REALITY AND ILLUSION IN OCEANOGRAPHIC SURVEYS[1]

By

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ABSTRACT

Care must be exercised in selecting time intervals and spacings between stations along oceanographic profiles in order to avoid erroneous conclusions regarding the mean circulation. By proper combinations of time intervals and spacings, the effect of internal waves of tidal periods, which are the source of these errors, can be suppressed. The application of these principles to the Marine Life Research cruises of the Scripps Institution is discussed.

INTRODUCTION

Generally oceanographic surveys are made by one or several ships occupying a series of oceanographic stations along specific profiles according to a predetermined plan. To obtain the best possible synoptic picture of the various oceanographic factors, the profiles and the stations along them should be spaced as closely as possible, and in order to obtain data that is as homogeneous as possible, the distances and the time intervals should be kept constant. Bjørn Helland-Hansen (1939) has indicated in his work with the ARMAUER HANSEN in the Norwegian Sea how difficult it is to fulfill these conditions of a quasisynoptic survey and how careful one must be in interpreting such observations.

With a single ship at disposal, it is difficult to reach a satisfactory compromise between two conflicting requirements. To fulfill the requirement of a *synoptic* survey the area under investigation should be covered in the least possible time. To obtain great *accuracy*, the number of stations in the area should be as numerous as possible. It is only by working a great number of ships simultaneously that the conflicting requirements can be met to a certain extent.

There is still another difficulty which is of no less importance but which has been neglected hitherto; in fact, it can even make the observations of an oceanographic survey completely worthless and meaningless. Here we refer to the difficulties associated with periodic variations of temperature and salinity (as well as other oceanographic factors). Although these variations occur in a more or less regular

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form, nevertheless they are capable of completely confusing the picture. In the following simple case I will discuss this problem more thoroughly.

THEORETICAL COMPUTATIONS

Let temperature (respectively salinity) at any point in an ocean vary periodically with time in such a manner that

$$T = T_o + a_1 \cos \frac{2\pi}{24} (t - \varepsilon_1) + a_2 \cos \frac{2\pi}{12} (t - \varepsilon_2) , \qquad (1)$$

where t is time in hours. The time variations of T result from a superposition of two waves, one of which is diurnal (period = 24 hours), the other semidiurnal (period = 12 lunar hours). The temperature T_o, the amplitudes a_1 and a_2, and the phases ε_1 and ε_2 (expressed in hours) depend upon the position x, y and the depth z. We do not have to specify the origin of these variations; for instance, they may be internal waves with a tidal period, or in the case of large horizontal temperature and salinity gradients they may be caused by the advection of different water bodies by the periodic tidal currents.

Let a ship occupy a profile along the x-axis starting at time $t = 0$ from a point x_o; at specific intervals there will be oceanographic stations (serial observations). If c denotes the average speed of the ship in knots, taking into account the duration of the stations, the position at time t is given by

$$x = x_o + c\,t\,. \qquad (2)$$

Should the ship register the temperature continuously, the observed variations would be given by

$$T = T_o + a_1 \cos \frac{2\pi}{24c} (x - x_o - \varepsilon_1 c) + a_2 \cos \frac{2\pi}{12c} (x - x_o - \varepsilon_2 c) \,. \qquad (3)$$

Therefore the observed temperature distribution of the profile would be periodic, although the mean temperature distribution does not show periodicities. The lengths of these simulated temperature waves would be 24 c n.m. and 12 c n.m. respectively. Should the ship occupy intermittent oceanographic stations (serial observations) at the points x_n, which are at constant distances from each other, the temperature T_n observed there will be given by

$$T_n = T_o + a_1 \cos \frac{2\pi}{24c} (x_n - x_o - \varepsilon_1 c) + a_2 \cos \frac{2\pi}{12c} (x_n - x_o - \varepsilon_2 c) \,. \qquad (4)$$

The observed temperatures are critically dependent on the selection of x_n, and it might prove difficult to disentangle the temperature distribution thus obtained.

One might then raise the question: Is it possible to select x_n in such a manner that the effect of the semidiurnal tide vanishes or is at least greatly reduced? One would expect the former to be the case if the condition

$$\frac{2\pi}{12c}(x_n - x_o - \varepsilon_2 c) = (2n - 1)\frac{\pi}{2} \tag{5}$$

be fulfilled. In this case the position of the stations would be given by

$$x_n = 3c\,(2n - 1) + (x_o + \varepsilon_2 c)\,, \tag{6}$$

or the distance between two successive stations by

$$x_{n+1} - x_n = 6c\,, \tag{7}$$

provided ε_2 remains constant along the profile. Therefore, the spacing of the stations depends *only* upon the speed of the ship c. For instance, with a ship speed of 8 knots the required distance of the stations is 48 n.m., a typical distance for oceanographic surveys.

From (1) and (2) it follows that stations will be occupied at times

$$t_n = \varepsilon_2 + 3\,(2n - 1)\,, \tag{8}$$

so that the time interval between two stations equals

$$t_{n+1} - t_n = 6^h\,. \tag{9}$$

At the start of the profile, the phase ε_2 is not generally given, and it is not possible to indicate beforehand the station times required for the complete elimination of the semidiurnal wave. If $t_n - \varepsilon_2 = 3^h, 9^h, 15^h$, etc., the semidiurnal wave will vanish; if $t_n - \varepsilon_2 = 0^h, 6^h$, etc., the semidiurnal wave will remain unchanged. If the time of the stations is selected freely, the probability that the effect of the semidiurnal wave in the values will be reduced to ¼, to ½ and to ⅔ is 17, 33 and 67 per cent. Therefore, in the case of a succession of stations with intervals of 6 hours, a more or less large portion of the semidiurnal wave will remain in the station values.

