

SEA TEMPERATURE VARIATIONS ASSOCIATED WITH TIDAL CURRENTS IN STRATIFIED SHALLOW WATER OVER AN IRREGULAR BOTTOM¹

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ABSTRACT

Unusual features of the large and nearly periodic variations in sea temperature which are observed in shallow stratified water along the coast of southern California may be caused by tidal stirring over an irregular bottom and by subsequent horizontal and vertical oscillating movements associated with tides.

PART I

Sea temperature variations having an average diurnal range of approximately 4° C during summer months are indicated on thermograph records obtained at the end of Scripps pier in the years 1926 through 1931. Other observations show that cold spots are found in certain localities along the coast, that the vertical temperature structure changes markedly with position, that the amplitude of local temperature variations changes systematically from week to week, and that large local temperature changes occur in a short time. The records have been analyzed here to determine the time, the frequency and the range of the variations at different depths and in different months. Analysis of the data and further investigations led to a theory which, when considered together with effects of the normal wave action associated with tides (see Arthur, 1954), accounts for most of the features of the variations. This theory makes use of a formula developed by R. H. Fleming for tidal current velocities in shallow water. The formula indicates that, in certain regions, widely different velocities may be found adjacent to each other. The differences lead to formation of eddies which, over irregular bottom, cause stirring. In highly stratified water, such as that found off southern California in summer, this bottom stirring causes cooling in the upper layers or tends to intensify vertical temperature

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gradients in any overlying thermocline. Oscillating tidal currents then cause the "cold spot" thus formed to migrate back and forth so that large temperature variations are observed in any locality where the cold water mass, during its horizontal migration, replaces normal unstirred waters. The intensification of the temperature gradient in the thermocline also results in more marked local temperature changes associated with vertical oscillations of the water.

In the following discussion, the proposed theory and a description of the kind of predictions which it permits establish a framework into which the various supporting empirical features may be fitted. Further details may be found in a dissertation by Leipper (1950).

Since tidal currents vary according to the stages of the tide, it is convenient to fix attention upon velocities at a certain tidal stage. In the following, attention shall be centered on the tidal stage having the maximum tidal-current velocity.

Intuitively, one would expect the maximum velocity of tidal current near shore on a continental shelf to be proportional to the distance from shore and to be inversely proportional to the wave period and depth, i.e.

$$V_{\max} = \frac{kx}{Th},$$

where x is the distance from shore, h the depth, T the wave period, and k a constant. Such a relation may be developed from physical considerations.

By using an expression derived by Lamb (1932: 254-256) from the equations of motion and from the equation of continuity and by introducing certain assumptions which seem reasonable for the continental shelf, Fleming (1938) developed a method for computing the maximum tidal-current velocity. It is assumed that the tidal amplitude is nearly constant over the small area near shore, that the wave length is great compared to the distances under consideration, and that the wave is a standing wave with node line parallel to the coast. The expression for the maximum velocity of the tidal current is then given by equation (2), where the constant k in equation (1) becomes the product of 2π times the wave amplitude η

$$V_{\max} = \frac{2\pi\eta x}{T h}. \quad (2)$$

A quantity C may be defined as

$$C = V \left(\frac{T}{2\pi\eta} \right). \quad (3)$$

That is, from equation (2), $C = x/h$.

When we examine charts showing details of bottom configurations in a band approximately five miles wide along the California coastline, we observe that many localities have configurations which, in the light of equation (2), lead to widely different tidal current velocities in areas not far removed from each other. Any locality where the spacing of the inshore bottom contours change suddenly along the coastline has associated velocity variations. Such changes in contour spacing are often observed where a point of land juts seaward. Different velocities in adjacent areas tend to cause a turning of the currents, the stronger one running ahead and turning toward the weaker; thus eddies are formed.

Mechanical stirring occurs in the presence of tidal currents. For example, Sverdrup, et al. (1946: 566-569), in discussing the effects of the bottom, have explained that currents must be deflected vertically or horizontally by submarine peaks. The stability of the water, the strength of the current, and the configuration of the peaks determine the amount and direction of deflection. Quantitative estimates of such modifications of tidal currents in shallow water and the effect of these modifications on the mixing processes have not yet been made.

Since the above difference between the velocities of maximum tidal currents is due to a difference in bottom slopes and since the resulting eddies form between the different currents, the eddies are formed over a region of changing bottom slope where they must have some associated vertical movement. Such movement intensifies both vertical and horizontal stirring of waters of different temperatures.

If the waters are nearly homogeneous, as is often the case in the upper layers during winter, stirring related to tidal currents has little or no effect in bringing about local changes in temperature. However, in summer the surface layers may become highly stratified. Stratification may be particularly marked in regions where cold upwelled water approaches the surface but where normal heating occurs at the surface. Under these circumstances any vertical stirring may markedly cool the surface layers. Thus, in summer we may expect a cold spot to develop over an area where bottom contours are favorable for variation in tidal currents, with consequent stirring and mixing. It is possible that the stirring action will occur in the underlying water only and will not reach the surface. In this case a shallow and more intense thermocline develops which may define a cold spot at some level below the sea surface.

In most localities the wave period of tides does not change significantly from day to day whereas the amplitude does. Since the maximum velocity of a tidal current is directly proportional to the

amplitude [eq. (2)], the local velocities also change from day to day. This causes changes in the intensity of eddying movements and in the amount of related stirring action. Thus, in any region where bottom contours favor the formation of eddies and where temperature stratification exists, it is to be expected that a cold spot will form and will increase in extent from day to day while the tidal range and the corresponding tidal mixing decreases.

