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SHALLOW WATER TURBIDITY STUDIES

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THE PROBLEM

Determine the effects of the environment on detection and classification of objects in the sea. Specifically, conduct research on the widely observed differences in the water transparency and determine the basis for the turbidity structure of water off Mission Beach, California.

RESULTS

1. The turbidity structure of the water off Mission Beach varies greatly in both depth and time.

2. There is usually a cycle in the distribution of water turbidity corresponding to the tidal cycle.

3. A relationship was demonstrated between water temperature, internal waves, and turbidity.

4. The level of maximum turbidity frequently lies at or near the level of maximum temperature gradient.

5. A sound scattering layer corresponding to the depth of maximum turbidity was observed by means of an upward directed echo-sounder.

6. Water turbidity is mainly due to concentrations of plankton and detritus in the water.

RECOMMENDATIONS

1. Additional studies should be conducted at the NEL Oceanographic Research Tower and in other geographical areas, and the data compared.

2. For continuous studies of several days' duration, multiple turbidity sensors and suitable continuous recording equipment should be employed.

3. A more detailed study of acoustical-biological-turbidity relationships should be made to determine the cause of patchiness in acoustic scatterers.

ADMINISTRATIVE INFORMATION

Work was performed under S-F011 02 19, Task 8027 (NEL L1-7) by members of the Signal Propagation Division. The report covers the period June 1960 to September 1961 and was approved for publication 26 July 1962.

Acknowledgments are made to E.G. Barham, M. Taylor, and M.M. Sullivan for their study of materials in the water, and to O.S. Lee, N.G. Litell, A.L. Nelson, J.C. Roque, and H.G. Kiner for setting up the equipment and making the measurements. We are indebted to G. H. Curl for reviewing the report, and to R. F. Dill for underwater visibility information.

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INTRODUCTION

The turbidity of coastal waters off Southern California has been under investigation for several years from surface ships using a portable hydrophotometer (alpha meter).[1] (See list of references at end of report.) The construction of the USNEL Oceanographic Research Tower,[2] 1 mile off Mission Beach, California, in 60 feet of water, provided a stable platform suitable for studying turbidity. This report describes the first results of turbidity and related studies made from the tower.

The wide variations in the turbidity structure of sea water in the area around the tower have been verified by previous work,[3,4] by divers, and underwater television studies. Divers have reported a visibility of about 15 feet at a particular depth and time, but almost zero visibility at the same depth a few minutes later, or at a slightly different depth. At other times visibility extends to distances of over 50 feet. The cause of such changes is as yet largely undetermined.

An attempt was made to correlate these turbidity fluctuations with time, tides, and internal waves or temperature structure. In addition, biological investigations were conducted to determine how turbidity is related to organic matter in the water. Living organisms were considered as a possible cause of short-period changes in turbidity and associated acoustic effects.

MEASUREMENT SITE

The measurement site was the open sea about 1 mile off Mission Beach (fig. 1). In this area the sandy bottom slopes gently to the west. There was no river runoff nor land drainage in the area during summer when the turbidity observations were made. Although there is a tidal flushing of Mission and San Diego Bays, under normal conditions the bay waters, more turbid than open sea water, do not reach the measurement site since the predominant flow is to the south (fig. 1). There is no significant tidal flushing nor draining of other bays within 70 miles to the north, the usual direction from which the coastal drift comes. Thus the local bays are not an important factor in turbidity changes at the measurement site.