If one wishes to eliminate the semidiurnal wave *completely*, this can be done only if all stations are occupied at the same phase-time of this wave; i. e., the difference in time must be independent of the speed of the ship c, and must always be 12 hours. In this case the values at *all* stations differ from the mean value by the same constant amount; there will be no oscillating disturbance.

If one takes the stations at intervals of more than 6 hours (about 7 or 8), the effect of the semidiurnal wave increases gradually from small amounts to larger according to the value of ε_2, and after having reached a maximum it decreases again. In this case, for instance, it would be possible that the effect of the semidiurnal wave is small in the first part of the profile but large in the second, or vice-versa.

In assuming that there are stations at a time interval of 6 hours, it follows from (4) that there will be at stations x_n, besides the reduced semidiurnal wave, a diurnal effect in the form:

$$T_n = T_o + a_1 \cos \frac{\pi}{4} (2n - 1) - \frac{\varepsilon_1 - \varepsilon_2}{3} . \qquad (10)$$

It is remarkable that these values are independent of the speed of the ship. Every *fourth* station will show a maximum of temperature so that local variations of temperature are simulated. However, they have nothing to do with the actual temperature distribution in the ocean. Such errors are present in all oceanographic observations, and they can become extremely important if the tidal influence on the oceanographic factors is large. In such cases phenomena are simulated which depend exclusively upon the speed of the ship and the distance between stations.

Until now we have supposed, in a special case, that ε_1 and ε_2 are constant; i. e., that the tide waves have a direction of propagation perpendicular to the profile. But for the general case, the cotidal lines of the semidiurnal wave cut the direction of the profile by an angle α, and ε_2 is dependent upon x. To determine ε_2 we have to consider only the component $c'/\sin \alpha$ of the velocity of the tidal wave in the direction of the ship movement. Analagous with the Doppler effect, it is easy to show that the time interval between stations required for the complete elimination of the semidiurnal wave is

$$t_{n+1} - t_n = 12/\left(1 - \frac{c}{c'} \sin \alpha\right) . \qquad (11)$$

The value of c' is approximately 150 knots and the ratio c/c' a small number. The effect in all cases is small, especially since profiles are mostly perpendicular to coast lines, α thus being a small angle.

In the following example let ε_2 have a constant value of 3 hours. A ship takes oceanographic stations every 6 hours at a distance of 40 n.m. The average speed of the ship is 40/6 knots. According to equation (8) the effect of the semidiurnal tide wave will be completely eliminated if the times at the stations are 0^h, 6^h, 12^h, 18^h; it is reduced by 50 per cent if the station times are 5^h, 11^h, 17^h, 23^h. In addition there will be a considerable influence of the diurnal wave, especially if the diurnal wave is large compared to the semidiurnal wave. In the observations, highest and lowest temperatures occur at an interval of 4 stations. These influences thus simulate local disturbances in the temperature (and salinity) field. Dynamic computation based on such temperature and salinity values are subject to similar errors.

THE CRUISES OF THE MARINE LIFE RESEARCH PROGRAM

The Marine Life Research Program[3] of the Scripps Institution of Oceanography, University of California, includes an oceanographic survey of the west coast of America between 25° and 43° N. Cruises involving three ships have been made at regular intervals of about a month since February 1949. Each cruise lasts about 15 days and is composed of 12 profiles perpendicular to the coast about 140 n.m. apart. At each station the normal serial observations extend to a depth of 1,200 m. For each survey, charts of the horizontal distribution of all oceanographic factors are given, among them a chart of the dynamic height of the sea surface relative to the 1,000 decibar surface, with an interval of 5 dyn cm (S.I.O., 1949).

The main purpose of this extensive oceanographic survey is to obtain an insight into the circulation variations in this area, which is characterized by the California Current. During my visit at the Scripps Institution of Oceanography the various quasisynoptic charts of the oceanographic elements of the first profiles were submitted to me for discussion. In general they showed the California Current running southward. Moreover, on the maps surprising disturbances in the form of cyclonic and anticyclonic eddies seemed to be superimposed upon the California Current.

A close inspection of the dynamic topographies of the surface showed that these eddies succeed each other along the profiles at approximately equal intervals. Similar intervals exist in the corresponding disturbances in the temperature and salinity distribution. This made me suspect that these eddies are simulated disturbances rather than real. This idea was supported by the fact that the average time interval from one station to another is about 6 hours, whereas the distances between the stations was 40 n.m. Consequently the average speed of the ship is 40/6 knots, and this value fulfills in a remarkable way equation (7). This corresponds to the case discussed previously, and the occurring eddies at an interval of about 4 stations (160 n.m.) would be due to the influence of a diurnal wave. Any possible influence of a semidiurnal wave would be weakened by the selected spacing of stations and the speed of the ship. In fact, most of the profiles scarcely showed the influence of the semidiurnal wave. Aside

[3] This program represents part of the Cooperative Sardine Investigation of the west coast, the latter including two other state agencies of California and a division of the U. S. Fish and Wildlife Service.

from the fact that the station spacing and ship speed would naturally favor the diurnal over the semidiurnal wave, as they appear in the observations, there are reasons why the diurnal wave should be of larger amplitude in the ocean off the California Coast. One reason is that the tide observations along this coast show a pronounced diurnal character. Another reason follows from the theory of internal waves (Defant, 1940; Sverdrup, et al., 1942), according to which the period T of free internal oscillations is given by relation

$$T = \frac{T_e}{\sqrt{1 + T_e^2/T_o^2}}. \tag{12}$$

Here T_o is the period of free oscillations on a nonrotating earth, and $T_e = 12/\sin \zeta = \frac{1}{2}$ pendulum day is the period of the inertia oscillations. For the ocean region under consideration, the magnitude of T_o is 150–200 hours, so that $T_e/T_o = 0.1$ and $T \approx T_e$. Since the area under investigation extends from 40° to 25° N, the period of inertia oscillations varies between about 20 and 25 hours. For Lat. 30° N it is exactly 24 hours. Since the diurnal and semidiurnal tide waves, which are forced waves, have periods of 24 and 12.43 hours respectively, the diurnal waves will be increased by *resonance*.

