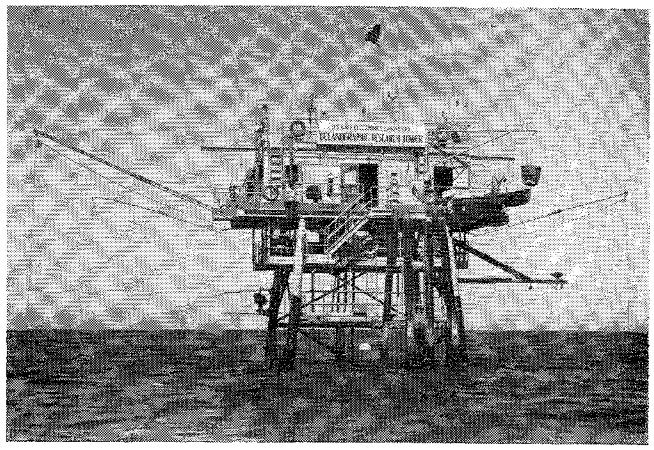

Fig. 2 U. S. Navy Electronics Laboratory's Oceanographic Research Tower located about a mile off Mission Beach, Calif.

Common Shallow-Water Thermal Structures

The vertical thermal structure of the sea has been measured by a number of instruments, which include thermistor beads, permanently fixed to the NEL tower. Other beads are floated downward from buoys or suspended at 2-ft intervals in a vertical string from a taut-wire buoy system and isotherm followers.

The closely spaced beads in the taut-wire buoy arrangement record the most detailed thermal structure. The position of isotherms is referenced to the bottom rather than to the surface (Fig. 4) in order to acquire more detail near the sea floor, since sampling is less affected by surface action. Signals from the 2-ft-spaced sensors, interpolated electronically for whole-degree centigrade isotherms, are recorded in a time-depth analog form.

At the relatively shallow tower site, the vertical temperature structure in summer may be considered as a two-layer

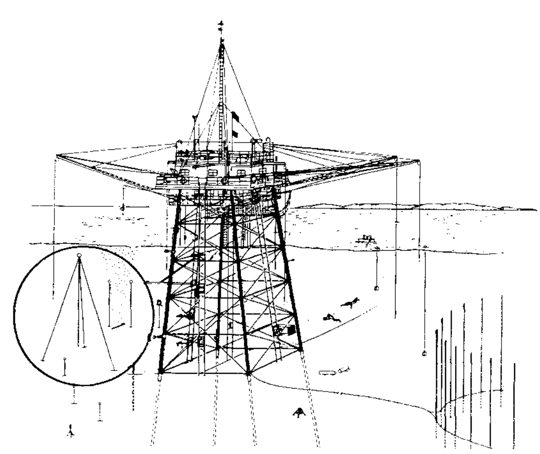

Fig. 3 Schematic of instruments used in a variety of studies. The circled area marks the location of vertical strings of sensors used to obtain temperature structure.

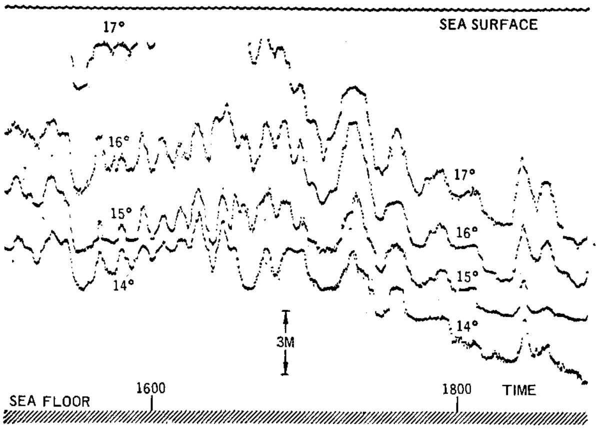

Fig. 4 Depth-time recording of isotherms showing progressive-type internal waves and afternoon lowering of thermocline.

system of warmer and colder water separated by a thermocline. The continuously recorded isotherms show vertical oscillations or internal waves throughout the water column. The principal vertical displacement of water particles takes place at the thermocline.[6] Many small internal waves, nearly in phase throughout the water column (Fig. 4), are present during the summer.

Speed, Height, and Propagation Direction

The speed, height, and propagation direction of internal waves at the tower site are determined from data supplied by three isotherm follower units, which record the depth of a given isotherm at three locations.