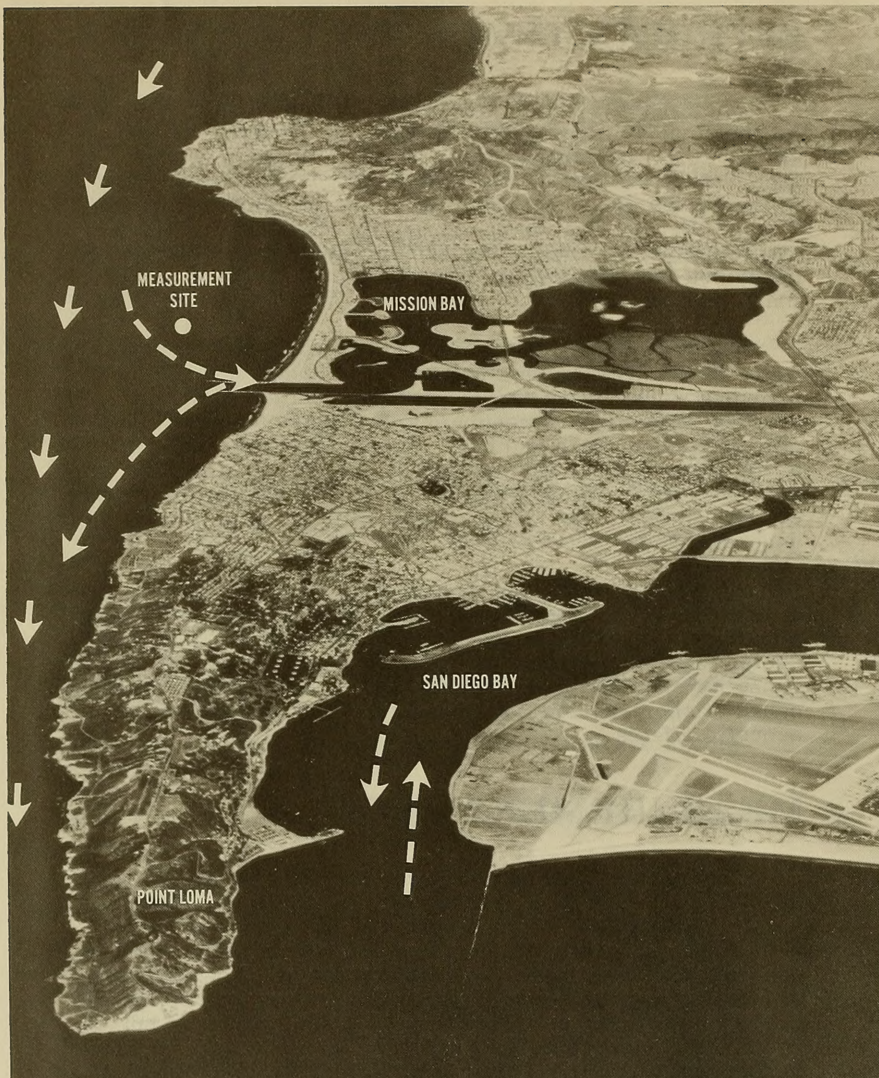

Figure 1. Photo of Point Loma and Mission Bay showing location of measurement site (tower) and general current flows (arrows) at Mission Bay and San Diego Bay.

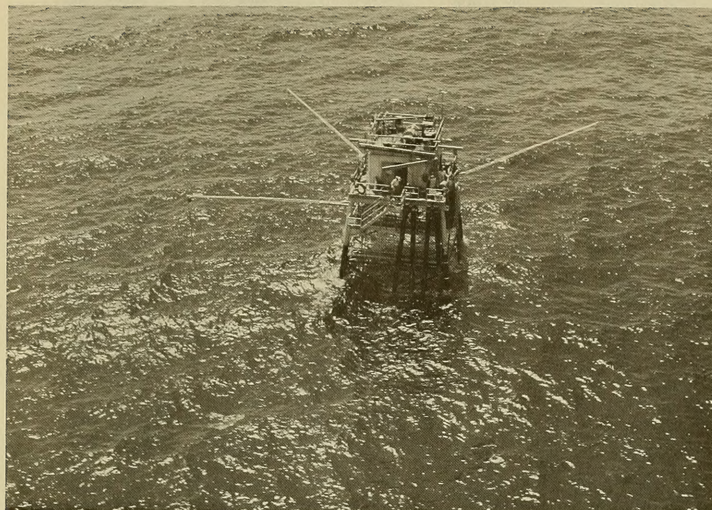

Figure 2. The U. S. Navy Electronics Laboratory Oceanographic Research Tower located a mile off Mission Beach, California, in 60 feet of water, where turbidity study was conducted.

TOWER

The turbidity measurements were made from the USNEL Oceanographic Research Tower (fig. 2). The tower is used to carry on shallow-water oceanographic research on waves; on acoustic, chemical, and biological properties of the sea; and on their interrelations.

The underwater part of the tower consists of large pipes welded together. This structure causes little interference to the waves and flow of water. On three sides of the tower are nearly vertical railway tracks running from the main deck to the bottom 60 feet below the surface. On the tracks, cars containing sensing instruments may be lowered and raised.

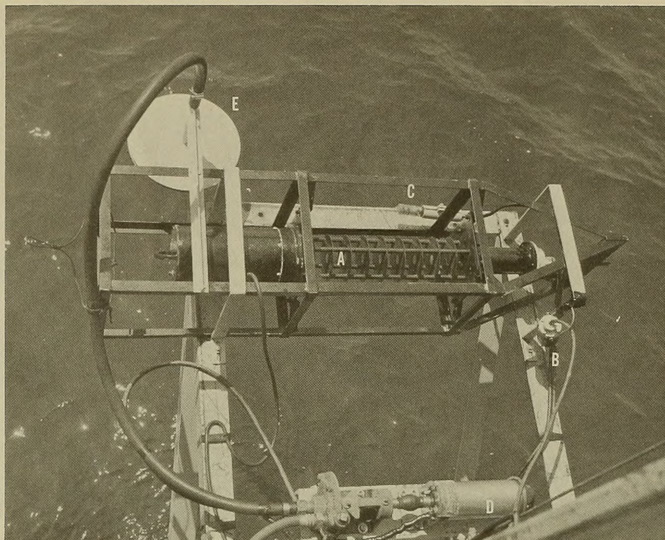

Figure 3. Top view of car on vertical railway tracks of the tower used to make vertical casts for water turbidity and temperature and to pump water for plankton.
A. Hydrophotometer (alpha meter)
B. Pressure transducer (for depth)
C. Thermistor (for temperature sensing)
D. Underwater pump
E. Pump intake

INSTRUMENTS

The car on the western or seaward track contains the sea instruments (fig. 3) used for the study.[5] They include a hydrophotometer, temperature sensor, pressure transducer, and a submersible pump with its underwater intake.

