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OCEANOGRAPHY OF THE EAST CENTRAL EQUATORIAL PACIFIC AS OBSERVED DURING EXPEDITION EASTROPIC

BY THOMAS S. AUSTIN

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CONTENTS

ABSTRACT

From September 23 to December 17, 1955, the U. S. Fish and Wildlife Service research vessel *Hugh M. Smith* participated in a multiple-vessel oceanographic survey of the eastern tropical Pacific (Eastropic). The results of physical and chemical oceanographic observations made from the *Smith* are described, with emphasis on those observations and results which are of significance to the distribution and abundance of the marine biota.

OCEANOGRAPHY OF THE EAST CENTRAL EQUATORIAL PACIFIC AS OBSERVED DURING EXPEDITION EASTROPIC

By THOMAS S. AUSTIN, *Oceanographer*
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Since early in 1950, the Pacific Oceanic Fishery Investigations (POFI),[1] U. S. Fish and Wildlife Service, has been studying the oceanography of the central equatorial Pacific. These studies have been centered in an area between 140° W. longitude and the 180th meridian and between 12° N. and 10° S latitude. The work has been directed toward determining circulation features and the associated distribution of the marine chemical and physical factors in order to more adequately understand the variations in the distribution and abundance of the biota, especially the yellowfin tuna (*Neothunnus macropterus* Temminck and Schlegel).

The earlier phases of the program were exploratory. As the resulting data were analyzed, the need for specialized studies became evident. One such study involved the east-west variations in the ecology of the northern boundary of the Equatorial Countercurrent; another, an extension of observations along the Equator to the east of 140° W. longitude. These two studies were carried out during a five-vessel, simultaneous survey of the eastern tropical Pacific (Eastropic). The survey extended from 160° W. longitude to the west coast of the Americas and was conducted during the fall and winter of 1955.

Data and descriptions of the circulation features and distribution of the variables in the general area surveyed during expedition Eastropic are available from several sources. These include, in part, the reports of the *Dana* (Thomsen 1937), the *Carnegie* (Sverdrup et al., 1944; Fleming et al., 1945), the *Albatross* (Bruneau et al., 1953), POFI vessels (see Sette et al., 1954; Austin 1957), and unpublished data kindly furnished by the Scripps Institution of Oceanography (SIO) from their operations Shellback and Capricorn.

The currents in the east-central equatorial Pacific are generally zonal (east-west). They include the westerly flowing North Equatorial Current with its southern boundary near 10° N. latitude, the westerly South Equatorial Current with its northern boundary near 5° N. latitude, and the easterly Equatorial Countercurrent in between. Centered about the Equator and beneath the South Equatorial Current is the easterly flowing Equatorial Undercurrent (Cromwell et al., 1954; Fofonoff and Montgomery, 1955).

Five agencies collaborated in expedition Eastropic. Personnel from POFI aboard the research vessel *Hugh M. Smith* (cruise 31) studied east-west variations in conditions along the northern boundary of the Equatorial Countercurrent and along the Equator. Representatives of SIO and the Inter-American Tropical Tuna Commission aboard the Scripps' vessels, the *Spencer F. Baird* and *Horizon*, operated southward from San Diego, Calif., to northern Peru and in the Gulf of Panama. The *B. S. P. Bondy*, assigned by the Peruvian Hydrographic Office, surveyed off the northwest coast of South America in the general area of the Peru Current, and the California Department of Fish and Game vessel, the *N. B. Scofield*, conducted longline fishing in the area studied by the *Horizon* and the *Baird*. The tracks of all the cooperating vessels are shown in figure 1.

The *Smith* departed Honolulu, Hawaii, on September 23, 1955, on a southerly course, crossed the westerly flowing North Equatorial Current and proceeded into the easterly Equatorial Countercurrent. The boundary between the two currents was determined by the variations in the vertical distribution of temperature (ridge in the thermocline at the northern boundary of the Countercurrent) and the change in direction of flow as shown by the geomagnetic electrokinetograph (GEK) until it became inoperative on

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[1] Redesignated Bureau of Commercial Fisheries Biological Laboratory, Honolulu, effective Jan. 1, 1959.

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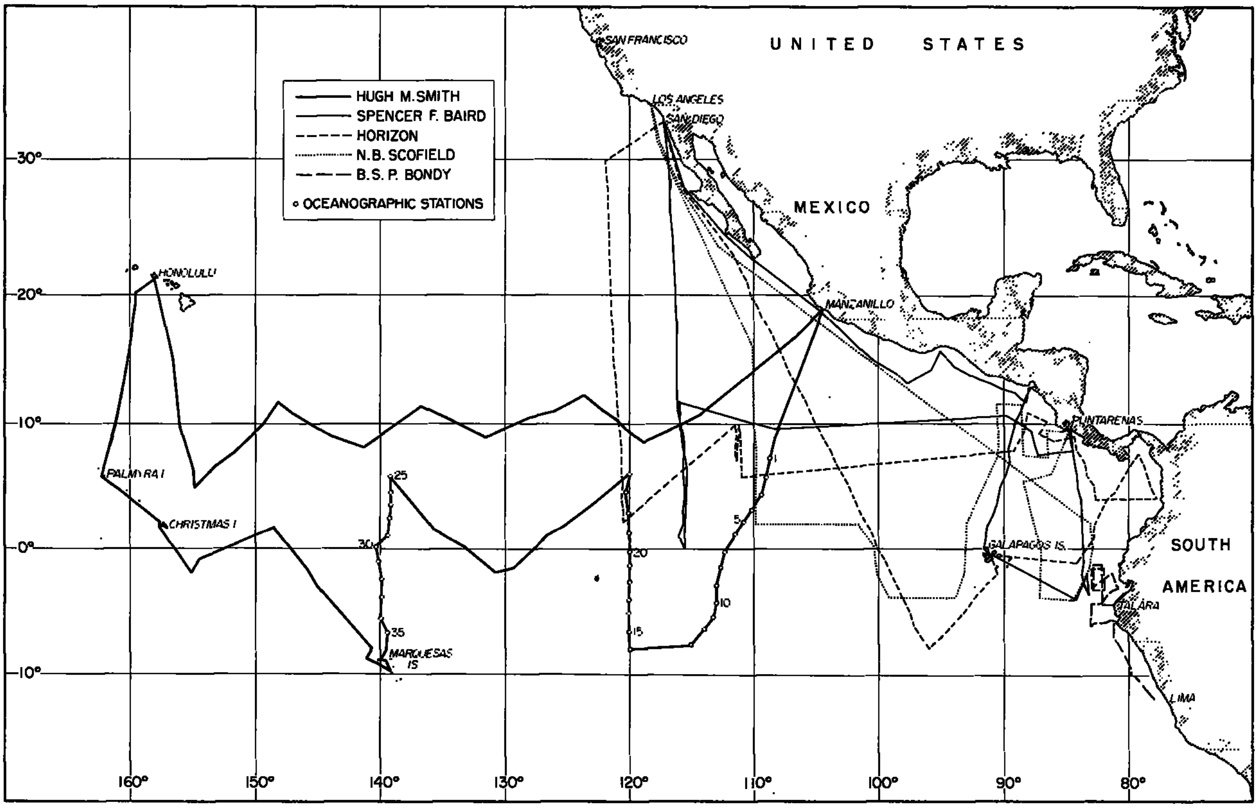

Figure 1.—Track chart of vessels participating in expedition Eastropic. Positions of oceanographic stations shown only for *Hugh M. Smith*.

October 10, 1955. The northern edge of the Countercurrent was followed east to 120° W. During this eastbound leg of the cruise, bathythermograph (BT) lowerings were made at 2-hour intervals and surface samples were collected twice daily for inorganic phosphate and salinity determinations. The vessel then proceeded to Manzanillo, Mexico, for refueling and supplies.

The *Smith* departed Mexico on October 24, 1955, on a generally southwesterly course across the coastal currents, the Countercurrent, and to 8° S. latitude in the South Equatorial Current. The westward passage was planned in order to study the equatorial divergence and the associated oceanographic and biological events. A series of standard oceanographic casts to 1,200 meters was made at approximately 90-mile intervals, between 6° N. and 8° S. latitude near 110° W., along 120° W., and along 140° W. longitude. The northernmost station of the 110° W. leg was in the Countercurrent. The rest of the stations were in the westerly flowing South Equatorial Current. Bathythermograph lowerings were made at each station and at 2-hour intervals between stations. Surface phosphate and salinity samples were taken at frequent intervals.

The data resulting from the observations and collections taken by the *Smith* during expedition Eastropic have been published by King, Austin, and Doty (1957); those from the *Baird* and the *Horizon* by the University of California (1956). Both of these publications include tabulations of the observed data and a description of the sampling and analytical methods used aboard the vessels. The report of King et al. also includes oceanographic station curves, tabulations of the biological data and a description of the methods used in the shore-based processing and analyses.

The purpose of this paper is, primarily, to describe the oceanic circulation features and the associated distribution of variables as determined from the data collected by the *Smith*, particularly those features having significant influence on the distribution and abundance of the biota. Data from other participating vessels and those from previous surveys to the Eastern Central Pacific, both by POFI and other agencies, will be used as needed.

RESULTS OF OCEANOGRAPHIC OBSERVATIONS

We shall, in general, describe the results of the oceanographic program of the *Smith* in the following order: The general circulation, the vertical distribution of variables, their horizontal distribution, and finally, a discussion of the significance of the circulation features to the distribution and abundance of the biota. In each section we shall describe first the conditions in the Countercurrent, then those in the South Equatorial Current; the latter with particular attention to conditions along the Equator.

CIRCULATION FEATURES

As an introduction to the discussions of the observed vertical and horizontal distribution of the oceanographic properties, we shall first describe the general circulation features for the area and period of the *Smith* cruise. The direction of flow normal to the three oceanographic sections (henceforth referred to as 110° W., 120° W., and 140° W.) was determined by means of geostrophic calculations. Inferences as to direction in the region of the Countercurrent and elsewhere in the area where density data were lacking, were made from variations in the temperature-depth distribution. Information on variations in velocity was derived from changes in wire angles between successive Nansen-bottle casts. Frequent references will be made to the results of the GEK measurements made aboard the *Baird* and the *Horizon*.

The geopotential anomalies were computed, with pressure terms neglected, directly from the oceanographic station graphs (see King et al., 1957, fig. 9). The average values of thermosteric anomaly for depth intervals of 100 meters in the deeper layers and 10 meters in the thermocline and mixed layer, were multiplied by the pressure interval in decibars and then were summed upward from the 700-db. level. The 700-db. surface was used as the reference level since the bottom bottle on several stations was down less than 800 meters due to large wire angles.

In figure 2, the heights of the sea surface in dynamic centimeters (as calculated from the stations along 110°, 120°, and 140° W.) have been contoured relative to the 700-db. surface. The configurations of the isopleths for the geopotential anomaly between the three longitudes were drawn from consideration of the temperature-depth data. The inferred direction of flow is shown by the heavy arrows.

The station-to-station variation (meridional slope) of the 0/700-db. surface for each of the three sections is shown in figure 3. The slope, indicative of the speed of westerly flow, is steeper between the Equator and 5° N. on the 110° W. and 120° W. sections being, respectively, 0.28 and 0.42 dynamic meters in 570 km. This is to be compared with 0.07 dynamic meter over the same distance along 140° W. The surface velocities relative to the 700-db. level (as well as the velocities for the remainder of the *Smith* sections) are given in the following table. As the geostrophic approximation is not considered applicable near the Equator, relative velocities between 3° N. and 3° S. have not been calculated.

Latitude	140° W.		120° W.		110° W.	
	Speed (knot)	Direction	Speed (knot)	Direction	Speed (knot)	Direction
7° N–6° N	--------	--------	--------	--------	0.2	E
6° N–5° N	--------	--------	0.4	W	.4	W
5° N–4° N	0.1	W	2.3	W	.7	W
4° N–3° N	.2	W	1.8	W	.8	W
3° S–4° S	.6	W	.2	W	.4	E
4° S–5° S	1.0	W	.8	W	1.1	W
5° S–6° S	.3	W	.7	W	.5	E
6° S–7° S	--------	--------	.3	W	.6	W

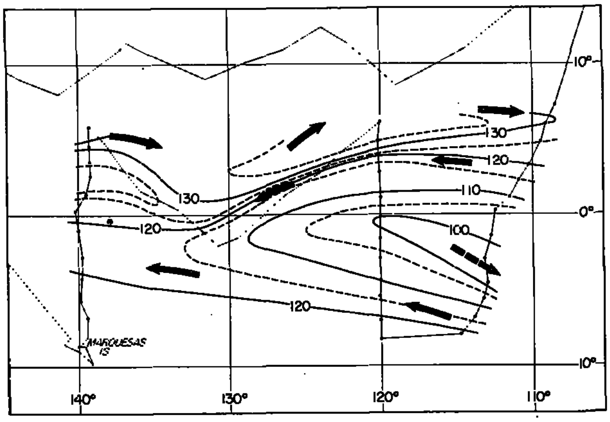

FIGURE 2.—Variations in the geopotential topography, 0/700-db. surface as calculated from Eastropic data. The arrows denote the direction of flow. (Contour interval, 5 dynamic centimeters.)