Approximately 90% of the measured internal waves propagate from a westerly and southwesterly direction. The speed of the progressive internal waves, designated c in Eq. (2), depends on the thickness of the two layers and difference of their densities. For internal waves that are long compared with their water depths,

$$c^2 = [ghh'/(h + h')][(\rho - \rho')/\rho] \qquad (2)$$

where h' is the thickness of the upper layer, h is the thickness of the lower water layer, and ρ' and ρ are the respective water densities.

In summer the internal waves pass the tower site depth of 60 ft at about 0.3 knot. As they approach the shore they decelerate, become more closely spaced, refract, develop long crests, and finally move onshore. Short-period waves, described by an isotherm in the middle of a summer thermocline, show a median height of 5.6 ft and a period of 7.3 min.[7]

Cycles in Thermocline Depth

A prediction of thermocline depth in shallow water is important to the Navy for acoustic and other operations. Knowledge of its relationship to environmental factors can best be acquired through an understanding of the processes involved. Diurnal cycles in sea breezes greatly affect the onshore and offshore surface-water displacement causing the thermocline to reach a maximum depth at 1800 hr and a minimum depth in the early morning. Fluctuations in the thermocline level can amount to 30 ft in 2 hr. A nearly continuous record of thermocline depth, recorded by isotherm followers through 4 summer months at the NEL Oceanographic Research Tower was compared with data on wind speed and direction and tide height for the same period. Interrelationships were established and empirical equations developed. Harmonic analysis of thermocline depth showed that 1) the nearly semidiurnal tide height is of primary importance, and 2) the diurnal wind speed direction (nearly parallel to the coast in accordance with the Ekman effect) is of secondary importance.

Harmonic analyses revealed peaks at 4.5- and 1-day cycles in both wind-predicted and measured thermocline depths. The tide was solely responsible for the half-lunar peak in the observed thermocline depth. The amount that the summer thermocline is lowered was empirically established to be 2.6 ft per knot of wind blowing parallel to the coast.

Since the thermocline response to the tide height follows 4 hr later, and to the wind 15 hr later, it is possible to predict, to a usable accuracy, the thermocline depth change at the tower site.[8]

Strength of Thermocline

Like the depth of the thermocline, its strength also undergoes cycles. A strong thermocline forms near the surface and increases in depth and strength as it descends late in the day. This is due to the sinking of warmer, near-surface water toward the thermocline, which acts as a barrier, the warmer water moving offshore at the top of the thermocline. Conversely, as the thermocline is rising in the early morning it becomes weaker since the divergent type circulation causes the upper part of the thermocline to ascend more rapidly.

Boundary Relations in Thermocline Depth

The shape of internal waves changes as the thermocline approaches the sea surface or bottom boundaries. The crests become flatter near the surface and the troughs flatten near the floor. Internal waves decelerate as they move up a shallowing slope and their crests become steeper and more closely spaced.

Topographic features, such as shallow seamounts, points of land, or islands, influence the thermal structure as a result of the 1) flow of currents over and around them, and 2) modification of internal wave character by a change in flow and shoaling of the layers. The net result of a seamount is wave refraction, with longer crested internal waves over the shoal.

Points of land projecting into a normal current cause a deflection in flow and corresponding modification in thermal structure, accompanied by turbulence and eddies off the point and upwelled colder water on the lee side. Similarly, evidence exists of turbulence along the side of the islands and large eddies in the down-current wakes. Off Hawaii, several topographic features simultaneously influence the thermal structure. Turbulence, and a ridge effect, are present south of the island of Hawaii and along its side. In the lee of Hawaii and Maui islands a large, counter-clockwise eddy causes divergence and upwelling. The thermal dome is 150 ft high and 80 miles in diameter.

Shallow Water-Mass Boundaries

Water-mass boundaries are frequently found near shore when two or more water masses impinge upon each other as the result of river discharge, differential flow modified by wind, or topographic features. These boundaries often appear near shore because of the more numerous changes there in types of water.

A water-mass boundary may produce a wide variety of thermal structures (one of which is depicted in Fig. 5) where the average temperature is shown to be nearly constant, but the isotherms evidence wider spacing on one side of the boundary than on the other. This is a vertical shear thermal front. The small internal waves have higher frequencies and lower amplitudes where the gradient is stronger.