As noted, the maximum tidal-current velocities at a given distance from shore are greatest where the depth is least. Thus the amount of stirring associated with these currents would be greater in shallow water. Also, in depths below the thermocline, the vertical temperature gradient is relatively small and a given amount of stirring here leads to smaller local temperature changes than at shallower depths where the temperature gradient may be larger. It is true that the greater stability in the thermocline region opposes vertical mixing. However, this is not significant in the face of the energy available in the currents related to the tides, and it may be expected that the largest temperature changes caused by tidal currents at a given distance from shore will occur in the shallowest waters where the vertical temperature gradient is largest.

Regions having large temperature changes associated with tidal stirring are limited in size. Limiting factors are: the dimensions of the area having bottom contours favorable for stirring; the size of the region having highly stratified water; and the distance which water migrates in a tidal cycle. Consideration of these factors leads to the conclusion that cold spots would be expected to have diameters not greater than approximately three miles.

Because of the nature of the currents in the region in which cold spots are formed, the spots must migrate or move with the tides. The astronomic tides are periodic, being semidiurnal in most regions, and the vertical and horizontal movements which are required to permit the rise and fall of the water level in tidal action are the tidal currents which affect the cold spots. These currents must also be periodic and oscillating, the periods being the same as those of the tides unless the currents are modified by other influences.

In a given locality the tidal current at a certain stage in one tidal cycle may be different from that at the same stage of other cycles. Differences occur which are related to the change in tidal amplitude and to the influence of varying local ocean currents not related to the tide.

Since cold spots are produced by stirring in tidal currents, they always exist in regions where they cannot remain stationary. They must move with these currents, migrating back and forth in a time

equal to a tidal period. The distance of such migration depends on the average tidal-current velocity. This is usually less than one-half mile per hour, thus limiting the migration of a cold spot in a semidiurnal tidal cycle to less than approximately three miles.

Seasonal or wind-driven currents which change their direction or speed but which are not related to the tides sometimes aid and at other times hinder the tidal migration of a particular cold spot toward an observation point. This accounts for the cold dip at a given locality occurring sometimes at one tidal stage and sometimes at another.

Since cold spots are formed by turbulence over an irregular bottom, their three-dimensional structure will be dome-like, with the broadest extent of mixed water and the lowest temperature in the deepest levels. As such a dome or crest moves toward a point of observation, decreasing temperatures will be noticed first at the bottom. As the dome pushes forward, the cold water will be observed at progressively shallower depths until the dome crest arrives at the observation point, at which time some of the original warm water mass may or may not remain above the dome. As the dome recedes, the warm water will return first at the surface and then will gradually occupy the greater depths.

The foregoing considerations permit the extrapolation of certain observed local temperature trends with greater accuracy than has been possible previously. For example, we may predict that the local temperature range in regions having cold spots will increase as stratification increases and that it will decrease as the waters of the surface layers become more homogeneous. Also, if temperature dips have been observed from day to day at a given tidal stage, we forecast that the next dip will occur at that same stage of the predicted tide, assuming that no significant change occurs in the wind or in other nonperiodic phenomena. In extrapolations, use may be made of day to day trends in the amplitude of temperature variations which are associated with increasing and decreasing tidal ranges.

Horizontal distributions of temperature in shallow water often may be explained or predicted by considering the tides, the water stratification, the bottom topography, and the tidal stirring process.

PART II

Data collected from 1916 to 1950 under the supervision of Dr. George F. McEwen have been used to study the validity of the model for temperature variation described above. These data include: daily sea-surface temperatures collected for more than 30 years at selected points along the coast; four years of thermograph records

taken 2 feet and 16 feet above the bottom at the end of the 1100-foot Scripps pier; hydrographic observations taken 5 miles and 11 miles west of the pier at two-week intervals over a period of several years. Following an analysis of these data, which brought to light several unusual and marked types of variation in the shallow-water temperatures, additional observations were planned and carried out over a two-year period to supplement the McEwen data and to provide information that was needed to serve as a further check on the explanation for the observed variations. (Bathythermograph [BT] records are in degrees Fahrenheit, the other records in degrees Centigrade; for convenient comparison with other data summaries, both of these respective units have been retained in this analysis.)

The quantity C , defined in eq. 3, has been computed for various locations off La Jolla, California by using a chart that shows bottom topography. Lines of equal C value (i.e., lines of constant relative theoretical velocity of maximum tidal current) have been drawn in Fig. 1. It is evident that there is a great variation in the value of maximum velocity with position. West of La Jolla, velocities are as much as $3\frac{1}{2}$ times greater than those north and northwest of La Jolla. A similar chart prepared in greater detail showed velocities in one area which were 9 times greater than those in a nearby area.

To obtain observed values for comparison with theoretical current velocities, simultaneous drifts of two submerged triplane buoys in a 3-hour interval between low and high tide were carefully plotted. The buoys were released in regions that were computed to have quite different tidal-current velocities, the ratio between velocities being approximately 7:3. The two paths of drift are shown in Fig. 1. The ratio of two *total* drifts was 3.26:1, that of *net* drifts (distances from beginning to end points) 2.19:1. The theoretically computed ratio of 2.43:1 compares favorably with observation, and the theory is supported. The observed velocities were from 0.2 to 0.6 knots.

Drift observations were carried out by John Blankenship who took particular care to eliminate the effect of wind on the buoys. The day selected was November 10, 1948, with a low tide of 2.5 feet at 1248 PST and a high tide of 4.3 feet at 1746. Buoys, dropped one hour after low tide, were picked up 58 minutes before high tide. Note in Fig. 1 that the drift was generally toward the southeast while the tide was rising.