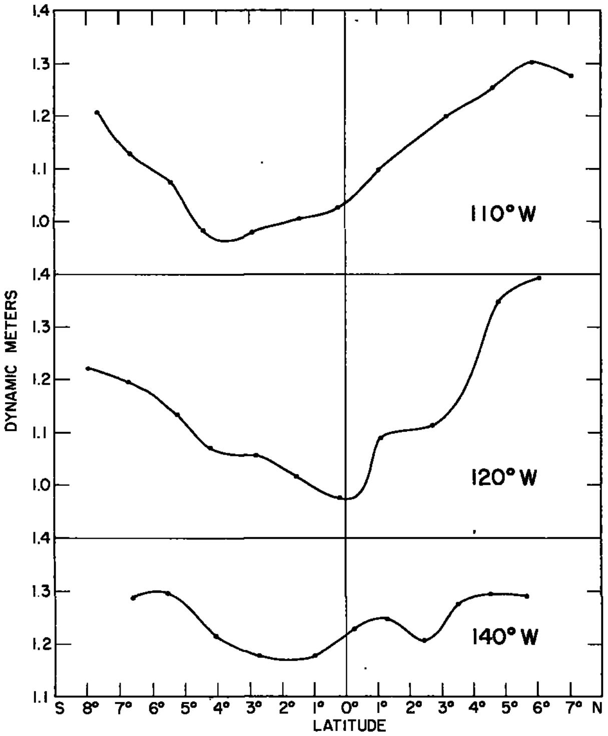

Figure 3.—Station-to-station variations in the geopotential topography (0/700-db. surface) for the *Hugh M. Smith*. 110° W., 120° W., and 140° W. sections.

Unfortunately, the *Smith* was not equipped to make direct measurements of velocities for these transects. Surface currents measured by the GEK aboard the *Horizon* (University of California, 1956), 5°09′ N. to 2°11′ N. latitude, near 120° W. longitude (October 11 and 12, 1955), varied between 0.86 knot (323° T.) at 2°48′ N. and 2.0 knots (324° T.) at 3°08′ N., the latter value being measured near a marked temperature discontinuity (front). The contours in the region of the front (fig. 2), also encountered by the *Smith* (near 4° N., 120° W.), are rather closely spaced reflecting the comparatively swift westerly flow measured by the *Horizon*. The *Baird*, near 115° W. longitude and between the same limits of latitude, observed velocities between 1.1 knots (063° T.) at 5°02′ N. and 5.7 knots (288° T.) at 0°43′ N. As can be seen from table 1, the calculated relative velocities for the *Smith*'s survey did not exceed 2.3 knots (3° N.–4° N. along 120° W.).

Referring to figure 3, the break in slope near the northern limit of the 110° W. section suggests the northernmost station was in the Countercurrent. The lack of a break in slope between the two northernmost stations of the 120° W. and 140° W. sections suggests these sections did not reach into the Countercurrent. In the southeastern portion of the survey area, the geostrophic considerations yield an easterly flow centered about 2° S. latitude (fig. 3, 110° W. section). The trough normally centered at or very near the Equator is, in this instance, positioned at 4° S. latitude.

Indirect evidence of the easterly flow in the surface waters, 1° S. to 4° S., is to be found in the wire-angle data for the Nansen bottle casts. Along the 110° W. section, the angles near to and north of the Equator (to 4°30′ N.) were large, 50° to 60° from the vertical. These large angles were the cumulative effects on the wire of the easterly winds on the vessel, the westerly surface flow and the decrease in velocities at the subsurface levels penetrated by the cast. Between 1° S. and 4° S., with 11- to 15-knot easterly winds, the angles fell to less than 10° (06° at 1°23′ S. and 03° at 2°54′ S.). The easterly surface flow exerted a "canceling effect" on the vessel and the wire angles thus were very small.

On both 110° W. and 120° W., there was an appreciable change in wire angle near the front, with smaller angles to the north of the front (10°) and larger angles to the south (50°). These differences in angle reflect the differences in velocity of the surface waters. The two stations on 120° W. nearest the front were station 22, approximately 90 miles to the south of the front, and station 23, approximately 30 miles to the north of the front. Referring to velocity measurements made aboard the *Horizon* (University of California, 1956), the speed of the surface flow decreased from near 4 knots in waters to the south of the front to 1 knot or less in those to the north. Considering that most of the Nansen bottles and wire were in deeper waters of low velocities, the comparatively swift surface currents south of the front would result in such large wire angles.

VERTICAL DISTRIBUTION OF PROPERTIES

Temperature

Temperature sections along selected longitudes (120° W. to 160° W.), each crossing the main features of the equatorial zonal circulation in the central Pacific, have previously been published in POFI oceanographic and biological reports (i.e., Cromwell 1954; Stroup 1954; Austin, 1954a and

1954b; and Murphy and Shomura, 1953). During Eastropic, no single leg of the *Smith's* track provided data for such a section. Therefore, in figure 4, two BT sections, one near 155° W. from 15° N. to 5° N. and one along 140° W. between 5° N. and 8° S. are used to illustrate the north-south temperature-depth distribution. The 60°, 70°, and 80° F. isotherms were drawn with the 72° and 74° F. isotherms included near the Equator.

From north to south (right to left in fig. 4, A) in the North Equatorial Current, the isotherms slope upward, reaching a minimum depth at the northern boundary of the Countercurrent, then slope downward to the southern boundary of the Countercurrent. This interpretation of the current boundaries is based on the assumption of geostrophic flow. In the next section (fig. 4, B), 140° W., 4° N. to 4° S., both the upward trend of the isotherms toward the Equator and their deepening south of the Equator, compatible with westerly flow, are discernible. Various mixing processes at or near the Equator resulted in the "irregularities" which mask the ridge expected from the distribution of mass when a westerly flow is centered about the Equator.

The mixing of the cooler subsurface waters with those at the surface near the Equator is reflected in the configuration of the 74° F. isotherm, which intersects the surface to the north and to the south of the Equator. A trough in the isotherms centered beneath the Equator is suggested in figure 4, but it is not as evident as generally found in meridional sections crossing the Equator in the central Pacific (Austin 1954b; Wooster and Cromwell, 1958).

The 60° and 70° F. isotherms at the southern limit of the 155° W. section (fig. 4, A) are about 50 meters deeper than those at the northern limit of the 140° W. section. This difference results from the rapid east-west deepening of the thermocline between 125° W. and 160° W. longitude.

To illustrate this deepening, temperature-depth data from BT's taken at eight positions along the Equator, 112° W. to 156° W. longitude, have been contoured in figure 5. Near 155° W., the top of the thermocline is at 150 meters, decreasing in depth to 50 meters near 125° W., then deepening slightly toward the eastern end of the section.

Other features in the temperature-depth distribution of the three meridional sections warrant attention. Of the sections that crossed the Equator (see fig. 1), three were made along courses nearly normal to the Equator. The temperature-depth profile for each of these sections is shown in figure 6, A (110° W.), 6, B (120° W.), and 6, C (140° W.). In all three, the well-developed two-layer system, characteristic of tropical waters, is evident. The principal variation among the three sections is in the depth of the thermocline.

Along the 110° W. section (fig. 6, A), there is a gradual decrease in depth of the thermocline from 5° N. latitude south across the Equator to 4° S. latitude. This suggests that between 0° and 4° S. there is a reversal in flow with the surface waters directed to the east, becoming westerly again south of 4° S. Two centers of cold water at

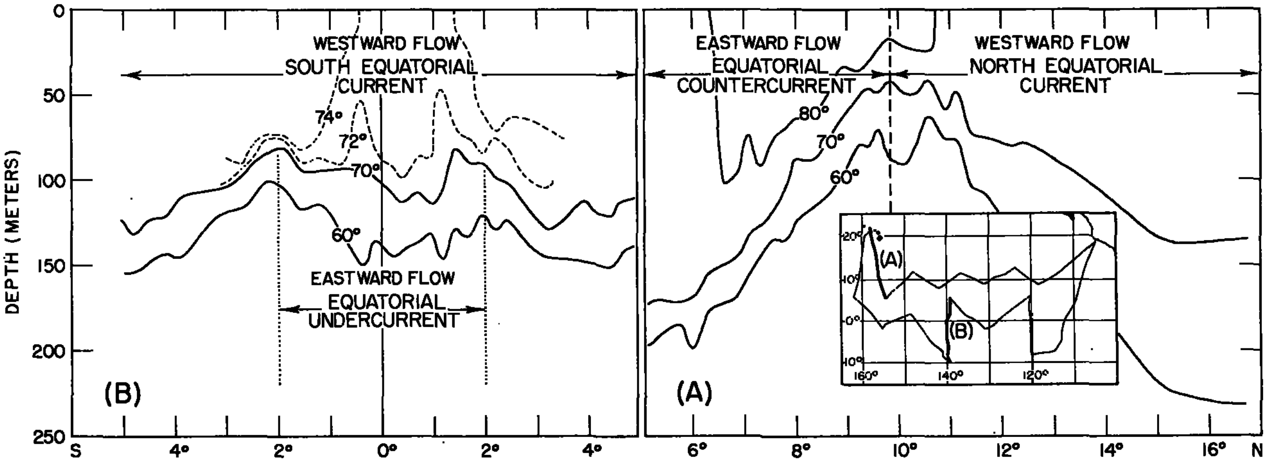

FIGURE 4.—Vertical temperature (°F) section from Eastropic BT records: composite of such records along 140° W. and 155° W. longitude.

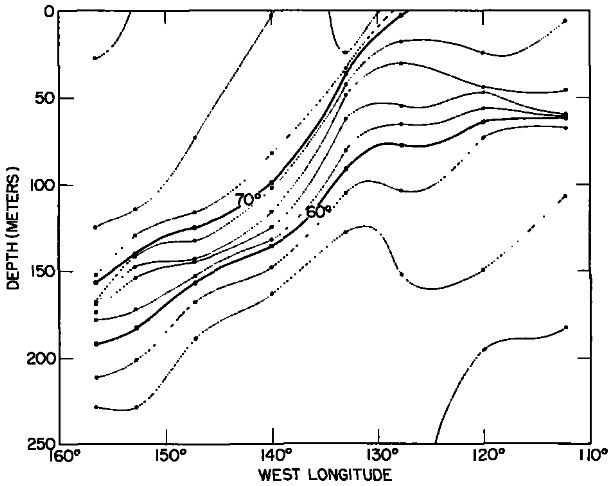

FIGURE 5.—Vertical temperature (° F.) distribution along the Equator illustrating the east-west slope of the thermocline.

the surface are shown. One center near the Equator and similar to that described for the 140° W. section (fig. 4) results from the effects of the wind-induced divergence and upwelling. At the second, near 4° S., the shallow thermocline, coupled with mixing by the wind and by the turbulence at the interface of the opposing easterly and westerly surface currents, results in cooler water at the surface.

The second meridional section, that along 120° W., is shown in figure 6, B. Within the comparatively short span of the section, 6° N. to 8° S., the thermocline approximates a dome with its center positioned at the Equator. Near the northern end of the section, the isotherms show a reversal in slope, decreasing in depth to either side. This trough undoubtedly approximates the position of the southern boundary of the Countercurrent. The domed configuration over the rest of the section reflects the flow of the westerly South Equatorial Current.

Near 4° N. latitude, 120° W. longitude, the isotherms (70° to 76° F.) abruptly descend from the surface. It was near here that the *Smith* crossed a marked front such as that encountered during a previous cruise to this area (Cromwell and Reid, 1956). A temperature-depth section drawn from BT data taken at and within a few miles either side of the front is shown in figure 7. One BT (No. 447), taken with vessel underway at 2 knots, was sufficiently close to the front so that the "up" and "down" traces in the first 20 meters differed by 3° F., and could be used as a reference to locate the position of the other BT records relative to the front. Following Cromwell and Reid (1956, figs. 3 and 4), the waters which were "nearly isothermal" have been shaded in figure 7.

The Scripps vessel, the *Horizon*, observed a similar feature 1 month later near 3° N. latitude, 120° W. longitude (Knauss 1957). Knauss interprets the circulation at the front as "cold water overrunning the less dense warm water and then plunging downward." He describes the feature as a "cold front" with the cold water to the south moving at right angles to the front at speeds in excess of 2 knots.

Along the 140° W. section (fig. 6, C), the decrease in temperature per unit of depth through the thermocline is less than in the previous two sections (110° W. and 120° W.), and the thermocline, 4° N. to 4° S., is 50–75 meters deeper. The influence of the Equatorial Undercurrent on the vertical temperature distribution is suggested between 2° N. and 2° S. latitude. With westerly surface flow along the Equator, a ridge centered near the Equator is expected. North and south of 2° N. and 2° S., respectively, the thermocline shows an upward trend toward the Equator. Between these two latitudes is a trough; i.e., warmer waters at greater depths. This trough may be interpreted as the result of advection of the warmer waters from the west into the lower part of the surface layer and to an unknown depth into the thermocline (Fofonoff and Montgomery, 1955). A similar situation, vertical spreading of the isotherms, may be seen (2° N. to 2° S.) on the 120° W. section (fig. 6, B) and to a lesser degree on the 110° W. section (fig. 6, A). On the latter section, however, is a southerly displacement of the trough, undoubtedly related to the easterly surface flow south of the Equator (1° S. to 4° S.). Further details of the 140° W. vertical temperature section were discussed in connection with figure 4.