The instrument used for measuring turbidity was a one-half-meter hydrophotometer (fig. 3-A), designed and constructed by the Scripps Institution of Oceanography Visibility

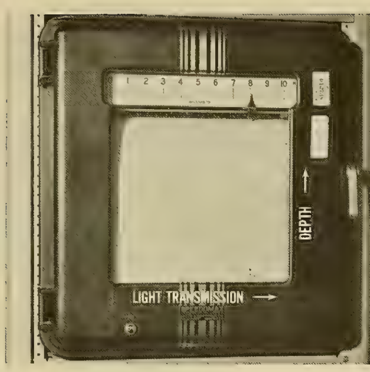

Figure 4. X-Y Recorder for water transparency (light transmission) vs. depth for vertical casts with the hydrophotometer.

Laboratory. The photometer consisted of a light source and a photocell mounted one-half meter apart. The light source was mounted in a watertight housing with a glass port, and the light was directed through the water column to a photocell in a second housing. The light source was a 6-volt light bulb (G. E. 964), with power provided by a variable power supply for calibration of the instrument. The light passed through a lens system to form a cylindrical beam of parallel rays in the water.

Several vertical baffles were mounted along the light path for the purpose of filtering out ambient light. The receiver, or photocell end of the photometer, was calibrated to receive the cylindrically limited bundle of rays. The photocell was a Weston 856-RR. The electrical output of the photocell was fed to the X-input (pen drive) of a Leeds and Northrup Speedomax X-Y Recorder (fig. 4). The Y-scale was depth of observation. The X-scale was calibrated in per cent light transmission per half-meter with reference to distilled water. The calibration was made in air in which the full scale reading was set at 93.5 per cent. The 6.5 per cent correction is due to increased reflection at the glass ports of the lens systems in air. The photometer should read 100 per cent transmission in pure distilled water.

Material in the water, such as plankton, sediment, or dissolved substances, reduces the percentage of light transmitted. The resulting values of transparency have been related to visibility by divers. Although considerable spread exists in the data, there is always a direct relation between the hydrophotometer readings and the horizontal distance at which a Secchi disc may be seen. Averages of such data are shown in table 1. For the visibility readings, the disc was held in a vertical position and observed by a submerged diver.

TABLE 1. RELATION OF HORIZONTAL TRANSPARENCY AND VISIBILITY.

Visibility (with Secchi disc, in feet)	Transparency (per cent) (with hydrophotometer)
2	33
5	44
10	61
15	73
20	82
25	87
30	90
35	92
40	93
45	94
50	96

To obtain temperature, a plastic-sealed thermistor was mounted on the cart at the same level as the hydrophotometer (fig. 3-C). The readout for this thermistor was located on a panel (fig. 5, lower right) near the X-Y recorder. Temperatures were read to the nearest tenth of a degree Fahrenheit.

A depth indicator (fig. 5, left), on the same panel, provided a quick visual check of the cart location. The sensing element for this indicator was contained in a junction box on the cart.

The wind speed and direction were continuously recorded on the tower. The instrument used for this purpose was an ML-400C/UMQ-5 anemometer manufactured by Rett Products Co.

In order to relate turbidity to organic material in the water, a sampling system was required. A submersible pump (fig. 3-D) mounted on the cart met this requirement. The intake to the pump was between two flat, horizontal discs about 30 centimeters in diameter and about 1 centimeter

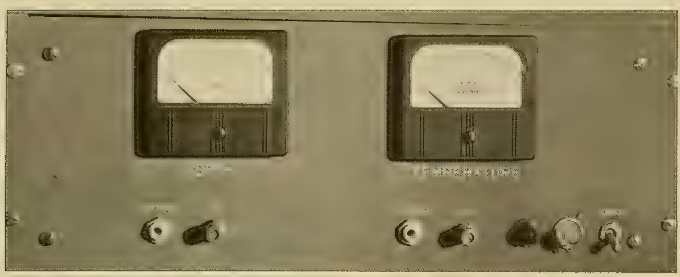

Figure 5. Temperature and depth indicators for the car containing the hydrophotometer.

apart (fig. 3-E). These discs made it possible to sample a very narrow cross-section of the water at the same level as the hydrophotometer. The samples were pumped to the surface for filtering and analysis.

OBSERVATIONAL PROCEDURE

The observational procedure was to run the cart and instruments vertically through the water column every half-hour, beginning with the cart on the bottom. Slightly less than 3 minutes (at a speed of 4 inches per second) was required for the traverse from bottom to surface and for making a continuous recording of light transmission (turbidity) and temperature. After the run was completed, the cart was again lowered to the bottom and left there until the start of the next run.

Water samples could be taken at any depth. If taken while the cart was moving, the length of time required for the water to be pumped through the hose had to be considered in determining the depth from which the sample came. Sampling while the cart was moving provided a continuous hydrophotometer trace with water samples every few feet, and made possible a direct comparison of the data. However, the water samples were taken normally on separate casts, the cart being stopped at 5-foot intervals for pumping of the biological sample. The turbidity of the water was obtained on these runs as well.

DATA

During four extensive observation periods, turbidity and temperature data were taken at 30-minute intervals. The first period was about 10 hours long, and the other three were from 26 to 29 hours long.