Thermal Structure Relation to Sea Surface Slicks

Sea surface slicks, characterized by capillary waves smaller than those on the surrounding surface, appear glassy because

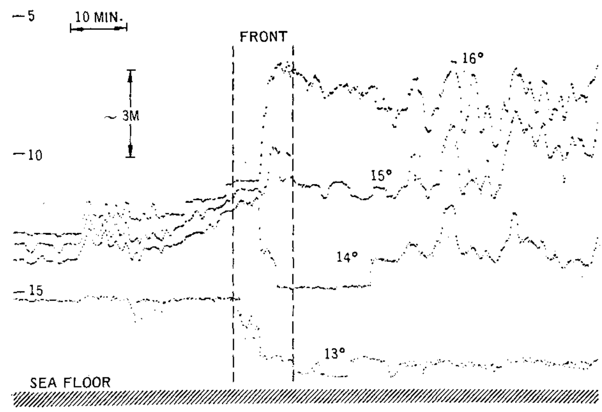

Fig. 5 Depth-time recording of isotherms showing the passing of a thermal front.

they reflect the sky better than the adjacent rougher water. Slick bands, occurring where lighter-than-water film is concentrated, are caused by the downward motion of internal waves and indicate the presence of active sinking zones. The orientation, speed, and direction of internal wave movement may be determined from time-lapse photographs of such surface bands, which make possible a three-dimensional study of subsurface thermal structure and movement unless high wind speeds break up the slicks.

Data Acquisition in Deep Water

Equipment

The NEL thermistor chain, a towed, vertical sensing device[9] operated from the NEL oceanographic research vessel USS Marysville (Fig. 6), is used to delineate the thermal structure in deep water. This rugged assembly, 37,500 lb in weight, is one of the largest of oceanographic instruments; it includes a deck subassembly of chain hoist and drum, and a sea subassembly of chain, thermistor beads, and weight.[10]

The chain itself is composed of flat links one ft long, 10 in. wide, and 1 in. thick. A 2300-lb, torpedo-shaped weight, called a "fish," is used to depress the end of the chain in the water. About 100 pairs of insulated electrical leads fit through grooves inside the flat links. The leads are attached at intervals of $7\frac{1}{2}$ m to the temperature sensors, or thermistor beads, and their upper ends are connected to a recorder in the ship's laboratory.

Signals from each of the beads, from the surface to the deepest, are scanned electronically every 12 sec. Since the chain is inclined backward at an angle, and is being moved

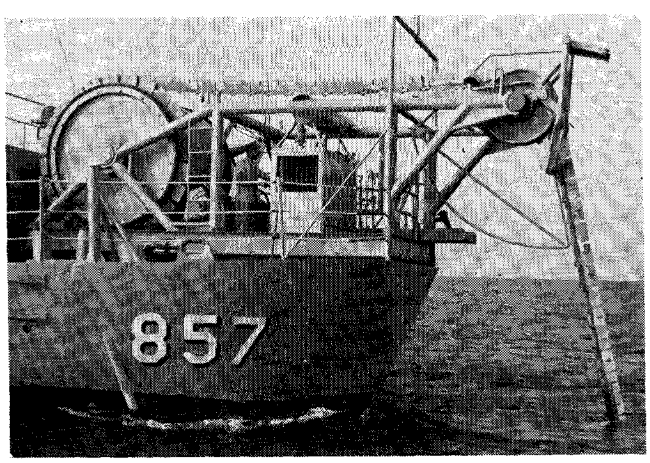

Fig. 6 Thermistor chain on the stern of the U. S. Navy Electronics Laboratory's oceanographic research vessel USS Marysville.

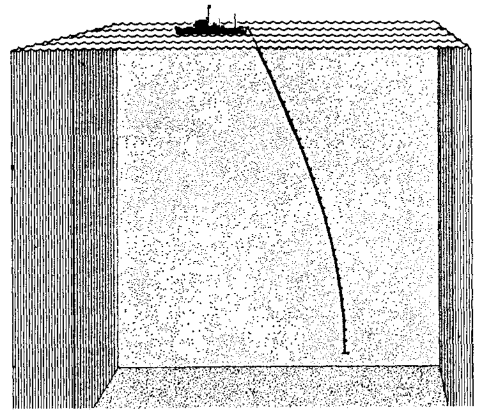

Fig. 7 The technique of acquiring two-dimensional thermal structure in the sea by towing the suspended 900-ft-long articulated thermistor chain containing 34 equally spaced temperature sensors.

forward by the ship, the sensing takes place approximately in a vertical line. The signals are interpolated electronically, and only the depth of whole-degree Centigrade isotherms is recorded on 19-in.-wide tape. This is equivalent to lowering a bathythermograph every 120 ft at a ship's speed of 6 knots. Also printed on the same tape, for each scan, is 1) the maximum depth of measurement (recorded by the bead at the end of the chain), and 2) the sea surface temperature (recorded by the uppermost bead).

