New Evidence of the Equatorial Undercurrent East of the Galapagos Islands[1]

Merritt R. Stevenson[2] and Bruce A. Taft[3]

ABSTRACT

Measurements made between the Galapagos Islands and Ecuador in June and October 1967 revealed the existence of a subsurface high-salinity core aligned beneath the southern edge of the Equatorial Front. *In situ* salinometer (STD) and direct current measurements made in June 1969 in the same area (84°W) showed that the core possesses a maximum salinity of 35.13 ‰ and an eastward velocity of 37 cm sec^{-1} relative to 310 m. A comparison of new information with previous observations west of the Galapagos Islands suggests that the subsurface current beneath the Equatorial Front is the eastward extension of the Equatorial Undercurrent.

Introduction. Since the discovery of the Equatorial Undercurrent in 1952 (Cromwell et al. 1954, Montgomery and Stroup 1962), a number of measurements have been made of the velocity and water characteristics of the Undercurrent west of the Galapagos Islands. The most extensive sets of measurements were those made on the DOLPHIN (April–June 1958) and SWANSONG (September–December 1961) expeditions of the Scripps Institution of Oceanography (Knauss 1960, 1966). These measurements showed the continuity of the Undercurrent from 140°W eastward to the Galapagos (about 92°W). Maximum speed of the Undercurrent decreased as the Galapagos were approached from the west, but the maximum speed at the equator during both expeditions was above 70 cm sec^{-1} at 93°W; on SWANSONG the eastward volume transport was 8×10^6 m^3 sec^{-1} at 93°W (Knauss 1966).

There have been few direct current measurements east of the Galapagos. Current profiles were measured at 1°S, 0°, and 1°N along 87°W on SWANSONG in November 1961; the profiles showed weak eastward flow below 100 m at all three stations (Knauss 1966). Eastward speeds were greater than 20 cm sec^{-1} at 1°N and less than 10 cm sec^{-1} at 1°S. The maximum eastward flow at 87°W was deeper (150 m to 200 m) and occurred at a lower specific volume

1. Accepted for publication and submitted to press 3 December 1970.

2. Inter-American Tropical Tuna Commission, c/o Scripps Institution of Oceanography, La Jolla, California, 92037.

3. Scripps Institution of Oceanography, La Jolla, California, 92037.

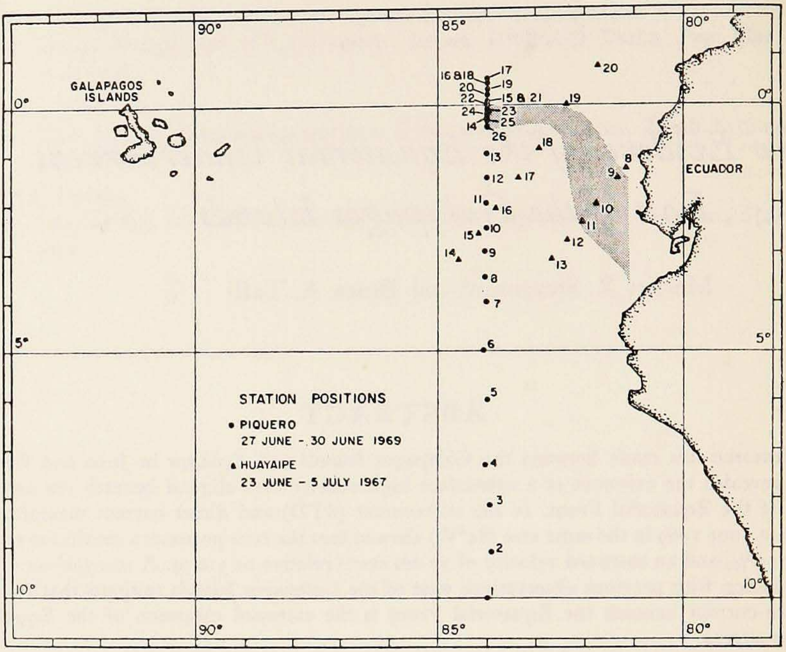

Figure 1. Location of stations used in the vertical sections of Figs. 2, 3, and 4. The position of the northern and southern boundaries of the Equatorial Front in June-July 1967 is shown by the shaded zone (Stevenson and Santoro 1967). The similarity in location of the Front during the two cruise periods is evident from the line of closely spaced stations that intersects the Front during June 1969.

than the maximum current in the Undercurrent west of the Galapagos at 93°W. Knauss proposed that this eastward flow was the eastward extension of the Undercurrent and that the effect of the Islands on the Undercurrent is to reduce its speed and deepen the core of the Undercurrent. Knauss also stated that most of the Undercurrent water appears to go around the north side of the Galapagos.