TURBIDITY STRUCTURE--TIME SERIES

From each turbidity run, the per cent transparency was scaled from the continuous trace every $2\frac{1}{2}$ feet from surface to bottom. These readings were plotted on charts and isolines were constructed. Thus the plot represents changes in the vertical distribution of turbidity with time. Figures 6, 7, 8, and 9 show these plots, with the numbers on the isolines referring to per cent transparency per half-meter (e.g., 20-per cent light transmission signifies very turbid water, 80-per cent very clear, etc.). The contours are in 10-per cent intervals. From the examples of data separately discussed below, it will be evident that the turbidity varies greatly with depth and time, and that sweeping changes take place rapidly, completely altering the existing pattern.

14 July 1960 (fig. 6)

This short series of turbidity measurements depicted a condition in which the near-surface layer had a high turbidity. The most turbid water occurred at high tide or shortly after high tide, with less than 20-per cent light transmission. At 1800, a mid-depth layer was clearly discernible with maximum turbidity between 8 and 18 feet. The clearest water, which occurred at the greatest depth (about 50 feet), had a transparency between 60 and 70 per cent as great as that of distilled water. It should be pointed out that on this day the turbidity was greater than usual throughout the water column.

19-20 July 1960 (fig. 7)

This depth-time series of turbidity measurements lasted for 26 hours. During this period the water column was clearer than on 14 July 1960. At the beginning of the series the water had a nearly uniform turbidity from surface to bottom. Around 1700, however, clearer water (78-per cent transparency) was introduced near the surface and, to a lesser extent, at greater depths. This change occurred just before a high tide, in contrast to the previous case where the most turbid water occurred at high tide. Another period of clear water occurred from 2130 to 0200. After the first intrusion of clear water, the upper or near-surface half of the water column remained clearer than the lower half.

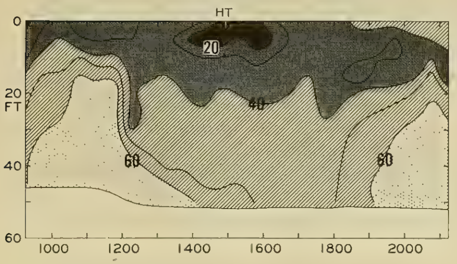

Figure 6. Time (hours) - depth (feet) plot of water transparency at the USNEL tower on 14 July 1960. The numbers on the contours between shaded areas represent the per cent light transmitted through one-half-meter of water, at that depth and time. Time of high tide (HT) is indicated along the surface.

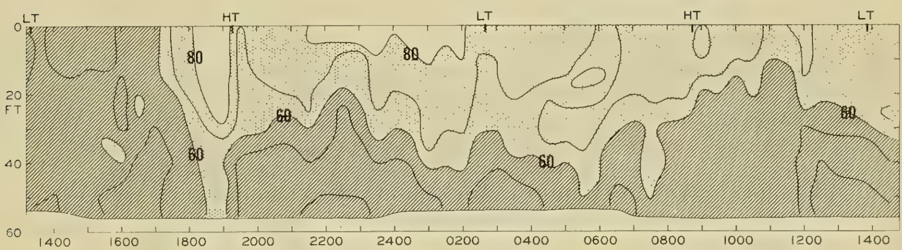

Figure 7. Time-depth plot of water transparency at the USNEL tower on 19-20 July 1960. Times of high tide (HT) and low tide (LT) are indicated along the surface.

<u>2-3 August 1960 (fig. 8)</u>

This 27-hour series was characterized by an intensely turbid layer near the surface and patches of turbid water with transparency of less than 20 per cent. The subsurface turbid layer was present at the beginning of the run and the turbidity increased with time, especially between depths of 10 and 20 feet. After 1500 the entire water column had a transparency of less than 60 per cent. There was a tendency for deeper turbid layers between low tide and the following high tide. In general, the entire water column remained fairly turbid, with maximum turbidity just below the surface.

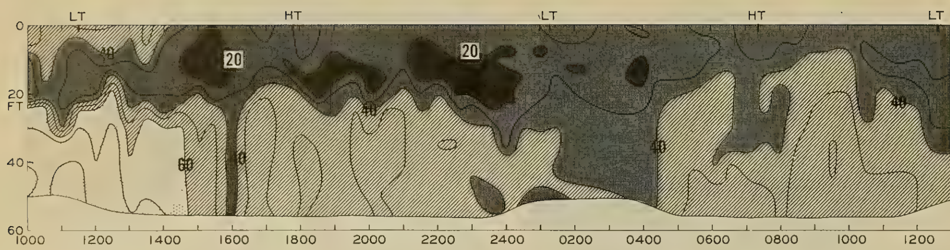

Figure 8. Time-depth plot of water transparency at the USNEL tower on 2-3 August 1960. Times of high tide and low tide are indicated along the surface.

4-5 August 1960 (fig. 9)

This 29-hour series was characterized by a periodic and mid-depth turbid layer. After the first low tide the mid-depth layer began to form, with maximum turbidity occurring between 20 and 40 feet. At high tide and shortly thereafter, the entire water column contained clearer water. However, after the next low tide the water column again became more turbid, especially at mid-depth levels. It cleared again after the following high tide. The most notable features here were the two very large patches of turbidity that appeared to be related to the phase of the tide.

