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Publication Date

1939-08-12

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(Reprinted from Proceedings of the Sixth Pacific Science Congress, Volume III, held at Berkeley, Stanford and San Francisco July 24 to August 12, 1939.)

The Gulf of California: Preliminary Discussion of the Cruise of the "E. W. Scripps" In February and March, 1939

By H. U. SVERDRUP

BETWEEN February 13 and March 19, 1939, the *E. W. Scripps*, the research vessel of the Scripps Institution of Oceanography, occupied 53 oceanographic stations in the Gulf of California, located on a number of lines across the Gulf. The work started off Cape San Lucas and the first line of stations was run between Cape San Lucas and Mazatlán. The other lines followed in succession from south to north, except that the last two stations were worked in the Ballenas Channel between the islands Angel de la Guardia and San Lorenzo and the peninsula (see fig. 1). By means of a sonic depth finder about 2500 soundings were made at distances which on an average were less than one mile apart. At all stations temperatures were observed and water samples collected between the surface and the bottom for determination of salinity, oxygen, and occasionally other chemical characteristics. Phytoplankton samples were obtained at seven different levels between the surface and 60 meters, vertical hauls for zoöplankton were made between 200 meters and the surface, and bottom samples were procured. Between March 18 and 25, 1939, the U. S. S. *Bushnell* occupied nine oceanographic stations between Balboa, C. Z., and San Diego, California, five of which were across the entrance to the Gulf. At these stations temperatures were observed and water samples collected for determination of salinity and oxygen.

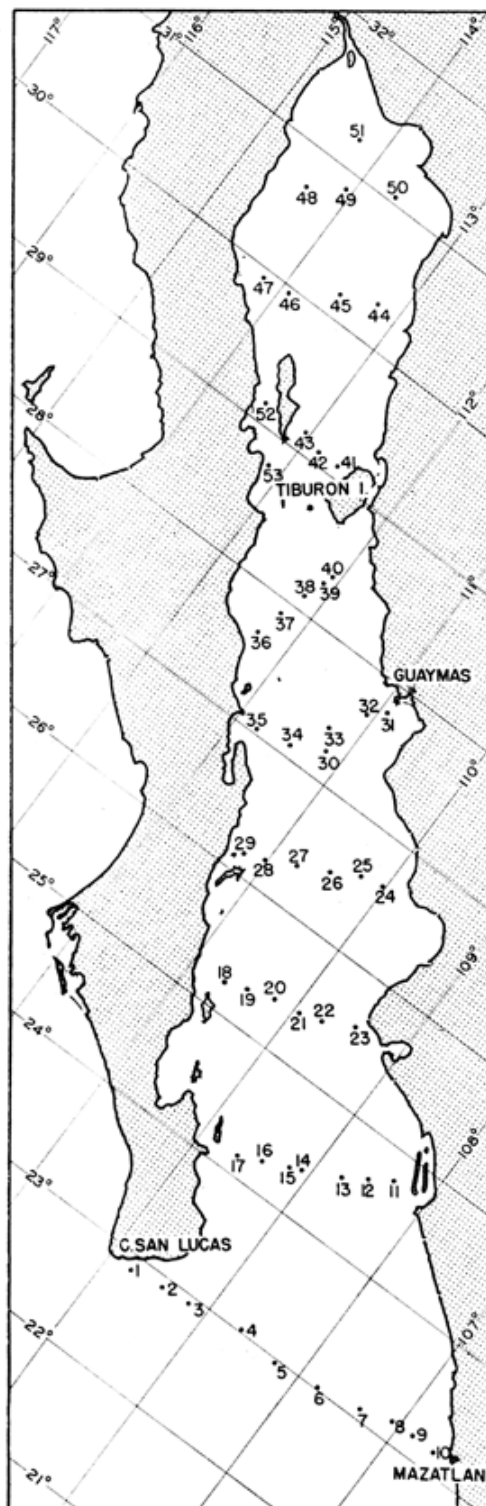


Fig. 1. Location of stations on the *E. W. Scripps* cruise in the Gulf of California, February 13–March 19, 1939.

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In the following only the preliminary results relating to distribution of temperature, salinity, and oxygen will be discussed.