The thermistor chain is deployed nearly vertically for temperature measurement while the research vessel cruises forward (Fig. 7). The thermistor beads, suspended from the fantail, sense from the surface to a depth of about 240 m. As the ship moves through the water, the chain measures two dimensions of coverage, depth, and distance. The 50,000 miles of detailed thermal-structure data gathered by the NEL thermistor chain have thus made it possible to determine some of the processes going on in the sea.[11]

Common Thermal Structure

An example of thermal structure measured two-dimensionally (Fig. 8) off Baja California shows the recording of isotherms by the thermistor chain while being towed at a speed of 6 knots. The vertical scale is magnified about 100 times; this causes the isotherms to appear steeper than in reality. Normally isotherms have a median slope of only 0° 25′.

Only 9 whole-degree isotherms, 20° to 12°C, were found in the upper 240 m. A mixed upper layer, without whole-degree isotherms from the surface to about 30 m below, was evident. The vertical spacing of isotherms immediately underneath

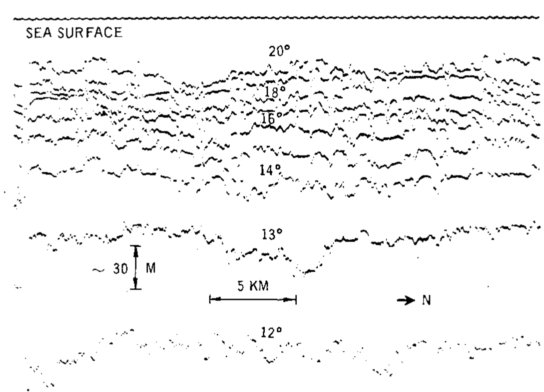

Fig. 8 Recording of thermal structure of encounter showing the small and large oscillations of isotherms in the thermocline.

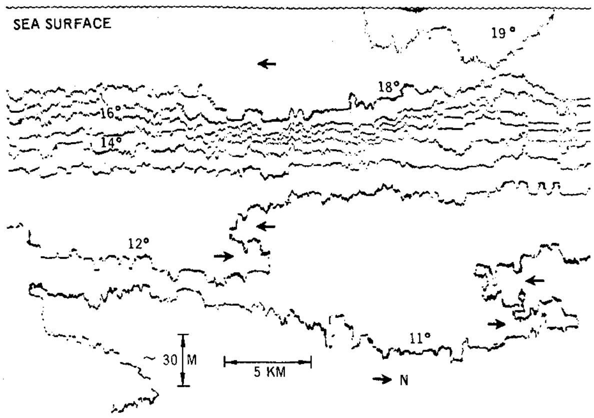

Fig. 9 Recording of thermal structure of encounter showing inversions in the isotherms just below the main thermocline, the result of differential flow at different levels.

the mixed layer revealed a strong thermocline. Below this was a gradual widening in isotherm spacing.

Small, vertical oscillations, generally occurring about two to four per mile, but also at five or six per mile, were frequent and displayed a range in amplitude up to 6 m. Such oscillations, found in each of the isotherms in the thermocline, were nearly all 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 and, at greater depths, the amplitudes were as high as 10 m.

Figure 8 reveals the most common type of vertical temperature structure in the upper layers of the oceans, and which, in the Pacific, is representative of 85% of the temperature structure.