The significant features of the seasonal temperature variation are indicated by the temperature-depth structures in Fig. 2, in which curves for winter and summer are compared. In Fig. 2a the curves were obtained by averaging all available BT observations taken in

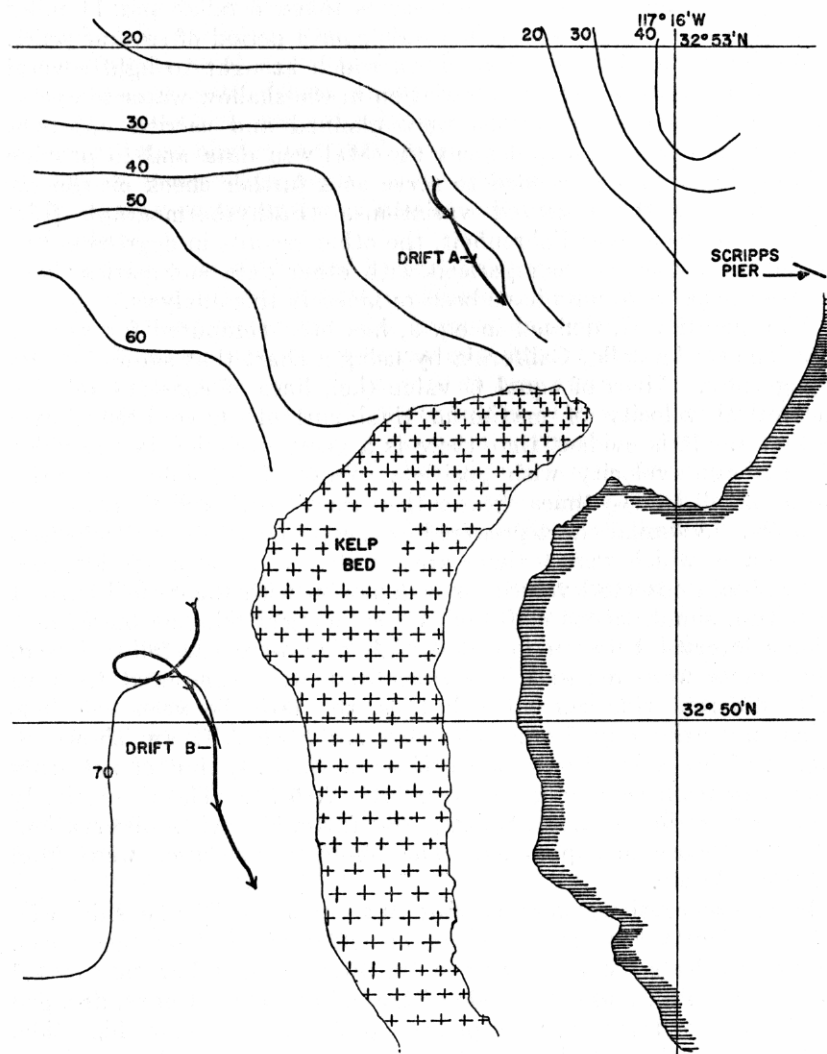


Figure 1. Simultaneous drifts of two submerged triplane buoys in a 3-hour interval between low and high tide; also, lines of constant relative theoretical velocity of maximum tidal current.

August and also in February from a region about 24 miles offshore. Above 100 feet the change from winter to summer is more or less typical of most ocean areas, with nearly isothermal water of low temperature in winter and more stratified water with higher surface temperature in summer. From 100 to 400 feet, however, the change is opposite that which might be expected in most regions, since the temperature in summer is lower than that in winter. This change is even more apparent in the example in Fig. 2b which is based on two single hydrographic observations made at the same place in March and

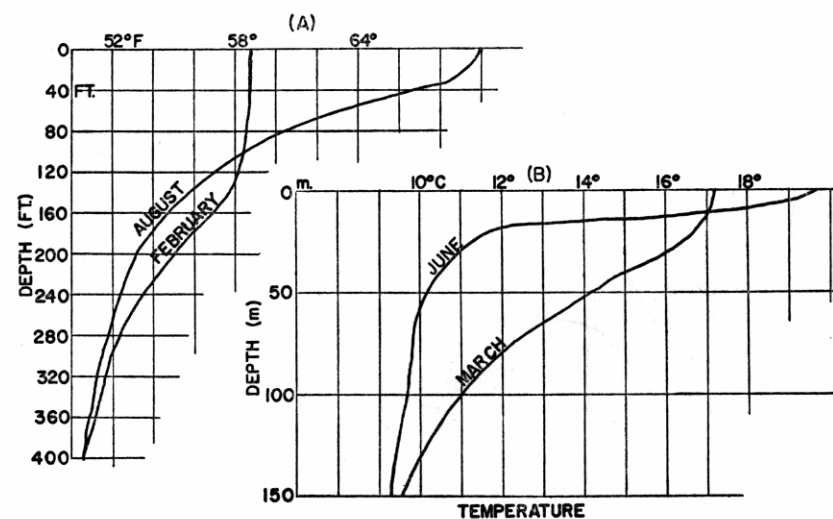


Figure 2. Comparison of winter and summer temperature-depth structures offshore near Scripps Pier.

June; all of the water below about 10 m dropped in temperature during the March-June interval. At about 30 m the temperature was about 5° C lower in summer than in winter. This type of variation, common to the region off southern California, has often been described (McEwen, 1916: 352-353, fig. 985). It has been explained that this phenomenon is due to upwelling brought about by strong northwesterly winds in the springtime north of Point Conception. After upwelling, this cold water flows southward and is gradually warmed through a thin layer near the surface; when it arrives in the southern California area, the temperature-depth structure in summer has the appearance of the June and August curves shown in Fig. 2.

