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VOLUME 118 : ARTICLE 3   NEW YORK : 1959

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BULLETIN OF THE AMERICAN MUSEUM OF NATURAL HISTORY
Volume 118, article 3, pages 113–152, figures 1–24

Issued July 24, 1959

Price: 75 cents a copy

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INTRODUCTION

THE PANAMA BIGHT may be defined as that part of the eastern tropical Pacific Ocean that lies between the Isthmus of Panama (about latitude 9° N.) on the north and Punta Santa Elena (about latitude 2° S.) on the south and that extends westward from the coasts of Panama, Colombia, and Ecuador to about longitude 81° W. As thus defined, the region lies to the north of the usual position of the Peru Current and is occupied by the warm surface waters common to tropical latitudes.

The Panama Bight is of great oceanographic interest because (1) it marks the eastward limit of waters of the Equatorial Countercurrent, (2) it is characterized by great seasonal variations in oceanographic conditions apparently related to changes in the position of the Intertropical Convergence, and (3) its waters are reputed to enter into *El Niño* phenomenon occasionally reported south of the region off the coast of northern Peru. Yet prior to 1941, only sporadic oceanographic observations had been made in the Panama Bight, usually incidental to other work of expeditions.

From February 9 to May 26, 1941, the American Museum of Natural History conducted an oceanographic expedition in this region aboard the diesel schooner "Askoy" under the leadership of Robert Cushman Murphy. Brief preliminary reports concerning the purpose, personnel, sponsorship, and work of the expedition have already been published (Murphy, 1941, 1942, 1944) as have descriptions of the collections of fishes (Nichols and Murphy, 1944), crabs (Garth, 1948), and marine mollusks (Hertlein and Strong, 1955).

During the "Askoy" expedition, temperature and salinity observations were made on about 80 stations (fig. 1) to depths of 125 meters or less. Most subsurface temperature measurements were made with the bathythermograph (Spilhaus, 1938), one of the first uses of this instrument in the Pacific; a few were made with reversing thermometers. Salinity samples were collected and subsequently analyzed at the Woods Hole Oceanographic Institution. The analysis of the "Askoy" data forms the basis of this paper.

As the "Askoy" observations were only exploratory and were made during a relatively brief period of time, they do not provide sufficient information to permit a definitive oceanographic study of the area. It is hoped, however, that their analysis here will facilitate further study when more data have been accumulated.

In preparing this report, I am especially indebted to Dr. Robert Cushman Murphy who made available all data from the expedition and who lent me his unpublished journal of the voyage. I am also grateful to Mr. Gunnar Roden who prepared the current charts and assisted in the analysis of other data, and to Messrs. Robert S. Arthur and Milner B. Schaefer who made many valuable suggestions. I wish also to acknowledge the stimulation afforded by many conversations with the late Townsend Cromwell whose wisdom and knowledge of the oceans meant so much to me during the years we worked together.

This work was supported in part by the Office of Naval Research, the Inter-American Tropical Tuna Commission, and the United States Fish and Wildlife Service.

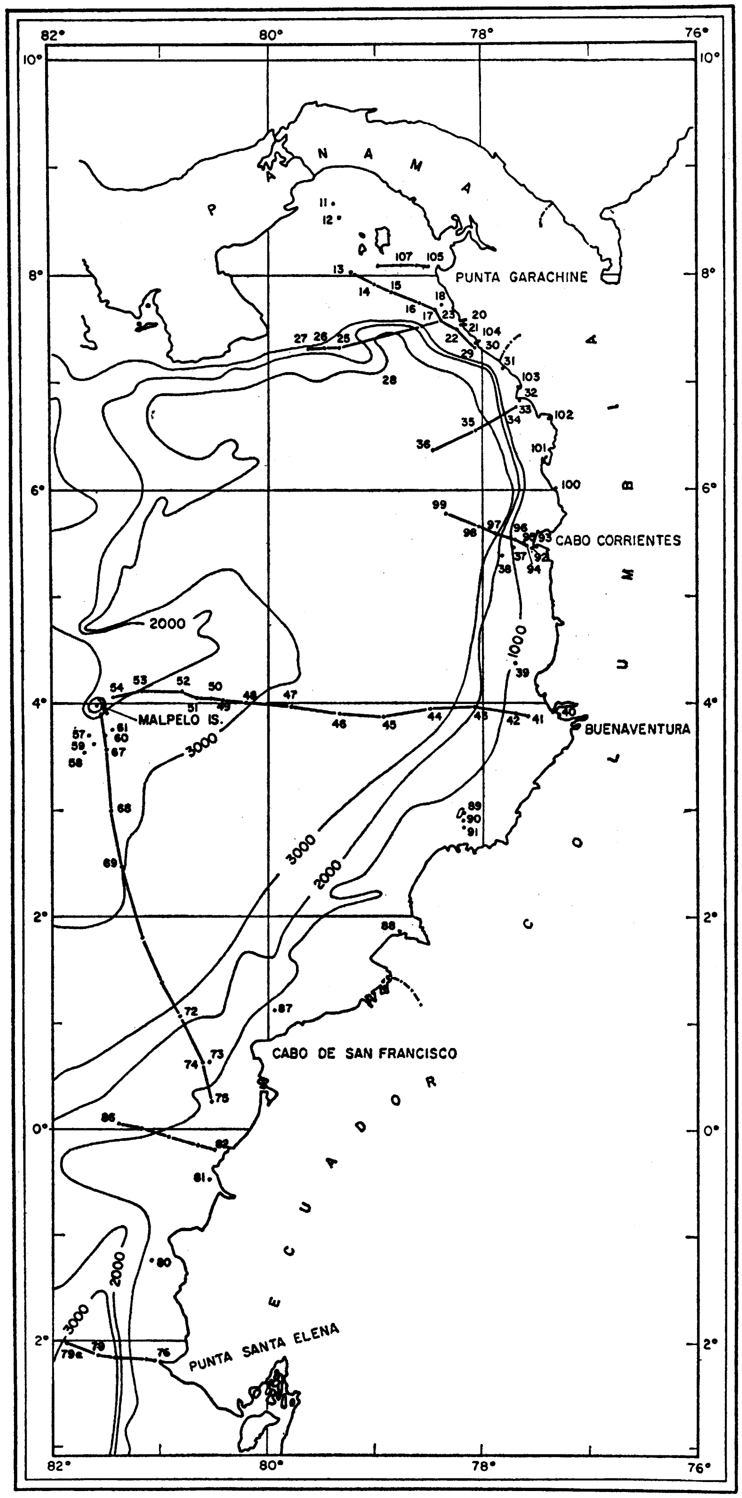

FIG. 1. Location of "Askoy" observations and generalized bathymetry of the Panama Bight (depths in meters) from sheets A'1 and A1 (1935) of the "Carte générale bathymétrique des océans" (International Hydrographic Bureau, Monaco, third edition).

PHYSICAL GEOGRAPHY OF THE PANAMA BIGHT

IN THE OPEN OCEAN the distribution of temperature and salinity near the surface is governed by advection and diffusion of heat and dissolved substances and by the exchange of energy and water between the sea surface and the atmosphere. In a coastal region such as the Panama Bight, oceanographic conditions are also influenced by the adjacent land mass and the submerged topography. Before the "Askoy" observations are discussed, therefore, it is desirable to describe briefly the physical geography of the region.

TOPOGRAPHY

Western South America, from latitude 50° S. to latitude 10° N., is dominated by the cordillera of the Andes. "There is no other mountain system in the world that possesses the combination of such length, continuity and altitude. This huge barrier rises almost from the Pacific, is 100 to 400 miles broad, and contains few passes lower than 12,000 feet for a distance of 3,500 miles" (United States Hydrographic Office, 1945).

East of the Panama Bight, the western branch of the Andes, the Cordillera Occidental, lies 30 to 100 miles inland. Between the Andes and the sea the coastal strip is relatively low, except from Cabo Corrientes north to Punta Garachiné where the Serranía del Baudó (also referred to as the Cordillera del Chocó) lies close to the coast. Although these mountains are in general less than 1000 meters high, the coast is steep, rivers are few, and most of the runoff goes into the Caribbean. Southward, between Cabo Corrientes and Cabo de San Francisco, stretches a broad forested plain. "This is the maritime Chocó, a flooded lowland of perpetual rains, of selva and morasses, of hundreds of streams, many or most of which pour into the Pacific through multiple mouths" (Murphy, 1939). South of Cabo de San Francisco the land rises, the shore becomes cliffy, and there are no large rivers until the Guayas is reached.

Bathymetric studies have shown the Panama Bight to be part of what has been termed "Panama Basin" (Shumway, 1954). This basin is enclosed by Central and South America, Cocos Ridge, the Galápagos Islands, and Carnegie Ridge (fig. 2). Cocos Ridge extends from the Galápagos Islands to Central America at a general depth of 900 to 1000 fathoms (1650 to 1830 meters). The inshore end of this ridge may be pierced by the Guatemala Trench. Carnegie Ridge is a relatively shallow sea-floor area west of Ecuador which is separated bathymetrically from the continental shelf by the northern extension of the Peru Trench (Shumway, 1954, 1957). About 7200 square miles of sea floor on the ridge lie shoaler than 800 fathoms (1460 meters), and the entire ridge appears to be shoaler than 1200 fathoms (2200 meters). There is some indication that the deep water of the basin is isolated from adjacent waters of the Pacific by these two ridges (Wooster, MS).

The deep portion of the Panama Bight may constitute a sub-basin, separated from the rest of the Panama Basin by the relatively shoal area around Malpelo Island (Jones, 1950, p. 912). A simplified picture of the bottom topography east of longitude 82° W. is shown in figure 1. Much of the basin lies deeper than 3000 meters, and between the Gulf of Panama and Punta Santa Elena the shelf is nowhere wider than 30 miles. The Gulf of Panama is a large shoal area less than 200 meters deep. The only oceanic island is Malpelo Island, a mile-long barren rock at latitude 3° 59′ N., longitude 81° 34′ W.

CLIMATOLOGY

The climatology of most regions of the world ocean is little known because of the lack of long and uninterrupted series of meteorological observations. In the Panama Bight, as in other oceanic areas, such observations are scarce, even along the coast where there are few large population centers. The discussion that follows serves only to delineate the broad features of climatological variations in the region and does not attempt to consider in detail the nature or causes of such variations.

The climatological model of general circulation in the tropics seems to apply in the least equivocal fashion to the eastern parts of oceans (Palmer, 1951). According to this model, when diurnal and seasonal perturbations of thermal and mechanical origin are omitted, one finds a system of trade winds blowing steadily from an easterly quarter towards the equator in the lower layers of the atmosphere. As the northeast and southeast trades approach one another, they become light and variable, this weakening being part of the observed horizontal velocity convergence in the two currents and the accompanying increased vertical component of the motion. At high altitudes, motion of the air is predominantly away from the equator, completing the circulation cells.

The region of light variable winds near the equator is called the "doldrums," and the region of convergence (in the atmosphere) located within the doldrums is often called the "Intertropical Convergence" (I.T.C.). Crowe (1952), in a statistical analysis of shipboard meteorological observations, has defined the location of the trades as those areas where 70 per cent of all winds blow from the predominant quadrant, and considers the doldrums as occurring within areas where less than 50 per cent of all winds blow from the predominant quadrant. The seasonal movement of the doldrums (as thus defined) in the eastern tropical Pacific is shown in figure 3. Within this doldrum "wedge," wind speeds have mean values no greater than 4 to 6 knots. Seasonal contrasts in weather within the Panama Bight are related to movement of the doldrum wedge and the Intertropical Convergence that lies within it.

In northern winter (January to March), the doldrums lie farthest south, covering all the Panama Bight except the Gulf of Panama. This is the dry season in Panama, when the Caribbean trades usually extend across the low lands of the Isthmus into the Gulf, or even farther south. These offshore northerlies cause upwelling within the Gulf, raising the surface salinity, lowering the surface temperature, and enriching the surface layer with subsurface nutrients (Fleming, 1940; Schaefer, Bishop, and Howard, 1958). At the same time, the Intertropical Convergence, accompanied by heavy rains, lies across the coast near the Ecuador-Colombia border, bringing the rainy season to the southern part of the Panama Bight.

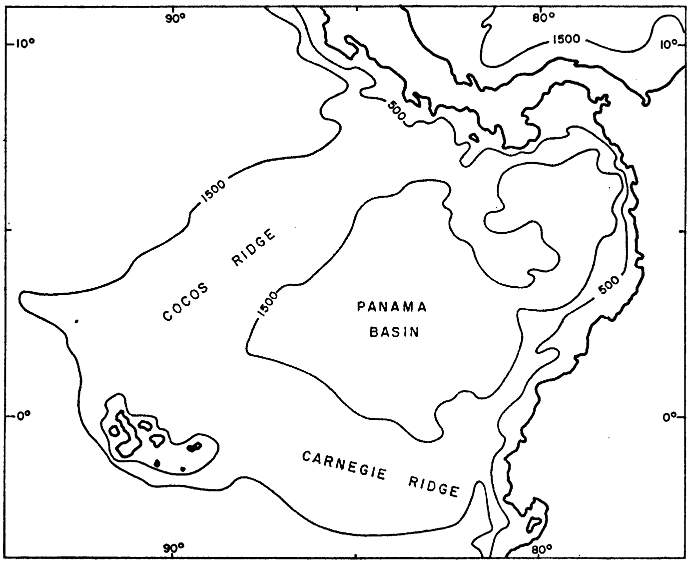

FIG. 2. Generalized bathymetry of Panama Basin (depths in fathoms), after Jones (1950) and Shumway (1953).

In northern summer (July to September), the doldrums lie farthest north, with the Intertropical Convergence and its associated heavy rains being found north of Panama. South of Cabo de San Francisco rainfall drops off abruptly during this season. At the same time, despite the position of the Intertropical

Convergence, the central part of the Bight receives heavy rainfall. These rains cannot be considered purely orographic, as they appear to represent merely the coastal intersection of a rain belt extending westward far out into the Pacific (United States Department of Agriculture, 1938, charts 97 and 98).

winds and precipitation may differ significantly from the mean climatological distribution discussed above. Extreme variations from the average picture probably have significant repercussions to the south of the Panama Bight, in the northern part of the Peru Current system.