Salinity

The most prominent feature in the subsurface distribution of this variable is the tongue of high salinity water south of the Equator at a depth of about 150 meters (fig. 8). In comparing the salinities in this feature on the three sections, there

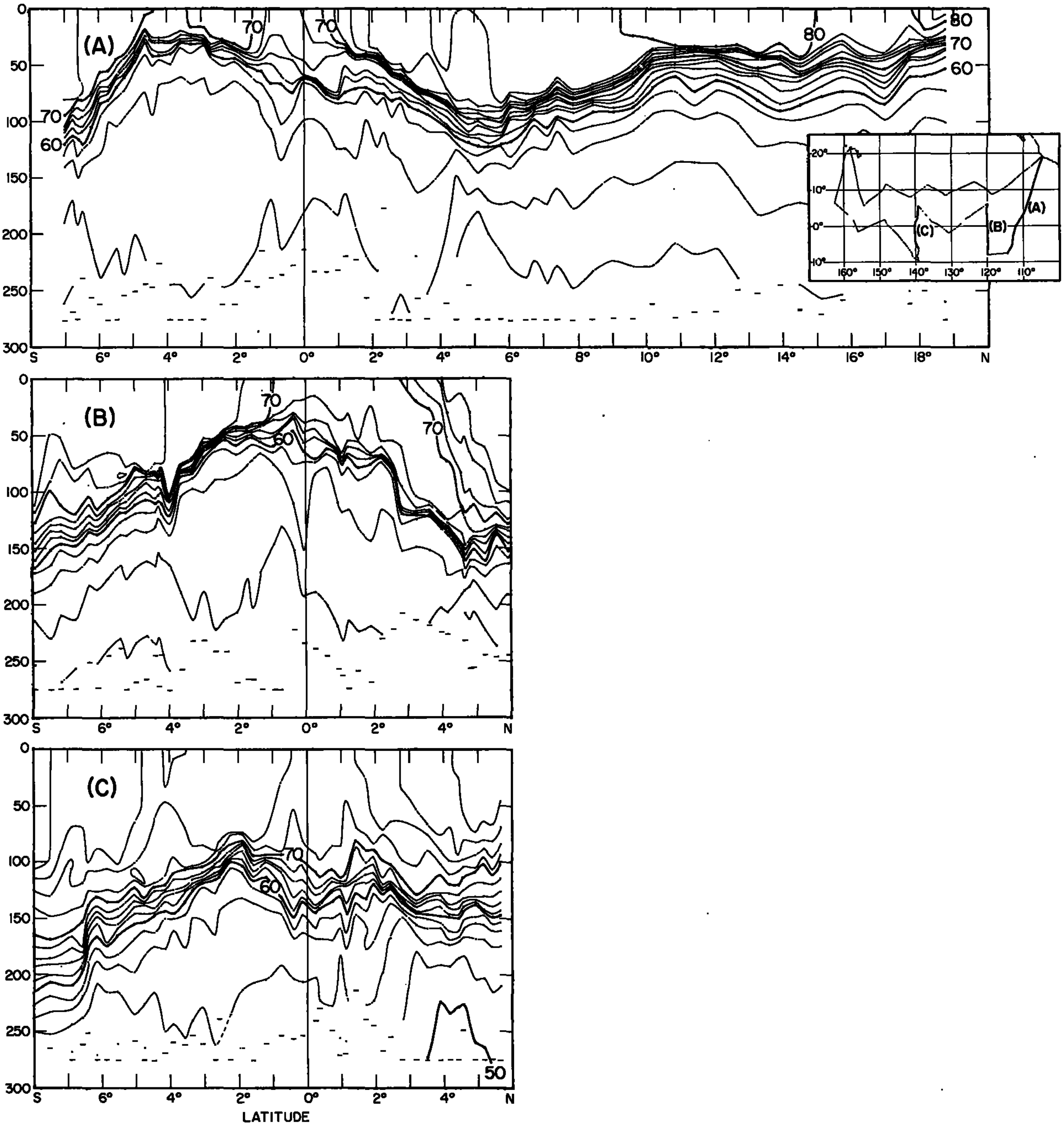

FIGURE 6.—Bathythermograph temperature-depth sections 110° W. longitude (A); 120° W. longitude (B), and 140° W. longitude (C). Contour interval 2° F. (from King et al., 1957).

is a progressive increase, east to west, from 35.30 °/₀₀ to 35.80 °/₀₀ to a maximum of 36.13 °/₀₀. From east to west there is an increasingly apparent northward extension of the tongue.

The source of these higher salinity waters at an intermediate level is a Southern Hemisphere salinity maximum in the surface waters positioned near 20° S., extending east to west between approximately 100° W. and 140° W. (Fleming et al., 1945, fig. 222). In this region of descending flow of air in the atmosphere above the ocean and associated evaporation from the sea surface, more saline waters are formed and sink, moving northwesterly then westerly at subsurface levels. The

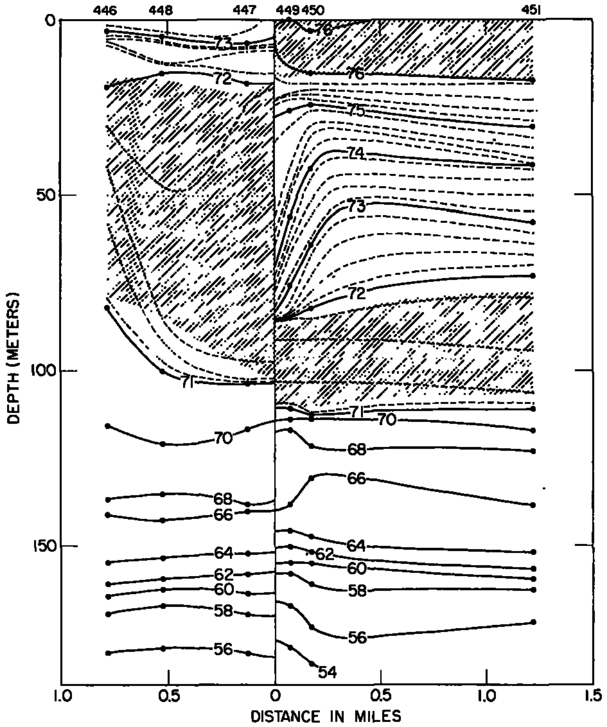

FIGURE 7.—Vertical distribution of temperature (° F.) across the front observed by the *Smith* near 4° N. latitude, 120° W. longitude.

relation between the position of the surface salinity maximum and the subsurface trajectory is reflected in the variations in the feature on the three longitudes (fig. 8); i.e., its northern extent ends abruptly near the Equator in the central and east-central Pacific. This was shown in previous POFI sections by Cromwell (1954), Austin (1954a, 1954b), Stroup (1954), Montgomery (1954), and by Fleming et al. (1945, figs. 119 and 143). Austin (1954b, fig. 21) has shown by the temperature-salinity characteristics that this abrupt termination of the salinity maximum at the Equator in the eastern Pacific is associated with the vertical mixing processes accompanying upwelling. In contrast, in the western Pacific the maximum penetrates into the Northern Hemisphere, reaching at least 5° N. (Mao and Yoshida, 1955). Austin and Rinkel (in press) suggest that this is evidence for less-intensive upwelling in the western Pacific.

Comparison of the temperature/salinity (T/S) characteristics for the Eastropic stations along 110° and 120° W. also reveals the longitudinal variation in the subsurface salinity maximum and the rather abrupt change near the Equator. Along 110° W. (fig. 9, A), the T/S curves south of the Equator all show a rapid subsurface decrease in temperature with small change in salinity. Similar curves for the stations along 120° W. (fig. 9, B) show a configuration for those stations south of the Equator which is attributable to the subsurface maximum. On the T/S curve for the first station north of the Equator (station No. 21), 1°06′ N.; 120° W., the Southern Hemisphere maximum is no longer in evidence.

Returning to figure 8, we note that the waters in the surface layer near the northern limits of the three sections, particularly those along 110° W. and 120° W., are characterized by low salinities. Along 110° W., the salinities in the surface layer are below 34.00 ‰ (a minimum of 33.49 ‰) at the northern two stations (07°06′ N. and 05°52′ N.). Westward along similar latitudes, there is a gradual increase to 34.47 ‰ on the 120° W. section and 34.72 ‰ on 140° W. These low salinities are attributable to dilution by rainfall and influence of waters moving in from the east and northeast. As shown by Schott (1935), a ridge of mean maximum rainfall is centered along 10° N., becoming increasingly prominent to the east and reaching a maximum in the Gulf of Panama. East of the *Smith*'s survey area, as revealed by the *Carnegie* data (Fleming et al., 1945, fig. 222) and by data taken aboard the Scripps Institution of Oceanography vessels during Eastropic (University of California, 1956), the salinities in the surface waters progressively decrease, reaching minimal values of 29.50 ‰ to 30.00 ‰ in the Gulf of Panama (3°–6° N. latitude).

In the deeper waters sampled during expedition Eastropic, at 500–1,000 meters, the salinities were those characteristic of the Antarctic intermediate waters with the axis of the lowest values rising toward the north on each section (King et al., 1957, figs. 11, 16, and 21).

Density

The vertical distribution of density along each of the three sections, expressed as thermosteric anomaly in centiliters per ton (following Montgomery and Wooster, 1954), is shown in figure 10. The most striking feature on each of the three sections is the rapid increase in density with depth (which we shall refer to as the stable layer)

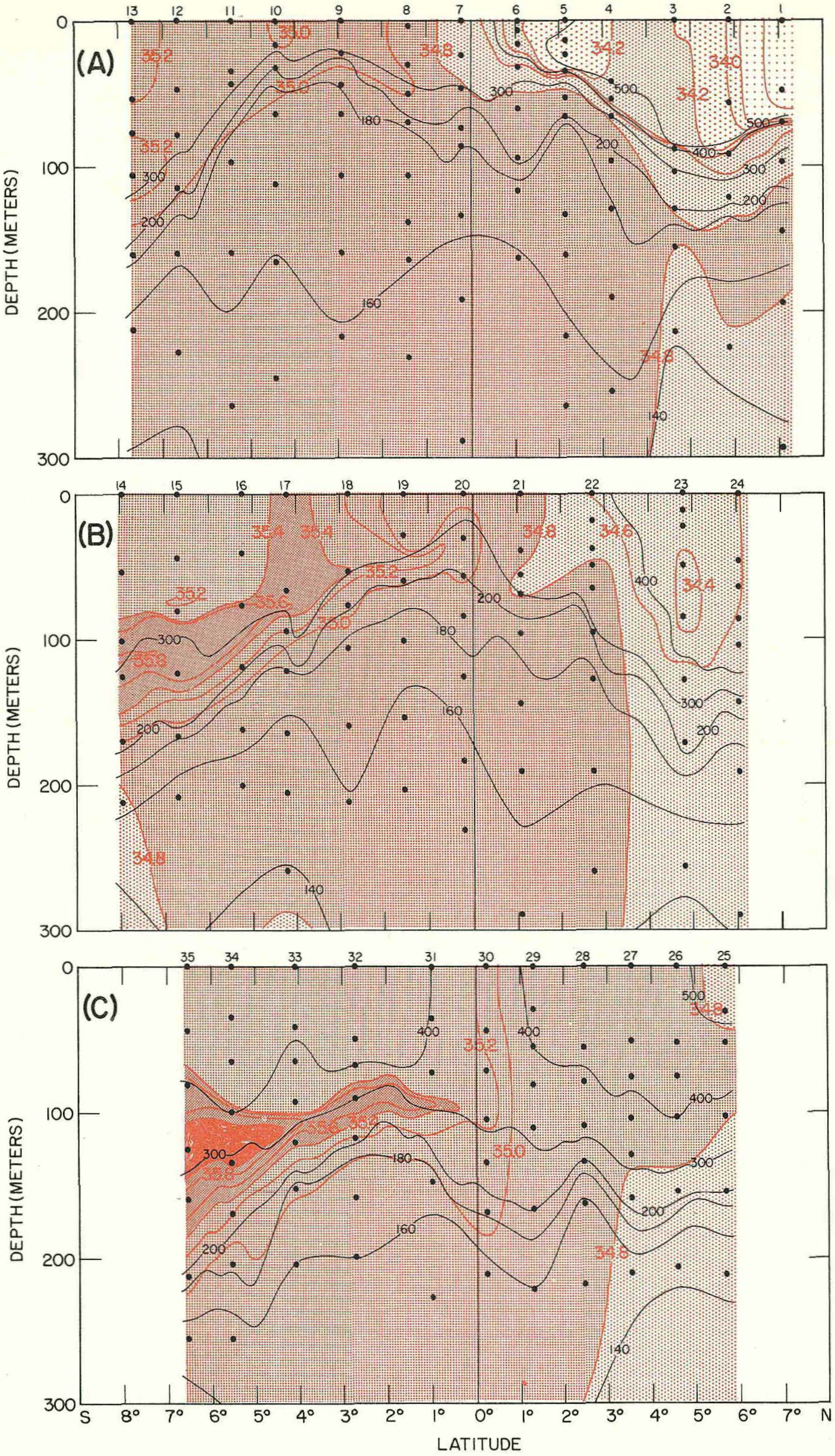

FIGURE 8.—Vertical distribution of salinity (°/₀₀) along 110° W. (A), 120° W. (B), and 140° W. (C). Contour interval 0.2 °/₀₀ (from King et al., 1957). Density isopleths in black (in centiliters per ton). Depths of observations are shown by dots; station numbers are given along the top of each panel.