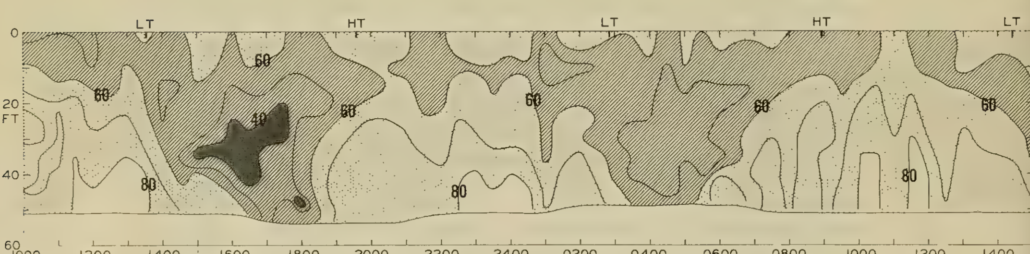

Figure 9. Time-depth plot of water transparency at the USNEL tower on 4-5 August 1960. Times of high tide and low tide are indicated along the surface.

TURBIDITY--TEMPERATURE

To show the relation of the thermal structure to the turbidity structure of the water, isotherms were superimposed on the lines of equal transparency of the preceding three figures. Figures 10, 11, and 12 are similar to figures 7, 8, and 9, but have isotherms drawn in to show the temperature structure. These illustrations show considerable correlation between turbidity and temperature, particularly with regard to long-period changes in the level of the turbidity isolines. However, there were several short-period fluctuations that cannot be correlated with the thermocline. It should be noticed that, in some cases, the clearer water was near the surface and in others near the bottom. In either case the long-period lowering of the isoline is associated with the lowering of the thermocline and vice versa.

By comparing figures 10 and 7, it can be seen that, on a large scale, the isotherms followed the same general cycles and levels as the lines of equal transparency. In both sets of isolines there appears to be a vertical oscillation having a period about equal to that of a tidal cycle. From the close correlation of the large features, it appears that on this day the clear water was a warm water mass and the more turbid water was a colder one. Small-scale fluctuations, however, do not always correlate.

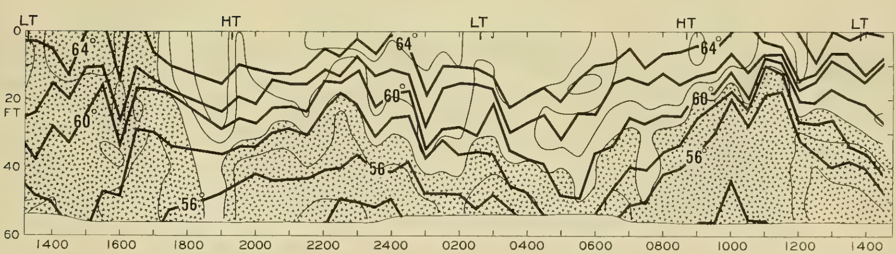

Figure 10. Time-depth plot of water transparency at the USNEL tower on 19-20 July 1960 and the corresponding temperature structure of the water (heavy lines) in degrees Fahrenheit. Transparency less than 60 per cent is shaded.

In figures 8 and 11, in contrast to the previous example, the more turbid water was near the surface and associated with the warmer water. The maximum turbidity occurred on the shallow thermocline which is the most frequent turbidity structure found in this area.

In figure 12 still another type of correlation between turbidity and temperature is shown. The two large patches of turbid water lay in the troughs of the long-period internal waves, undoubtedly related to the tide. The maximum turbidity in general occurred along the thermocline.

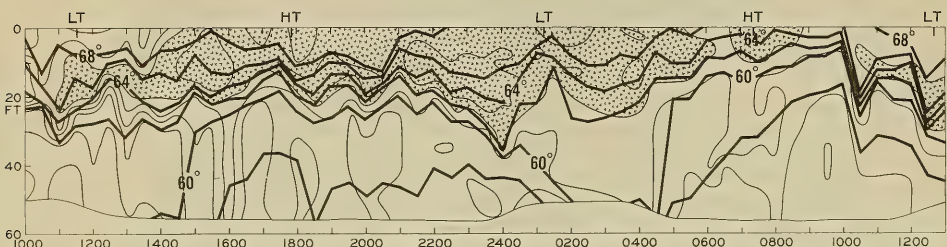

Figure 11. Time-depth plot of water transparency at the USNEL tower on 2-3 August 1960 and the corresponding temperature structure of the water (heavy lines) in degrees Fahrenheit. Transparency less than 30 per cent is shaded.

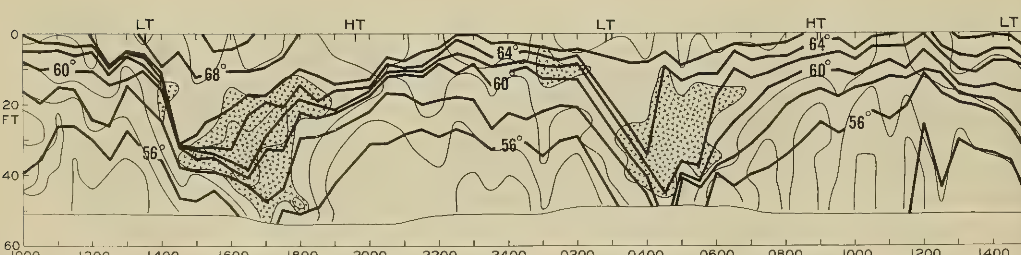

Figure 12. Time-depth plot of water transparency at the USNEL tower on 4-5 August 1960 and the corresponding temperature structure of the water (heavy lines) in degrees Fahrenheit. Transparency less than 50 per cent is shaded.