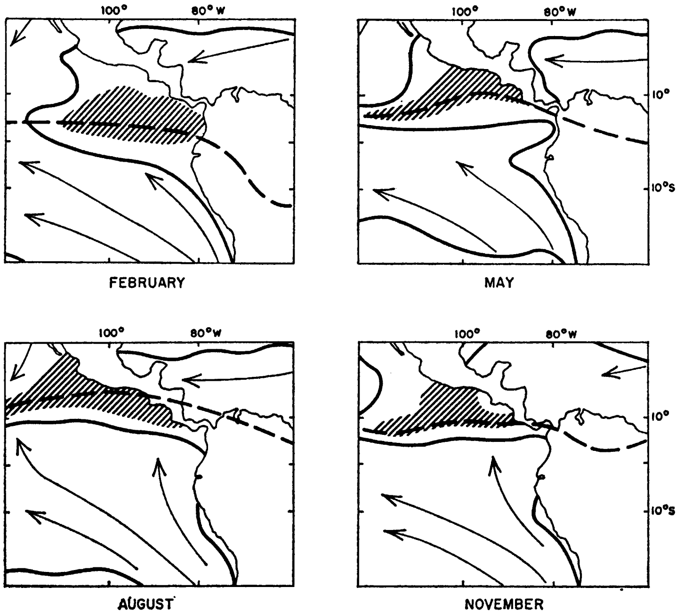

FIG. 3. Average positions of the limits of trade-wind circulation (heavy solid lines), doldrums (shaded), and the Intertropical Convergence (heavy dashed lines), after Crowe (1952). Arrows indicate average direction of air flow.

Most of the Panama Bight is dominated by southwest winds from June through November. These winds are part of the "southeast" trade-wind circulation, which in the region of the Panama Bight curves towards the northeast, roughly paralleling the coast. Although it is tempting to suggest that this curving is caused by the position of the Andes, it should be noted that the Atlantic southeast trades curve eastward in similar fashion into the Bight of Biafra in equatorial Africa where a similar mountain range does not exist (United States Department of Agriculture, 1938, charts 15 to 26). This phenomenon has been discussed by Riehl (1954, p. 8) and by Godske and his co-authors (1957, pp. 261, 493).

At any given time the local distribution of

AVERAGE SURFACE OCEANOGRAPHIC CONDITIONS

A description of average surface temperature and salinity in the Pacific Ocean, based on an analysis of observations made by merchant and naval vessels, has been prepared by Schott (1935, pls. 20–28). Conditions in the Panama Bight in February and in August are shown here in figures 4 and 5 (Schott also has surface temperature charts for May and November, but does not describe the salinity distribution for those months).

In February, over most of the Panama Bight, surface temperatures of 26° to 28° C. and surface salinities of 34 to 35 parts per mille are found. Only in a small area off the coast of Colombia near Buenaventura does the salinity drop to less than 33 parts per

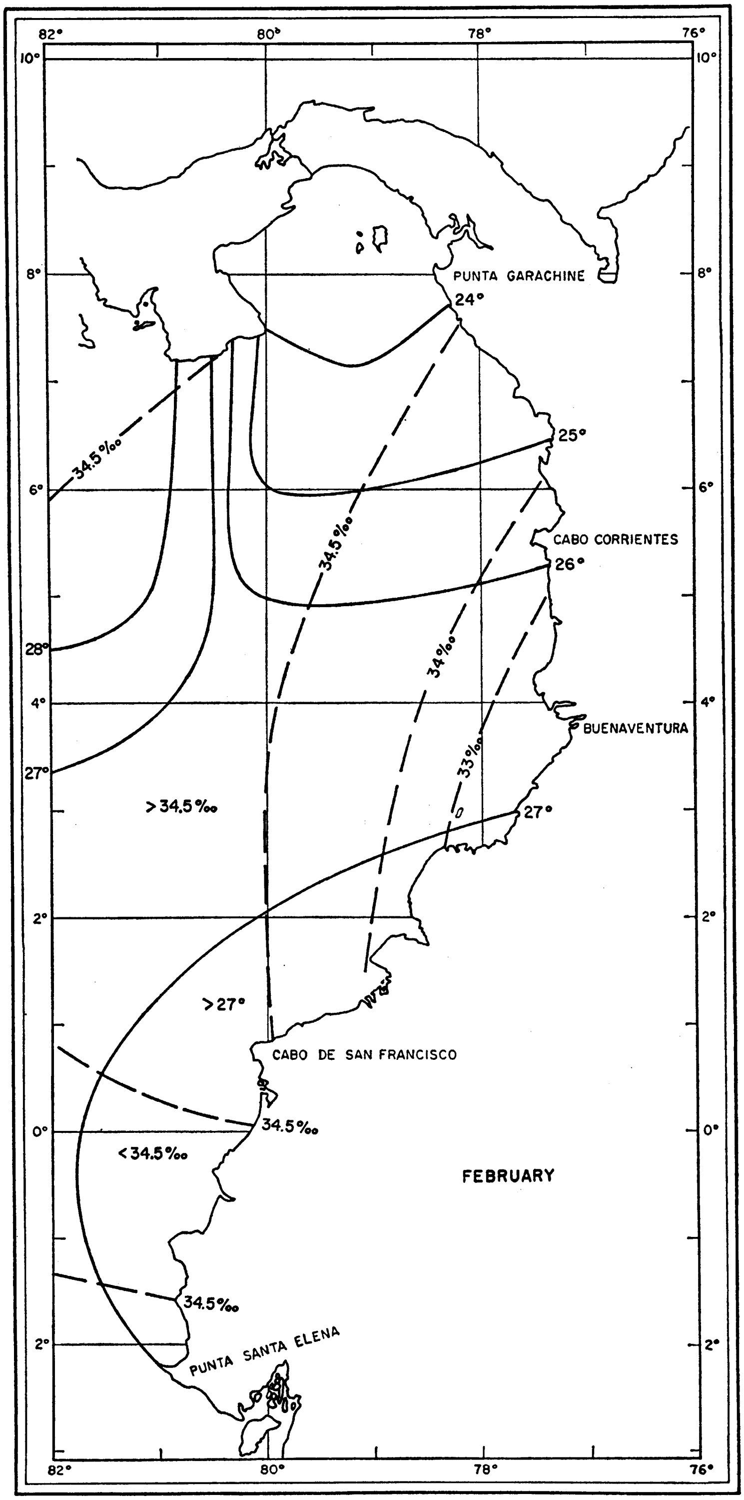

FIG. 4. February average distribution of surface temperature, in degrees Centigrade (solid lines), and surface salinity, in parts per mille (dashed lines), after Schott (1935).

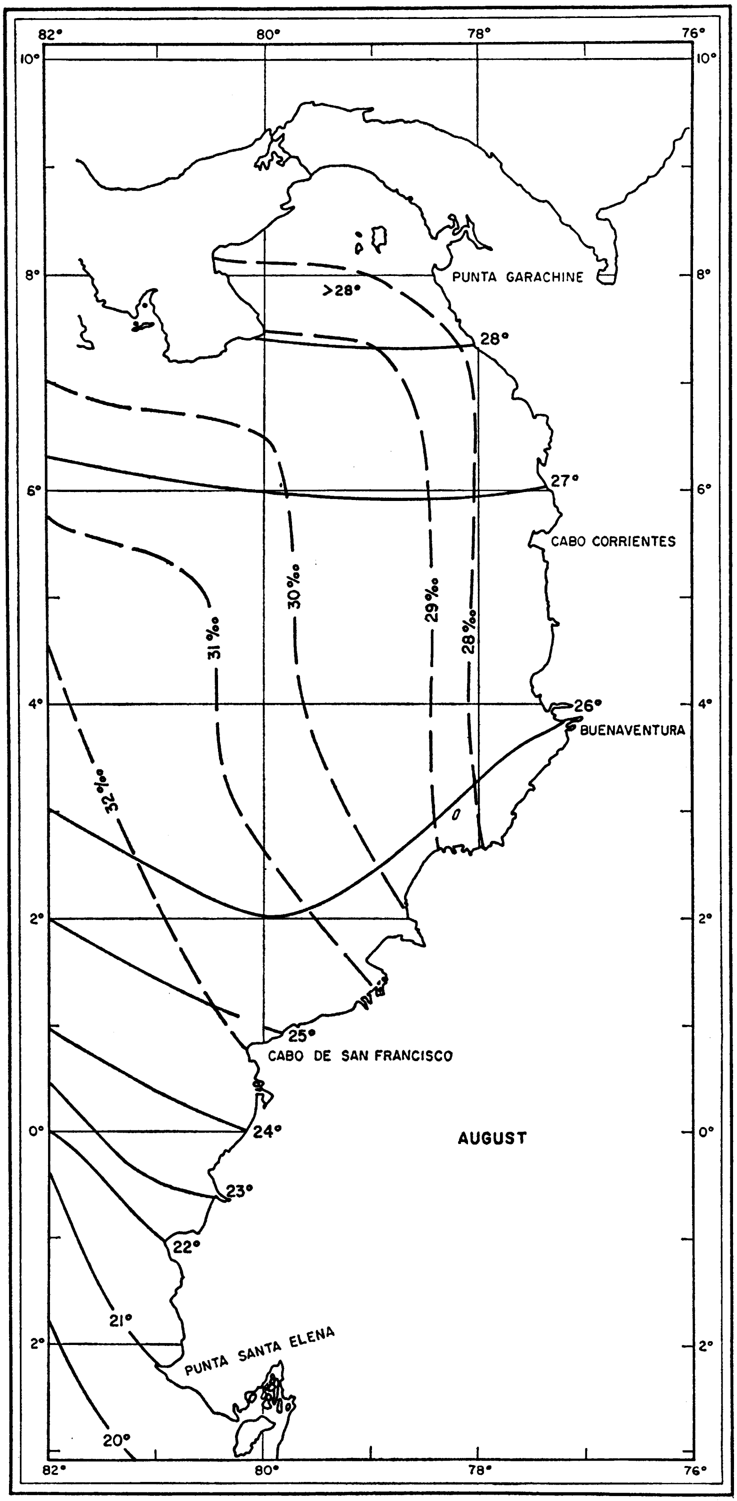

FIG. 5. August average distribution of surface temperature, in degrees Centigrade (solid lines), and surface salinity, in parts per mille (dashed lines), after Schott (1935).

mille, and temperatures lower than 26° C. occur only in the Gulf of Panama and for a hundred miles or so to the south. The relatively low surface temperatures of the Gulf are attributed to winter upwelling, as mentioned above.

By May low surface temperatures have disappeared in the Gulf, and surface waters cooler than 26° C. are found south of Cabo de San Francisco. This region of relatively cool water extends farther north in August, the isotherm of 26° C. reaching Buenaventura. The distribution of surface salinity in August is strikingly different from that of February, the whole of the Panama Bight now being covered with surface waters of low salinity (less than 33°/₀₀). Along the coast of Colombia and in the Gulf of Panama, surface salinities of less than 28 parts per mille are found, showing clearly the effect of the heavy rainfall and runoff of this season.

It is difficult to estimate how reliable these charts are as a description of surface conditions in the sea. Figures 4 and 5 represent greatly enlarged portions of Schott's original charts and are based on a small number of observations. There are not enough hydrographic stations to permit a meaningful comparison. The few winter data available show that temperatures along the shelf are comparable, but that observed salinities may be several parts per mille less than those shown by Schott. Summer data show surface salinities in the open ocean somewhat higher than those of Schott, with rather comparable values of temperature and salinity along the shelf. Although in detail the comparison between observed values and the average distributions is not very good, at least the striking difference in surface conditions between February and August as shown by Schott appears to be real.

A representation of the average surface circulation in the Panama Bight at different seasons is given in figures 6 to 9. The current vectors in these charts were determined by averaging for three-month periods the values given in "The atlas of surface currents, northeastern Pacific Ocean" (United States Hydrographic Office, 1947), weighting each monthly vector by the number of observations used in the computing of it. When 10 or fewer observations were available in a given 1-degree square during the three-month period, no average was determined. Similar values were not available for the region south of the equator. It should be remembered that these charts represent averages of ship drift observations, and the surface currents observed at any given time may be quite different from those shown by the charts.

These charts show a surface current flowing towards the north along the coast of South America north of Cabo de San Francisco during each quarter. This current appears to be weak during summer and autumn (less than 20 cm. per sec.) and somewhat stronger during winter and spring (20–30 cm. per sec.). It seems unlikely that this current carries water from the Peru Current as has been suggested (see discussion of the Colombia Current below).

Throughout the year these charts show a current towards the south (30–40 cm. per sec.) in the Gulf of Panama. The strongest currents (50 cm. per sec. or greater) in the whole area are found in the northwest corner of the Panama Bight during the winter. These currents set towards the southwest and are presumably related to the prevailing northerlies during this season. However, during all seasons the weak set in this area is in the same general direction. In the central and southern parts of the Bight, currents are quite weak (usually less than 20 cm. per sec.) except during the first three months of the year, and in general have an eastward component. West of longitude 80° W. during the winter, currents are stronger (up to 40 cm. per sec.) and have a westward component, carrying surface water out of the Bight.

In summary, these average charts suggest that the surface waters of the Panama Bight circulate in the counterclockwise sense, being fed from the west in the southern and central parts and discharging to the west in the northern part. During the winter, currents are strongest over most of the Bight, and supply from the west apparently takes place farthest south.