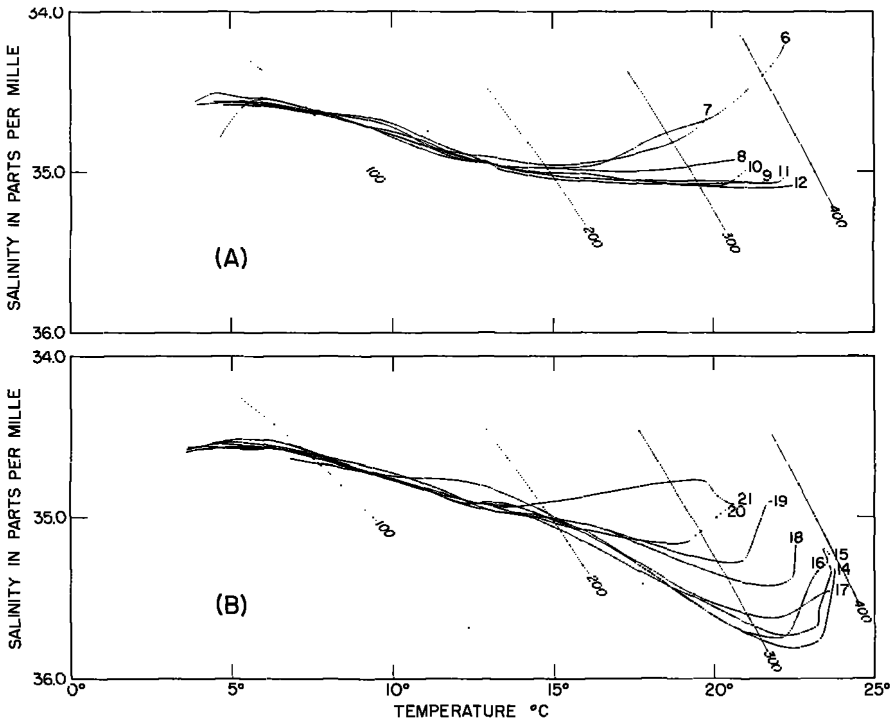

FIGURE 9.—Temperature (° C.)-salinity (°/oo) curves at selected stations, Southern Hemisphere along 110° W. (A), 120° W. (B). Density (oblique lines) in centiliters per ton.

through the thermocline. Although variations in salinity, as well as temperature, affect the vertical distribution of density of sea water, in tropical waters salinity usually plays a minor role. To illustrate: from east to west (particularly between the 120° W. and the 140° W. sections) there is a general increase in depth of both the thermocline and the stable layer. There is a trough in each at the southern boundary of the Countercurrent and a marked ridge near the Equator on 140° and 120° W., and near 4° S. on 110° W. The change in temperature and density across the front is reflected in the "bunching" of the density isopleths at their intersection with the surface near 4° N. on 120° W. and 1° N. on 110° W.

Oxygen

The vertical distribution of oxygen is shown in figure 11. Selected isopleths for δ_t are shown on each section. On the four longitudes, the oxygen content in the surface layers, surface to the top of the thermocline, was uniformly high, 4.0 to 5.5 ml./L., decreasing through the thermocline to the oxygen minimum, then increasing to maximum depths sampled. Near 100° W. and 110° W., the minimum with values of less than 0.5 ml./L. was continuous from the Southern to the Northern Hemisphere. Along the 120° W. and 140° W. sections, values less than 0.5 ml./L. were observed only in the Southern Hemisphere. On each section a narrow, vertical tongue of water with higher oxygen content was centered beneath the surface waters at the Equator.

The low oxygen values in the minimum south of the Equator (300–500 meters) are in waters which have moved westerly from the coast of Peru and, at least in part, result from the consumption of oxygen at subsurface depths by decomposition of the organic material which was in these waters when they departed from the surface and of the organic detritus sinking from the euphotic zone.

North of the Equator in the eastern Pacific is a large subsurface body of water within which the oxygen content is low (0.1 ml./L. or less). As described by Sverdrup et al. (1942, p. 729), this body of water is found off the American coast between 28° N. and the Equator, extending to the west as far as 140° W. More recent data (Cromwell 1951) bring this westward extension to at least 172° W. The lowest oxygen concentrations,

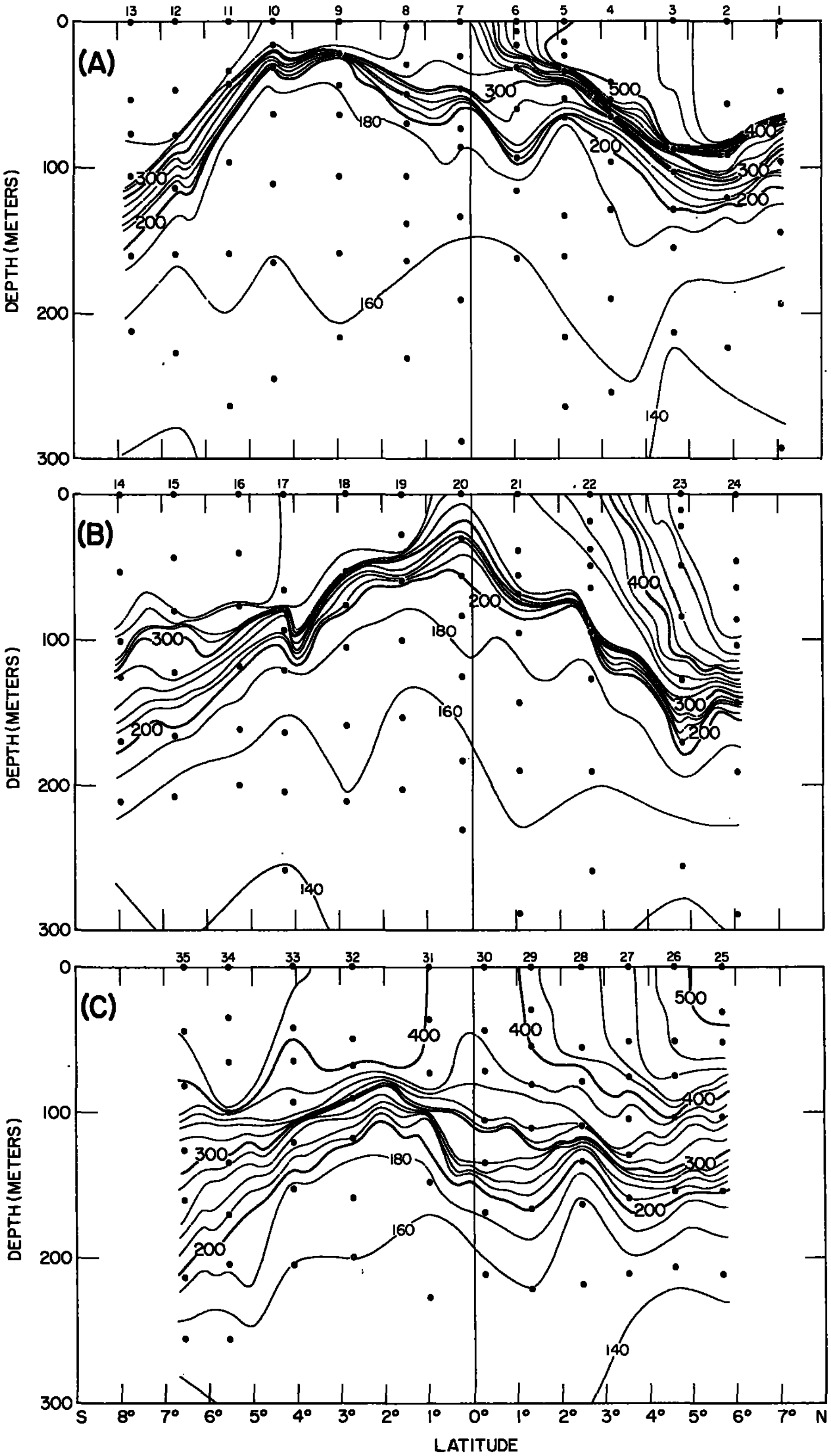

FIGURE 10.—Vertical distribution of density expressed as thermosteric anomaly along 110° W. (A), 120° W. (B), and 140° W. (C). Contour interval 20 centiliters per ton (from King et al., 1957). Depths of observations are shown by solid dots; station numbers are given along the top of each panel.

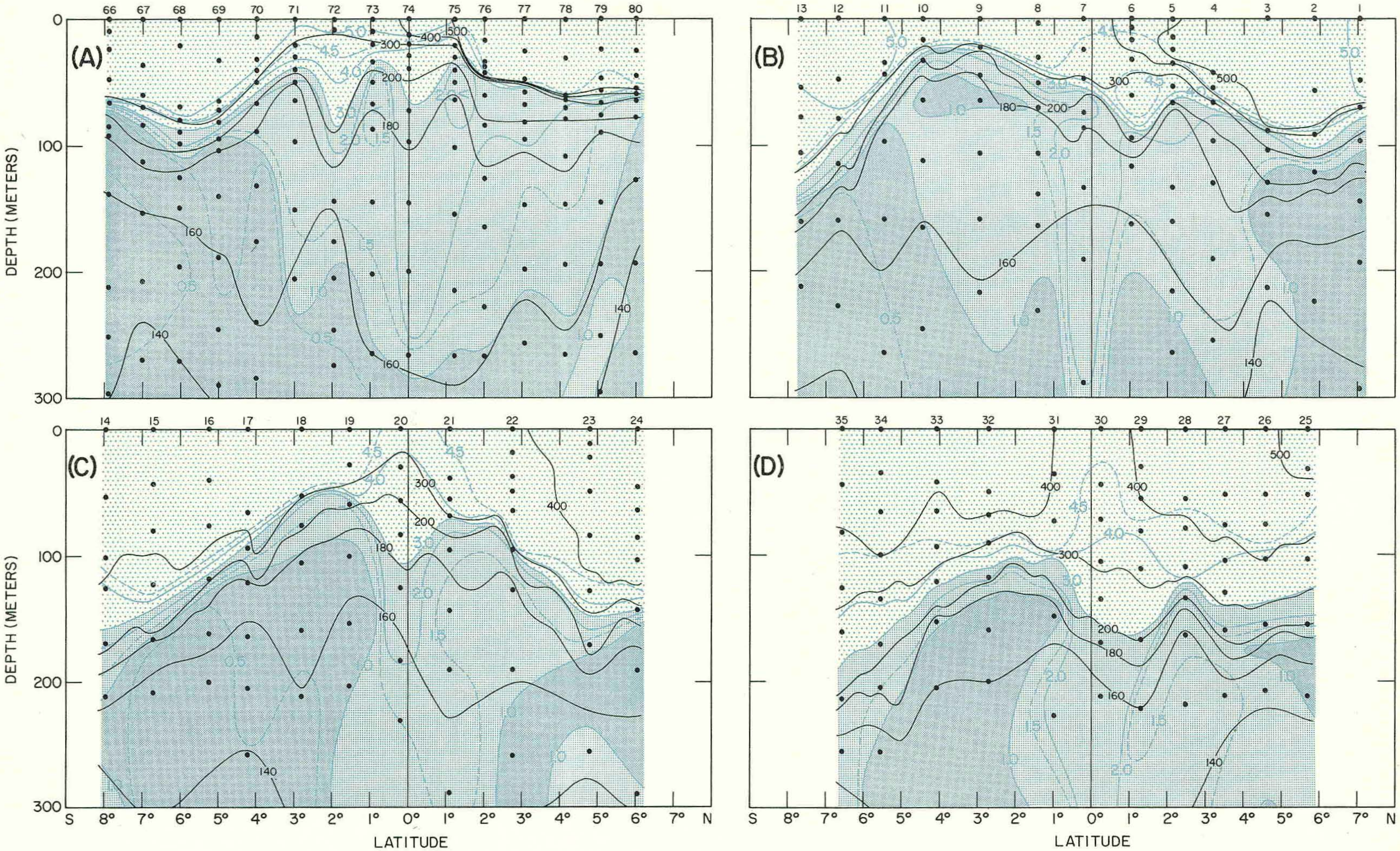

FIGURE 11.—Vertical distribution of oxygen expressed in milliliters per liter (ml./L.) along sections near 100° W. (A), 110° W. (B), 120° W. (C), and 140° W. (D). Contour interval 0.5 ml./L. (data for A from University of California, 1956; B, C, and D modified from King et al., 1957). Depths of observations are shown by dots; station numbers are given along the top of each panel.

without separating the double minima, have been contoured in figure 12. Values equal to or below 0.1 ml./L. have been shaded. The values in the minimum near the Equator are somewhat higher than those to the north or to the south.

Phosphate

The Automatic Servo-Operated Photometer used for the determination of inorganic phosphate broke down at station 8 along the 110° W. leg. Subsequently, samples were frozen from selected depths at the remainder of the stations along this leg, and at less frequent depth intervals (surface to 200 m.) along 120° W. The meridional sections resulting from these data are shown in figure 13.

Along 110° W., the phosphate concentrations in the mixed layer were low (0.4 µg. at./L. or less) between the northern limit of the section (7° N.) and about 2° N. The values progressively increased to a maximum of slightly more than 1.0 µg. at./L. at about 3° S., then decreased to less than 1.0 from 5° S. to the southern limit of the section (8° S.). Values in the mixed layer were also low (0.4 µg. at./L. or less) at the northern stations of the 120° W. section, but increased suddenly (0.4 to 1.0 µg. at./L.) upon crossing the front near 4° N. The highest values in the surface waters were near the Equator (1.2 µg. at./L.), decreasing to less than 1.0 µg. at./L. near 1° S. and remaining less than this value to 8° S.

Comparison of the phosphate concentrations in the mixed layer of the two sections reveals the association of this nonconservative property with the previously discussed vertical distribution of density (the thermocline) and zonal flow. In the northern portions of the sections, the low phosphate concentrations are in the impoverished waters of the Countercurrent. Near the Equator on 110° W., some enrichment results from upwelling, but the highest values on this section, near 4° N., result from the very shallow thermocline and wind "plowing" (Sverdrup 1952) into the deeper, nutrient-rich waters. Near the Equator on 120° W., the surface enrichment probably results primarily from upwelling. The northern transport of these waters is reflected in the higher phosphate values, from the Equator north to the latitude of the front.

HORIZONTAL DISTRIBUTION OF PROPERTIES

Although this section will deal primarily with the surface distribution of temperature, salinity, and phosphate, we shall, as necessary, include concurrent consideration of the vertical distribution of the property in question. The direction of the flow, as determined by geostrophic calculations (see fig. 2) has been reproduced on the charts.