THE TIDAL EFFECT IN OBSERVATIONS AT THE SCRIPPS PIER

It would be desirable to check these conclusions by means of anchor stations, for according to the results of those taken on the METEOR Expeditions over the West African shelf, 1937 and 1938, such tidal influence is probable (Defant 1937, 1948). But unfortunately no such anchor stations are available. However, for numerous years temperature recordings have been taken at the end of Scripps Pier at depths of 2 and 16 feet above bottom (water depth 18 feet). Leipper (1949), in discussing these observations, has pointed out the existence of large quasiperiodic variations in which the tidal periods seemed to be especially prevalent. In examining the tidal influence numerically, I have subjected the observations for August 28 through 31, 1927 (represented in fig. 2 of Leipper's paper) to harmonic analysis and have compiled the results in Table I (see also Fig. 1).

The tidal influence is very pronounced. The tide and temperature curves are almost completely reversed, and the phase differs by half a period. The variation in temperature with semidiurnal tide in the surface and bottom layers attains an amplitude of more than 3° C; with the diurnal wave in the surface layer it attains a magnitude of only 1° C. The half-hourly bathythermograms made at the end of

TABLE I. Harmonic Analysis of Observations Taken at Scripps Pier from August 18 through 31, 1927 (See Also Fig. 1)

	Mean value	*Diurnal wave (period = 24 h.)*	*Semidiurnal wave (period = 12 lunar hours)*
Tidal variation in ft.	6.5	$+ 1.32 \cos \frac{2\pi}{24} (t - 16.4^h)$	$+ 2.05 \cos \frac{2\pi}{12} (t - 6.7^h)$
Temp. °C 16′ above bottom:	17.80	$+ 0.31 \cos \frac{2\pi}{24} (t - 2.9^h)$	$+ 1.69 \cos \frac{2\pi}{12} (t - 0.6^h)$
at the bottom:	17.76	$+ 0.18 \cos \frac{2\pi}{24} (t - 12.8^h)$	$+ 1.74 \cos \frac{2\pi}{12} (t - 11.6^h)$

the pier during two days (fig. 20 of Leipper's paper) prove that the entire water mass in the vicinity of the coast is subjected to this tidal influence, the boundary layer rising and falling with an amplitude of over 7 feet. According to all these observations, periodic variations exist in both temperature and salinity in the entire water column and they follow the tides.

ELIMINATION OF TIDAL EFFECT FROM OBSERVATIONS OF THE MLR CRUISES

According to the foregoing considerations, it is most probable that the observations made off the California Coast include tidal influence, this influence being primarily responsible for the complicated structure of the dynamic topographies. The semidiurnal influences are weaker than the diurnal ones, and they are further suppressed by the selected distances between stations and the average ship speed. To obtain an undistorted dynamic topography of this surface, an effort should be made to eliminate the diurnal component also. A method for this is now given.

The method is much more complicated if some residues of the semidiurnal disturbance are left. The difficulty of completely eliminating the disturbances is dependent on three considerations. In the first place, the extent of these tidal influences varies according to localities, and consequently one must take into consideration many irregularities. Secondly, the distance between stations as well as their duration are subject to irregular variations which, although not great, change the *average* speed of the ship somewhat. The indicated anomaly of dynamic height at a station refers to a time interval of about 1 to 1½ hours, and this uncertainty as to time and locality enters fully into the observational values. In this one recognizes that the time values can