Average Subsurface Oceanographic Conditions

Because of the general scarcity of data, there have been few attempts to describe average subsurface conditions anywhere in

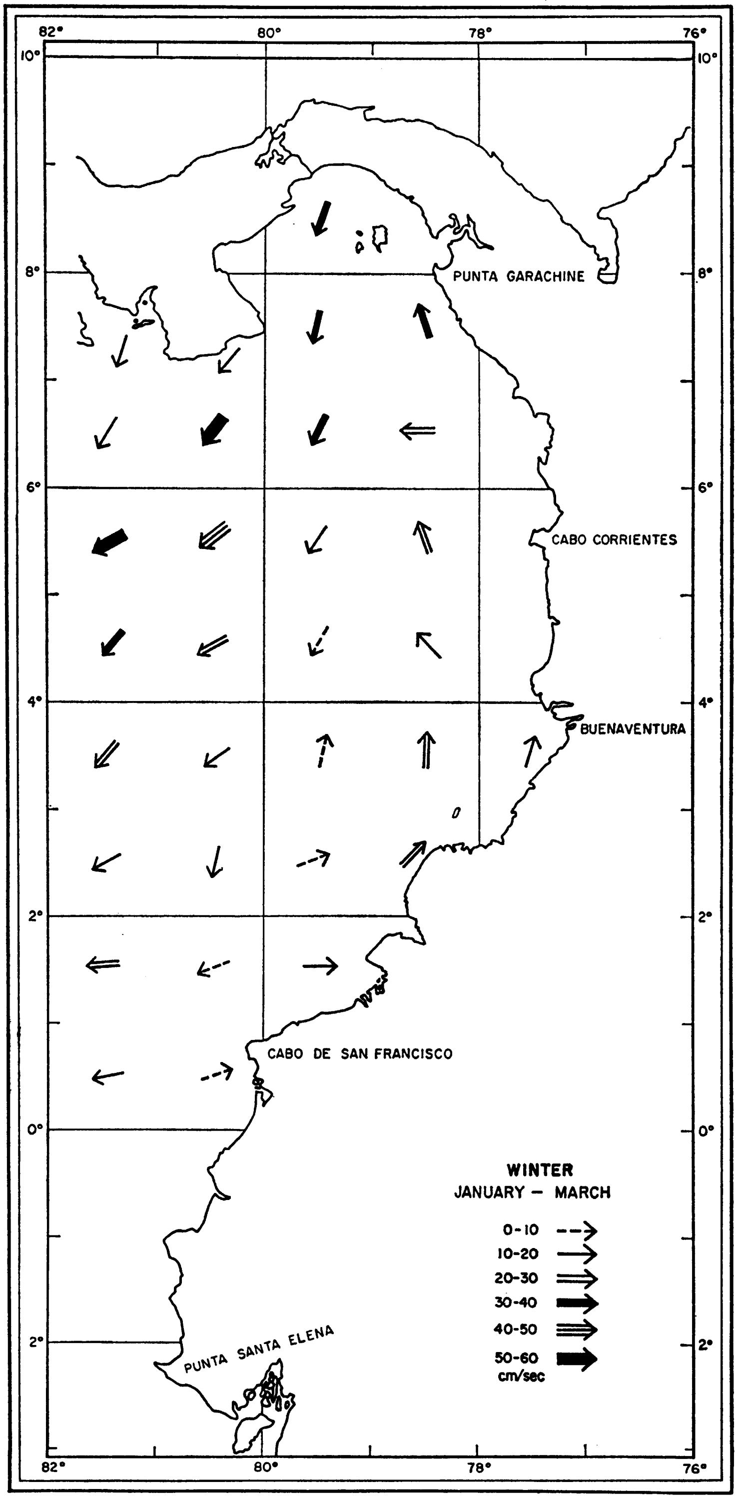

FIG. 6. Average direction and speed of surface currents by 1-degree squares, after United States Hydrographic Office (1947).

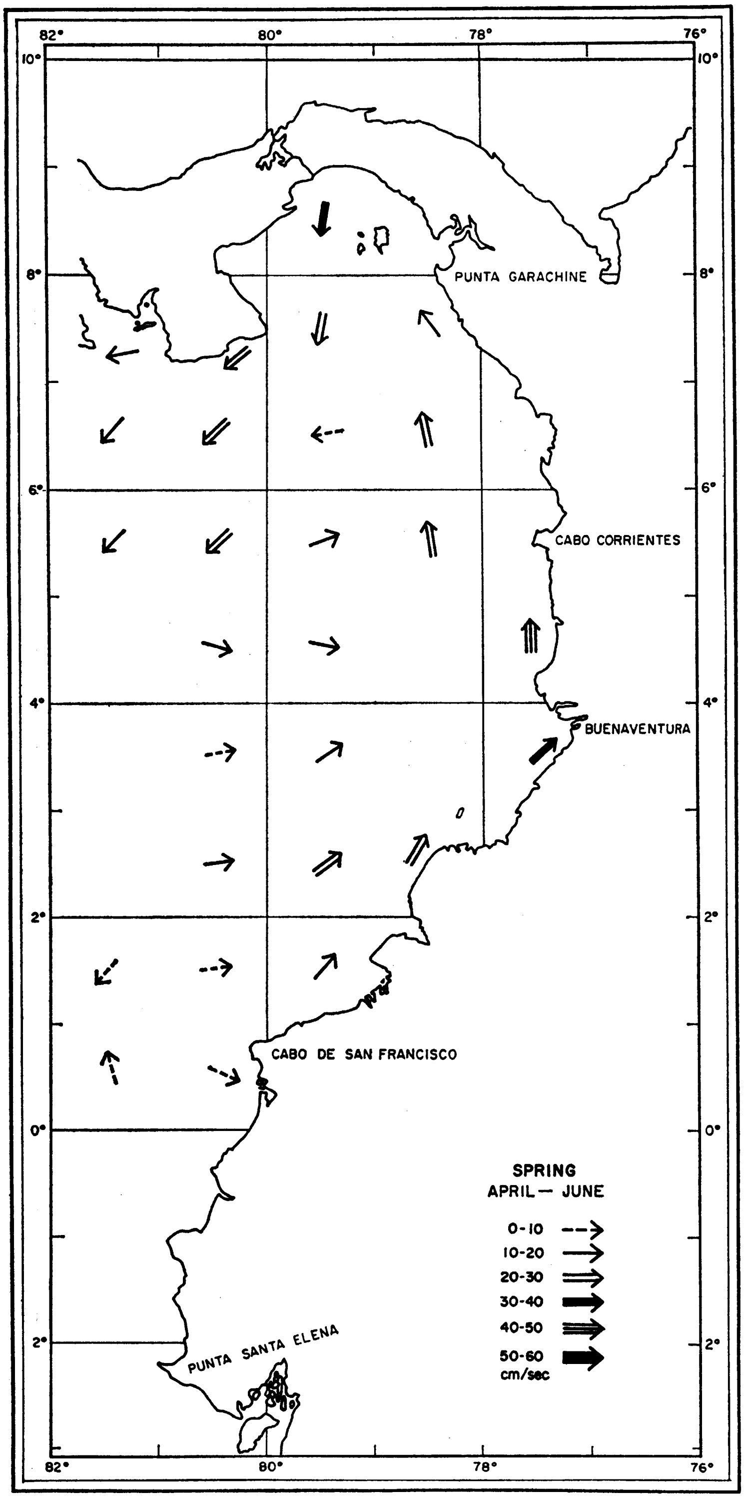

FIG. 7. Average direction and speed of surface currents by 1-degree squares, after United States Hydrographic Office (1947).

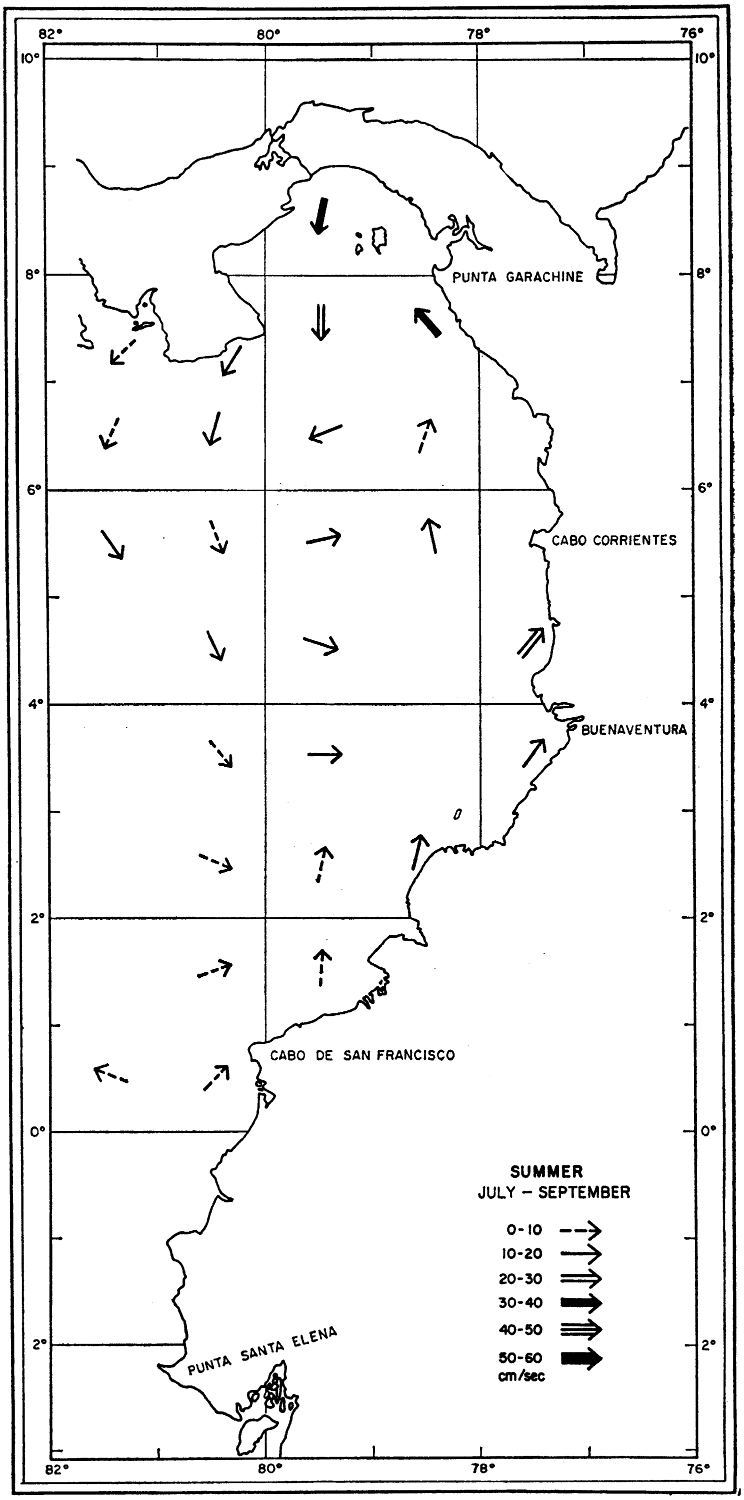

FIG. 8. Average direction and speed of surface currents by 1-degree squares, after United States Hydrographic Office (1947).

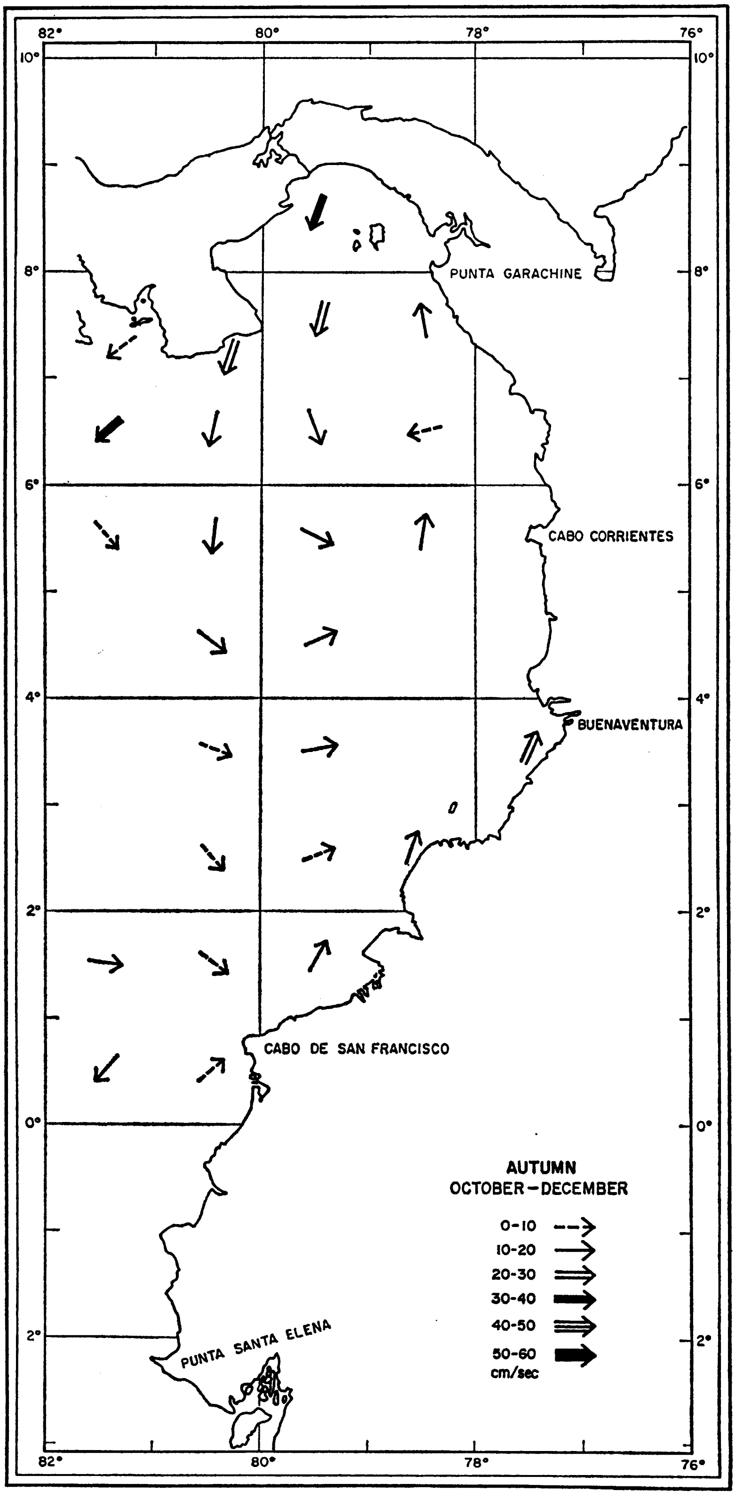

FIG. 9. Average direction and speed of surface currents by 1-degree squares, after United States Hydrographic Office (1947).

the Pacific. Schott (1935, pls. 31, 32), however, has drawn charts of the average temperature at depths of 200 and 400 meters. These charts show the average temperature in the Panama Bight to be 13° to 14° C. at 200 meters, 9° to 10° C. at 400 meters. No average subsurface salinity or current charts have been prepared for the Pacific.

The characteristic diagram showing the relationship of temperature and salinity provides a useful description of average subsurface conditions. Sverdrup, Johnson, and Fleming (1942, p. 707) show the entire equatorial Pacific to be underlain by an Equatorial Water mass of remarkably uniform character. This Equatorial Water is defined by an envelope enclosing observed points on a temperature-salinity diagram, as shown in figure 10. The water mass as defined lies deeper than 100 meters, because shoaler observations are subject to seasonal variations and local modifications.