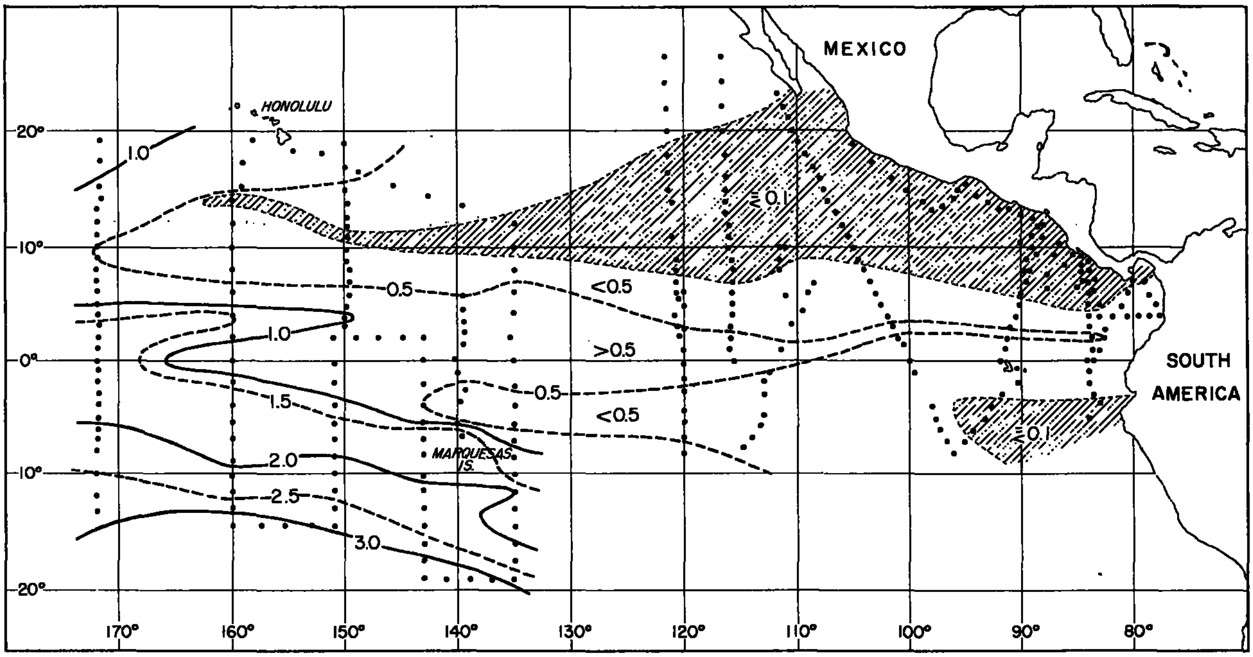

FIGURE 12.—Concentrations in the oxygen minimum. (Data from POFI and Scripps cruises.)

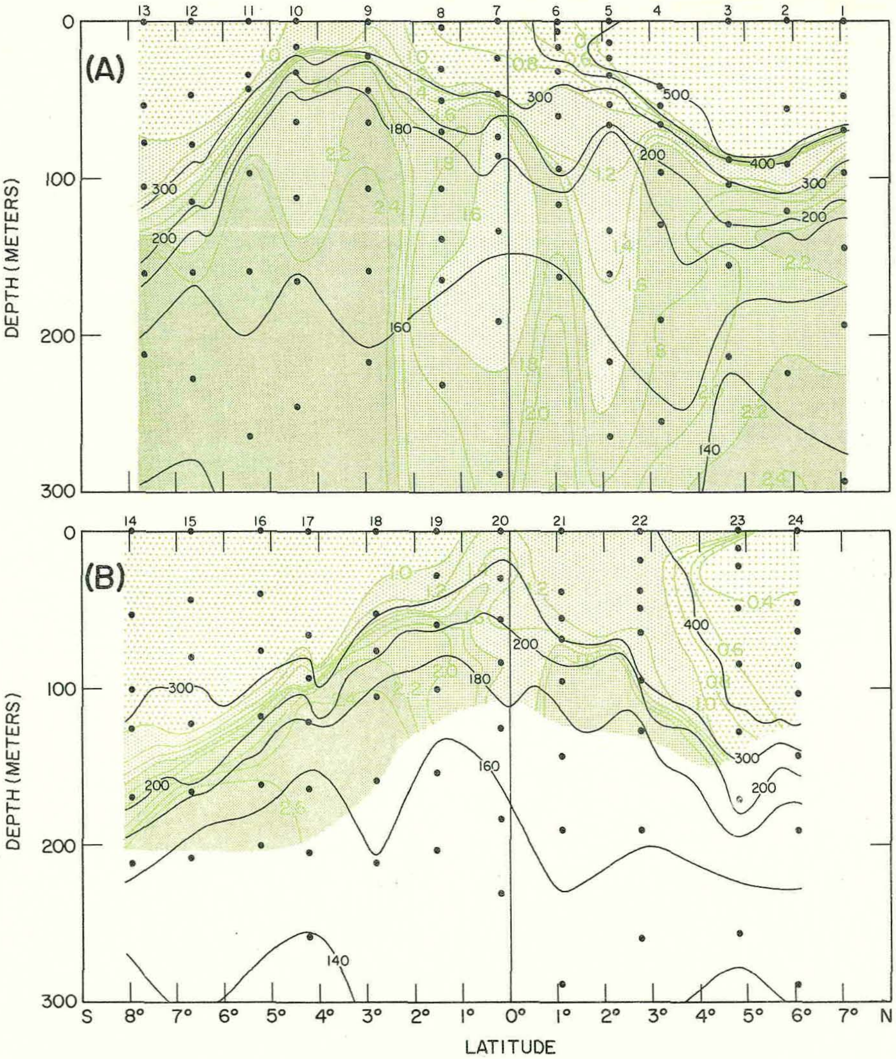

FIGURE 13.—Vertical distribution of phosphate expressed in microgram-atoms per liter (μg. at./L.) along sections near 110° W. (A) and 120° W. (B). Contour interval 0.2 μg. at./L. (from King et al., 1957). Depths of observations are shown by dots; station numbers are given along the top of each panel.

Surface Temperature

The surface temperatures, as measured in the bucket samples taken at each BT lowering (generally at 2-hour intervals, 15 to 20 miles apart) are shown by the black contours in figure 14. Mean surface temperature distribution for the month of November, as published in an atlas prepared by the British Air Ministry (1950), is shown by the red contours.

In the Countercurrent (5° N. to 10° N. latitude) there is general agreement between the Eastropic surface temperatures and the mean. Over most of the area the 80° F. isotherms in each case straddle the somewhat warmer waters in the center of the current, but swing northerly from the latitude of the axis in the eastern part of the survey area. This northerly shift in position of the isotherms reflects the influence of the warmer waters moving to the west away from the coast of Central America. A similar configuration of the surface isotherms is evident in the report by Jerlov (1956, fig. 3) describing the results of the Swedish *Albatross* expedition to the same area and during the same months (October–November 1948).

The distribution of surface temperatures (also salinity and phosphate) suggests that there was a southerly bulge in the Countercurrent centered

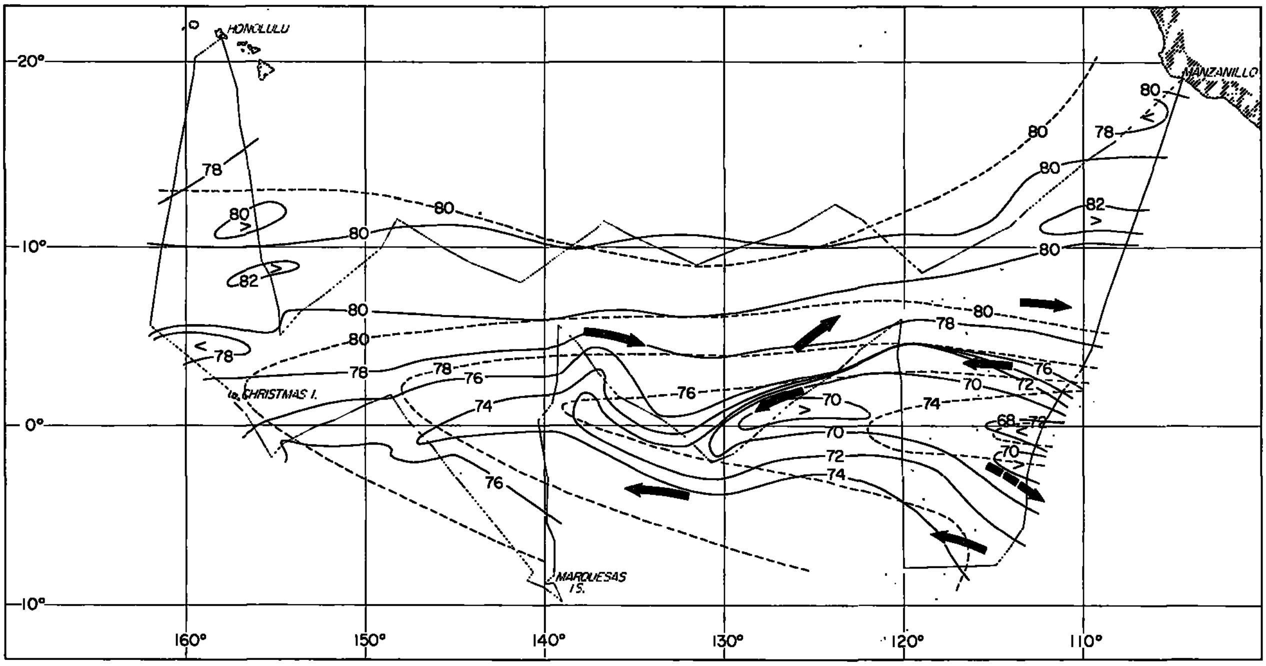

FIGURE 14.—Surface temperature (° F.) distribution from temperatures of bucket samples taken at position of BT lowerings in black; mean temperatures from British Air Ministry Atlas (1950) in red. The arrows denote current direction as determined from geostrophic calculations.

near 132° W. longitude. Although this feature appears to be real, there is the possibility that it is an artifact resulting from the V-shape of the vessel track in this area. There is an acceptable comparability, however, in the shape of the contours defining the bulge among all the surface variables measured. Similar variations were reported by Cromwell (1956, p. 29) during expedition Eastropic.

The cooler surface temperatures in the South Equatorial Current, particularly along the Equator, are strikingly evident. In fact, those observed near the Equator during the period of Eastropic were from 2° to 4° F. cooler than the mean. At any point along the Equator, these cooler waters reflect both the mixing of the deeper waters with those at the surface and, in varying degrees, advection from the east. The mixing involves at least two separate physical processes, one related to the divergence of the surface waters under the influence of winds with an easterly component, the other, mixing by the wind which is more effective in the east because of the west-to-east shoaling of the thermocline. At present, quantitative estimates of the relative roles of each of these two processes are not available.

The oceanic front described in earlier sections was evident near 4° N. latitude on 120° W. longitude, across which there was an abrupt change in surface temperature of nearly 4° F. (fig. 14). This circulation feature was discernible in varying degrees near 4° N., 135° W. and 2° N., 112° W. That it may be a semipermanent feature in this region of the Pacific is evidenced by the fact that during expedition Eastropic the Scripps vessel, the *Horizon*, observed it 1 month later than did the *Smith* (Knauss 1957), and a similar feature was previously detected by the *Smith* near 1° N., 120° W. on October 27, 1952 (Cromwell and Reid, 1956). However, a front was not detected by the *Albatross* during October–November 1947 when she crossed the Equator at 137° W. (Jerlov 1956, p. 150), nor by the *Baird* which was working during expedition Eastropic only 300 miles to the east of the *Horizon* (Knauss 1957).

Depth of Thermocline

From the preceding discussion of the distribution of temperature, it is evident that there was considerable variation in depth of the thermocline throughout the area surveyed by the *Smith*. The thermocline depths, as read from the BT slides, have been plotted and contoured in figure 15.

On and near the Equator an objective determination of the thermocline depth is generally difficult since in this region there often is either more than one inflection of the curve or a continuous negative gradient from the surface to the maximum depth of the BT trace (fig. 16). In both figures 15 and 16 this region has been indicated by shading, and the contours in figure 15 have been terminated at their points of intersection with the northern and southern boundaries of this region. This was done because there is a question as to whether or not the two well-defined thermoclines, one south of the Equator and one to the north, are the result of the same physical processes.

Certain inferences to the circulation features may be drawn from the spacing and configuration of the contours in figure 15. The northern boundary of the Countercurrent was coincident with the ridge near 10° N. (<100 ft.) and the southern boundary was centered along the trough in the thermocline depth near 5° N. latitude. In the southeastern portion of the area, a second ridge is evident at about 4° S. latitude. This reflects the distribution of mass associated with easterly flow there (see the results of the geostrophic calculations in fig. 3).

Surface Salinity

The lowest surface salinity values (fig. 17) were measured along the northern boundary of the Countercurrent, with the minimal value (33.6 °/₀₀) being near 10° N., 128° W. This distribution reflects the extension of low salinity water westward from the coast of Central America and is also coincident with the zonal band of high rainfall located near 10° N. (Schott 1935, plate XIX).

As the *Smith* proceeded south across the Countercurrent and into the South Equatorial Current, surface salinity generally increased, reaching the maximum observed values at the southern extremities of the *Smith's* tracks. Somewhat farther south (near 20° S. latitude) was the southeastern Pacific salinity maximum, with surface values of 36.00 °/₀₀ or greater (Sverdrup et al., 1942, chart VI).