TURBIDITY AND TEMPERATURE GRADIENTS

The relations between temperature and turbidity structures may also be illustrated by their respective vertical gradients. To show this, the data of each series were divided into 5-hour periods. For each period, the average turbidity and the average temperature were computed for every 5 feet of depth. Graphs were then constructed showing the average turbidity, the average temperature, and the first derivative of each with reference to depth for every 5-hour period. Figures 13 and 14 are examples of the variations of temperature and transparency with depth from the data of 4 and 5 August 1960.

The vertical temperature gradients, dT/dZ, are always negative in summer at the measurement site, which indicates consistently colder water with depth. However, the vertical transparency gradients, dTr/dZ, may be either positive or negative. Positive values signify clearer water with depth. In figure 13 the transparency shows nearly all positive gradients with depth. The highest positive gradient occurs at a level just below the level of the maximum thermocline. In this case the level of maximum transparency (deepest

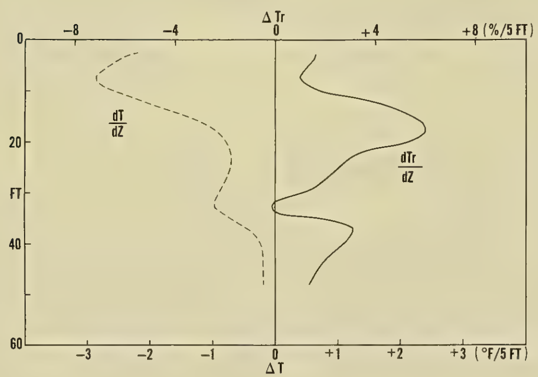

Figure 13. Comparison of vertical temperature and transparency gradients 1000-1430 on 4 August 1960 showing a positive maximum transparency gradient below the thermocline.

observation) is also the level of minimum temperature. In the example of figure 14, the transparency decreases (dTr/dZ is negative) in the upper 15 feet and reaches a minimum ($dTr/dZ=0$) close to the level of maximum temperature gradient.

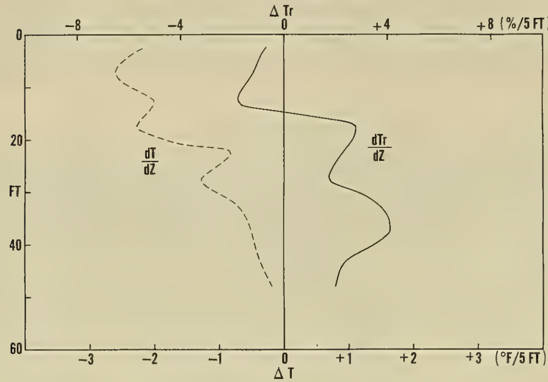

Figure 14. Comparison of vertical temperature and transparency gradients 1230-1500 on 5 August 1960 showing a negative maximum transparency gradient below the thermocline.

SHORT-PERIOD CHANGES IN TURBIDITY

Visual

Water turbidity is often visually apparent from the discoloration of the sea surface. The most conspicuous discoloration in this area occurs periodically during the summer months, when the surface water has a reddish appearance. The phenomenon is called "red water," and is principally caused by *Gonyaulax polyedra*, a very small, one-celled, plant-like organism. Another dinoflagellate, *Gymnodinium flavum*, was conspicuous in 1961, and gave an orange cast to the water. Water transparency is greatly reduced during a plankton bloom.

The surface discoloration of the water is not uniform, but shows in patches or lines. This effect is believed partly due to the variation in depth of the aggregations of organisms as a result of internal wave action, as well as to their varying concentrations.

On one occasion, 30 May 1961, an especially heavy bloom of phytoplankton discolored the near-surface layers of the sea in the vicinity of the tower. The maximum turbidity was slightly below the sea surface, but bands of red water were separated by clear or only slightly red water (fig. 15). The surface showed more dense coloration at position B near the slick and parallel to it than at position A preceding it. The water under and slightly behind the slicks (areas C, D, and E) was clearer than adjacent water. Following this area (area F), the water became red again, but not with the intensity of the band just forward or landward of the slick.

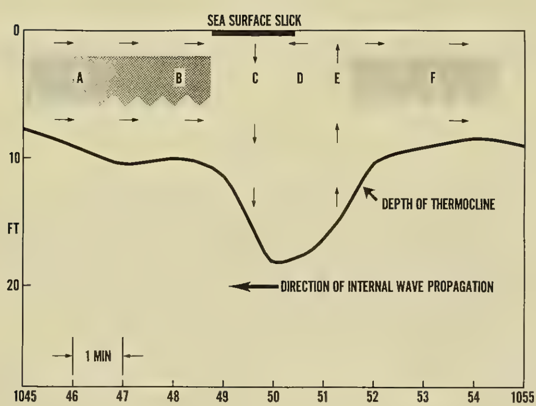

Figure 15. Observations from the USNEL tower on 30 May 1961 of an internal wave, its associated slick, and red water. The shaded areas represent different degrees of discoloration.