In figure 10, temperature-salinity observations have been plotted for 21 stations in the

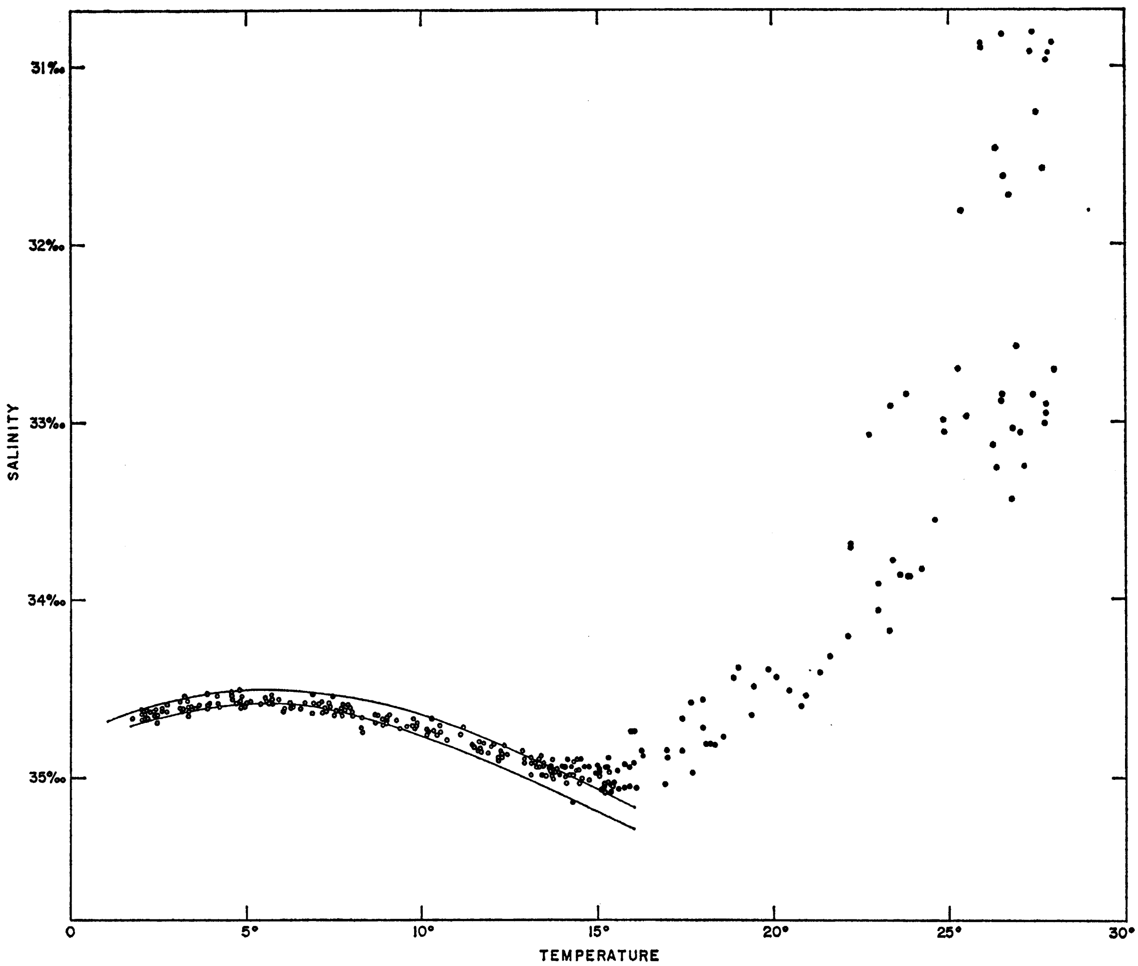

FIG. 10. Temperature-salinity relationship in the Panama Bight. Values at 100 meters and above shown by filled circles. Solid lines show equatorial Pacific water as defined by Sverdrup and others (1942, p. 707). The following stations were used: "Arcturus" 26 (Beebe, 1926); Swedish Deep-Sea Expedition 43, 45 (Bruneau, Jerlov, and Koczy, 1953); "Carnegie" 35, 36, 38, 39, 40 (Fleming and others, 1945); "William Scoresby" 717, 718, 719 (Discovery Committee, 1949); "Dana" 1203, 1205, 1210 (Schmidt, 1929); "Dana" 3548, 3549, 3550 (Carlsberg Foundation, 1937); "Velero" 9 and "Hannibal" 37, 135, 143 (United States Hydrographic Office, 1934).

Panama Bight. These stations include all "Carnegie," "Dana," "Arcturus," and Swedish Deep-Sea Expedition stations in the area, plus representative "William Scoresby," "Valero III," and "Hannibal" stations. All observations from the surface to the greatest depth are plotted, those between the surface and 100 meters being indicated by filled circles. Although the shoal values reflect the lack of uniformity in surface conditions, it is apparent that below 100 meters the waters of the Panama Bight correspond quite closely to the characteristics of Pacific Equatorial Water.

"ASKOY" OBSERVATIONS

Treatment of Data

"Askoy" station data[1] usually consisted of the following observations:

1. Description of Sea Surface Conditions: Wind, sea state, weather, cloud coverage, air temperature, and surface temperature.
2. Bathythermograph Record: In degrees Fahrenheit and fathoms, reaching depths as great as about 70 fathoms (128 meters).
3. Temperature Measured by Reversing Thermometer: Occasional values at various depths.
4. Salinity: At various depths on certain stations.

Only a few reversing thermometers were used, and their index corrections are not known. For this reason, when temperature-depth curves were drawn for each station, bathythermograph values were used in preference to reversing thermometer temperatures. Although possibly less accurate, the bathythermograph temperatures appear as a continuous function of depth and thus permit the drawing of a detailed temperature profile.

Salinity values were plotted as functions of temperature on the same station graphs on which the temperature-depth curves appeared. When smooth temperature-salinity curves were drawn, data from nearby stations were used as a guide in interpolation. During this analysis occasional salinity values appeared to be incorrect and were rejected.

Depths of standard isotherms and isohalines were read off from the station graphs and plotted on the temperature and salinity sections. After smooth isotherms were drawn on a temperature section, the appropriate salinity section was placed over it on a light table, and the isohalines were drawn parallel to the isotherms where this did not violate observed values. Thus an attempt was made to eliminate meaningless inconsistencies from the final drawing.

Distribution of Surface Temperature and Salinity

The observations of surface temperature and salinity made by the "Askoy" are shown in figures 11 and 12. No attempt has been made to contour these values because of the sparse areal coverage and the non-simultaneity of the observations.

During the southbound trip, surface temperatures of 26° to 28° C. were observed over most of the region, in agreement with Schott's February chart. Only in two areas were temperatures markedly different from Schott's averages: (1) southwest of Malpelo Island surface temperatures exceeded 29° C., about 2° C. higher than average; and (2) in the Gulf of Panama and to the south, surface temperatures were 3° to 4° C. higher than average as far south as latitude 7° N.

During the northbound trip, surface temperatures near the equator were about 3° C. warmer than those shown on Schott's May chart, off Cabo Corrientes about 1° C. warmer, and in the Gulf of Panama about 2° C. warmer than those of Schott.

Comparison of "Askoy" surface salinities (fig. 12) with Schott's February chart shows values distinctly low in the Gulf of Panama and south to latitude 6° N. Where Schott shows surface salinities of 34 to 35 parts per mille, "Askoy" values were less than 34 parts per mille, most observations falling between 32.5 and 33.8 parts per mille. Observations off Punta Santa Elena were in fair agreement with Schott's values, and those in the central part of the Bight were somewhat lower than average. The one station southwest of Malpelo that had both salinity and temperature measurements showed a very low surface salinity (33.13‰) as well as the high temperature (29.54° C.) noted above. Northbound surface salinities were somewhat lower than the earlier values, but there is no average chart of May salinities with which to compare them.

Temperature and Salinity Profiles

The subsurface distributions of temperature and salinity are shown in a series of profiles (figs. 13 to 20), the locations of which are shown in figure 1. Certain implications of

[1] Copies of the station data and bathythermograms are on file at the Scripps Institution of Oceanography.

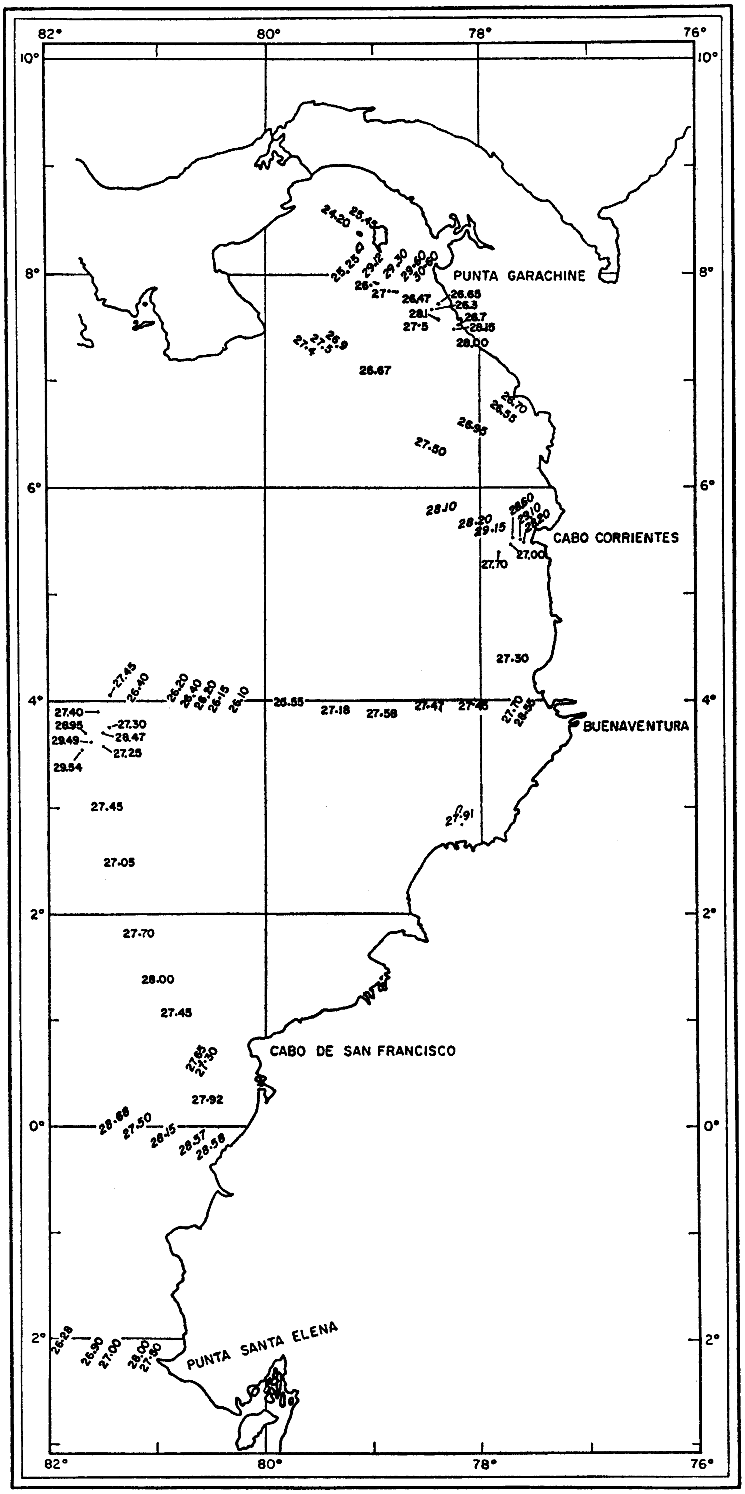

FIG. 11. "Askoy" surface temperature observations, in degrees Centigrade. Upright numerals refer to observations from February 9 to April 12 (southbound); italic numerals, to observations from April 13 to May 23 (northbound).

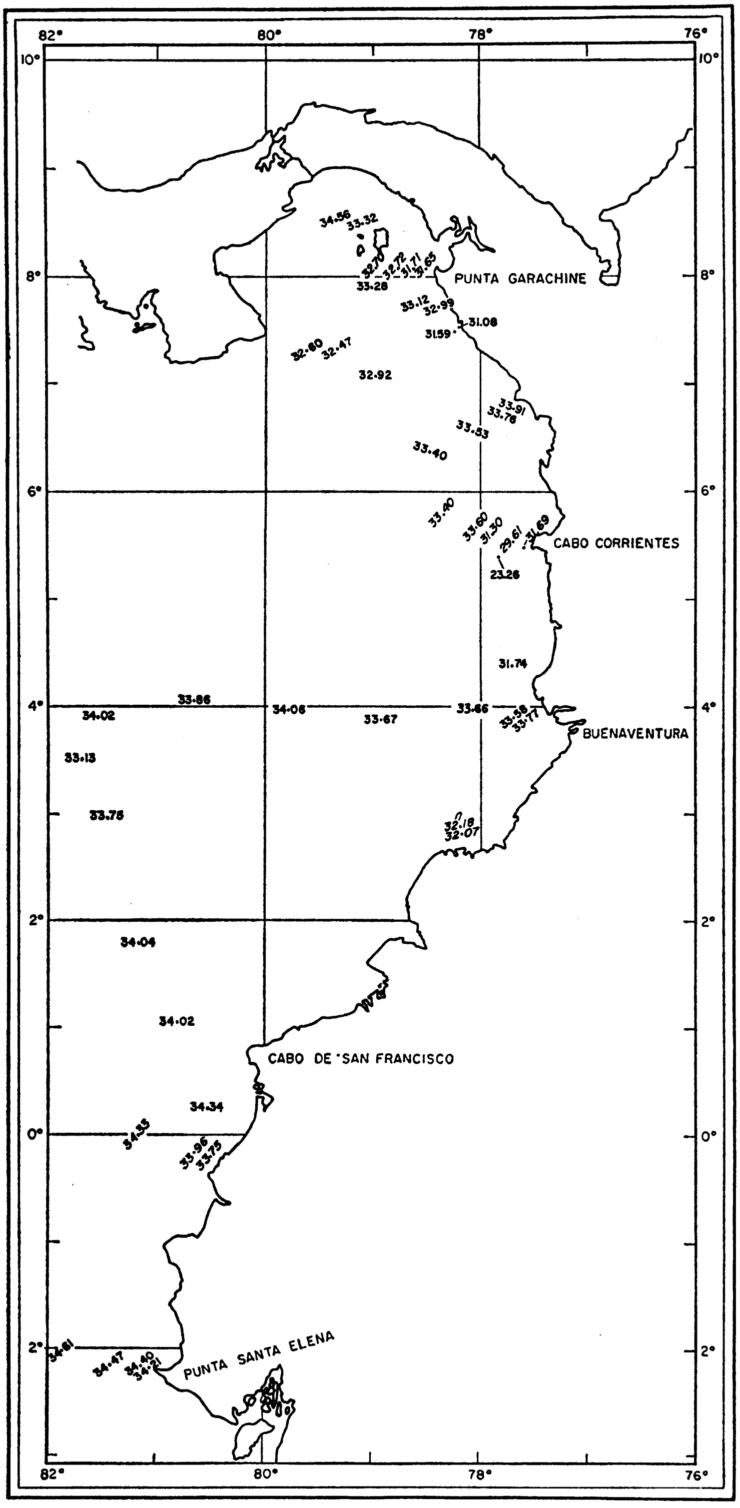

FIG. 12. "Askoy" surface salinity observations, in parts per mille. Upright numerals refer to observations from February 9 to April 12 (southbound); italic numerals, to observations from April 13 to May 23 (northbound).