The combination of normal surface heating and abnormal cooling

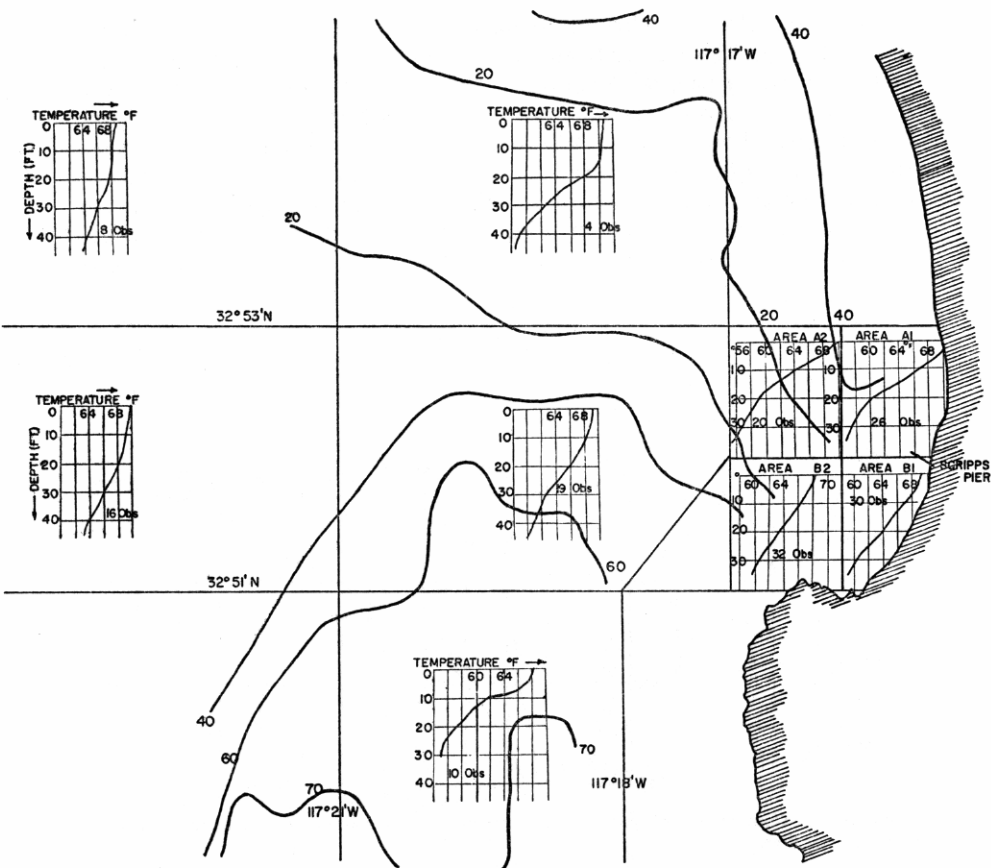


Figure 3. Average temperature-depth structure in summer in different areas near Scripps Pier; also, lines of constant relative theoretical velocity of maximum tidal current.

which is indicated at some depths below the surface results in a sharp temperature contrast between the surface layers and those immediately below them. This contrast sets the stage for the development of local cold regions near the surface when the two layers are stirred in places by varying tidal currents.

Another important feature of the temperature distribution is that the temperature structure of the water near shore differs from that farther out. For example, Fig. 3 shows that the vertical temperature gradient in summer near the surface off Scripps pier is much greater than that farther offshore. For the 0 to 30-foot depth interval, the average temperature decrease with depth along the coast is always 8° F (at

times greater than 14°) for the regions shown, whereas in offshore areas the average decrease is only 3° F. Thus, along the coast a given stirring of the surface waters might result in a large temperature decrease, whereas farther offshore, where the water is more nearly isothermal, the same amount of stirring would change the surface temperature but little.

In winter, vertical temperature differences are small over the entire area, being usually less than 1° F per 30 feet of depth. Hence a given amount of stirring could result in only a small decrease in surface temperature; furthermore, the possible temperature drop brought about along the coast would not be appreciably different from that in the region offshore.

TABLE I. AVERAGE MONTHLY DIURNAL RANGE OF SEA TEMPERATURE AT SCRIPPS PIER (°C)

Month	J	F	M	A	M	J	J	A	S	O	N	D
2 feet above bottom	0.5	0.5	1.0	1.3	1.4	1.3	1.8	1.7	1.6	1.0	0.5	0.4
16 feet above bottom	0.6	0.7	0.9	1.2	1.2	0.9	1.6	1.3	1.3	0.9	0.6	0.6

On 19 days throughout the year, series of observations were made at one mile intervals on a line perpendicular to the coast extending 10 to 15 miles offshore. Temperature-depth sections of these data showed 18 sections with isotherms rising toward shore. This appears to be a general tendency.

To compute the average amplitude of the diurnal temperature variation on ordinary calendar days, values were read from the Scripps Pier thermographs at two-hour intervals beginning at midnight; monthly averages were then calculated for each hour read. The difference between the lowest and highest average for a given month is the diurnal range for that month. Monthly ranges were computed for three separate years, and these were then averaged together by months (see Table I).

Note two unusual features of the data in Table I. First, from March through October the diurnal range of variations near bottom is greater than the range 16 feet above bottom. Since solar radiation is absorbed rapidly near the surface and since only about 6% of it reaches a depth of 5 m or 16.8 feet (Sverdrup, et al., 1946: 107), an important diurnal process other than radiation is indicated. Second, the diurnal ranges in July near the bottom are large, reaching a value of 1.8° C or 3.2° F. The maximum average diurnal variation caused by solar heating is smaller and may be calculated approximately by assuming that the incoming energy is uniformly distributed by intense mixing throughout a surface layer 5 m in depth. Using the maximum average

insolation at the Pier, 484 g cal/cm² (McEwen, 1938: 236), the maximum daily increase in sea temperature at a depth of 5 m is 1° C. The increase which would be expected is considerably less than this because of heat lost by evaporation, conduction and radiation from the sea surface. Thus the observed variation is much larger than that due to the processes usually considered.