In an analysis of temperature, salinity, and oxygen data from an Eastropac cruise of the Alaminos in February–March 1967, Cochrane and Zuta (personal communication) proposed that the Undercurrent east of the Galapagos was split into two bands of eastward-moving water located north and south of the equator. In a more comprehensive analysis of the observations made during the Alaminos cruise, White (1969) concluded that at 84°W the southern branch of the Undercurrent was present on isanosteric charts at 120, 160, 200, and 280 cl/ton at latitudes from 2°S to 4°S. The position of the Undercurrent was inferred from the distribution of acceleration potential on the isanosteric surfaces. The Undercurrent is marked by high oxygen values on all four surfaces. For the two deeper surfaces (120 and 160 cl/ton), White showed

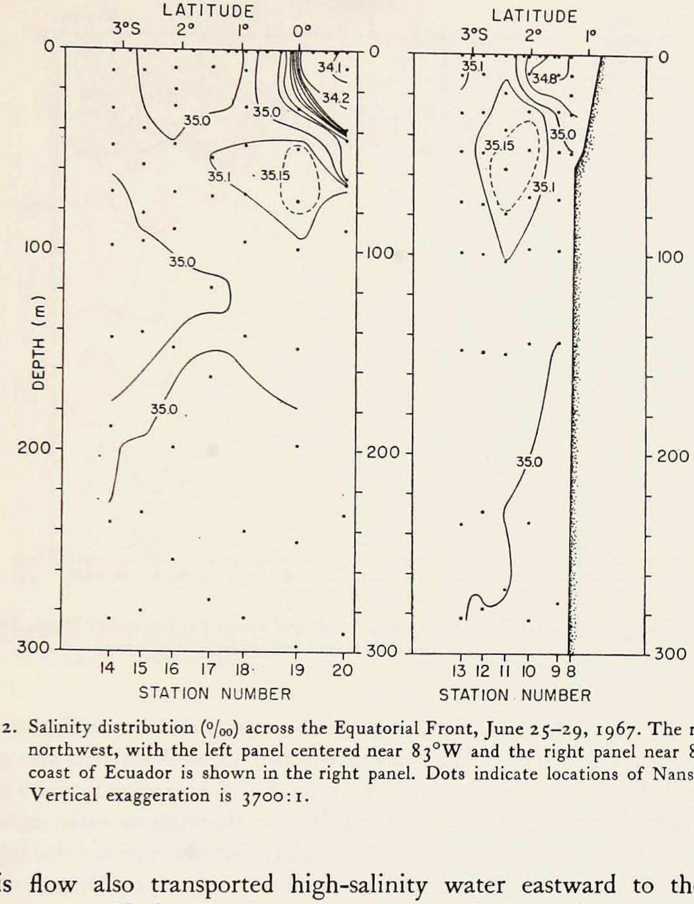

Figure 2. Salinity distribution (‰) across the Equatorial Front, June 25–29, 1967. The reader faces northwest, with the left panel centered near 83°W and the right panel near 82°W. The coast of Ecuador is shown in the right panel. Dots indicate locations of Nansen bottles. Vertical exaggeration is 3700:1.

that this flow also transported high-salinity water eastward to the South American coast. Unfortunately there were no direct current measurements made aboard the Alaminos that could confirm the existence of the proposed eastward flow south of the equator.

Additional information about the eastward extension of the Equatorial Undercurrent came about unexpectedly from measurements made during oceanographic cruises of Huayaipe in 1967–1968 by the National Fisheries Institute of Ecuador (INPE) and the Inter-American Tropical Tuna Commission (IATTC) in connection with the Eastropac Expedition (Stevenson and Santoro 1967, 1968a, 1968b). The objective of the cruises was to monitor the Equatorial Front that extends between the Galapagos and the northern border of Peru. The locations of two sections from the June–July Huayaipe cruise are shown in Fig. 1. Data from these cruises clearly show details of the Front and its location. Measurements between 86°W and 82°W on the June–July cruise, when the flow of the Peru Current is seasonally the strongest