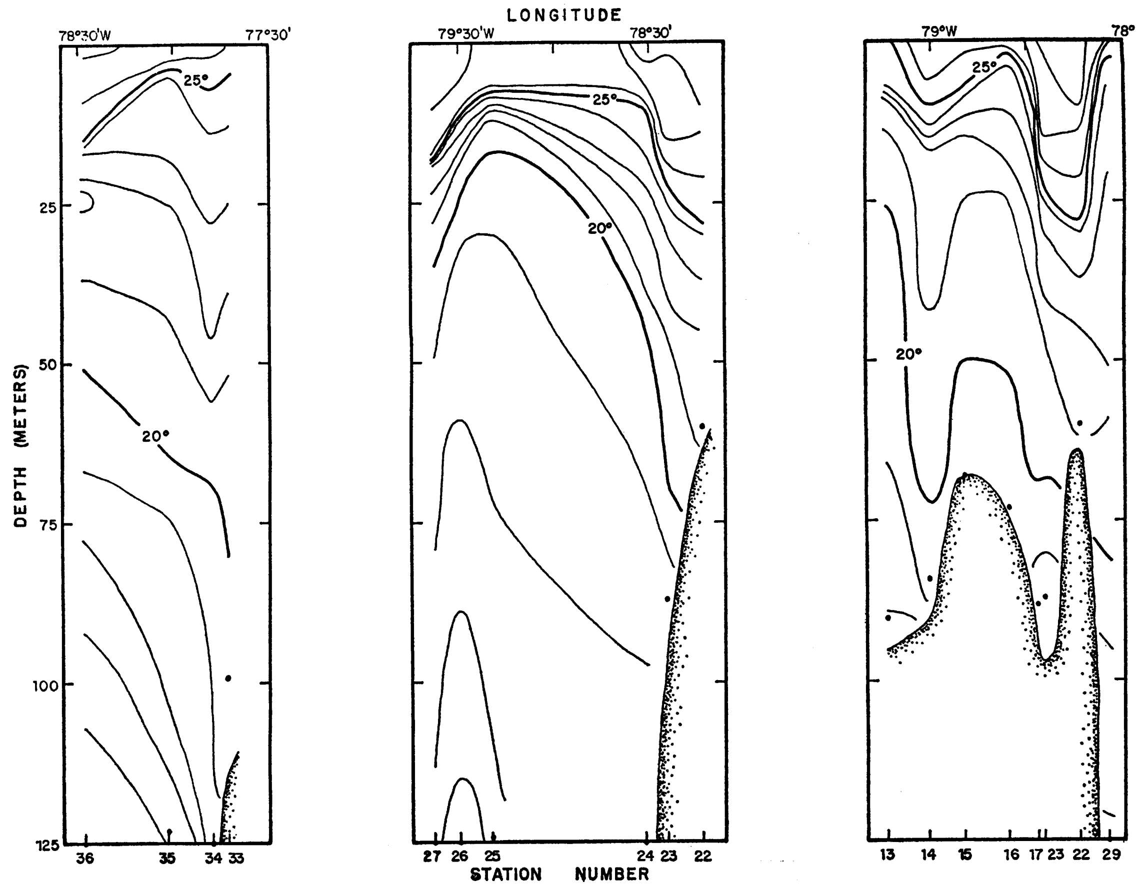

FIG. 13. "Askoy" temperature profiles, in degrees Centigrade, stations 33–36 (March 8–9, 1941, latitude 6° 30′ N.); 22–27 (February 26–27, 1941, latitude 7° 30′ N.); 13–29 (February 22 to March 3, 1941, latitude 8° N.).

the distribution of properties shown in these profiles are discussed below, but here only a general description is attempted.

The relatively high surface temperatures (26° to 29° C.) discussed above are characteristic of only a rather thin surface layer. This surface homogeneous layer is nowhere deeper than 25 meters, a relatively shallow thermocline being found over the entire area. At a depth of 100 meters temperatures range from 15.8° to 19.5° C., 84 per cent of the observations falling between 16.0° and 18.0° C. In the northern part of the Panama Bight isotherms show a general downward trend as they approach the coast (stations 13 to 22, 25 to 22, and 36 to 33, fig. 13; stations 99 to 94, fig. 19). South of Cabo Corrientes this does not seem to be the case (figs. 15 and 19), except possibly very close inshore on the profile west of Buenaventura (fig. 15).

The relatively low surface salinities (less than 34°/oo) are also found only in the surface layer, a halocline occurring at about the same depth as the thermocline. At a depth of 100 meters the range of salinity is very small (34.87 to 35.05°/oo), 59 per cent of the observations falling between 35.00 and 35.05 parts per mille. The isopleths of salinity also show a downward trend towards the coast north of Cabo Corrientes (fig. 14). However, neither the profile west of Corrientes (stations 99 to 94, fig. 20) nor the profiles farther south (figs. 16 and 20) show this feature.

On the two long profiles (figs. 15 to 18), on the other hand, both the isotherms and the isopleths of salinity offshore trend downward towards the vicinity of Malpelo Island. This trend and those discussed above are consistent with the general counterclockwise surface circulation inferred for the area.

Effects of Heavy Precipitation and Runoff

The relatively low coastal salinities (less than 33°/₀₀) off Buenaventura shown in Schott's February chart (fig. 4) and the characteristically low salinities (from 33°/₀₀ to less than 28°/₀₀) throughout the Panama Bight shown in Schott's August chart (fig. 5) are undoubtedly influenced by heavy precipitation and runoff. During August average surface salinities increase steadily with distance from the coast, and the mean surface salinity of the Equatorial Countercurrent, probably the chief advective source of surface water to the region, is in excess of 33 parts per mille.

An attempt was made to estimate the effect of rainfall and runoff on coastal surface salinities, although such an estimate must be crude because of the approximations involved in the computation. The assumptions involved in this estimate are as follows:

1. The average annual river discharge from the Pacific watershed of Colombia is 8000 cubic meters per second (Manuel, 1955, pp. 40–41).
2. The total annual precipitation in the area is 300 cm., and the seasonal precipitation and evaporation can be estimated by the methods of Jacobs (1951).

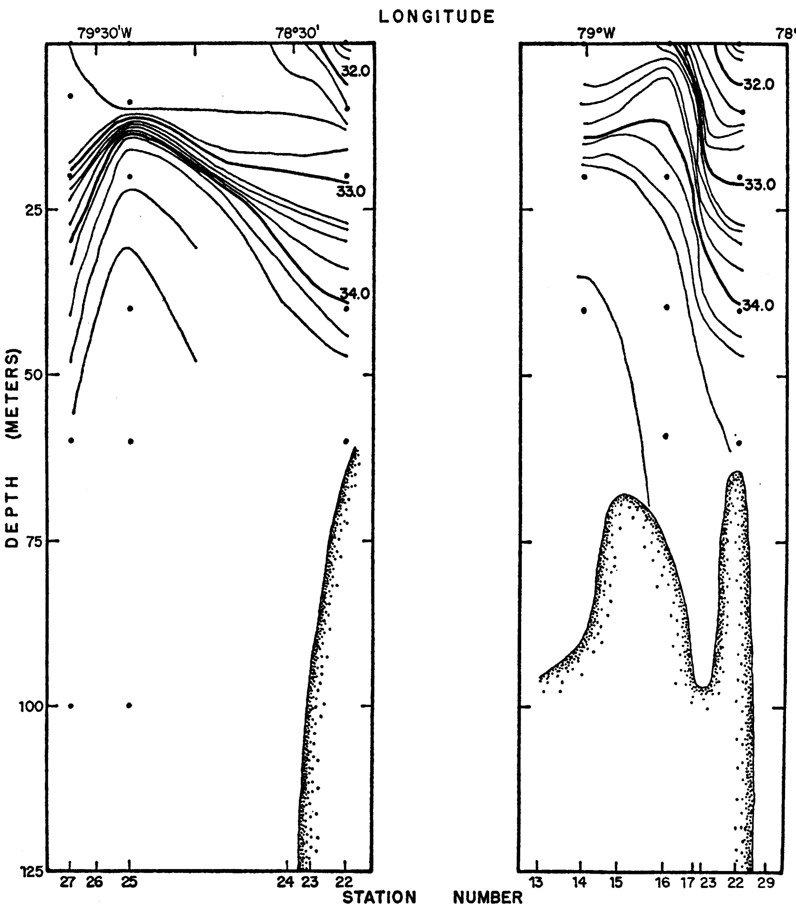

Fig. 14. "Askoy" salinity profiles, in parts per mille, stations 33–36 (March 8–9, 1941, latitude 6° 30′ N.); 22–27 (February 26–27, 1941, latitude 7° 30′ N.); 13–29 (February 22 to March 3, 1941, latitude 8° N.).

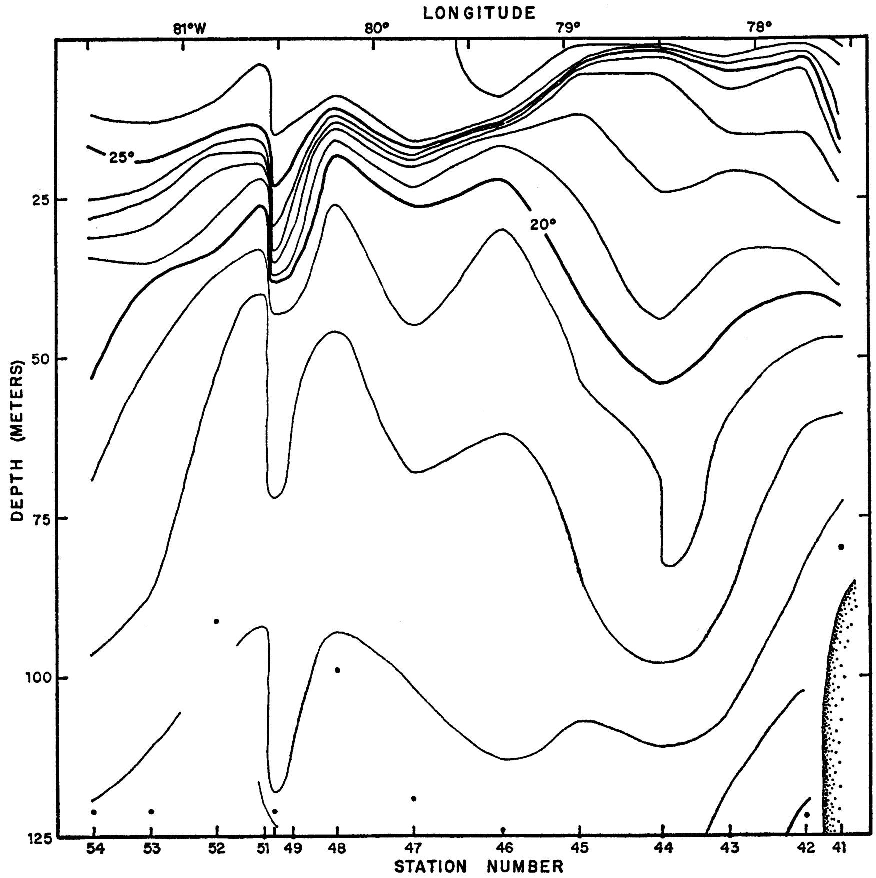

FIG. 15. "Askoy" temperature profile, in degrees Centigrade, stations 41–54 (March 20–25, 1941, latitude 4° N.).

3. Fresh water added to the surface layer of the region being examined is neither carried out of the region nor mixed with deeper waters.

The results of this calculation show that during the period June to August the salinity of a 10-meter layer of water 300 miles long by 60 miles wide could be reduced by rainfall and runoff from 33 parts per mille to 28 parts per mille in 78 days. During the rainiest period, September to November, only 65 days would be required, while during the period December to May 172 days are necessary.

UPWELLING IN THE GULF OF PANAMA

As mentioned above, during the months of January through March the effect of the prevailing northerlies is to drive surface water out of the Gulf of Panama, leading to replacement and mixing with deeper water. The seasonal march of surface conditions shows the lowest temperatures and highest salinities during February and March, and the average sea level, which is in large part a function of the specific volume of the water, is also lowest during the same period (see Fleming, 1940, fig. 6; and Schaefer, Bishop, and Howard, 1958, figs. 1, 3).

Although this "spring" upwelling is a consistent annual phenomenon, its intensity appears to vary considerably from year to year. This is clearly shown in figure 21, based on records of the Panama Canal Company. It is obvious, for example, that the average February-March sea level was higher in 1941 than in all other years of the record, and that the average February-March surface temperature was higher, and the number of cold days fewer, than in all other years, with the exception of 1928. Conditions in 1933, in contrast, seem to have been much closer to average (as shown by the 42-year mean).

A comparison of profiles made in March, 1933, by the U.S.S. "Hannibal" (United States Hydrographic Office, 1934) with those of the "Askoy" in late February, 1941, shows the striking difference between these two years (fig. 22 shows the locations and dates of the compared profiles).

In February, 1941 (fig. 13), a thin layer of warm water (warmer than 26° C.) covered the surface, a strong thermocline centered on the isotherm of 23° C. was located at depths of 10 to 40 meters, and waters between 50 and 100 meters had a temperature of 17° to 21° C. Surface salinities (fig. 14) were low (31.6 to 33.4°/₀₀) above a strong, shallow halocline, and waters between 50 and 100 meters had a salinity of 34.5 to 34.8 parts per mille. In March, 1933 (fig. 23), on the other hand, surface temperatures were usually less than 20° C., a weaker thermocline centered on the isotherm of 17° C. lay at a depth of less than 20 meters, and waters between 50 and 100 meters had a temperature of less than 15° C. Surface salinities (fig. 24) were high (34.6 to 34.8°/₀₀), there was no pronounced halocline, and waters between 50 and 100 meters had a salinity of 34.8 to more than 35.0 parts per mille.