Near the front, the configuration of the isohalines showed an abrupt discontinuity in salinity, with higher salinity water, reaching 34.9 °/₀₀, on the northern side of the front and surface waters with lower salinity, 34.2 to 34.4 °/₀₀, to the south

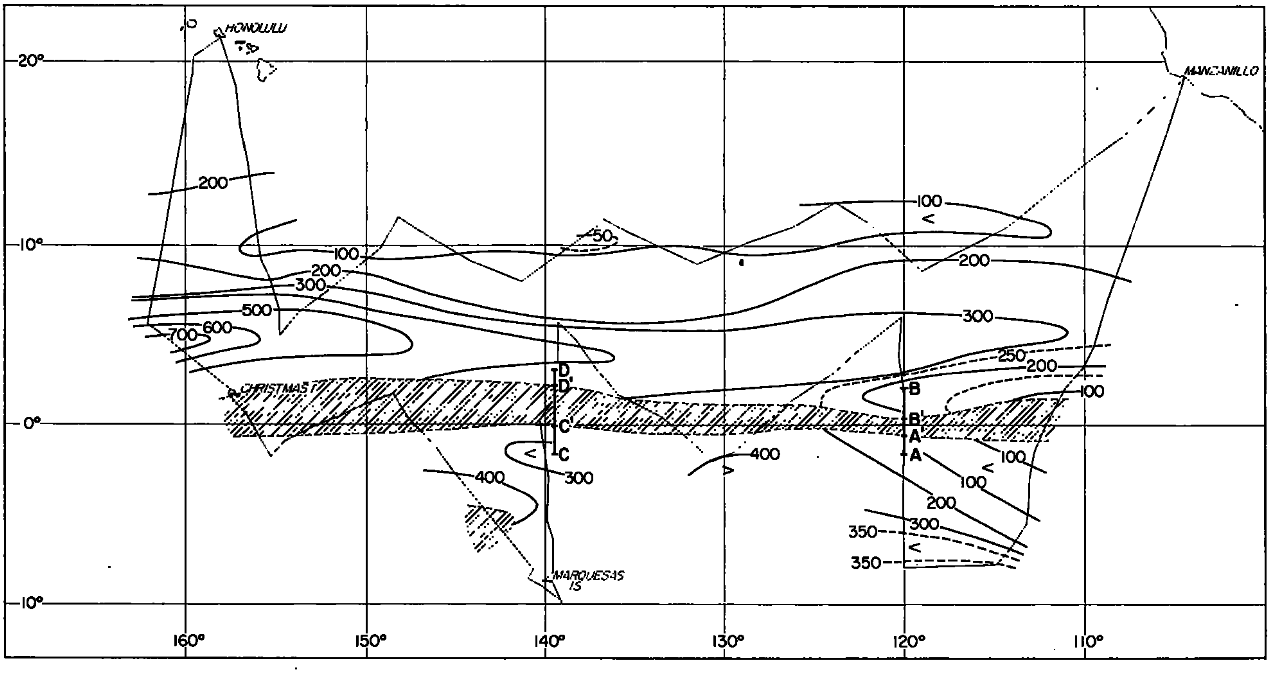

FIGURE 15.—Depth of the thermocline as determined from the BT data. (For explanation of shaded section, see text above.)

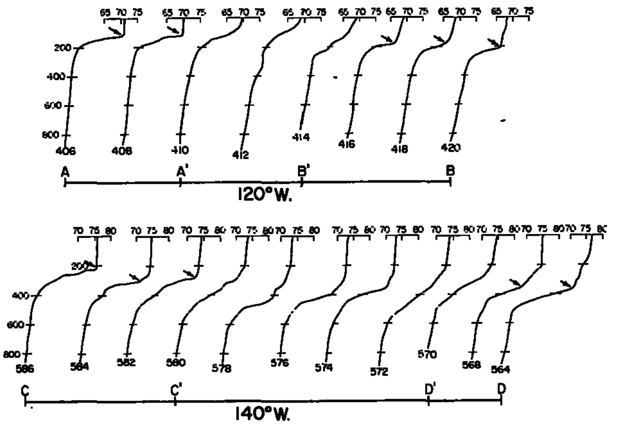

FIGURE 16.—Temperature-depth traces for selected BT records between A–B and C–D, figure 15. Arrows denote the thermocline depth as plotted in figure 15; the BT number is noted at bottom of each trace.

of the frontal line. Knauss (1957, table 1) reported a somewhat dissimilar situation, with higher salinities in the cooler surface waters to the south of the front (34.49 to 34.54) and a lower salinity to the north (34.46).

Phosphate

The concentration of inorganic phosphate (PO_4-P) in the surface waters was determined at frequent intervals during the cruise. The results are shown in figure 18.

In the surface waters of the Countercurrent, the supply of this nutrient was relatively low. These are "old" waters in the classification of Steemann Nielsen (1954)—they have been at the surface for a considerable period of time as they have moved from the west in a current in which stabilization is markedly developed and vertical mixing is limited. East of 140° W., the surface values are below 0.5 μg. at./L., a level regarded by Ketchum (1939) as limiting photosynthesis. These relatively low values (0.3 to 0.4 μg. at./L.) in the surface waters represent the balance in the mixed layer among utilization by the phytoplankton, biological regenerative processes, and vertical diffusion.

In the South Equatorial Current, the phosphate concentrations generally peak at or near the Equator with values of 1.0 μg. at./L. or more. The concentrations decrease rapidly to the north and south, and more gradually east to west. Along 110° W. the highest concentration of phosphate was south of the Equator, peaking at about 4° S. This results from the proximity of the thermocline to the surface and wind mixing discussed in the section on surface temperature. The con-

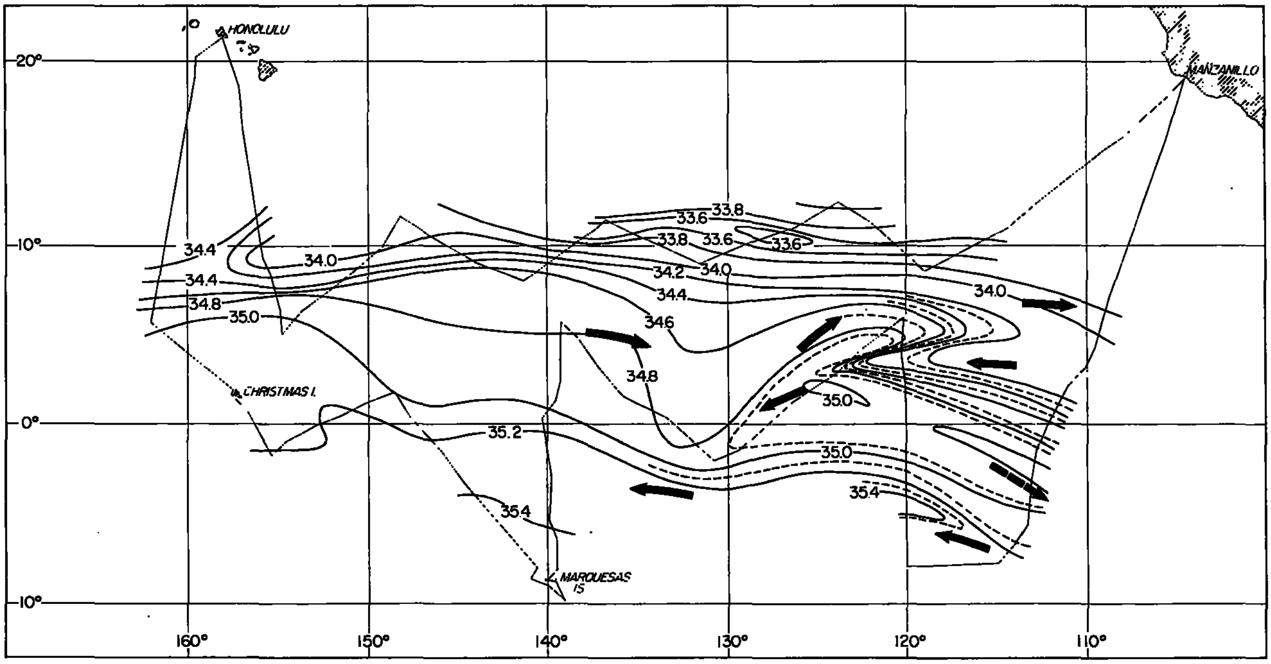

FIGURE 17.—Surface salinity (°/$_{oo}$) distribution. The arrows denote current direction as determined from geostrophic calculations.

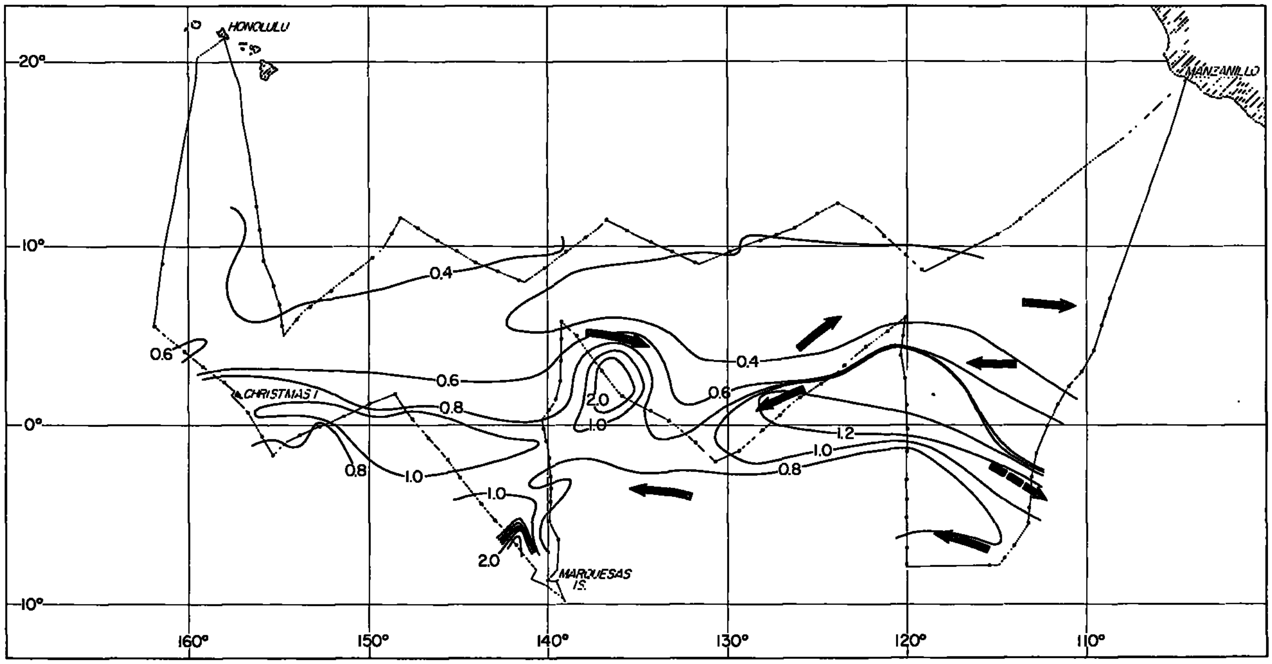

FIGURE 18.—Distribution of inorganic phosphate (μg. at./L.) in surface waters. Surface samples were taken at the position of the oceanographic stations and at the time of the BT lowerings. The positions at which the samples were taken are indicated. The arrows denote current direction as determined from geostrophic calculations.

centrations of 1.0 to 2.0 μg. at./L. near 137° W. and 3° N. are difficult to explain. Unfortunately, there are no subsurface phosphates available for analysis of vertical transport, and no indications of such in the temperature fields. There are no apparent indications of analytical error. More than one sample is involved and the high values are consistent among these samples. One explanation is that these waters reached the surface near the Equator and moved to the position where sampled from the *Smith*. A similar situation was described by Sette et al. (1954) near 3° N. and 165° W. The high value near the Marquesas, 7° S., 142° W., may have resulted from some as yet undetermined circulation feature(s) associated with the islands. Similar concentrations in this area were observed during the recent participation of the *Smith* in Equapac (Austin 1957).

DISCUSSION OF RESULTS

Eastropic was a combined physical and biological study of the eastern central equatorial Pacific. The results of POFI's oceanographic observations have been described in the preceding sections of this report. The results of the biological sampling program will be considered in relation to these environmental features. Before this can be done we must consider the question, "How typical were the environmental factors?" It appears that the oceanographic conditions were somewhat atypical.

The surface temperatures along the Equator (fig. 14) were 2°–4° F. cooler than normal; those in the Countercurrent showed little variation from normal. Waters were also cooler than normal at four stations in the eastern Pacific (fig. 19) one each off California, Panama, Peru, and Christmas Island (Line Islands group). Rodewald (1956) demonstrates that these below-normal surface temperatures were typical for the entire eastern Pacific during 1955, particularly the latter half of the year. North to south, he reports anomalies in 1955 of −0.9° F. for Alaskan waters, −1.7° F. for Washington and Oregon, −1.2° F. for California, and −0.6° F. for Chile and Peru. These temperatures and the cooler water observed by the *Smith* in the South Equatorial Current may be considered to be "eastern Pacific temperatures," while the normal temperatures in the easterly flowing Countercurrent more or less reflect conditions farther to the west. In the western Pacific near the Philippines, the anomaly in 1955 was +0.2° F., exceeding +1° F. for August through November.

The comparatively high measured and calculated speeds of surface flow in the South Equatorial Current, as well as the cooler than normal waters at the surface in the eastern Pacific, suggest that the circulation during expedition Eastropic was more vigorous than normally observed. If such was the case, this should be reflected in the distribution of mass.