Temperature Inversion

Thermal structure recorded off the west coast of Baja California (Fig. 9) shows colder water and a difference in thermocline detail from Fig. 8. The deeper isotherms reveal a radically different pattern. The surface layer depicted in the left section of Fig. 9 (or southern) is about 50 m thick; in the right section (or northern) is visible a weak gradient containing one isotherm above the main thermocline. The unusual temperature inversion below the thermocline is the result of the surface current and layer, including the thermocline, moving from north to south and overriding the deeper water (note arrows, Fig. 9), which moved either more slowly or in a northerly direction. The difference in speed of the two layers was measured in 1965 by means of recording current meters attached to the chain, and was found to be 0.7–1.2 knots. The motion created a weak shear, or temperature inversion, as shown by the S shape of the 11° and 12°C isotherms. These fairly weak (1°C) inversions were 50–60 m in height. The main thermocline, between 50 and 90 m, contained smaller waves. The spectrum of their wavelengths was broad; some were 200–300 m long, some (in the upper right) were 4 miles long, and others averaged 2 to 4 per mile.

Thermal Front

Figure 10 shows a thermal front where one water mas impinged upon another, the warmer, lighter water mass flowing over the colder water. This structure, observed 160 km southeast of the end of the Baja California peninsula, was in the boundary between two water masses with colder water on the left (northern) and warmer water on the right (southern) part. A 2°C change in surface temperature in the central part was detected with airborne infrared equipment. The nearly vertical shift in the depth of isotherms was detectable to depths as great as 100 m. An S-shaped thermocline was present at 45 m, which implied that warmer southern water was overriding colder northern water, but about 20 m deeper, the structure was reversed, as with a Z pattern, and indicated a mid-depth intrusion. The relative directions of motion (Fig. 10) are indicated by arrows. A frontal area is usually made up of several such large-scale, turbulent areas, separated by a near-normal thermal structure. The thermocline strength is greater on the far right of the front than on the far left. The wavelengths of the smaller waves are correspondingly smaller in the stronger thermocline.

Ridge

Figure 11, representing a thermal structure measured just south of Baja California, shows a general ridge. Colder water is present at the surface where the isotherms curve up to intersect it. Maximum bowing occurs on the uppermost isotherms, but some doming is detectable to a depth of 150 m. The upper isotherms have a dome height of 45 m. The sloping isotherms of the ridge imply a geostropic current and thus probably reflect the presence of a current boundary ridge. The water shows a net divergence type of transport away from the ridge as well as parallel to it.

Two parts of Fig. 11 were enlarged to permit closer examination of the recorded thermal structure. The detail on the left is made up of waves of encounter averaging about 0.44 mile in length. This may be a natural geographical phenomenon, but it could also be the result of a Doppler effect, which would cause the waves to appear longer than they really are when progressing in the same direction as the ship. The smooth shape of the 7-m waves is evident. If surface waves were influencing isotherm depth, the internal waves would appear as irregular marks, since each recorded 12-sec scan would give an irregular outline to the curve, the scan falling at all phases of the surface wave. The shape thus indicates that surface waves have little or no effect on the recording of smooth, nearly sine-shaped internal waves.[12]

The detail on the right (Fig. 11) presents a different record from that of only $1\frac{1}{2}$ hr earlier, though towing was at the same direction and speed. In this example the isotherms are shown to fluctuate widely and have a rough aspect. The irregularity is attributed to short-length internal waves, or those propagating in a direction opposite to that of the ship. The waves of encounter are so short that the 12-sec-interval scan falls on all phases of the wave. If one scan falls on the wave crest, and the next scan, made only 37 m distant, falls well off the crest, an abrupt change in the normally smooth isotherm is recorded. Other wave phases are recorded on successive scans; thus a rough appearance is created when short waves are encountered.

Since the isotherms in the northern part of this section are more irregular and reflect higher-frequency internal waves than do those in the southern part, the ship may have been

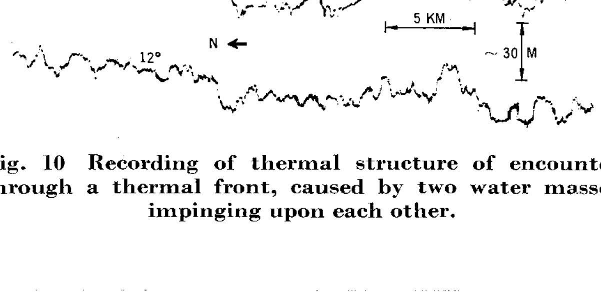

Fig. 10 Recording of thermal structure of encounter through a thermal front, caused by two water masses impinging upon each other.