At the Scripps pier the temperature variation within a given day, strangely enough, is more regular in winter than summer. In sum-

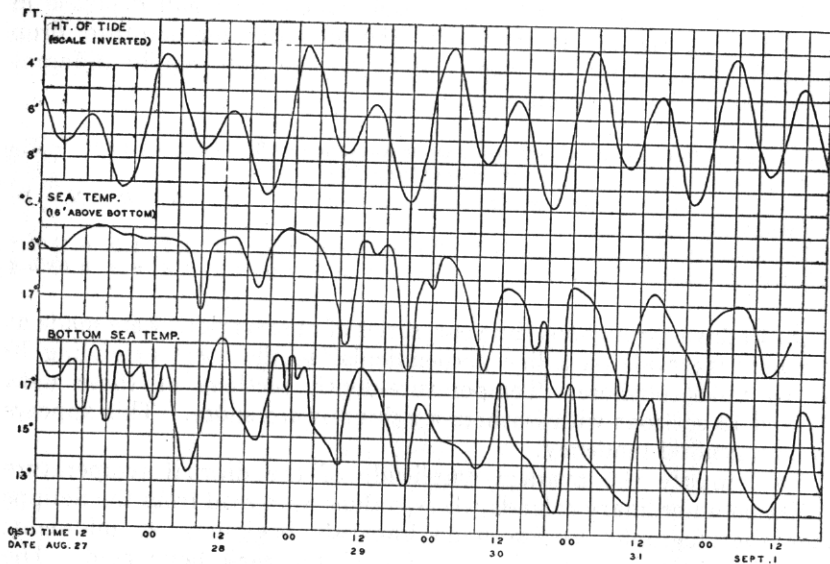


Figure 4. Tide and sea temperature variations at Scripps Pier, 1928.

mer it is masked by other types of temperature fluctuations, including a series of dips which usually occur daily at intervals approximately equal to tidal periods. See Fig. 4 for an example of temperature variations observed during a week in the summer of 1928 together with the associated heights of the tide. The dips shown on the thermograph traces do not have the appearance of sinusoidal variations; many of them are of the type which might be expected when one water mass is rapidly replaced by another of different temperature. In some cases, changes as great as 7° C occur in periods as short as 15 minutes. As these dips increase in size from day to day, the average temperature as well as the daily maximum at Scripps pier decreases (see Fig. 4).

Variations of the type shown in Fig. 4 are absent during winter, and their nature varies considerably from day to day and from week

to week during the summer months. In 1928 the lowest temperatures occurred regularly with the high tide. In other weeks, however, they occurred with the low tide. As will be shown, the former occurrence is more common, but cases where the coldest water is associated with every stage of the tide have been observed. Correlation by harmonic analysis should not be attempted because of the obvious shift in phase.

Tabulations show that the majority of maximum daily temperature dips occur during the night. Since these dips appear to be related to tidal currents, diurnal characteristics might be expected when it is considered that the solar tidal component is 43% of the lunar component and that tidal currents are subject therefore to a large diurnal influence. The regular occurrence of the larger nocturnal dips lowers the night-time average temperatures and thus increases the amplitude of the ordinary diurnal variation.

To study temperature variation within diurnal tidal periods, time was counted from one high tide to the second following high tide. In this manner 'tidal days' were defined as 24 to 25 hours in duration.

A frequency diagram in Fig. 5 shows the number of times that dips occurred on each hour of the tidal day. Fig. 5a is based on only the maximum dip which occurred each day, while Fig. 5b is based on all distinct dips, usually two for each day. Greatest frequencies were observed at approximately 0000 and 1200 h, which correspond to high tides. Least frequencies were observed at about 0600 and 1800, the times of low tides. Of the total number of dips, 55% occurred within two hours of the high tide while only 24% occurred within two hours of the low tide. For given series of successive days, the time of the dips did not shift erratically in the tidal time scale.

An effort has been made to determine under what conditions temperature dips may be expected at high tide and under what conditions they may be observed at other times. There appears to be a systematic seasonal deviation of the time of occurrence from the time of high tide as the year progresses (see Leipper, 1950).

To study further the tidal effects on temperature, the ordinary diurnal heating was eliminated. Average monthly temperatures were obtained for each 2-hour period of the day, and the sine curve of best fit was drawn through the 12 averages. It was assumed that this curve represented the ordinary diurnal variation; deviations from the monthly mean shown by this curve at various hours of the solar day were used as corrections to the observed temperature values to eliminate the diurnal effect.

On each tidal day the temperature range was obtained by subtracting the minimum from the maximum, using the adjusted data.