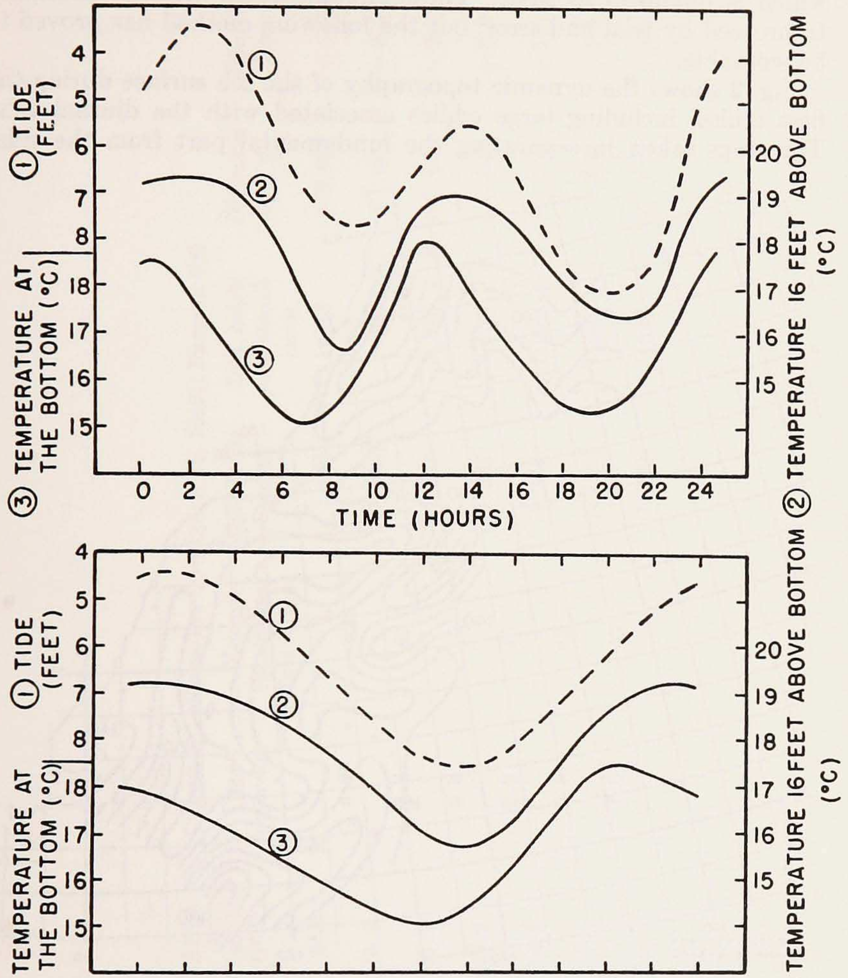

Figure 1. Above: Mean tidal curve for the period from August 28 through 31, 1927, and simultaneous temperature variations at the bottom and 16 ft. above the bottom at the end of the Scripps Pier at La Jolla, California. Below: Mean semidiurnal tide (period 12 lunar hours) and corresponding temperature variations for the same time at the end of the Scripps Pier at La Jolla, California, 16 ft. above the bottom.

have a margin of error of $\pm$ 1 hour. Thirdly, the tidal disturbances are superimposed on an average dynamic topography of the sea surface which is unknown at first. These circumstances make it necessary to proceed by trial and error, but the following method has proved to be workable.

Fig. 2 shows the dynamic topography of the sea surface during the first cruise, including large eddies associated with the diurnal tide. The steps taken in separating the fundamental part from the tidal

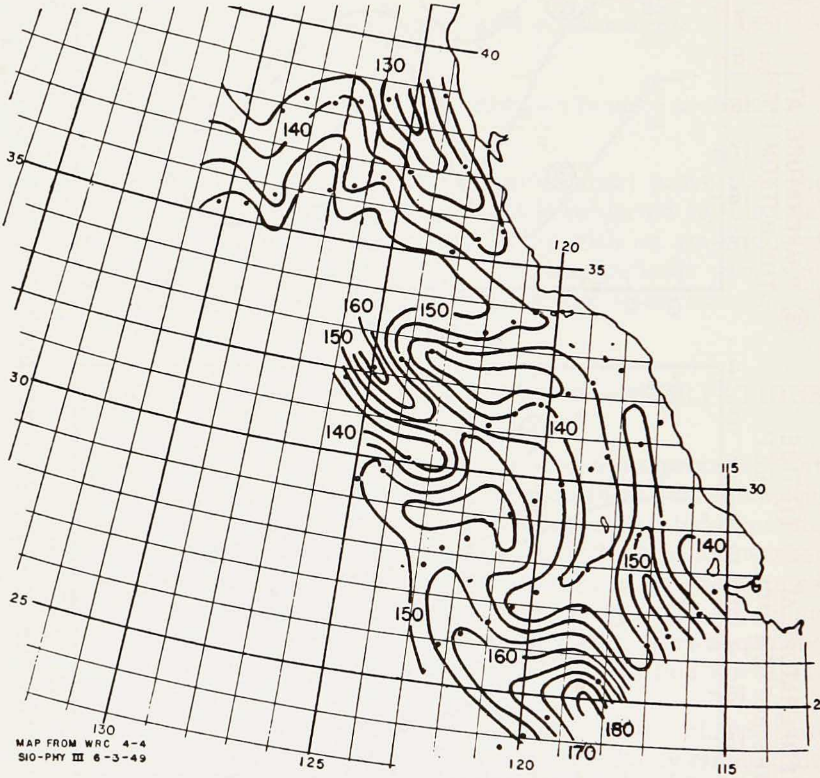

Figure 2. Marine Life Research Cruise 1 (Feb. 28 to Mar. 15, 1949): Dynamic height anomalies (0 over 1000 Decibars). Contour interval 5 dyn cm. The nearly normal lines to the coast are numbered consecutively from north to south, the southernmost line shown being the 1200 series.

influence will be shown by means of profiles 500, 800 and 1200. Tables II and III give all of the data of profiles 500 to 800 as well as the average difference in time (~ 6 hours) and the distance between stations (~ 40 n.m.) Figs 3 and 4, in their upper part, show the observed values of dynamic height along the profiles at various sta-

TABLE II. CRUISE 1. (FEBRUARY 28–MARCH 16, 1949): PROFILE 500

Station	*Date*	*Mean time GCT*	*Time-difference*	*Distance between stations in n.m.*	*Dyn. height Dyn. m.*	*Dyn. height from smooth curve*	*Difference Dyn. m.*	*Effective Time*
501	1. III	9.5^h			1.401	1.303	+ 0.098	$+ 1.5^h$
			5.8^h	46				
502		15.3			[1.280]	1.320	− .040	− 3.2
			5.8	45				
503	1. III	21.1			1.262	1.336	− .074	− 2.9
			6.8	40				
504	2. III	03.9			1.393	1.352	+ .041	+ 3.9
			6.8	45				
505	2. III	10.7			1.366	1.370	− .004	+ 1.3
			6.5	42				
506	2. III	17.2			[1.340]	1.387	− .047	− 5.2
			7.6	40				
507	3. III	00.8			1.379	1.396	− .017	+ 0.8

TABLE III. Cruise 1. (February–March 16, 1949): Profile 800

Station	*Date*	*Mean time GCT*	*Time-difference*	*Distance between stations in n.m.*	*Dyn. height Dyn. m.*	*Dyn. height from smooth curve*	*Difference Dyn. m.*	*Effective Time*
808	14. III	06.6^h			1.534	1.558	− 0.024	− 2.4^h
			7.9^h	38				
807		14.5			1.638	1.512	+ .126	+ 5.5
			6.2	39				
806		20.7			1.480	1.468	+ .020	+ 0.3
			5.5	34				
805	15. III	02.2			[1.370]	1.420	− .050	− 5.3
			7.4	40				
804		09.6			1.400	1.390	+ .010	+ 0.6
			6.6	40				
803		16.2			1.415	1.366	+ .049	+ 4.8
			5.6	46				
802		21.8			1.412	1.424	− .012	− 1.8
			5.4	39				
801	16. III	03.2			1.468	1.486	− .018	− 6.0