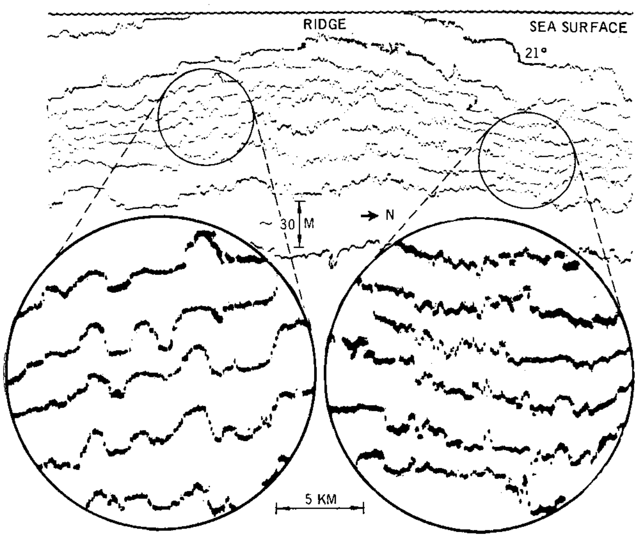

Fig. 11 Recording of thermal structure of encounter across a thermal ridge. Enlargements show detail on either side.

moving, in one case, in the same direction as internal-wave propagation and, in the other case, in the opposite direction.

The ridge may be considered a front, with a sloping density structure rising toward the crest. Small internal waves, propagating at an angle with this boundary, may be refracted as on the continental slope and propagated toward the crest from both sides. A Doppler effect will therefore be experienced when towing toward, and away from, the crest, i.e., from left to right in Fig. 11. Waves propagating toward each other will create mixing, and irregular patterns where they meet. This may account for the large difference in wavelength measured on either side of the rise, and the mixed structure measured over the crest.

Power Spectrum

The preceding examples of thermal structure show that isotherms are composed of vertical oscillations of varying frequencies. Numerous small oscillations appear to range from $\frac{1}{4}$ to 1 naut mile. To determine the most common frequencies of this range, isotherm depths were subjected to power-spectrum analyses.

The power spectrum represents the energy ($\frac{1}{2}$ amplitude squared) per unit bandwidth, which emphasizes the bandwidths in which the dominant frequencies occur. Power spectra were computed from a long series of successive half-minute readings of isotherm depths and thus provide a spectrum of isotherm depth-of-encounter variation. Computations were made for all directions of tow and for different locations in the eastern Pacific (Fig. 12). This spectrum is fairly typical and shows a number of small peaks, with no one frequency dominant. The units for power spectrum are given in ft^2/cpm and might better be designated as variance.

Three of the peaks shown here are centered around 0.17, 0.25, and 0.29 cpm, two of which correspond to 0.59 to 0.34 naut mile. When a large number of power spectra are averaged, frequencies around these values continue to display a small increase over background noise.

Summary and Conclusions

The internal temperature structure of the ocean, recorded in detail in the upper layers by the newest oceanographic

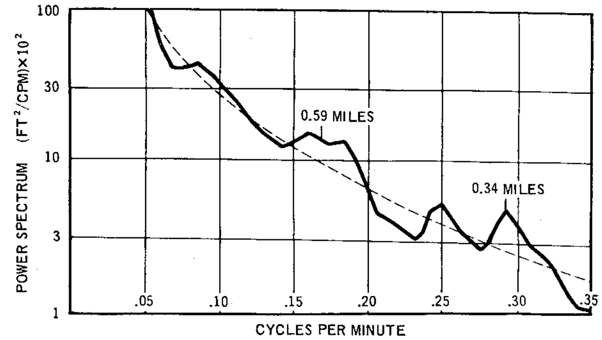

Fig. 12 Power spectrum of the depth of encounter of an isotherm in the thermocline. This case shows the greater power peaks in the frequencies of 0.17 to 0.29 cpm, which correspond to internal wavelengths of 0.59 and 0.34 naut mile.

sensing instruments, reveals a complex of processes taking place. The isotherms are seen to be a composite of vertical oscillations exhibiting a wide spectrum of wave periods. The thermal structures associated with upwelling, fronts, differential current motion and shoaling water are indicative of the internal motion taking place and are of major importance. Thus the two-dimensional measurement of internal sea temperature structures of encounter makes possible an understanding of the processes of mixing, turbulence, differential flow, and various types of internal wave motion. This knowledge finds wide application in the problems of acoustic detection and other naval operations.

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