As the slicks and bands of discolored water passed the tower, the depth of the thermocline was recorded with isotherm followers. One distant sea-surface slick that contained foam was found to be oriented parallel to the crest of an internal wave and on the descending side of the thermocline. This location (area C) is the usual one for surface convergence associated with internal waves.[6] The clearest near-surface water was over the maximum depression in the thermocline, that is, in the internal wave trough. In this convergence-type circulation, the water above the thermocline was moving toward the slick and sinking there. Since the upper 1 or 2 feet of the water column was clearer, the accumulated surface water gave a clearer appearance to the water over the trough (area D), since the phytoplankton were at a greater depth in this location. Where the thermocline was near the surface just ahead of the slick (area B), the organisms causing the turbidity were close to the surface and more visible. As the internal waves moved shoreward at a speed of about 0.3 knot, the bands of discolored water also moved shoreward.

This behavior is an example of those short-period changes in the vertical distribution of turbidity that are controlled by internal waves. In the Mission Beach area, internal waves have an average period of 5-6 minutes, and thus turbidity fluctuations at the surface and at thermocline depth have similar periods. Furthermore, the orientation parallel to internal waves continues as a group of internal waves moves shoreward, thus tending to create a band distribution of clear and turbid water easily distinguishable by eye.

ACOUSTIC SCATTERING FROM TURBID LAYERS

Plankton and other organisms are capable of causing echoes when high-frequency sound is directed through the water. Since some of the organisms that produce turbidity may be the same as those that are responsible for the acoustic scattering, another approach to the study of short-period changes and patchiness in turbidity is by way of acoustics.

One such study was made at the NEL tower by placing an NK-7 echo-sounder on the ocean floor with the sound beam directed upward toward the surface.[7] The instrument was operated at 21 kc/s with a beamwidth of 20 degrees at the 6-db down points. The purpose was to determine the distribution, the behavior, and if possible, the nature of the sound scatterers.

Although the nature of the sound scatterers was not determined with certainty, their reaction to temperature oscillation was observed. In most cases the scatterers were found to lie near the level of a strong temperature gradient. As the internal temperature waves passed the tower they were continuously followed with the isotherm followers and, at the same time, the sound scatterers were tracked by the echo-sounder (fig. 16). The depth of maximum acoustic scattering underwent vertical oscillation, with periods of from 5 to 10 minutes, in coincidence with the internal waves. It was apparent that internal waves were responsible for short-period changes in the level of maximum sound scatterers.

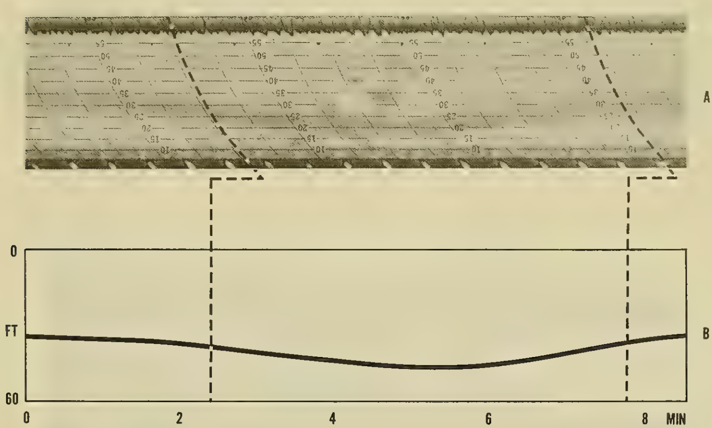

Figure 16. The NK-7 echogram (A) compared to the depth of an isotherm in the thermocline (B).

With an upward-directed echo-sounder, it was also found that a stronger scattering layer appeared in the early evening and disappeared again by morning. Figure 17 shows a comparison of an echogram made during the day without noticeable scatterers (A), and one made in the evening with scatterers throughout the water column (B). It was found that the acoustic scatterers (with the exception of fish) also have a negative reaction to artificial light, that is, they will dive and disperse away from the light. After the light is turned off the scatterers return, but not as quickly as they dispersed. From the behavior of the scatterers it is believed that they are biological in nature and are probably the shrimp-like mysids. Mysids, about $\frac{1}{2}$-inch long, are characteristically night feeders.

The study of turbidity structure (figs. 7, 8, 9) revealed no apparent difference between day and night, suggesting that light scatterers may be predominantly smaller than the sound scatterers. However, the two types may be closely related to each other. The sound scatterers either move nearer the coastline from deeper water daily, or rise from the bottom. It is likely that the food for these organisms, the phytoplankton, is most common in or near the thermocline. This food (and to some extent the larger organisms) is the principal cause of turbidity. Since the acoustic echoes are patchy, it is probable that turbidity follows the same patchiness.