The distribution of temperature in the Gulf of California is best represented by means of a series of vertical sections across the Gulf (fig. 2). The left-hand section in the figure is the most southerly, between Cape San Lucas and Mazatlán, and the right-hand top section is the most northerly, south of Tiburon Island. The two sections shown in the bottom right-hand corner represent one from Tiburon Island

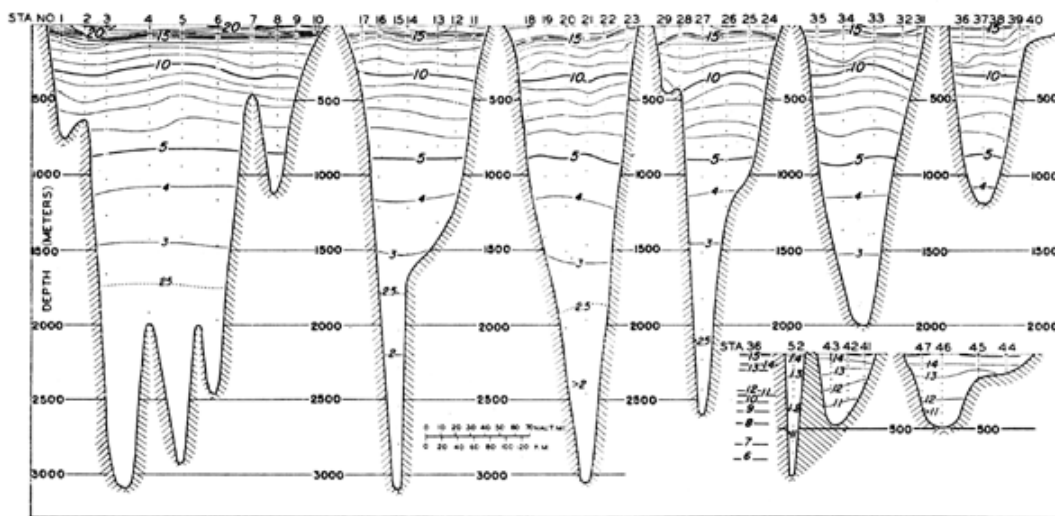


Fig. 2. Temperature profiles across the Gulf of California, *E. W. Scripps* cruise, February 13–March 19, 1939.

Fig. 2. Temperature profiles across the Gulf of California, *E. W. Scripps* cruise, February 13–March 19, 1939. across Angel de la Guardia Island toward the peninsula, and one section across the middle part of the inner portion of the Gulf.

It is seen that in the outer portion of the Gulf, south of Tiburon Island, the surface temperature decreased toward the north. Between Cape San Lucas and Mazatlán the surface temperature was above 21° at two stations, whereas off Tiburon Island the surface temperature was barely above 15° . Near the surface, evidence of upwelling is found on the eastern ends of Sections 3 and 6. Below a depth of 200 or 300 meters the temperature was very uniform and decreased regularly towards the bottom, where a temperature of less than 2° was found below 2600 meters in the outer sections. The somewhat higher temperatures in the deeper portions of Sections 3 and 4 indicate that transverse sills are present.

In the inner portion of the Gulf the distribution of temperature was entirely different. Even in the deepest parts a temperature of about 11° was found. This indicates that the inner portion is separated from the outer by a sill, which probably runs about south-southeast from Tiburon Island and