Montgomery and Palmén (1940), using data from one station near 99°07′ W. and the mean of three near 135° E., calculated the mean slope of the sea surface (0/400 db. reference level) to be 4.0×10^{-8}, with a difference in level of 0.7 dynamic meter. In figure 20, using data from more recent cruises, the longitudinal variations in level of the sea surface over the 400-db. level are shown for the span between 100° W. and 140° E. longitude. Data from stations between 00°30′ N. and 00°30′ S. were used. The 400-db. level was chosen in order to increase the number of available stations. The slope from Montgomery and Palmén's report is also shown.

Of particular interest to this discussion is the slope between 100° W. and 140° W. For comparative purposes, the data from *Smith* cruise 35 (August–October 1956) and cruise 38 (January–March 1957) have been added. It may be seen that the slope during Eastropic was steeper than that for either of these two cruises or for the mean. Comparative values, 120° W. to 140° W., are: mean, 4.5×10^{-8}; *Smith* cruise 38, 5.3×10^{-8}; and Eastropic, 13.1×10^{-8}. A reversal in the calculated slope of the sea surface during Eastropic is evident near 120° W. (fig. 20). This reversal results from the deepening of the thermocline east of 130°–120° W. (see fig. 5) and the accompanying increase in depth of the warmer, less-saline, and thus less-dense waters of the mixed layer.

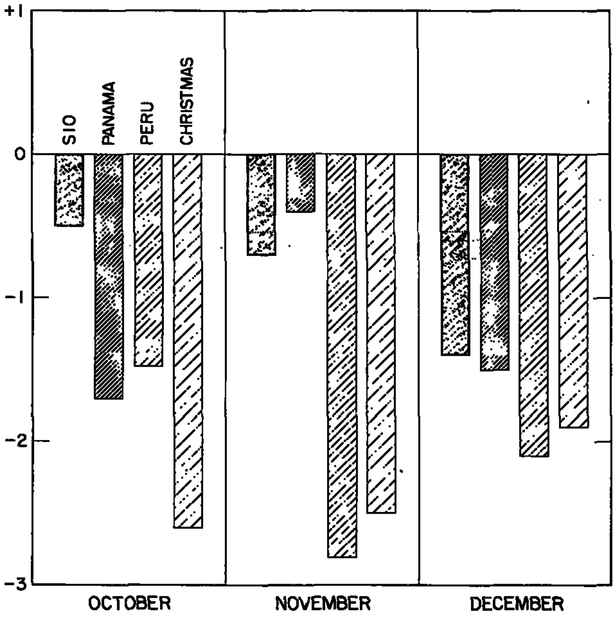

FIGURE 19.—Surface temperature anomalies (° F.) for four stations in the eastern Pacific for October, November, and December, 1955.

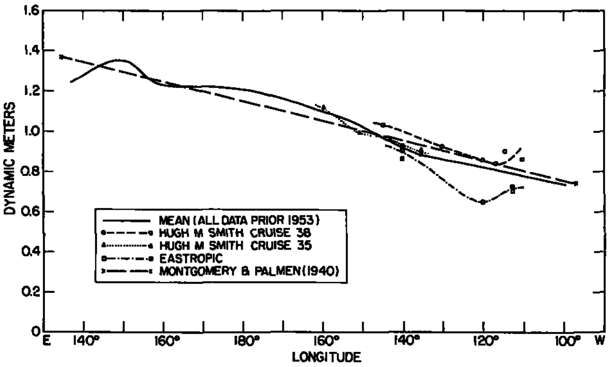

FIGURE 20.—Longitudinal slope, sea surface, 0/400 db. level.

The same features and conclusions can be inferred from the distribution of the depth of the 70° F. isotherm along the Equator (fig. 21). This isotherm is normally found near the center of the depth range of the thermocline (Austin 1954a), and thus exhibits the same variations in depth as the thermocline.

In figure 21, prepared from all available BT data from POFI files and those furnished by Scripps Institution of Oceanography, between 2° N. to 2° S., the variations in depth of the 70° F.

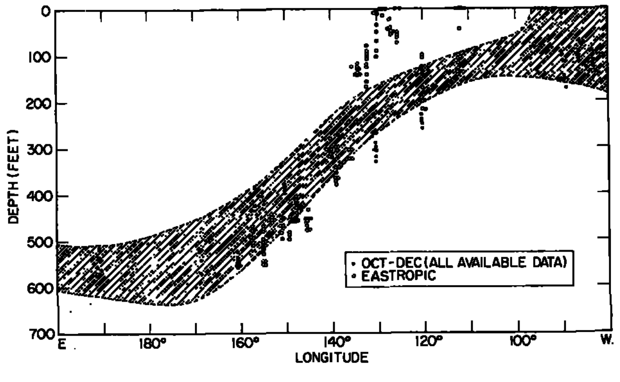

FIGURE 21.—Depth of 70° F. isotherm, 2° N. to 2° S.

isotherm, 80° W. to the 180th meridian are shown. The hatched "envelope" shows the approximate range of variation in depth among these data. Part of this variation results from seasonal fluctuations in the depth of the thermocline (Austin 1958), and part from the ridgelike configuration of the thermocline between 2° N. and 2° S. latitude. Data obtained prior to Eastropic for the months October through December (Eastropic cruise period) are shown by the solid dots and those during Eastropic by the small circles. Comparison of the mean (a curve through the center of the hatched band), the October–December data (dots), and Eastropic data (circles) demonstrates the comparatively steep slope of the thermocline during Eastropic. It is concluded that the comparatively steep slopes of the sea surface and the thermocline are associated with a more than normally active zonal circulation.

In the section describing the vertical distribution of temperature, we mentioned the 2-layer system which is typical of the tropics—the essentially homogeneous water from the surface down to the top of the thermocline, the thermocline (stable layer) through which the temperature decreases rapidly with increasing depth, and the extensive depth range below the thermocline to the ocean floor through which there is but a comparatively slight further decrease in temperature. This situation is typical of waters in the low latitudes throughout the seasons. In the middle and high latitudes, however, a deep mixed layer exists at the end of winter. As the season progresses, the depth of the mixed layer decreases to the midsummer minimum and the depth of vertical turbulence is thus progressively restricted.

The development in the spring of the seasonal thermocline is termed "stabilization" by Sverdrup (1953, p. 291). He demonstrated that the onset of stabilization following the period of deep winter mixing played an important role in the vernal increase in biota. In the low latitudes, there is no such period of stabilization—the vertical density structure during all months is characterized by a mixed layer below which the density increases rapidly with depth and turbulence is suppressed. Therefore, when considering geographical and temporal variations in measurements of the biota in tropical oceans, we must look for mechanisms that will affect the degree of stability or the depth of this stable layer in relation to the compensation depth. Within the area studied from the *Smith* during expedition Eastropic, we have mentioned several such mechanisms, including divergence of the surface waters and upwelling at or near the Equator, the effects of sheer and associated mixing at the boundaries of opposing currents, and the shallowing of the stable layer to a depth that will bring it within the euphotic zone, e.g., at the northern boundary of the Countercurrent. Although there may be seasonal variations, these mechanisms are all primarily related to horizontal and vertical transport features (as contrasted with the spring warming and stabilization and the fall cooling and overturn in the higher latitudes).

In higher latitudes, following stabilization, the nutrients in the mixed layer are quickly depleted by biological utilization and fallout of the organic material into or beneath the stable layer. Until the fall overturn and associated replenishment from below, the nutrient concentration in the mixed layer represents, primarily, a balance between utilization by the phytoplankton and the biological regenerative processes within this layer, with vertical diffusion playing a comparatively minor role. This situation characterizes vast areas of the tropical oceans during all months of the year. In figure 22, the vertical distribution of various properties is shown to illustrate conditions within the mixed, the stable, and the deeper layers at a position in the region of convergence north of the Equator (3° N.). It is to be noted that, at the particular station illustrated, within a very limited range of depth ($\leqq 50$ meters), there is an abrupt change in the fields plotted. The temperature decreases nearly 10° C., the thermosteric anomaly nearly 300 centiliters per ton (60 percent of total change, surface to 800 meters) and, of particular biological importance, the phosphate suddenly increases from 0.6 to 1.4 μg.at./L. The other nonconservative property, oxygen, decreases from nearly 4 ml./L. to slightly less than 2.0 ml./L. within the same depth increment.

Nearer the Equator, however, the vertical distribution of properties differs somewhat from that shown in figure 22. In the discussion of the vertical distribution of oxygen, we described a feature with waters of comparatively high oxygen content that was positioned beneath the Equator. In each

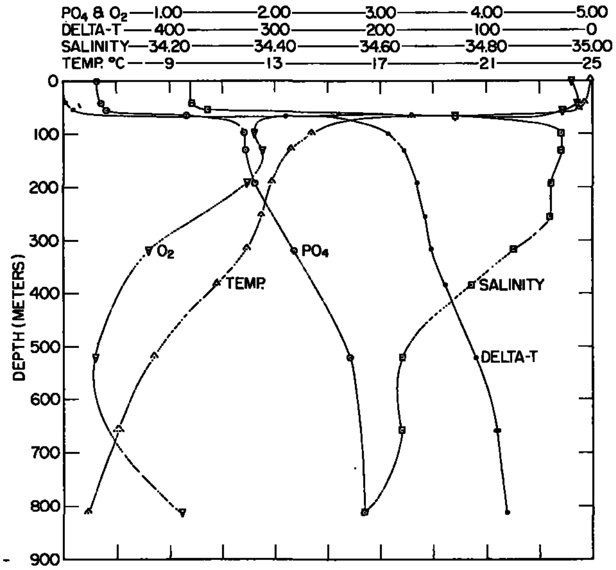

FIGURE 22.—Vertical distribution of temperature (° C.), density (cl./ton), oxygen (ml./L.), and phosphate (µg.at./L.) from *Hugh M. Smith* station 4, 03°13′ N. latitude, 110°12′ W. longitude.

of the four sections shown in figure 11, this feature extended vertically from within or immediately below the thermocline to a maximum depth of between 300 and 400 meters and was approximately 200 miles wide. The oxygen content near its center was 2.8 to 3.0 ml./L. at 140° W., decreasing eastward to 2.5 to 2.7 near 100° W.

Consideration of the possible causes for this geographically restricted feature leads to the conclusion that it is the result of advection. In the first place, the deeper waters are essentially isolated from the oxygen-rich waters of the mixed layer above the thermocline. Even though isentropic principles may not apply near the Equator, the configuration of the density field shown in figure 10 suggests that there is little mixing between the waters in the surface layer and those beneath the thermocline. The oxygen content at depths between 100 and 300–400 meters decreases both to the north and to the south of the Equator.

To emphasize the meridionally limited extent of this feature, the distribution of oxygen on a surface of constant density (180 centiliters per ton) is shown in figure 23. In a narrow band along the Equator, between 140° W. and 120° W., the oxygen values are 3.0 ml./L. or greater. Between 120° W. and 110° W., the values decrease somewhat, then increase again farther to the east. If lateral mixing were significant across the Equator, the feature in question would be eliminated.

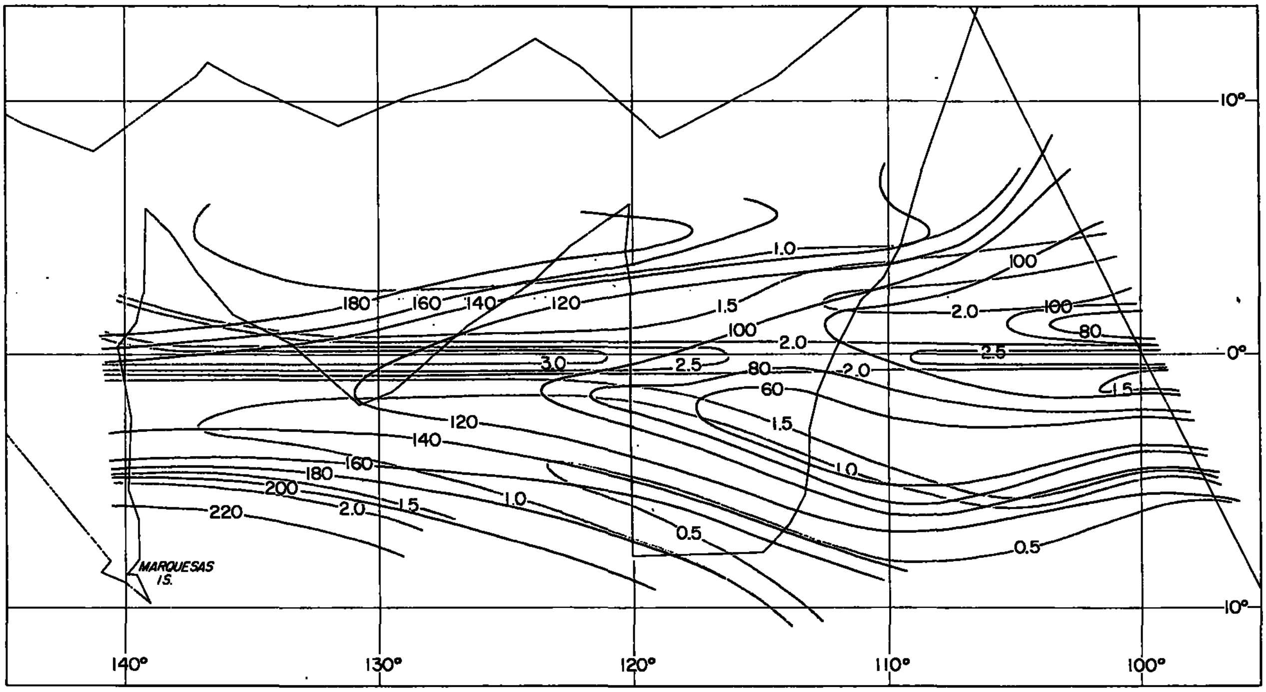

FIGURE 23.—Distribution of oxygen (ml./L.) in red on density surface (180 cl./ton) in black. Depth of density surface in meters.