Thus it seems likely that, whereas upwelling was well developed in 1933, it was weak or missing in 1941. One might expect the explanation of this difference between the two years to lie in a difference in the strength of the northerly winds, as Schaefer and his coauthors have demonstrated the significant

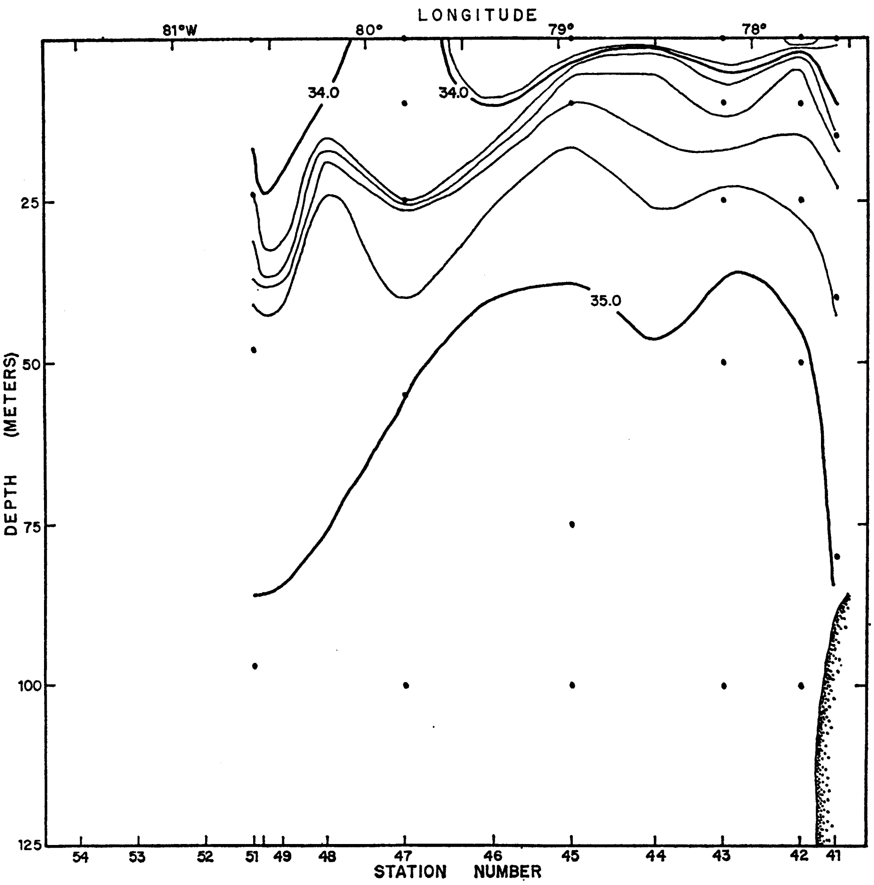

FIG. 16. "Askoy" salinity profile, in parts per mille, stations 41–54 (March 20–25, 1941, latitude 4° N.).

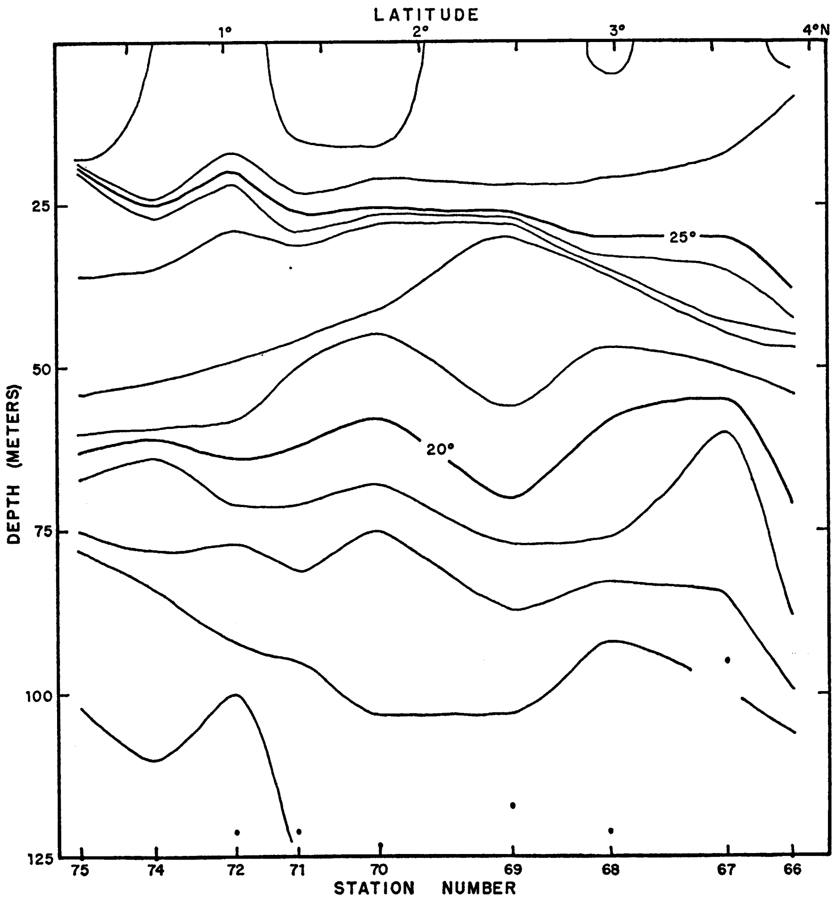

FIG. 17. "Askoy" temperature profile, in degrees Centigrade, stations 66–75 (March 29 to April 2, 1941, longitude 81° W.).

correlation between the spring (January through April) values of all northerly winds (total miles of winds from north, northwest, and northeast) and mean spring sea levels at Balboa.

In an attempt to refine their analysis, an index of northerly wind stress was computed for the February-March period of each year. This period was selected as the time when mean sea levels and sea surface temperatures are usually lowest, that is, the period when upwelling is best developed. The wind-stress index was computed by adding the total miles of wind from true north for February and March to the northerly component of the total miles of northwesterly winds for the same period (northeasterly winds at Balboa are negligible). This sum, divided by the number of hours in the two-month period, gave an average northerly component of the wind velocity in miles per hour, the square of which is the wind-stress index.[1]

The lowest panel of figure 21 shows the year-to-year variations of this index. Correlation of the index with the average February-March sea level gave the significant correlarion coefficient, r, of -0.54. As the figure shows, the wind-stress index was smaller (46.5) in 1941 than in 1933 (63.4), the 42-year average being 65.9. However, the difference is clearly not sufficient to account for the marked departure from mean sea level observed in 1941.

Thus the full explanation must lie else-

[1] The force of friction of the wind on the sea surface, the wind stress, is proportional to the square of the speed of the wind relative to the water.

where. Schaefer and his co-authors investigated the multiple correlation between Balboa sea surface temperature, Balboa northerly winds, and offshore temperatures in a 5-degree square at approximately latitudes 5° to 10° N., longitudes 80° to 85° W. (from records of the Japanese Imperial Marine Observatory at Kobe for the years 1916 to 1938), and concluded that Balboa spring temperature anomalies were affected partly by local effects of northerly winds, and partly by factors affecting the temperatures over a large area (as measured by the offshore temperatures).

Unfortunately, because of the lack of published offshore data after 1938, it is not easy to investigate the possibility that the unusually high sea level in the Gulf of Panama in 1941 was associated not only with a reduction in the northerly wind stress but also with some other large-scale process affecting the temperature over a large area. There is some evidence from the "Askoy" observations that this was the case (see below), and the fact that both in 1941 and 1953 (another year with unusually high sea level) *El Niño* was observed in Peru makes this possibility particularly intriguing.

El Niño in 1941

One of the most celebrated of oceanic disturbances is that known as *El Niño*, which is occasionally reported from the coast of Peru. There is fairly convincing evidence that this phenomenon occurred during the early months of 1941 (see Schweigger, 1942; Sears, 1954; Lobell, 1942; Fiedler, Jarvis, and Lobell, 1943; Vogt, 1942). Because it is likely

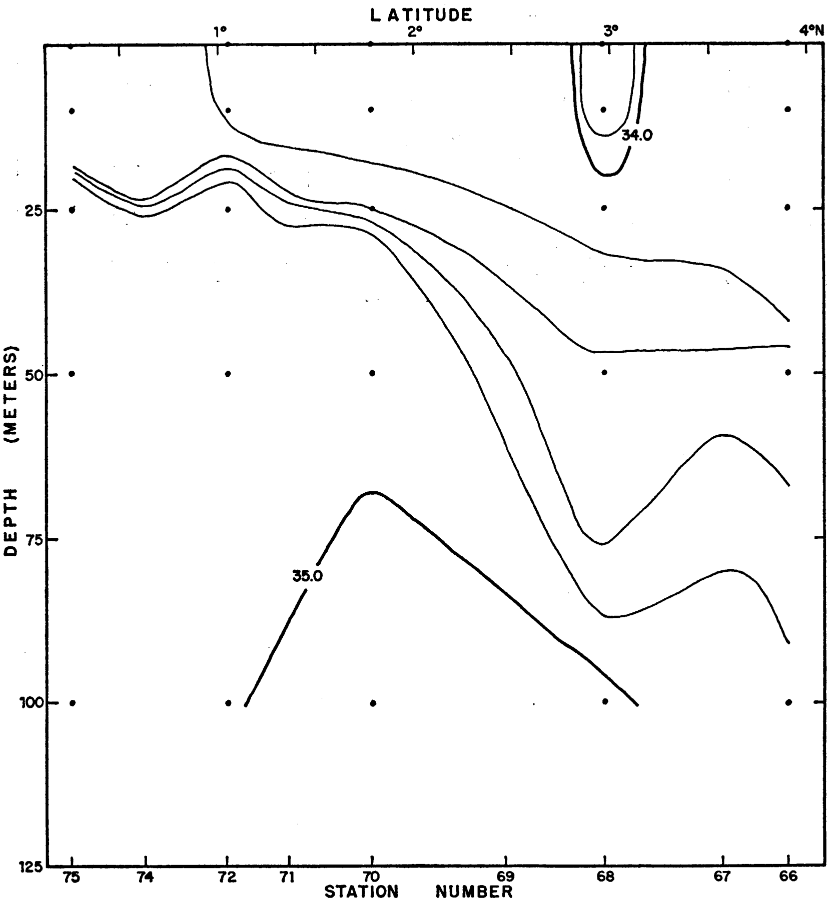

FIG. 18. "Askoy" salinity profile, in parts per mille, stations 66–75 (March 29 to April 2, 1941, longitude 81° W.).

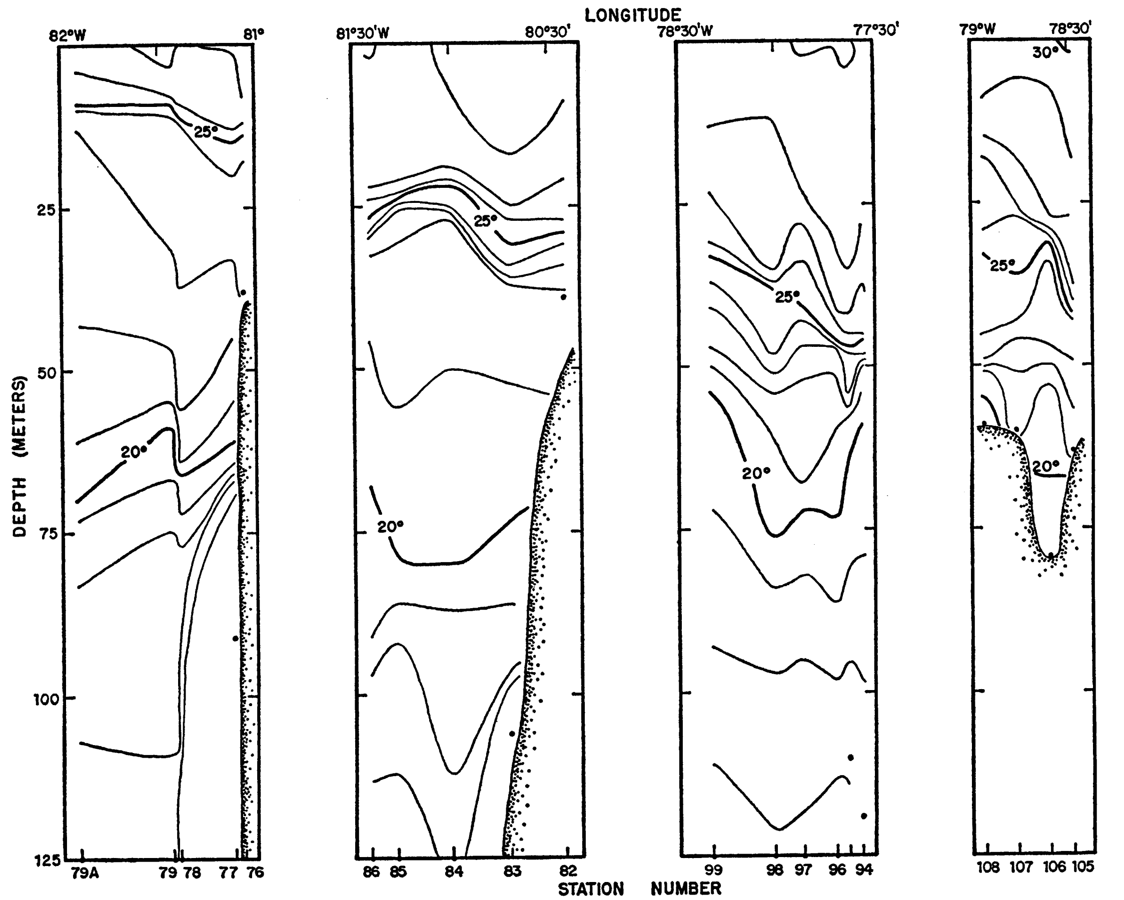

FIG. 19. "Askoy" temperature profiles, in degrees Centigrade, stations 76–79A (April 10–11, 1941, latitude 2° S.); 82–86 (April 15–16, 1941, 0°); 94–99 (May 13, 1941, latitude 5° 30′ N.); 105–108 (May 22–23, 1941, latitude 8° N.).

that *El Niño* is not merely a local Peruvian condition, but rather reflects a large-scale change in atmospheric conditions, it is of interest to compare the "Askoy" observations with those to be expected during such an event.

The generally accepted description of *El Niño* is that of Schott (1931). According to him, the Intertropical Convergence, which usually lies across the coast near the Ecuador-Colombia border during the early months of the year, occasionally and for unknown reasons penetrates southward several hundred miles to northern Peru. The southeast trades of that region are replaced by calms or northerlies, bringing heavy rains to this otherwise desert area. At the same time warm, low-saline waters flow southward from the Equatorial Countercurrent, covering or replacing the usual cold and high-saline waters of the Peru Current southward nearly to latitude 15° S.