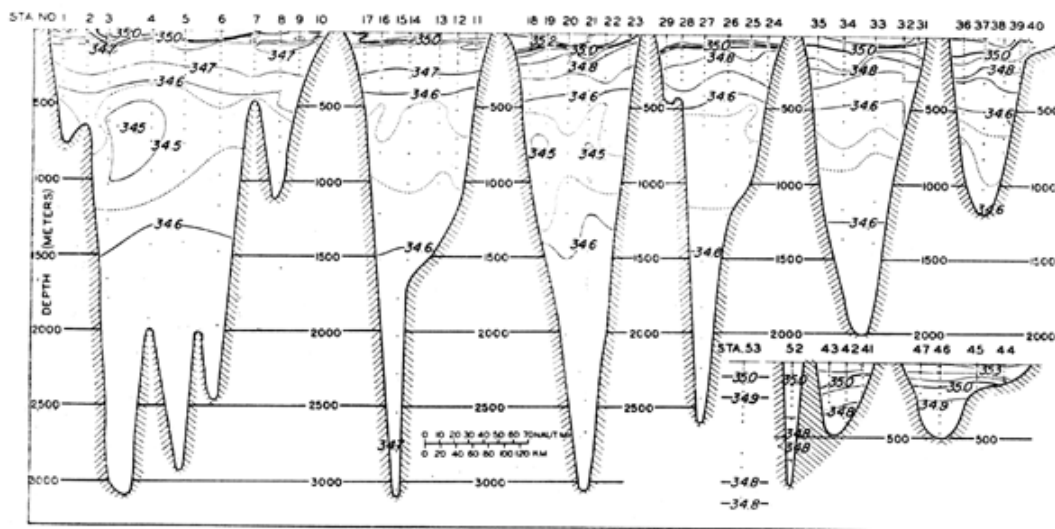


Fig. 3. Salinity profiles across the Gulf of California, *E. W. Scripps* cruise, February 13–March 19, 1939.

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has a maximum depth of 200 to 250 meters. Thus, basin conditions exist in the inner portion.

The distribution of salinity (fig. 3) showed similar features. Everywhere, the highest salinities were found near the surface, but the maximum values increased somewhat from the opening toward the head of the Gulf. Near the surface the salinity curves also indicate upwelling at the eastern ends of Sections 3 and 6. In the outer portion a layer of salinity minimum is present at depths between 500 and 1100 meters. The lowest values, slightly below 34.5‰, are near the mouth of the Gulf. Farther north they are between 34.5‰ and 34.55‰. The salinity distribution also indicates that basin conditions exist in the inner portion. From the course of the isohalines in the two northern sections of the outer portion it appears, however, that an exchange of water takes place at a depth of 150 to 200 meters. The highest surface salinity,

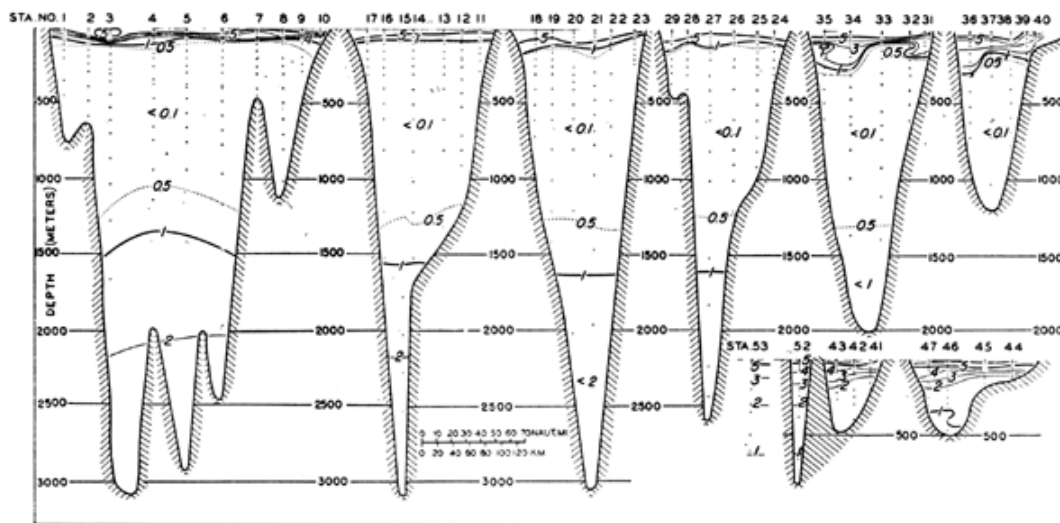


Fig. 4. Oxygen profiles across the Gulf of California, *E. W. Scripps* cruise, February 13–March 19, 1939.

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35.5%, was found in the central part of the inner portion of the Gulf, but about forty miles from the mouth of the Colorado River the salinity was nearly as high, being 35.12%. Thus, a direct effect of the fresh water of the Colorado River is not evident, probably because of the excessive evaporation in winter.