From consideration of the standing crops of the biota in the euphotic zone near the Equator, oxygen values in the waters beneath the thermocline at the Equator should essentially be depleted and lower than to the north and south unless there was active replenishment. An inference to the standing crop of the phytoplankton may be made from the results of the use of the carbon isotope during expedition Eastropic (fig. 24). The highest rates of photosynthesis were at or very near the Equator where there is enrichment by upwelling (fig. 18). It is reasonable to assume that these higher rates of carbon fixation were associated with the larger standing crops of the phytoplankton. The different rates of photosynthesis among various species in, and the ages of, the populations (whether vigorously growing or senescent) are quantitatively unknown variables. King and Hida (1957, figs. 8 and 10) have shown that the standing crop of zooplankton reaches a maximum between approximately 1.5° N. and 1.5° S. latitude.

These facts and our present knowledge of the pattern of flow near the Equator lead to the conclusion that there is advection of waters with higher oxygen content from the west by the Equatorial Undercurrent. This subsurface, easterly directed flow was first reported by Cromwell, Montgomery, and Stroup (1954). They observed that the Undercurrent was both in the lower part of the surface layer and in the upper part of the thermocline. Its total depth range, however, was not determined.

More recently, Knauss and King (1958), presenting preliminary results of a detailed survey of the Undercurrent made at 140° W. longitude, report that the vertical extent of the Undercurrent is between about 30 and 300 meters with the highest easterly velocities (2.0 to 3.5 knots) recorded at a depth of 100 meters. The Undercurrent was symmetrical about the Equator. At 2° N. and 2° S. latitude, the average thickness had decreased to 30 meters and the average maximum velocity to 0.6 knot. Of particular interest to the discussion of the results from expedition Eastropic, Knauss and King report that during the period of their cruise (March–June 1958), the Undercurrent showed no diminution in velocity between 140° W. and 92° W. and that the depth of its core rose from 100 meters at 140° W. to 42 meters at 98° W. Farther to the east, at 95° W. and 92° W., it once again deepened. At 89° W. the Undercurrent was missing.

In the section on vertical distribution of temperature (fig. 6), we discussed the configuration of the isotherms, particularly in the thermocline, as related to the Undercurrent. Between 2° N. and 2° S. there was a spreading of the isotherms, resulting in a shallow ridge and a deeper trough

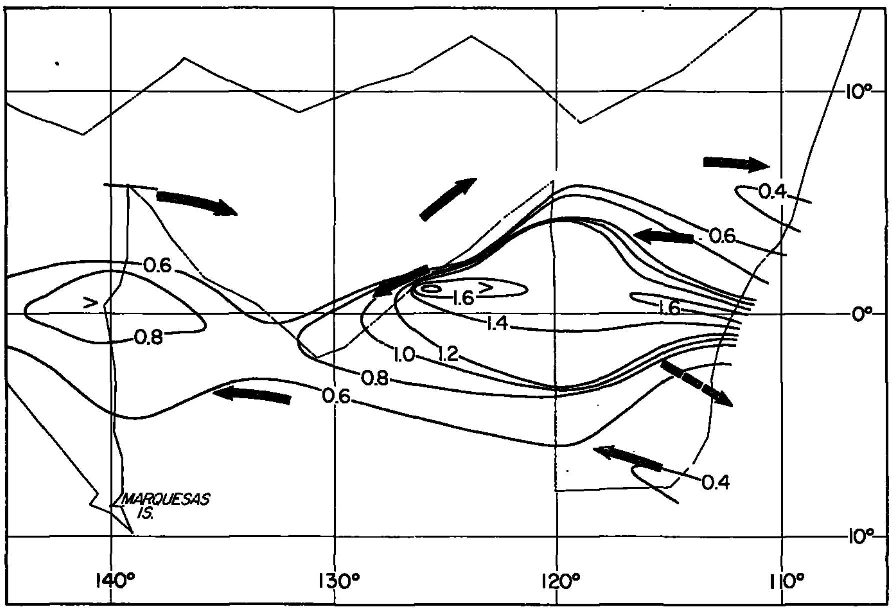

FIGURE 24.—Rate of carbon fixation (mg.C./hr./m.^{3}) by photosynthesis as measured by uptake of the isotope carbon 14. (Data from King et al., 1957.)

about the Equator. This was interpreted as resulting from advection from the west of the somewhat warmer waters of the Undercurrent. Near the Equator, the thermocline shallowed between 160° W. and 120°–125° W. (fig. 5), then deepened once again. Considering these data and the results reported by Knauss and King (1958), it is assumed that, during Eastropic, the core of the Undercurrent exhibited a west-east variation in depth similar to that of the thermocline.

Oxygen and inorganic phosphate are both nonconservative (biologically affected) properties. Their concentrations normally exhibit reciprocal variations in the sea. This was the case in the waters beneath the Equator during Eastropic, at least along the 110° W. section (fig. 13), the only one for which adequate phosphate data are available. Between approximately 2° N. and 2° S., the meridional extent of the Undercurrent, the higher oxygen values previously discussed were accompanied by lower inorganic phosphate values, 1.6 μg.at./L. or less as compared with 2.0 μg.at./L. or greater at comparative depths to the north and south. Thus, the distribution of the two nonconservative properties and of temperature beneath the thermocline at the Equator is largely governed by the easterly flowing Undercurrent, while their distribution in the shallower portion of the thermocline and the mixed layer is largely related to upwelling.

There are various references to the oceanographic conditions along the northern boundary of the Countercurrent which use the words "divergence" or "upwelling." Relative measurements of the standing crops of the marine biota, especially zooplankton, have been used to support the hypothesis that divergence of the surface waters along this boundary has resulted in enrichment within the euphotic zone. Sverdrup et al. (1942, p. 711), suggest that a transverse circulation is superimposed on the flows to the east (the Countercurrent) and to the west (the North and South Equatorial Currents). Such a transverse circulation would require a divergence at the northern boundary of the Countercurrent and a convergence at the southern boundary. Referring to the relative volumes of the plankton samples taken aboard the *Carnegie* as reported by Graham (1941), they suggest that the relatively high volume at *Carnegie* station 151 (13° N.) was associated with a divergence centered near 10° N. (Sverdrup et al., 1942, fig. 219). This biological evidence may be somewhat speculative as Graham (1941, p. 193) states that this sample (station 151) was "not quite comparable as it contained a large colony of salps." The sample (expressed as dry weight and not as volume) was not used by Graham in his analyses of plankton abundance along the *Carnegie's* transequatorial section (his fig. 41).

Jerlov (1956, p. 150), discussing the results of the *Albatross* expedition in the central equatorial Pacific, assumes from consideration of the relative distribution of particles that "there is ascending water movement along σ_t-surfaces which enriches the upper layer with nutrients." His figure 34 shows a maximum concentration of particles at the northern edge of the Countercurrent. Jerlov suggests that the distribution of these particles "largely represents phytoplankton population and plankton remnants, as the supply of terrigenous components in this area must be low."

Austin (1954a) does not recognize the presence of upwelling at the northern boundary of the Equatorial Countercurrent in the central Pacific, but does acknowledge the fact that the shallow thermocline in this area (see fig. 15, this report), coupled with wind mixing, may result in an increase in the biota. A question of semantics may be involved. Austin and Rinkel (in press) have defined upwelling as a local, wind-induced divergence of the surface waters resulting in a mixing of the deeper, cooler, nutrient-rich waters with those at the surface. Within the scope of this definition, there is no evidence of upwelling along the northern boundary of the Countercurrent in the Eastropic data. Although there was a marked ridge in the thermocline, there was no evident cooling of the surface waters (see fig. 14). At the northern edge of the Countercurrent any upwelling would result in a band of more-saline waters and waters with higher phosphate concentrations. Salinities were comparatively low, increasing to either side of the northern edge of the Countercurrent (fig. 17). Phosphate concentrations were low, averaging 0.4 μg. at./L. or less, these to be compared to 0.8 to 1.0 μg. at./L. near the Equator (fig. 25).

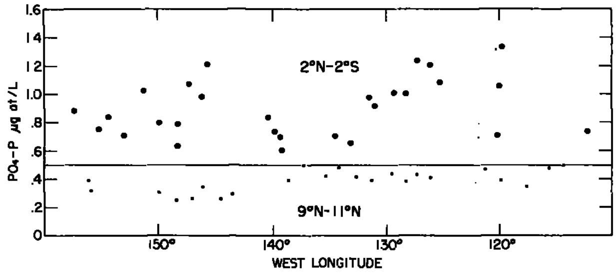

Figure 25.—East-west variations in surface inorganic phosphate concentrations (µg.at./L.) between 2° N. and 2° S. latitude and 9° N. and 11° N. latitude.

An important biological consideration is the fact that along the northern boundary of the Countercurrent the thermocline in the eastern Pacific is sufficiently shallow to be within the euphotic zone. If we assume that in these tropical waters seasonal variation in light is not a limiting factor, Sverdrup's concept of critical depth is applicable (Sverdrup 1953). With the thermocline penetrating into the euphotic zone (shallower than the compensation depth, ca. 100 meters), the phytoplankton in the mixed layer is retained within the depth range of active photosynthesis; i.e., not carried by vertical mixing to a depth during the day where respiration exceeds photosynthesis. To the north and south of the northern boundary of the Countercurrent, and west of about 150° W., the thermocline deepens and is normally deeper than the compensation depth.

Biological data from this area are pertinent. King and Hida (1957), discussing the results of POFI's zooplankton program in the central equatorial Pacific, 1951 to 1954, show that zooplankton volumes in the Countercurrent are comparatively low, 180th meridian to 150° W. longitude (ca. 25 cc./1000 m.^{3}) but increase to nearly 45 cc./1000 m.^{3} between 140° W. and 120° W., a volume approximately equal to that of the region of the divergence near the Equator. They also demonstrate (fig. 11) that, between 8° N. and 11° N., the plankton volumes increase west to east (170° W. to 140° W.) as the depth of the thermocline decreases. Thus, the available empirical data suggest that any relative increase in the standing crops of the biota along the northern boundary of the Countercurrent is more directly related to the presence of a shallow thermocline than to a divergence and upwelling in the surface waters.

SUMMARY

A cooperative oceanographic survey of the central and eastern tropical Pacific (expedition Eastropic) was conducted during the period September–December 1955, with five research vessels participating, representing five agencies: Scripps Institution of Oceanography, Inter-American Tropical Tuna Commission, California Department of Fish and Game, Pacific Oceanic Fishery Investigations (POFI) of the U. S. Fish and Wildlife Service, and the Peruvian Navy.

As POFI's participation in Eastropic, the *Hugh M. Smith* (cruise 31) completed an 86-day, 14,000-mile cruise, obtaining information on east-west gradients in temperature, salinity, phosphate, zooplankton, and forage fish abundance along the northern boundary of the Equatorial Countercurrent and along the Equator between 110° W. and 156° W. longitude. A survey of tuna baitfish was conducted in the Marquesas Islands and, in collaboration with the University of Hawaii, carbon fixation and chlorophyll measurements were made on the westbound leg of the cruise.

Sea surface temperatures along the Equator were from 2° to 4° F. cooler than normal; those in the Equatorial Countercurrent deviated little from normal. Temperature anomalies for the eastern Pacific, Alaskan waters south to Peru, were generally negative (−0.6° F. to −2.0° F.) for the latter half of 1955.

Near the Equator, the observed east-west slope of the thermocline was considerably steeper than normal, shallowing from near 500 feet beneath the surface at 160° W. longitude to at or near the surface at 125°W., then deepening somewhat to the east.

A pronounced oceanic temperature front, across which there was a temperature change of approximately 3° F., was observed near 4° N., 120° W. The same or a similar feature was observed (1 month later) from the Scripps Institution of Oceanography vessel, the *Horizon*, near 3° N., 120° W.

Calculated current velocities in the warmer waters to the north of the front were westerly, 1.8 to 2.3 knots, decreasing to 0.2-knot westerly flow in the cooler water to the south of the front. In the eastern portion of the area surveyed from the *Smith* (Equator to 4° N., 120° W.), velocities measured from Scripps vessels were as high as 2.0 knots (324° T., measured at 3°08′ N. near 120° W.).

The calculated east-west slope of the sea surface (0/400-db. level) was greater than the mean; 0.66 dynamic meters at 120° W. (mean=0.85) sloping upward to 0.90 dynamic meters near 140° W. (mean=0.92) for a difference of 0.24 dynamic meter as compared with 0.07 for the mean.

Upwelling and wind mixing, coupled with a shallow thermocline, resulted in considerable enrichment of the surface waters along the Equator. Concentrations of inorganic phosphate at the surface were between 0.8 and 1.2 μg. at./L. in the region of the shallow thermocline (near the Equator and 125° W. and near 4° S. and 115° W.). Phosphate concentrations in the surface waters of the Countercurrent and along the northern edge of the Countercurrent were uniformly low, ≦0.4 μg. at./L.

Cooler than normal surface temperatures, comparatively steep east-west slopes in the sea surface and the thermocline, comparatively high calculated and measured current velocities, and high inorganic phosphate concentrations in the surface layer, all suggest the horizontal and vertical circulation features, 5° N. to 5° S. along the Equator, were more dynamic during Eastropic than normally observed.

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