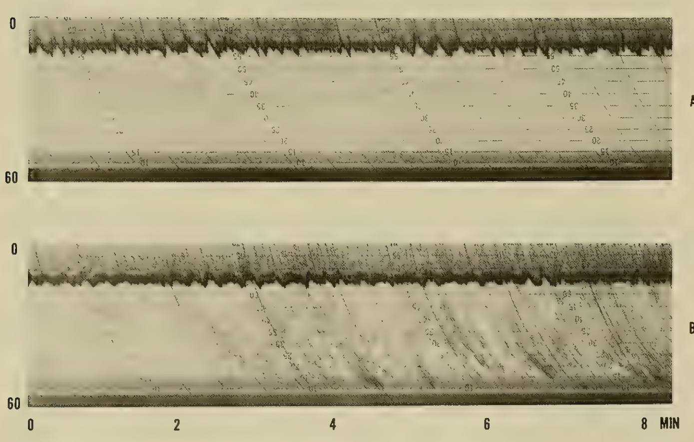

Figure 17. Appearance of an echogram during the day (A) and the following evening (B).

BIOLOGY

The pumped water samples taken in conjunction with the turbidity measurements were filtered, and the materials in the water studied. Although small quantities of inorganic matter were found, especially in samples taken near the bottom, it was concluded that the major materials causing the turbidity were organic. During the summer runs, the chief organisms that reduced the transmission of light, and hence visibility, were phytoplankton. Usually there is a mixture of several different kinds of organisms (fig. 18). However, under certain favorable conditions one organism, such as *Gonyaulax polyedra*, will dominate the population. Concentration of these organisms gives a distinct color to the water. They are often most numerous in the near-surface euphotic zone. When they die, they accumulate in the near-bottom layers. Zooplankton do not usually reduce visibility or light transmission as much as the more numerous phytoplankton.

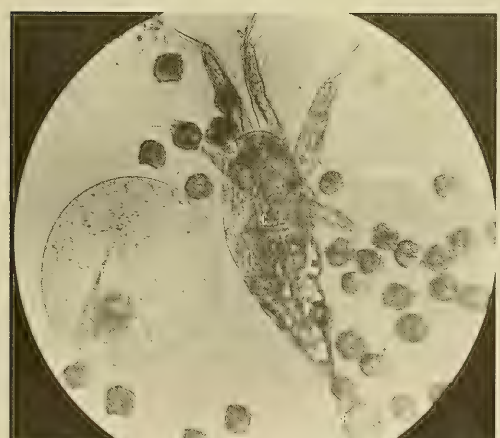

Figure 18. Sample of coarse red water showing *Gonyaulax polyedra* (A), about 50 microns in diameter. Also .lso present in the sample are *Peridinium* (B), a nauplial larva (C), and a *Noctiluca* (D).

DISCUSSION

The ocean in the area where these studies were conducted may be described as consisting of two water masses, one above the thermocline and one below. The thermocline serves as a water-mass boundary. The turbidity structure of the water depends on the turbidity of the two water masses and their movements.

It may be seen that on some days, such as 19-20 July 1960 (fig. 10), the water mass above the thermocline is relatively clear whereas the water below the thermocline is turbid. On other days, such as 2-3 and 4-5 August 1960 (figs. 11 and 12), a turbidity layer occurs in or near the water-mass boundary. There is a tendency for the turbidity to appear in patches. Possibly interaction of the water masses at the thermocline provides conditions that at the moment are favorable for living organisms. On the other hand, the organisms that make the water turbid commonly have a particular density. Seeking a level at which their buoyancy becomes neutral, they may float on the density boundary of the thermocline, as appears to be the case in figures 11 and 12.

The vertical fluctuations of the turbidity can be accounted for to a large extent by the presence of internal waves. These waves contribute to the "patchy" pattern that occurs near the thermocline. In view of the "patchiness," a geographic curve of single observations may be misleading.

SUMMARY AND CONCLUSIONS

The studies described in this report were conducted to investigate the widely observed differences in the transparency of ocean water. Light transparency was measured by means of a hydrophotometer. The data were recorded in such a way as to relate turbidity to time, temperature, and biological aspects.

Vertical runs through the water column were made with the hydrophotometer every half-hour. These were conducted during four extended periods, one about 10 hours long and three of 27 to 29 hours in duration. It was found that certain relations existed between temperature structure, internal waves, and turbidity. The level of higher turbidity gradients usually fell on or just below the maximum temperature gradient. The most turbid water was frequently found on the thermocline which moves up and down with internal waves.

Long-period changes in the depth of turbidity maxima followed closely the changes in the level of the thermocline (which has a tidal cycle), but short-period changes could not be explained in this manner. Turbidity was found to be caused principally by concentrations of living plankton and detritus or decayed plankton.

RECOMMENDATIONS

1. For continuous studies of several days' duration, several hydrophotometers should be assembled in a string and the data indicated by some type of multichannel recorder. It would be desirable to use for this purpose either an interpolating contour recorder which would automatically print turbidity isolines, or a digital system which would punch the information on computer tapes.

2. Further turbidity studies should be conducted at the NEL tower, and as before should be supported by temperature and biological studies.

3. Additional data should be obtained in other geographical areas for comparison with the data from Mission Beach.

4. Acoustical-biological-turbidity relations should be studied in more detail to determine the cause of patchiness in the distribution of acoustic scatterers. Use should be made of a high-frequency sea scanner that can be tilted to delineate the size and shape of scattering patches.

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* NEL Technical Memoranda are informal documents intended primarily for use within the Laboratory.

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1. Sea water - Temperature
2. Sea water - Turbidity
3. Shallow water - Turbidity

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