The temperature and salinity combined clearly show that the deep water in the outer portion of the Gulf is of the type encountered over a great part of the equatorial regions in the Pacific Ocean. Water of similar character has previously been found off Central America and at least as far west as to longitude 180°. This water is characterized by a salinity minimum of approximately 34.5% at a temperature of about 5° and by very small amounts of oxygen at intermediate depths.

The lack of oxygen at intermediate depths is also very characteristic of the waters of the Gulf. The oxygen sections (fig. 4) show that the oxygen content is higher than 1 ml/L in the upper 100 m. only, and that at a depth of less than 150 m. has decreased to 0.5 ml/L. The oxygen distribution also indicates upwelling at the eastern ends of Sections 3 and 6 and shows that an exchange of water takes place between the inner portion and the outer portion of the Gulf. Between about 150 meters and 900 meters the oxygen content has been entered as being less than 0.1 ml/L and was probably less than 0.05 ml/L, because the amount was too small to be accurately determined. The

deep water again contains more oxygen, up to 2.6 ml/L, as does the deep water of the central Pacific Ocean. In the inner portion of the Gulf the oxygen content is higher than in the outer, values below 1 ml/L being found only near the bottom in some localities. The higher oxygen content indicates that the deep water in the inner portion is formed by a mixture of water flowing over the sill and water which in winter may sink to great depths because of excessive cooling and evaporation. This process of vertical mixing in the inner portion and the process of upwelling account for the great fertility of the waters of the Gulf.

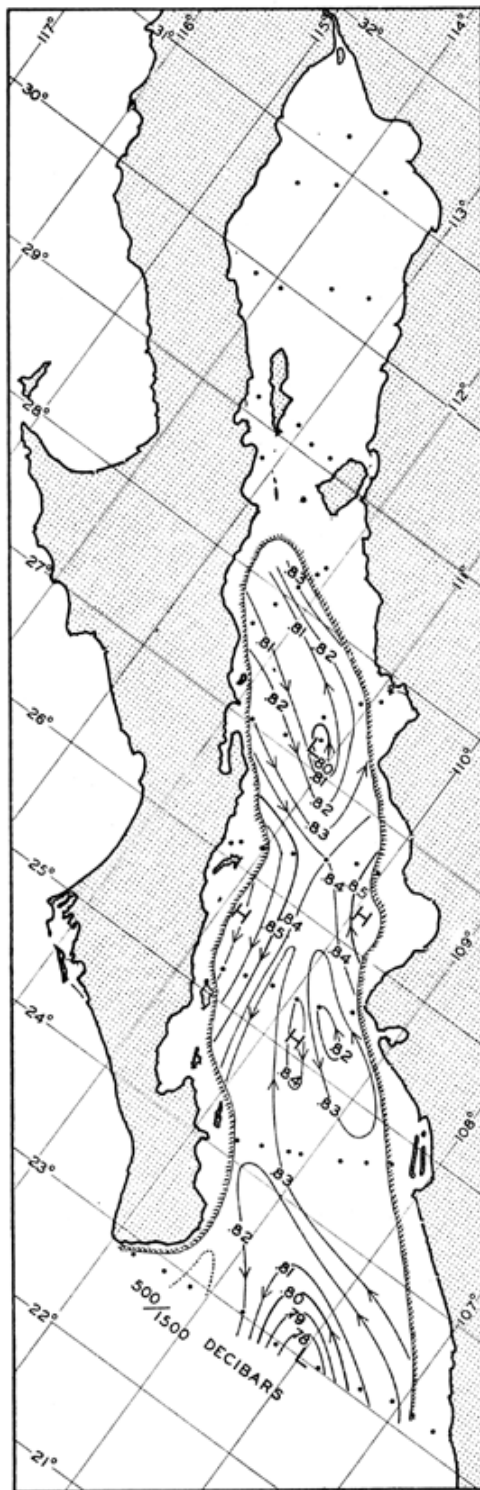


Fig. 5. Dynamic topography of the 500-decibar surface relative to the 1500-decibar surface. Gulf of California, *E. W. Scripps* cruise, February 13–March 19, 1939.