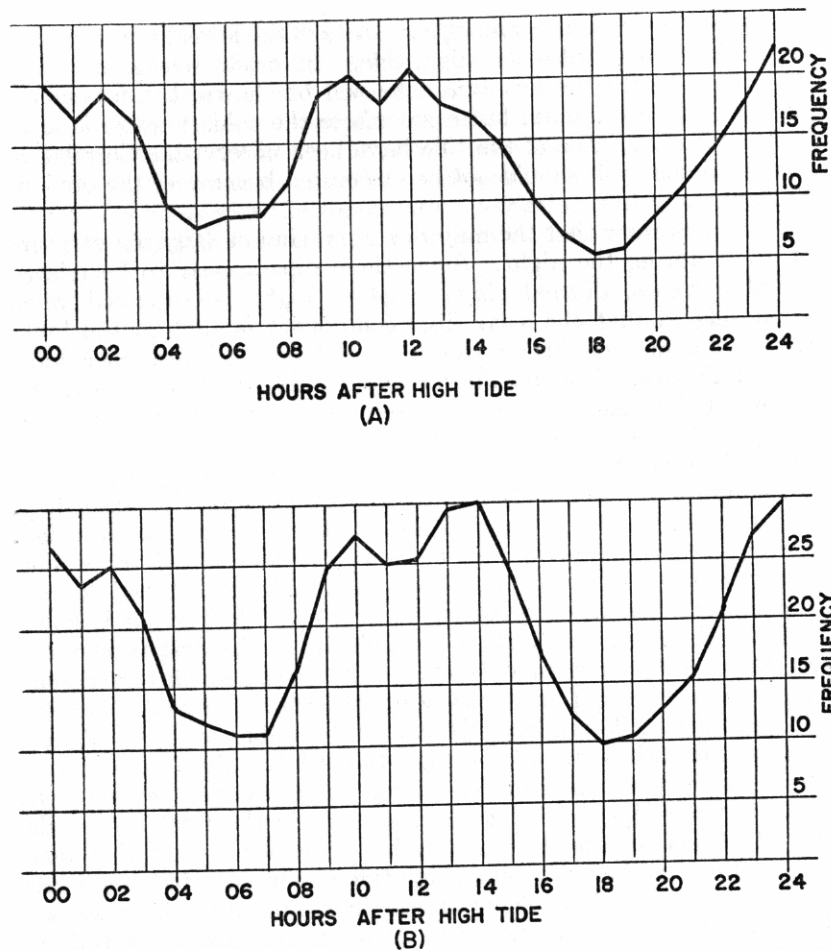


Figure 5. Frequency of occurrence of temperature dips at Scripps Pier in different one-hour intervals after high tide.

Ranges were then averaged by the month (see Fig. 6a). Data for the near-bottom changes are presented, since changes at this level are more marked and more consistent than those at the upper level. In winter the temperature range on tidal days is small, but the range increases in spring, and in summer it averages more than 4°C (see Fig. 6a). On the original thermograph traces it is difficult to observe any dips in December, January and February. During summer, dips have occurred on individual days which have lowered the temperature at Scripps pier below the lowest values observed in winter months.

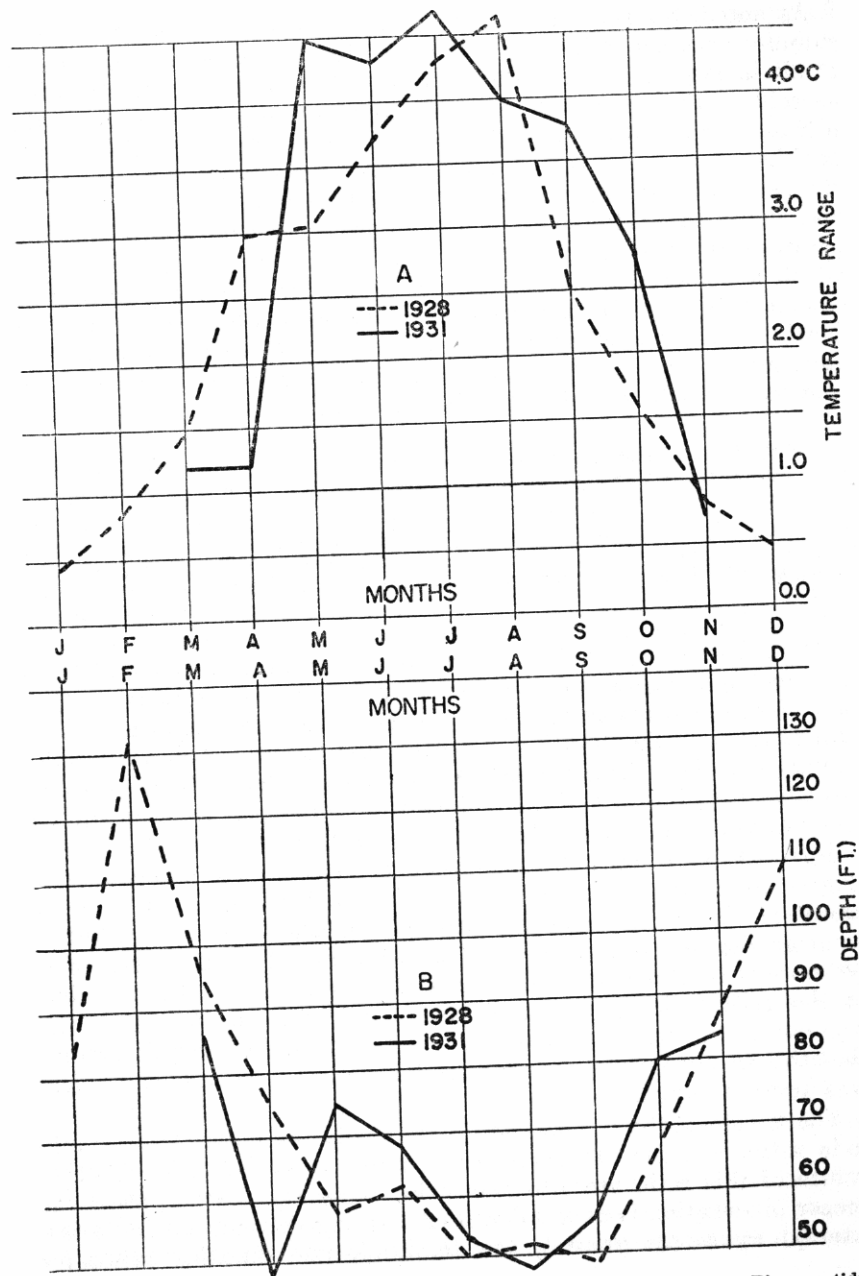


Figure 6. Monthly average range of sea temperature at bottom, Scripps Pier, on tidal days. Depth of water offshore which is colder by the amount of the average daily tidal deviation than the average observed at the bottom.