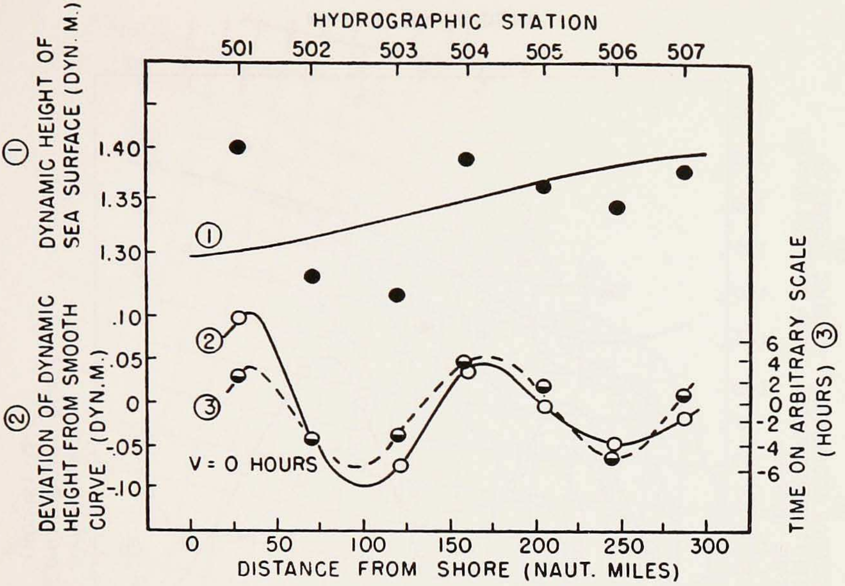

Figure 3. Cruise 1, Stations 501–507: Above: Dynamic heights at stations and smooth curve along the line. Below: Deviations of dynamic heights from the smooth curve (solid line) and effective times (dotted line) along the entire profile.

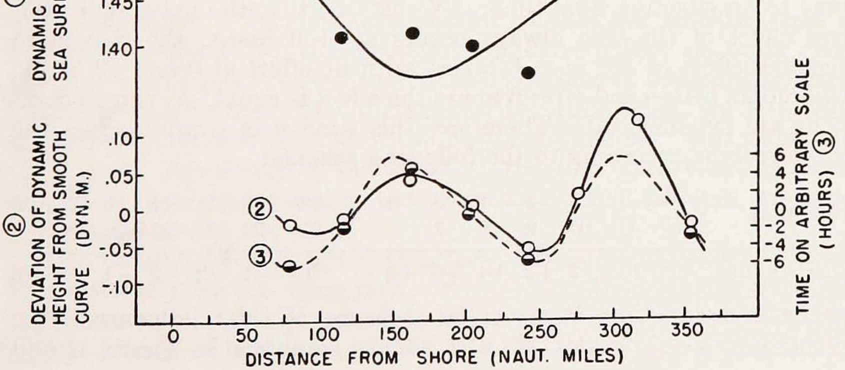

Figure 4. Same as Fig. 3 for stations 801–808.

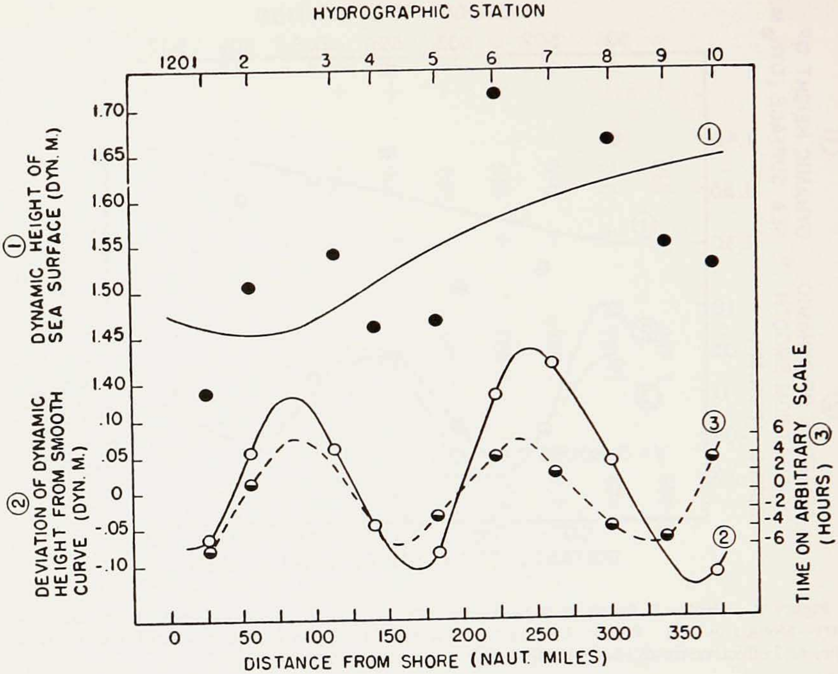

Figure 5. Same as Fig. 3 for stations 1201–1210.

tions at the correct distance from the coast. Through these values we draw a smooth mean curve which corresponds to the average dynamic topography that was prevailing when the profile was made. The deviations from this curve will show the tidal influence. To emphasize this tidal influence, it is advantageous to change the local time to an effective tidal time. We assume that the maximum positive effect of the tide always occurs at $+6$ hours, the maximum negative effect at $18^h = -6$ hours, with no effect at 0 and 12 hours. At n hours before and after 6 hours the effect is equal, provided conditions are symmetrical. Therefore, this time n is considered as the effective time according to the following scheme:

Tidal time	0^h	1	2	3	4	5	6	12^h	13	14	15	16	17	18
	12^h	11	10	9	8	7		24^h	23	22	21	20	19	
Effective time	0^h	+1	+2	+3	+4	+5	+6	0^h	−1	−2	−3	−4	−5	−6

The effective time is a *relative* measure of tidal influence. The effective times of profiles 500 and 800 are contained in Tables II and

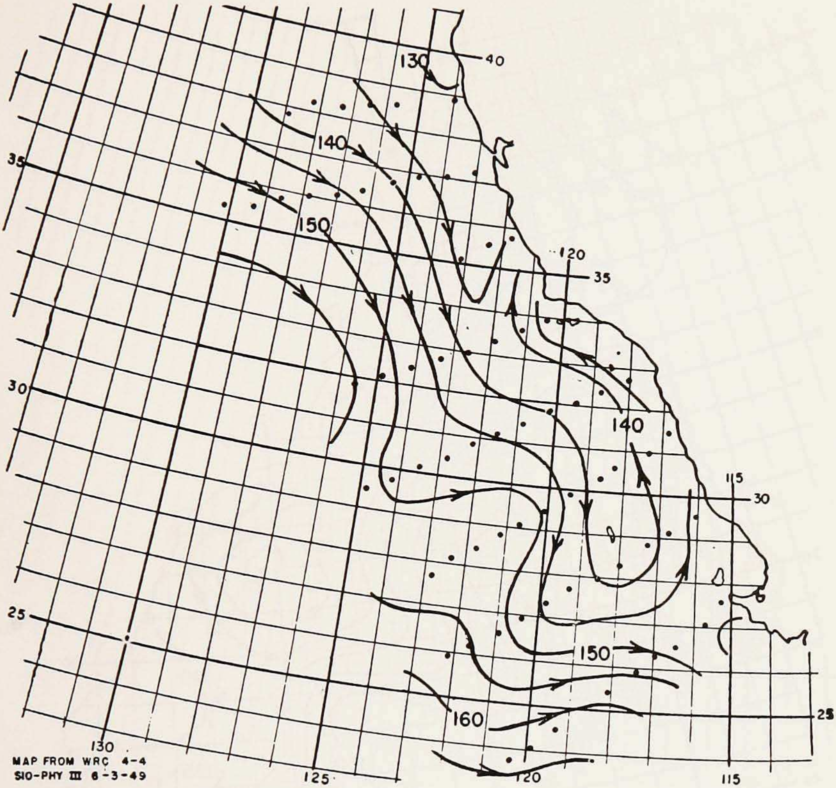

Figure 6. Cruise 1 (Feb. 28 to Mar. 15, 1949): Dynamic height anomalies (0 over 1000 Decibars) after elimination of tidal effect. Contour interval 5 dyn cm.

III. The scale of local time is shifted so that the effective time 6 hours corresponds to the maximum positive effect of tide. The drawing of the mean (basic) curve, the deviations of the station values from this mean curve, and the shift of the time scale, are mutually dependent, and one must seek the best compromise. This might be done quite objectively if the effect of the tide were constant with respect to time and locality, but since this is not the case we have proceeded by trial and error.

The full drawn curve in the lower part of Fig. 3 gives the distribution of deviations from the mean curve, whereas the dashed curve gives the effective times, here incidentally without a displacement of the time scale. The good agreement between both curves shows the relation

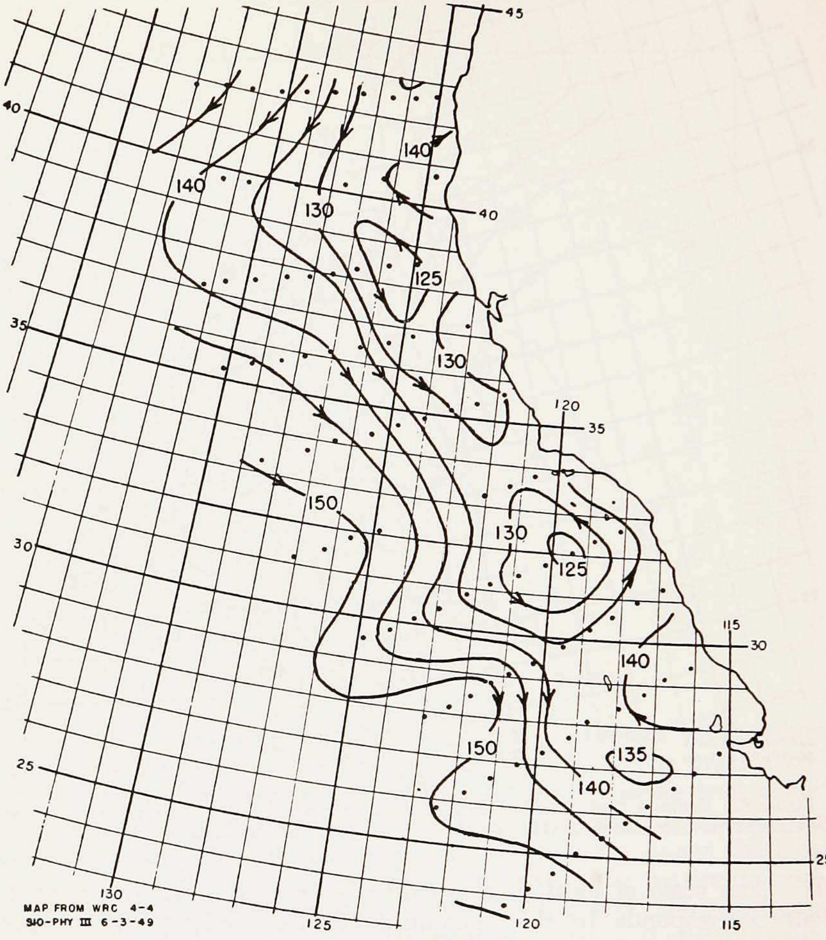

Figure 7. Cruise 2 (Mar. 28 to Apr. 12, 1949): Dynamic height anomalies (0 over 1000 Decibars) after elimination of tidal effect. Contour interval 5 dyn cm.