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A study of the currents in the outer portions of the Gulf by means of dynamic computations led at first to very discouraging results. The topography of the 500-decibar relative to the 1500-decibar surface (see fig. 5) does not indicate any regular exchange of water between the Gulf and the adjacent part of the Pacific, but shows a sequence of separate highs and lows. A further examination of the data brought out the fact that the character of the water below 200 m. is the same at all stations in the outer portion of the Gulf, but at some stations the temperature, salinity, and σ_t curves appeared to be displaced upward, while at other stations they appeared to be displaced downward. The displacements are clearly seen in a longitudinal section (fig. 6) based on data from stations along the center line of the Gulf. To the left in the figure is shown a small map of the Gulf on which are indicated the stations in the Gulf and the *Bushnell* Station 305, which have been used for constructing the section. On the central part of the figure are shown the wave-shaped σ_t curves. It should be observed that the vertical scale is highly exaggerated relative to the horizontal, the ratio between vertical and horizontal scales being equal

to 1/800. To the right in the figure are shown the profiles of a series of isobaric surfaces relative to the 1500-decibar surface.

The wavy character of the curves suggests the possibility that they may be associated with a standing internal wave. The observations are not simultaneous,

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but at the top right-hand corner of the figure are shown the number of days elapsed between occupation of Station 5, the central station of the southern section, and the other stations used for constructing the profile. It is evident that if the observations indicate a standing wave, the wave period must be such that when traveling up the Gulf the vessel remained nearly in phase with the wave. This gives immediately an indication of the possible period length. Station 14 appears to have been occupied near a node of the wave, and in this case the time difference is of no importance. Station 21 appears to have been occupied shortly before the wave reached its highest value, and the wave period may therefore have been greater than $12.6/2$, which means greater than 6.3 days. Station 27 was occupied after the wave had reached its crest and the wave period may therefore have been less than $15.3/2$, which means less than 7.65 days. Station 30 appears to have been reached approximately at the time when the wave at the surface reached its lowest position and the wave period may therefore be approximately $19.3/3$, which means approximately 6.4 days. Finally, Station 38 must have been reached nearly at the time of greatest elevation. Therefore the period may be approximately $25.3/4$, which means about 6.3 days. Thus, the period may lie between 6.3 and 7.65 days and probably lies closer to the former value. A period length of about 6.6 days or 5.7×10^5 seconds appears to fit the data very well, but no multiple of this period length will do so. No use has been made of the time interval between Stations 5 and 305 because the latter also appears to have been occupied near a node. Thus, the data can be interpreted as showing the existence of a standing internal wave with a node near the broad opening of the Gulf and with three more nodes located in the Gulf. In the outer portion of the Gulf the wave length appears to be of the order of magnitude of 1000 km., but it decreases greatly toward the inner end. This decrease is undoubtedly associated with the decrease of depth. A wave length of about 1000 km. and a period of about 5.7×10^5 sec. gives a velocity of progress in the outer portion of 175 cm/sec. Furthermore, it is evident from the σ_t curves that one has mainly to deal with an internal wave of the first order having a maximum amplitude at an intermediate depth and zero amplitude at the surface and at the bottom. From the σ_t curves one finds that the maximum amplitude lies between 500 and 600 m. and is of the order of magnitude of nearly 100 meters.

It is possible to check these conclusions by a computation of the possible internal waves, using Fjeldstad's method (1933) of numerical integration. One difficulty is, however, encountered because the bottom of the Gulf is so irregular that what may be called the "effective" depth cannot readily be determined. From the observations at the deepest stations it appears that continuous communication between the various depressions is present only above 2000 meters. In computing the possible internal waves it has therefore been assumed that the depth to the bottom can be taken as 2000 meters, but it can be added that results would not be very much altered by assuming a greater or somewhat lesser depth. On this assumption the computation of the possible internal waves by Fjeldstad's method leads to the result that between Cape San Lucas and Mazatlán the internal wave of first order has a velocity of progress of 175 cm/sec. and that the maximum amplitudes occur at a depth of 775 meters. The agreement between these values and those which were derived directly from the observations is so good that the existence of a standing internal wave during the time of the cruise cannot be doubted. A study is in progress of the modifications of the wave length due to the decreasing depth. It is hoped that it will be possible to find theoretically the location of the nodes near the northern end of the Gulf.