As noted, the presence of cold upwelled water near the surface in summer together with vertical and horizontal tidal movements can result in large local temperature dips. As shown in Fig. 6b, water as cold as that observed in the average cold dip in summer at the pier may be found within 50 feet of the surface off the San Diego area. (Offshore temperatures for this comparison were obtained by averaging BT observations taken about 24 miles from the coast.) Fig. 6b also shows that, although the dips in spring and fall lower the temperature an average of only about 1° C, water comparable to that which is colder than the average by one degree at the pier bottom cannot be found offshore in these seasons at less than 80- to 90-foot depths. Water with a temperature that is low enough to cause the extremely cold summer dips is closer at hand than that required to cause the moderate dips in fall and spring.

TABLE II. RATIOS OF MONTHLY AVERAGE AMPLITUDES AND OF DURATIONS OF TEMPERATURE DIPS 2 FEET ABOVE BOTTOM TO THOSE 16 FEET ABOVE BOTTOM

		J	F	M	A	M	J	J	A	S	O	N	D
Amplitude	1928	—	0.7	0.8	1.3	1.4	1.6	1.4	1.5	1.3	1.0	0.9	—
Ratio	1931	—	—	0.5	0.7	1.4	1.8	2.6	3.3	2.0	2.4	1.8	—
Duration	1928	—	0.8	0.9	1.1	1.2	1.4	1.3	1.3	1.0	0.8	0.8	—
Ratio	1931	—	—	0.3	0.8	1.1	1.4	1.5	1.8	1.5	1.6	1.0	—

The relative magnitudes of tidal changes in near-surface and near-bottom temperatures were analyzed by defining two ratios: (1) that of bottom to surface temperature change, called the 'amplitude ratio,' and (2) that of the duration of bottom dip to surface dip, called the 'duration ratio.' Ratios were computed from data which were not adjusted for diurnal variation, since the diurnal effects near surface and bottom were found to be nearly equal.

For 1928 and 1931, the amplitude ratio had minimum values in winter, maximum values in summer (see Table II). In winter the amplitude is greater near the surface than near the bottom, but in summer the situation is reversed and the near-bottom change may be more than three times that near the surface. The larger values of the 1931 ratio are probably associated with the fact that this was one of the warmest years on record; it is quite likely, therefore, that this was one of the years when the vertical temperature gradient was unusually high.

The trends of the duration ratio are similar to those of the amplitude ratio, but the variation is not quite so great. The monthly values of this ratio are also shown in Table II. Except when the deeper observation is at the depth of a strong thermocline and when internal waves are present, the amplitude and duration ratios for

most parts of the ocean would be less than unity, since nearly all factors that affect sea temperature have their maximum influence at the surface. The fact that the pier ratios are greater than unity demonstrates that interval waves, tidal oscillation, or both are present.

If the theory presented is applicable at Scripps pier, then it should be possible to locate a cold region which would be close enough to the pier to be carried in and out from the pier by tidal migrations. Since such migrations are about three miles, a cold region should exist within a few miles of the pier area. In an attempt to locate such a region, a series of temperature observations were made in the summer of 1947 with surface bucket thermometers and BTs.

It was hoped that the cold areas could be located by use of surface temperature data alone, but this did not turn out to be the case, since in this particular area the mixing appeared to take place largely just beneath the surface. However, it was found that BT observations in certain regions were markedly different from others in adjacent regions (see Fig. 3), and that these differences would lead to the expected local temperature changes during tidal migrations. This variation in structure may be explained by considering the variation in maximum tidal current velocity with position, shown also in Fig. 3.

It was possible to make a series of observations showing the relation of cold dip to currents.

For a short time in 1947 a thermograph was again installed at the end of Scripps pier. By observing the variations indicated by this instrument and by considering the nature of the fluctuations shown by past records, it was possible to predict that a cold dip would occur about noon on July 25. The dip occurred as expected. Observations of it were made by B. K. Couper with a 40-foot BT and a bucket thermometer. Currents were determined by the movement of wooden chips thrown onto the water. The dip persisted from 1324 until 1557 PST, during which time the currents were toward the southeast and south. High tide occurred at 1525. At 1625 the currents had begun to shift and the temperature had begun to change. At 1725 relatively isothermal warm water was observed and the currents were toward the east and east-northeast.

To ascertain the temperature-depth structure over a 24-hour period, a series of BT observations was taken from the Scripps pier at half-hour intervals. From these it is possible to determine the temperature variation at any depth (see Fig. 7).