The southward displacement of the Intertropical Convergence has other effects farther north. A tongue of cold water extends southwestward from the Gulf of Panama nearly to the equator, with temperatures less than 25° C. and salinity higher than 34 parts per mille. These characteristics of low temperature and high salinity are attributed to the arrival of subsurface waters at the surface, presumably owing to the action of northerly winds in removing surface waters of the Gulf. On the basis of observations made by the "Königsberg" in March, 1931, Schott seems to accept the fact that such characteristics may always be present in and south of the Gulf of Panama during the first months of the year, although he leaves the impression that they are more exaggerated during a year of *El Niño.*

Farther offshore the Equatorial Countercurrent lies south of its usual position, eastward currents having been reported from the Galápagos. During the 1891 event the "Albatross" also reported heavy rains and lush vegetation in the Galápagos during March. Schott considers that the warm, low-saline waters west of the Panama cold tongue and in the countercurrent are the source of *El Niño* "current."

Because none of the "Askoy" observations were made off the coast of Peru, they cannot be used to test the validity of Schott's model in that region; nor do they help in our determining the westward extent of the phenomenon of *El Niño.* They do, however, fall exactly in that region where, according to Schott's description, should be found the cold tongue extending southward from the Gulf of Panama.

Examination of the "Askoy" data does not reveal such a tongue. Surface temperatures lower than 25° C. were observed on only one station, and temperatures in the Gulf and south were several degrees higher than usual. Salinities higher than 34 parts per mille were consistently observed only south of about latitude 2° S., and north of there most values fell between 32.5 and 33.8 parts per mille, or somewhat lower than usual.

The data from the Gulf of Panama suggest

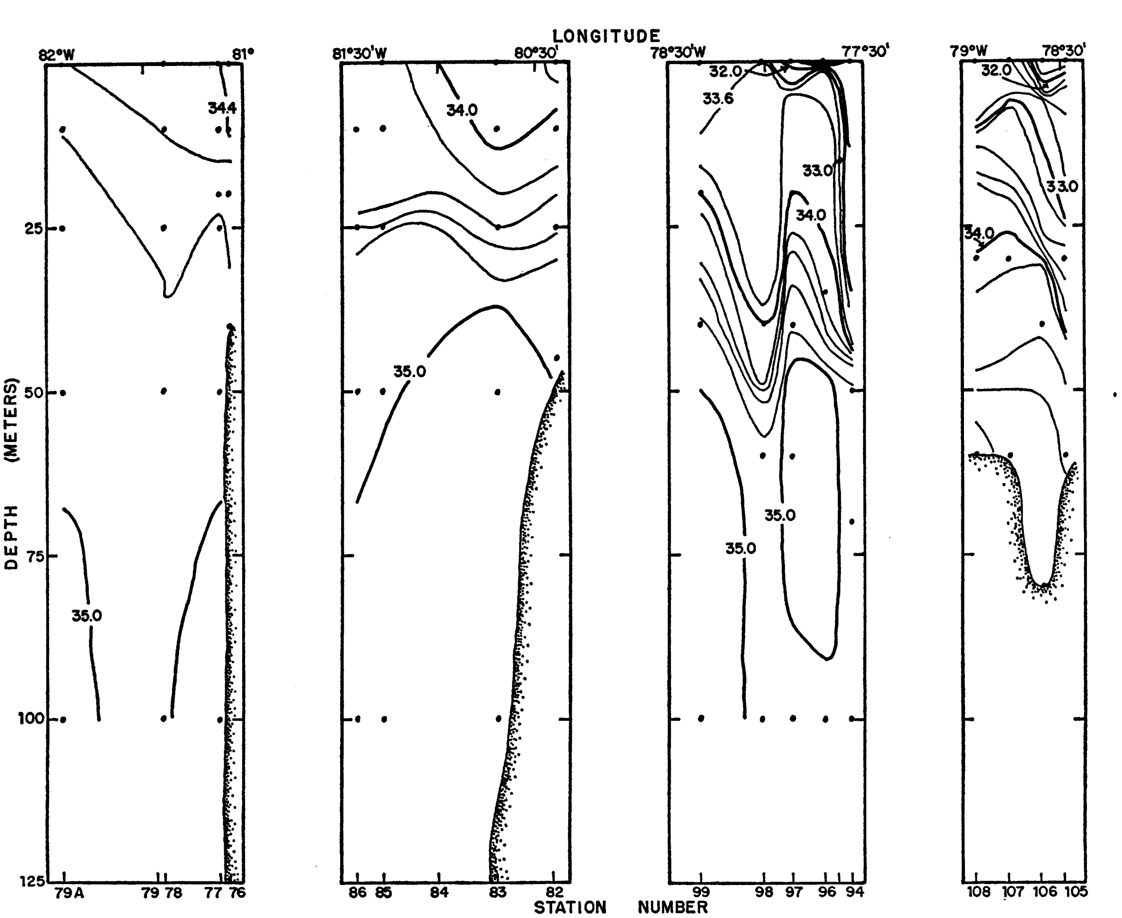

FIG. 20. "Askoy" salinity profiles, in parts per mille, stations 76–79A (April 10–11, 1941, latitude 2° S.); 82–86 (April 15–16, 1941, 0°); 94–99 (May 13, 1941, latitude 5° 30′ N.); 105–108 (May 22–23, 1941, latitude 8° N.).

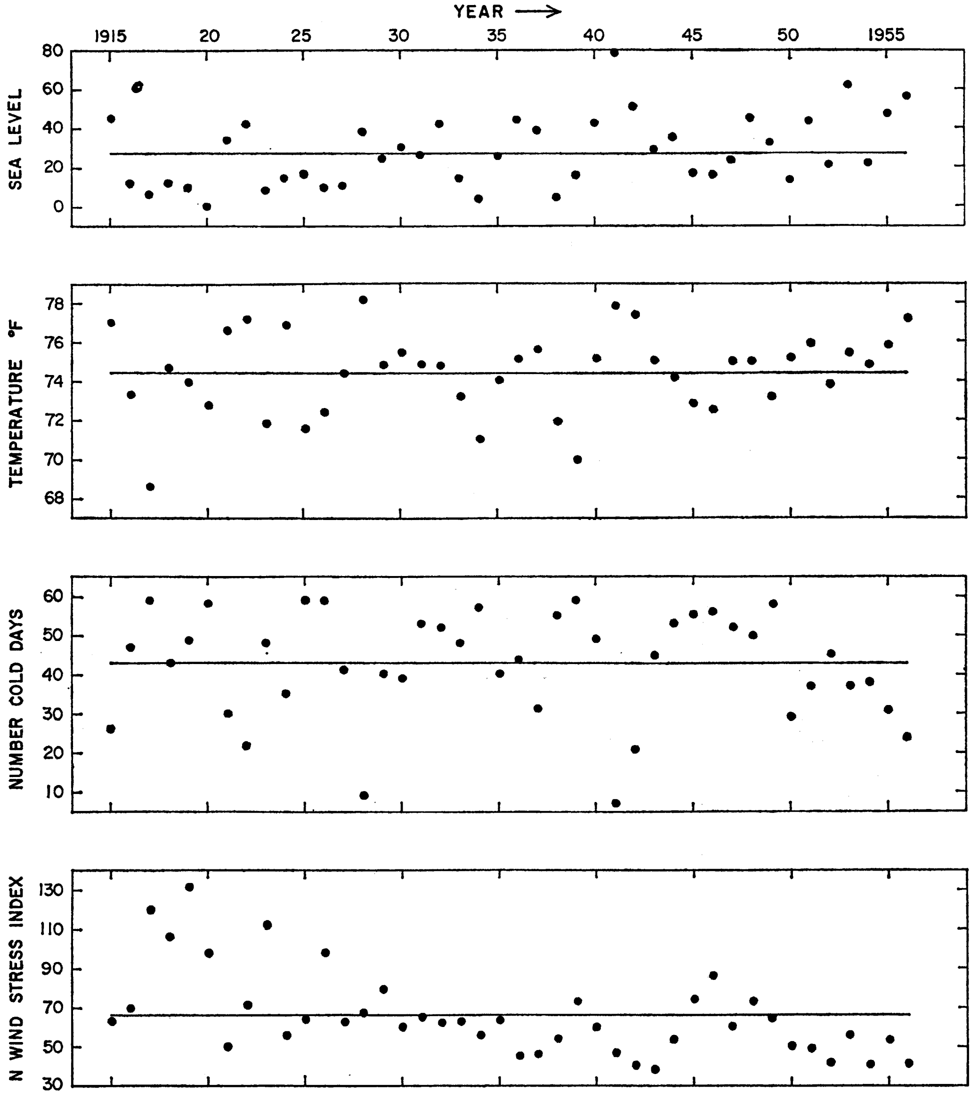

FIG. 21. Year to year variations in February–March values at Balboa of average sea level (hundreds of feet), average sea surface temperature (in degrees Fahrenheit), number of cold days (when sea surface temperature fell below 76° F.), and northerly wind-stress index (see text). In each case, horizontal line shows 1915–1956 mean.

that, far from being a year of unusually intense upwelling in the Gulf, 1941 was a year of much reduced upwelling. As discussed above, waters in the Gulf were much warmer and less saline in 1941 than in 1933, and the pronounced shallow thermocline at the time of the "Askoy" observations is further evidence that upwelling was not active. In 1925, on the other hand, both sea level and sea temperatures were lower than usual. Thus *El Niño* of 1941, at least as shown by conditions in the Gulf of Panama, was significantly different from that of 1925 as described by Schott.

In the region northwest of the cold tongue, Schott found the highest surface temperatures (higher than 28° C.) and low salinities (less than 32°/₀₀ to less than 33°/₀₀), and this water, coming from the Equatorial Countercurrent, he considered as the source of *El Niño* waters. During the 1953 *Niño* (Posner, 1957), a center of warm water (higher than 28° C.) and low salinity (31–32°/₀₀) was observed south of Costa Rica. Wooster and Jennings (1955), who described this situation, suggested that southward movement of this water contributed to the unusual conditions observed between Ecuador and the Galápagos.

It seems likely that similar conditions were observed by the "Askoy" west of Malpelo Island. It will be recalled that surface temperatures of greater than 29° C. and surface salinities as low as 33.1 parts per mille were recorded on station 58 southwest of Malpelo. Data from this and a neighboring station (66) show that the warm, fresh water was confined to a surface layer only about 20 meters thick.

Murphy, in his unpublished journal, comments on this layer of warm water and on the great change of horizontal velocity at about 20 meters, as evidenced by the pronounced wire angle developed when instruments reached that depth. He estimated that this surface layer was moving southward at a speed in excess of 1.5 knots, and speculated: "This warm water may represent one of the major transgressions of northern hemisphere water across the equator. It may be an early stage of a *Niño* phenomenon in Peru, or it may even be synchronous with one. In the latter case the inference would be that the warm Pacific water moves more or less eastward toward the land all along the northerly half of the South American coast."

Observation of an Oceanic Front

In a recent paper Cromwell and Reid (1956) described a phenomenon which they call an "oceanic front." The front is defined as a band along the sea surface across which there is an abrupt change of density. The front is often visible as a narrow band of agi-

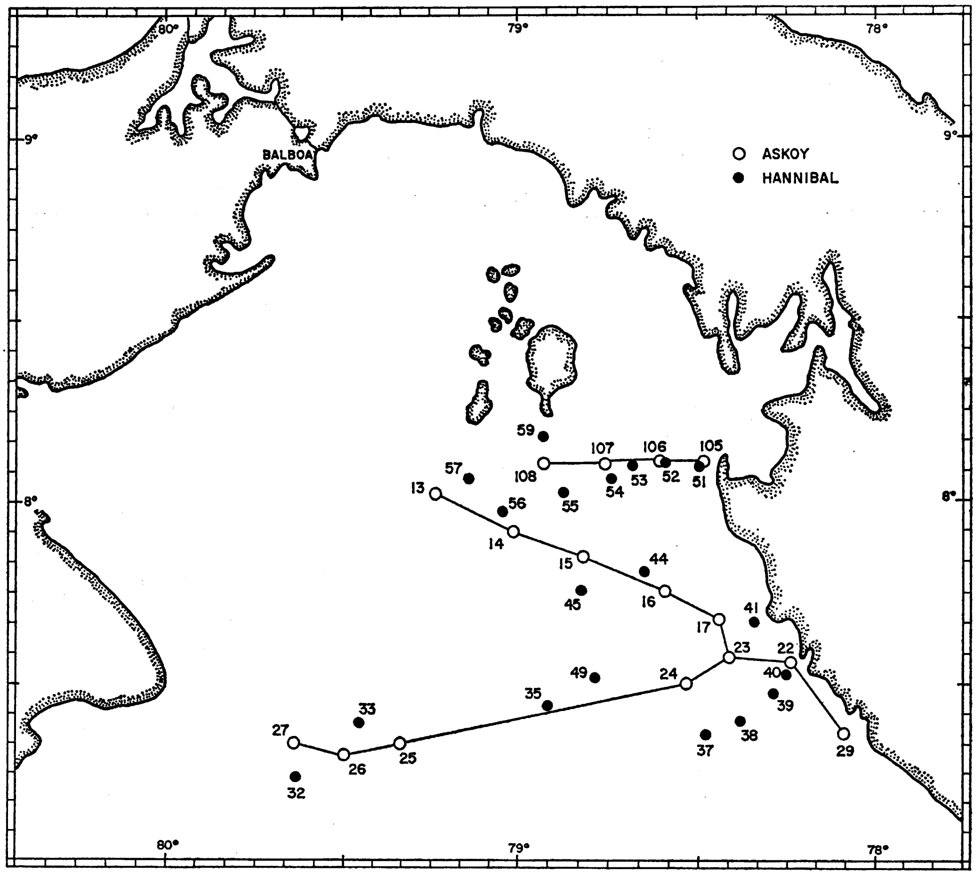

FIG. 22. Location of "Hannibal" stations used in the preparation of figures 23 and 24.