between deviations and tides. The profiles 800 and 1200 (Figs. 4 and 5) have been analyzed in the same manner, except that it was necessary to shift the time scale. Not all profiles show equally good agreement, and it is often necessary to adjust the basic curve repeatedly in order to reach the best compromise. In trying to make the curves of the deviations correspond to the curves of effective times, no attention should be given to the amplitude of the time curve, for the values are

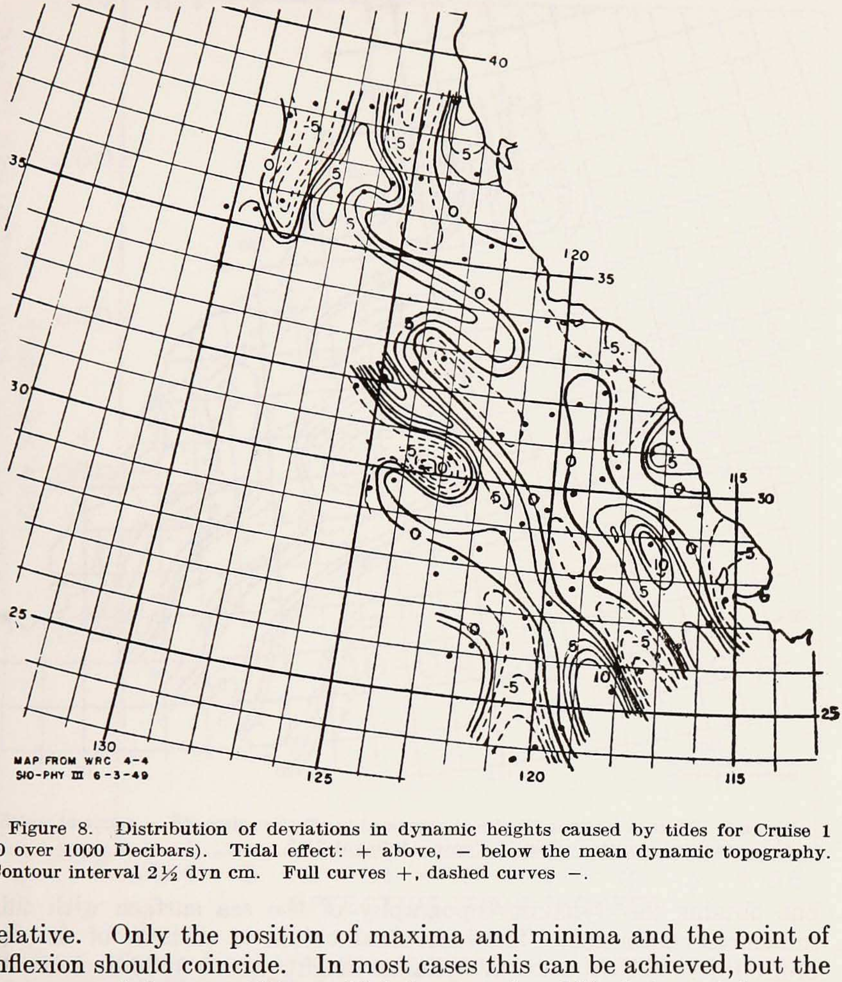

Figure 8. Distribution of deviations in dynamic heights caused by tides for Cruise 1 (0 over 1000 Decibars). Tidal effect: + above, − below the mean dynamic topography. Contour interval 2½ dyn cm. Full curves +, dashed curves −.

relative. Only the position of maxima and minima and the point of inflexion should coincide. In most cases this can be achieved, but the accuracy of the quantities, which have to be shifted, is ± 1 hour at most.

If there is a definite semidiurnal effect in the deviations of station values from the basic curve, then it is necessary to subject these values to harmonic analysis if we wish to designate this effect as a tidal effect and if we wish to separate semidiurnal and diurnal influences from one another. The work connected herewith increases considerably but it can hardly be avoided.