Variations were plotted for the depths 2 and 16 feet above bottom and it was found that the resulting curves were typical of many obtained on the thermographs. It was apparent that large dips did

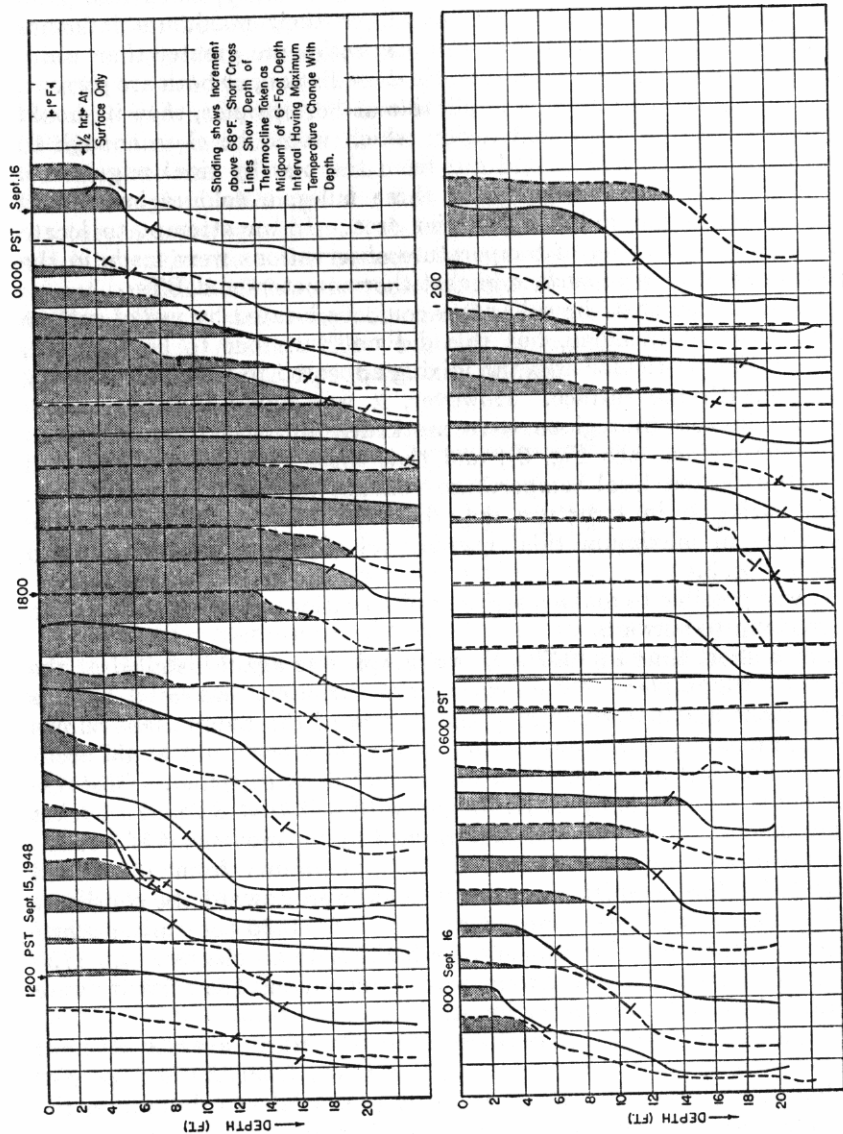


Figure 7. Half-hourly bathythermograms at the end of Scripps Pier.

occur, that these were of approximately tidal period (except for an irregularity at 0730 on September 16 at the bottom), that the smaller dips and those of shorter duration occurred at the surface and at the upper level, and that the ranges are approximately of the correct magnitude for comparison with the average for September shown in Fig. 6. Thus, comparison showed that these BT observations indicate the structural changes which occurred on other days when temperature dips were indicated at two fixed depths by thermographs only.

On the same day as the BT observations used in Fig. 7 were made, Dr. Donald Pritchard² arranged to have two ships make similar observations at 18 miles WNW and NW of the Scripps pier. Variations in depth of the thermocline at these positions and at the Scripps pier were determined and plotted. From these data three conclusions could be drawn. First, internal waves having a period of approximately 12 hours occurred at all three locations; second, the range of vertical motion was as great as 40 feet; third, the thermocline was found at a greater depth offshore than at the pier.

Further information on the nature of internal waves near shore was obtained from BTs obtained by a vessel which went out and returned along the same path, repeating observations in the same locations on both legs of the cruise. The temperatures at given longitudes changed markedly between outgoing and return trips.

In August 1948 a cruise to Lower California observed the width of certain low-temperature areas which had been found by Dr. Carl Hubbs along the coastline. In one observed area close to the coast the temperature averaged 58.4° at four stations and in another area 57.2° at six stations, while all of the temperatures seven miles or more offshore, except one, were above 64° F. The width of these near-shore low temperature bands was approximately two miles, and progressing seaward, a transition band of about five miles was measured before the warmer offshore water was reached. From shore seaward, the isotherms dropped so rapidly that the water inshore was many degrees colder than that observed at any depth down to 45 feet at the seaward end of the BT sections across these cold regions. In one section, the inshore stations were somewhat warmer than those a short distance offshore, indicating that the major cooling effect had not occurred at the immediate coastline in this locality. Comparing pier temperatures with values some 15 miles offshore, it is apparent that the maxima of surface temperatures at the pier from April through August occur at times when the water from the coast outward is of uniform or nearly uniform temperature.

² Then at the U. S. Navy Electronics Laboratory at San Diego, California.

On the the other hand, when a dip occurs at the pier, the inshore water seems to be much colder than that offshore. This supports the conclusion that offshore changes are more gradual and less marked than temperature changes within one or two miles of the coast and it indicates further the presence of cold dips near shore.

CONCLUSION

The erratic nature of certain coastal sea temperature records which are based on a few observations at specific times of day are explained by the action of internal waves and by periodic migration of cold spots formed over shallow regions of irregular bottom by horizontal variations in velocity of tidal current in the presence of stratified water layers. Proper understanding of the observed variations greatly increases the value of coastal observations. Such observations should be fully utilized since they may readily be obtained from the shore or from piers and docks.

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