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It is evident that this internal wave completely obscures any distribution of density which may be related to the circulation of the deep water. Such circulation probably is present and consists of a slow exchange of water between the Gulf and the adjacent part of the Pacific, but the nature of this exchange cannot be found on the basis of our data.

It should, however, be observed that the upper isobaric surfaces slope upward from the inner part of the Gulf toward the opening of the Gulf. This general slope is indicated on the right-hand graph in figure 6, from which

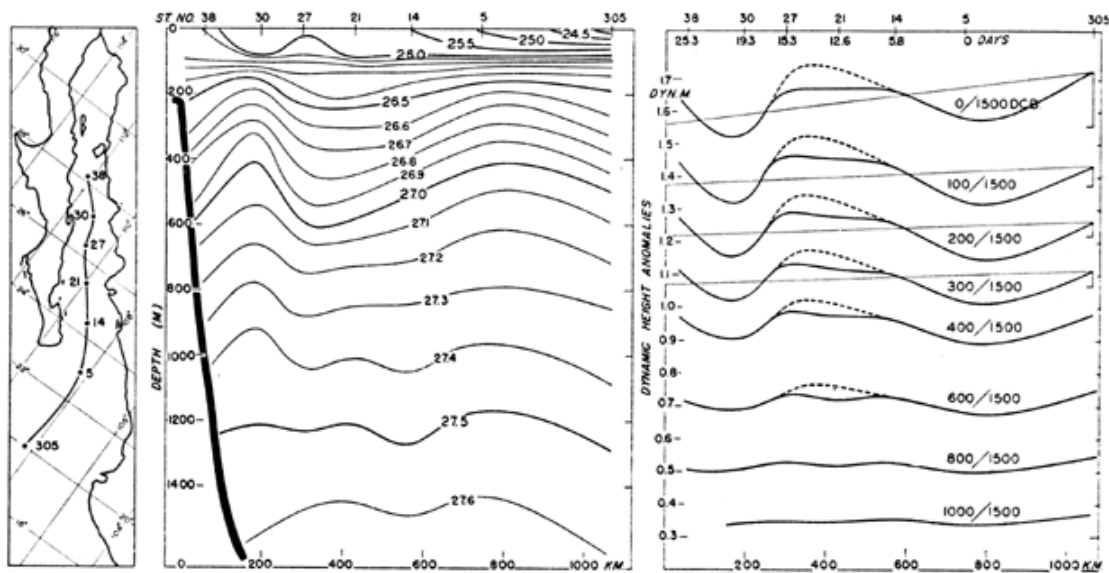


Fig. 6. Center: Longitudinal section of the Gulf of California showing distribution of σ_t according to observations at stations plotted on chart to the left. Right: Longitudinal profiles of isobaric surfaces relative to the 1500-decibar surface.

Fig. 6. Center: Longitudinal section of the Gulf of California showing distribution of σ_t according to observations at stations plotted on chart to the left. Right: Longitudinal profiles of isobaric surfaces relative to the 1500-decibar surface.

it is seen that the upward slope of the free surface is much greater than that of the 100-decibar surface. It thus appears that a certain amount of piling up of surface waters takes place which is probably a result of the prevailing northerly and northwesterly winds during February and March. When cruising up the Gulf, the *E. W. Scripps* encountered several strong winds blowing intermittently out of the Gulf. The pilot charts show that winds from the north and northwest prevail in the spring and that the average velocity of these winds is about 3.5 m/sec. When discussing data from the Caribbean Sea (1939) I have been able to show that the average wind velocity can be computed from oceanographic data if one knows the variation of the distribution of density in the direction of the wind. The application of this method to the data from the Gulf is made difficult by the presence of the internal wave. The selection of stations to be compared can be made in various ways, and different combinations lead to computed wind velocities between 3.5 and 7.5 m/sec., the former value being the more probable. This value is in good agreement with the general average wind velocity and it can therefore safely be assumed that the piling up of the light surface waters at the entrance of the Gulf is caused by the prevailing northerly winds.

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[Contribution from the Scripps Institution of Oceanography, New Series, No. 109.]