In this manner all of the profiles of a cruise can be analyzed so that

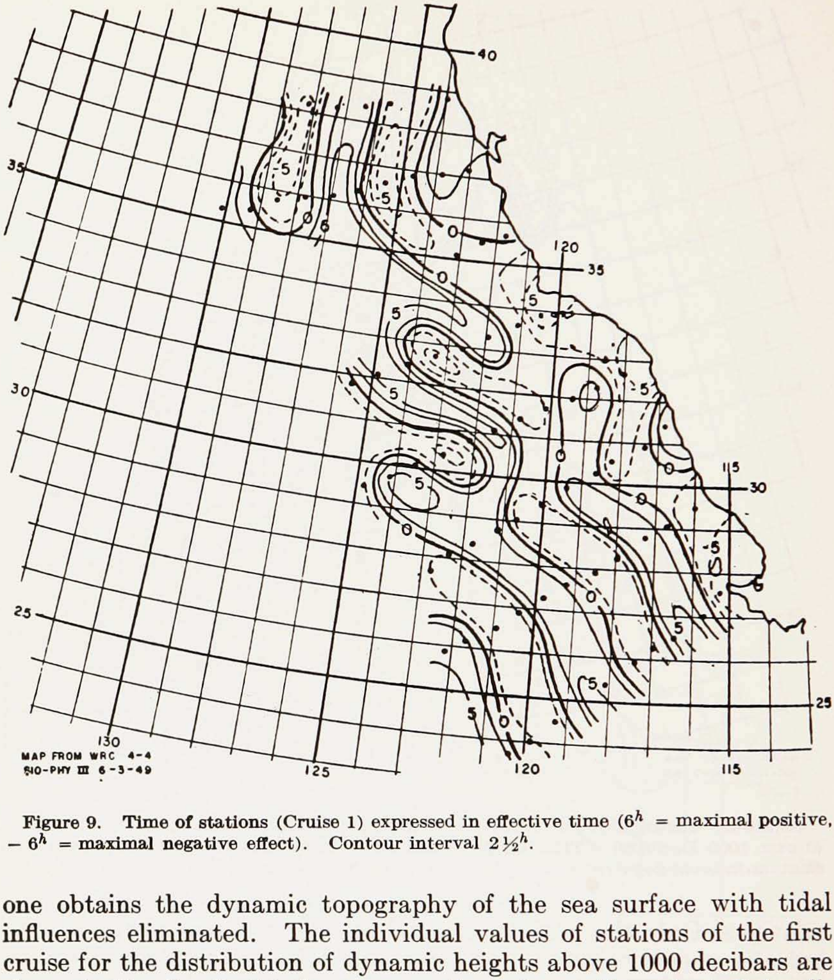

Figure 9. Time of stations (Cruise 1) expressed in effective time (6^h = maximal positive, -6^h = maximal negative effect). Contour interval $2\frac{1}{2}^h$.

one obtains the dynamic topography of the sea surface with tidal influences eliminated. The individual values of stations of the first cruise for the distribution of dynamic heights above 1000 decibars are shown in Fig. 6. In this figure one notices at once the extent of simplification. Off the entire California Coast, at a distance of 100–150 n.m., there is a trough where the physical ocean surface is low; toward the open ocean and toward the coast the surfaces rise fairly uniformly, which correspond to the California Current in a SSE direction on the one hand and to a coastal countercurrent to the NNW just off the coast on the other hand. The trough between both currents is probably connected with the phenomenon of upwelling and will be subject to variations.

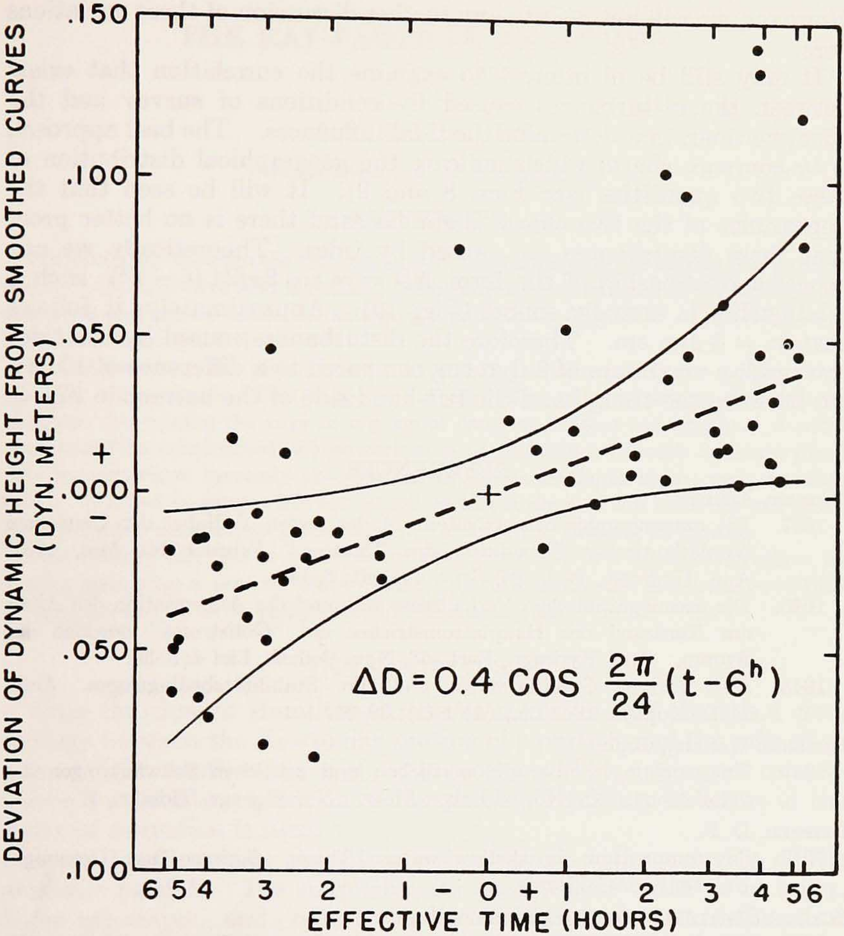

Figure 10. Relation between deviations of dynamic heights from the mean dynamic topography and the effective times.

Once the dynamic charts of all cruises are freed from extraneous influences, the basic data will be available for study of the system of currents off the entire area during intervals between cruises, and it will be possible to go into problems regarding the causes of these variations. That such variations in the dynamic topography actually occur can be seen by a comparison with the dynamic topography of the second cruise (March 28–April 12, 1949), which is given in Fig. 7.

However, we will not go into any further discussion of these variations here.

It may still be of interest to examine the correlation that exists between the disturbances caused by conditions of survey and the effective times that determine the tidal influences. The best approach is to compare charts which indicate the geographical distribution of these two quantities (see Figs. 8 and 9). It will be seen that the appearance of the two charts is similar, and there is no better proof that these disturbances are caused by tides. Theoretically we can expect a relationship of the form $\Delta D = m \cos 2\pi/24\ (t - 6^h)$; such a relationship is actually found (Fig. 10). Approximately, it follows that $m = 4$ dyn cm. Therefore the disturbances caused by the tides can reach a maximum of 8 dyn cm, compared to a difference of 10 dyn cm between the trough and the left-hand side of the current in Fig. 5.

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