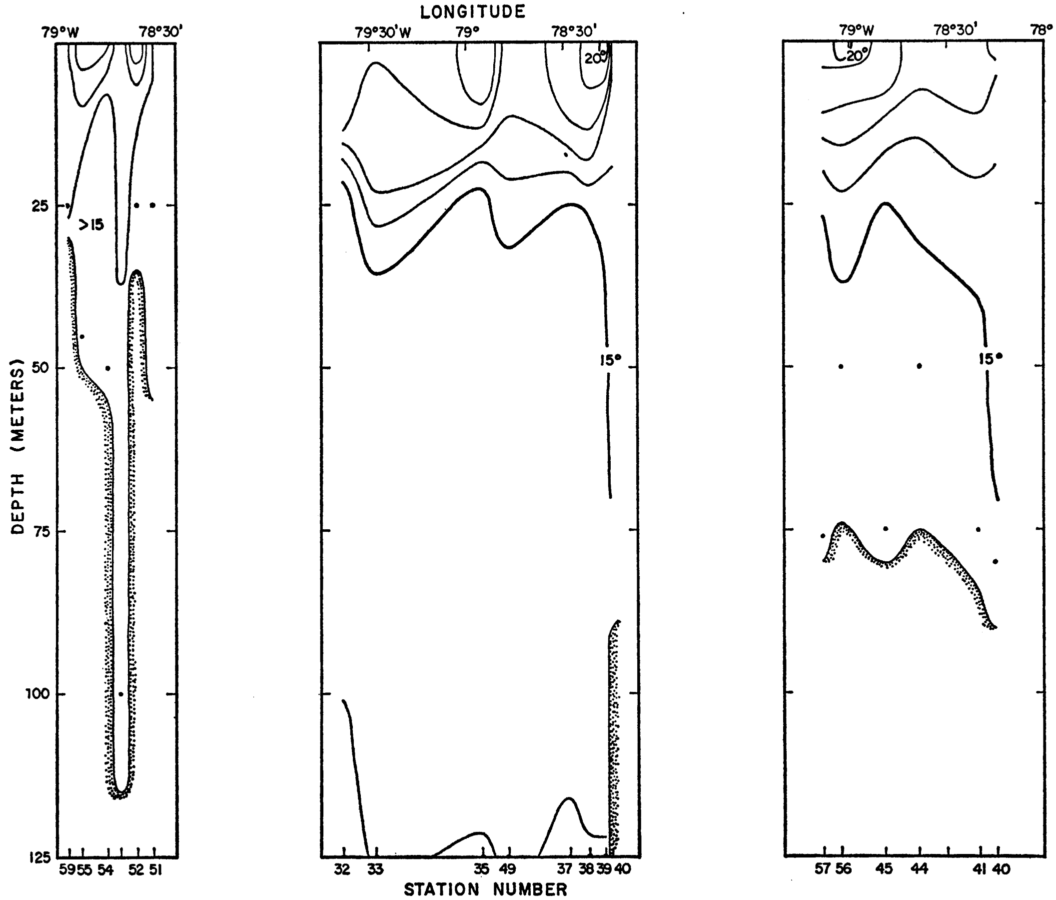

FIG. 23. "Hannibal" temperature profiles, in degrees Centigrade, stations 51–59 (March 15–16, 1933, latitude 8° N.); 32–40 (March 10–12, 1933, latitude 7° 30′ N.); 40–57 (March 12–15, 1933, latitude 8° N.).

tated wavelets following a sinuous path, and often floating debris is concentrated along this band. Frequently there is also a distinctive sound, apparently produced by the breaking wavelets.

The unusual distribution of isotherms between stations 49 and 51 on the profile west of Buenaventura (fig. 15) is very reminiscent of the subsurface distribution at a front (see Cromwell and Reid, 1956, fig. 3), although on the "Askoy" stations no abrupt change in surface temperature was observed. Below the surface, however, there was a pronounced discontinuity in temperature from east to west. East of the feature there was a warm isothermal layer lying above a strong thermocline, and also apparently there occurred the deep penetration of warm water as described by Cromwell and Reid. West of the feature the vertical temperature gradient in the thermocline is much smaller and the warm surface layer somewhat shallower.

The surface manifestations of this phenomenon near station 49 have been vividly described by Murphy (*in* Nichols and Murphy, 1944). He writes of areas of "dancing water" and of the sound produced by this motion, with glassy calm on one side of the front and turbulent water on the other. In the vicinity of the front were concentrated great numbers of organisms, ranging in size from blackfish (*Globicephalus*) to minute plankters.

There are not enough closely spaced bathythermograph observations to permit detailed comparison with the oceanic fronts described by Cromwell and Reid. According to the surface temperature data (26.15° C. on station 49, 26.20° C. on station 50, 26.40° C. on station 51), this was not a front as these authors define one, because there was apparently no abrupt change in surface density. Yet the other surface manifestations and the subsurface distribution of temperature seem to correspond very closely with the phenomenon they describe.

The Colombia Current

The surface current charts discussed above (figs. 6 to 9) show throughout the year a northward-flowing surface current along the coast of South America north of Cabo de San Francisco. This current is apparently well known, being described in the "Sailing directions for South America" (United States Hydrographic Office, 1952, p. 21) as follows: "1.82 Ecuador and Colombia—The Peruvian Current divides at Parinas Point, one branch setting to the westward and the other along this coast and into the Bay of Panama. Off the coast of Ecuador this current is constant within 60 miles of the land, and is of great assistance to vessels bound to Panama."

Murphy (1939) has indicated the unlikelihood of the coastal current's being derived from the Peru (Humboldt) Current. Because of the permanence of this current, and because (as discussed below) it does not seem to be a branch of the Peru Current, I propose that this current be called the "Colombia Current." The average current charts suggest that it has a mean speed of about 25 cm. per

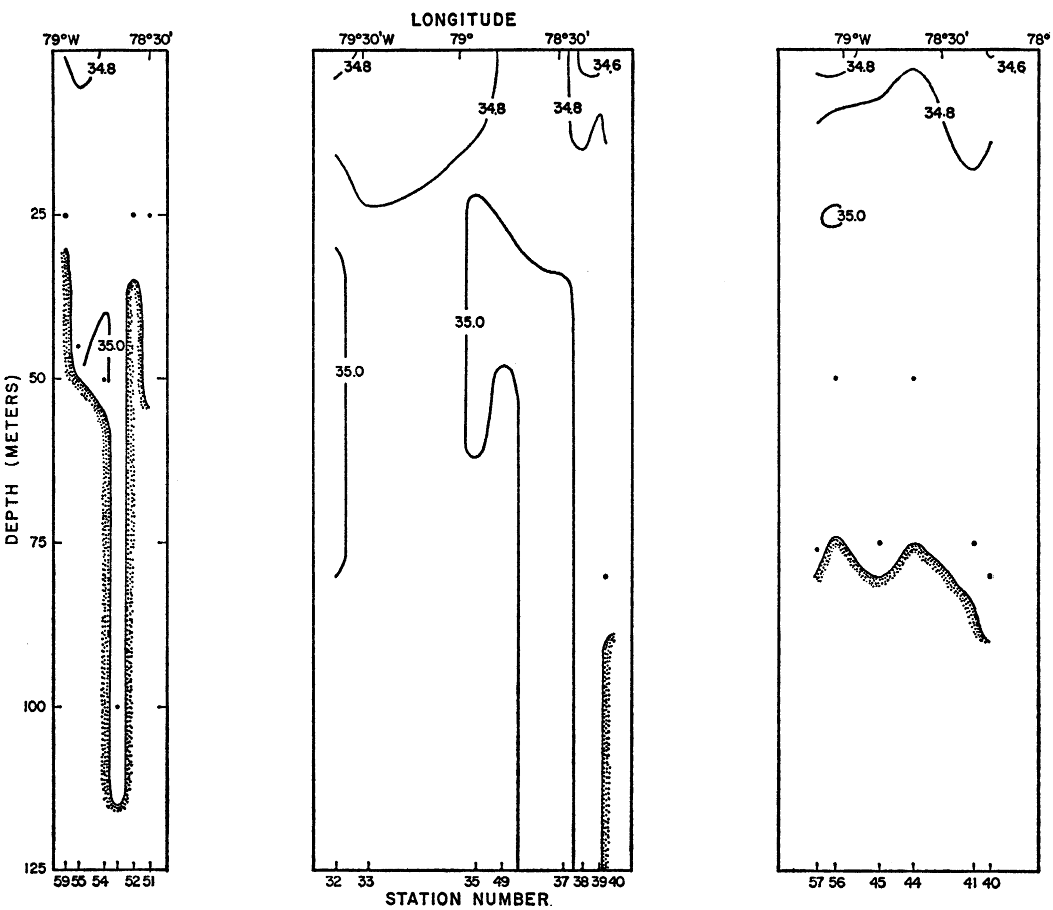

FIG. 24. "Hannibal" salinity profiles, in parts per mille, stations 51–59 (March 15–16, 1933, latitude 8° N.); 32–40 (March 10–12, 1933, latitude 7° 30′ N.); 40–57 (March 12–15, 1933, latitude 8° N.).

second (0.5 knot) and a width of less than 100 miles.

The prevailing winds along the coast of Colombia blow from the south parallel to the coast during most of the year, blowing from the north only during the winter. Within a few degrees of the equator, where there is very little deflecting force due to the rotation of the earth, one would expect transport of the surface wind-driven current to be in the direction of the wind; farther north, transport would be to the right of the wind. Thus, during the seasons when the modified southeast trades prevail, one would expect a northward current along the coast converging with the coast and having a thermocline deeper inshore than offshore (thus with the sea surface sloping downward away from the coast). As mentioned above, this appears to be the case north of Cabo Corrientes and possibly close inshore off Buenaventura. On these profiles lowest surface salinities are also found close inshore, contributing to the shoreward increase in height of the sea surface. As the "Askoy" data are so shallow, and so many of the observations are close to the equator, it seems futile to attempt a calculation of velocity or transport of this current.

Neither the circulation suggested above nor the distribution of properties observed is consistent with the existence of coastal upwelling. Offshore, however, the thermocline is very shallow (less than 10 meters on stations 42 to 45), in part because of the equilibrium distribution of mass resulting from the wind-driven circulation. Such a shallow thermocline (designated a "dome" by Cromwell, 1958) may be associated with high productivity both because of the ready availability of waters of high nutrient content in the thermocline to the stirring action of the wind, and because the euphotic zone may extend downward into the thermocline where nutrients can be supplied by lateral mixing.

Direct measurements of the surface current were attempted during the "Askoy" expedition with a Coast and Geodetic Survey log line and pelorus. On station 91, inshore of Gorgonilla Island, where 34 observations were made between 1335 on April 25 and 1600 on April 26, 1941, the surface current was usually towards the east (044° to 095° magnetic) parallel to the coast, with a mean speed of about 25 cm. per second (during the first hour and a half the current was stronger than 50 cm. per sec.; later it varied from 10 to 45 cm. per sec.). On station 92, less than a mile west of Cabo Corrientes, nine observations were made between 1145 and 1635 on May 12, 1941. Here the direction varied from northward to southward, the speeds from 5 to 30 cm. per second. Because these stations were so near shore, the measurements tell little about the mean drift of the Colombia Current.

It is conceivable that the waters of the Colombia Current are derived from the Peru Current. If so, they are extensively modified by mixing, local heating, and freshening due to rainfall and runoff. Although one might look for the presence of Peru Current indicator species, it seems unlikely that many of the indigenous plankton organisms of the Peru Current will be found in the Colombia Current, because near-surface conditions are drastically different. Crossings of the north boundary of the Peru Current show an abrupt change in the distribution of temperature and dissolved substances (Wooster and Cromwell, 1958), and it is probable that most of the waters of the Peru Current turn westward south of the equator. At our present state of knowledge, the Colombia Current must be considered merely the eastern limb of the general counterclockwise circulation of the Panama Bight.

SUMMARY

THE PANAMA BIGHT may be defined as that part of the eastern tropical Pacific Ocean that lies between the Isthmus of Panama (about latitude 9° N.) and Punta Santa Elena (about latitude 2° S.) and extends westward from the coasts of Panama, Colombia, and Ecuador to about longitude 81° W. Oceanographic observations discussed in this region were made by the "Askoy" expedition during the period February 9 to May 26, 1941.

Bathymetrically the region is part of the Panama Basin which is enclosed by Central and South America, Cocos Ridge, the Galápagos Islands, and Carnegie Ridge. Most of the Panama Bight is deeper than 3000 meters, the shelf being nowhere wider than 30 miles except in the Gulf of Panama which is less than 200 meters deep.

Seasonal contrasts in weather within the Bight are related to movement of the Intertropical Convergence. In January–March the Intertropical Convergence is farthest south, offshore northerlies cause upwelling in the Gulf of Panama, and the Gulf experiences its dry season. In July–September the Intertropical Convergence is farthest north, and the region south of Cabo de San Francisco receives its least rain. The central part of the Bight receives heavy rainfall throughout the year. From June to November most of the Panama Bight is dominated by southwest winds.

These seasonal changes are reflected in the average surface distribution of temperature and salinity. In February surface temperatures of 26° to 28° C. and salinities of 34 to 35 parts per mille are found in most parts of the Bight, with lower temperatures in the Gulf of Panama. By August low surface temperatures have disappeared in the Gulf, and the whole region is covered with surface waters of low salinity (less than 33‰). It is estimated that during the rainiest period the salinity of a 10-meter layer of water 300 miles long and 60 miles wide could be reduced by rainfall and runoff from 33 parts per mille to 28 parts per mille in a period of two to three months.

During the "Askoy" expedition, surface temperatures of 26° to 28° C. and surface salinities of somewhat less than 34 parts per mille were observed in most of the region. These high surface temperatures and relatively low surface salinities were characteristic of only a rather thin surface layer (reaching 25 meters or less) which was underlain by a shallow pycnocline. At 100 meters temperatures range from 15.8° to 19.5° C., salinities from 34.87 parts per mille to 35.05 parts per mille.

In the Gulf of Panama high surface temperatures, low surface salinities, and the presence of a strong shallow pycnocline suggest that upwelling in early 1941 was less intense than usual. This was confirmed by comparison with "Hannibal" observations in March, 1933, and by examination of long-term measurements of sea level and surface temperature at Balboa by the Panama Canal Company.

Correlation of a northerly wind-stress index for February–March with the average sea level for the same months over a 42-year period gave the significant correlation coefficient of −0.54. However, although the 1941 northerly wind-stress index was somewhat lower than average, it was not low enough to account for the unusually high sea level observed in 1941. Thus it seems likely that some other large-scale process affecting sea temperatures over a large area was operating.

During the first half of 1941 *El Niño* was observed off the coast of northern Peru. Schott's explanation of this phenomenon, based on its characteristics in 1891 and 1925, calls for a cold tongue extending from the Gulf of Panama nearly to the equator. Although this cold tongue was not detected by the "Askoy," unusually high temperature, low salinity, and a strong southward surface current measured west of Malpelo Island may be related to the influx of northern waters on the coast of Peru.

Observation of a pronounced subsurface temperature discontinuity 200 miles west of Buenaventura, accompanied by other indications at the surface, suggests that a well-developed oceanic front was present on March 24, 1941.

Examination of average surface current charts shows a northward coastal surface

flow north of Cabo de San Francisco throughout the year, with a mean speed of about 25 cm. per second (0.5 knot) and a width of less than 100 miles. "Askoy" measurements in the northern part of the Bight show a subsurface distribution of mass consistent with such a current which appears to be the eastern limb of the general counterclockwise circulation in the Panama Bight. It is proposed that it be called the "Colombia Current."

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