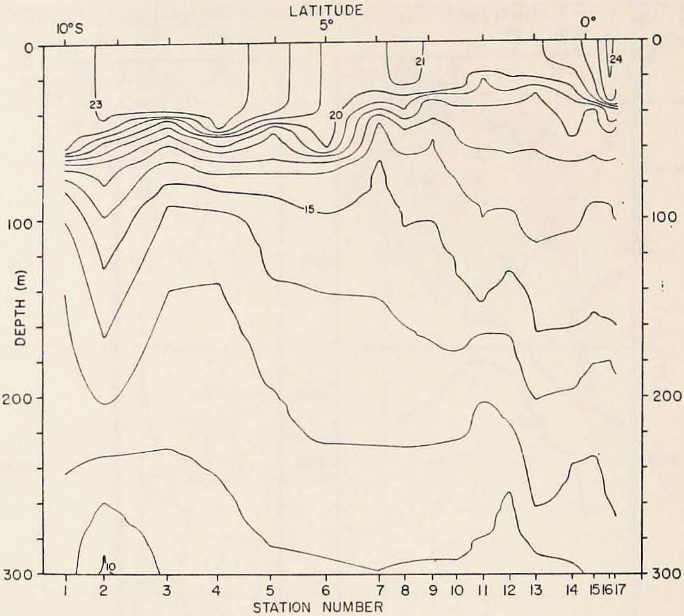

Figure 3a. Temperature (°C) distribution along 84°W and across the Equatorial Front, June 26–29, 1969. The reader faces westward. Vertical exaggeration is 3700:1.

(Wyrtki 1965), and on the October cruise, when the Peru Current is still strong, both show a core of high-salinity water located beneath the southern edge of the Front at a depth of 50 m to 90 m. Salinity distributions based on Nansen cast data are plotted in Fig. 2 for two northeast-southwest-oriented sections observed on the June–July cruise. Both sections crossed the Equatorial Front. Salinity in the high-salinity core is greater than 35.15‰ on both sections and is located farther to the south on the eastern section (right-hand panel).

South of the equator there is a high-salinity core in the Undercurrent that can be traced eastward across the Pacific to the Galapagos (Knauss 1966, Tsuchiya 1968). If water from the Undercurrent were transported southward around the Galapagos, high-salinity water from this core would be a tracer for Undercurrent water east of the Galapagos, if it were not dissipated by mixing with adjacent waters. The Equatorial Undercurrent was considered to be the probable source of water in the high-salinity core measured aboard Huayaipe at 82°W to 83°W, but there were no direct current measurements in the high-salinity cores, so the direction of flow was not known.

Piquero *Measurements*. An opportunity to make direct measurements of currents along the Equatorial Front came during June 1969 when, on the

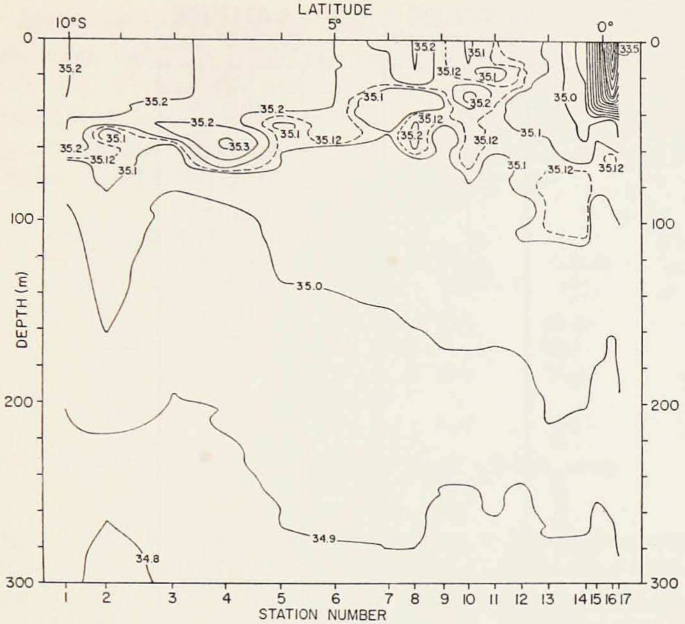

Figure 3b. Salinity (‰) distribution along 84°W and across the Equatorial Front, June 26–29, 1969. The reader faces westward. Vertical exaggeration is 3700:1.

PIQUERO expedition, the Scripps Institution of Oceanography vessel THOMAS WASHINGTON made two sections in the area between the Galapagos and the mainland of Ecuador and Peru (Fig. 1). The position of the Equatorial Front was determined by continually monitoring the surface temperature and salinity and by making *in situ* salinometer (STD) casts along a northbound track on 84°W (Fig. 3). After the Front had been located, a southbound track of closely spaced STD casts were made to obtain a detailed vertical profile of temperature and salinity across the Front (Figs. 4a, 4b). The high-salinity core appeared beneath the southern edge of the Front on both the northbound and southbound sections; its position, as indicated by the 35.12‰ isohaline, was similar to its location in June and October 1967. Additional STD meridional sections were made on PIQUERO at 86°, 93.5°, and 115.5°W after the work was done at 84°W.

In order to measure the velocity distribution south of the Front, parachute drogues were deployed near the surface at 15 m, in or near the high-salinity core at 75 m, and beneath the Front at 310 m. The positions of the 15-m and 75-m drogues are indicated on Fig. 4. Progressive drogue positions, relative to the position of the 310-m drogue, were obtained over a period of several hours by sequential radar measurements; the observations were treated as relative trajectories. Though a longer tracking period was intended, the high rate of

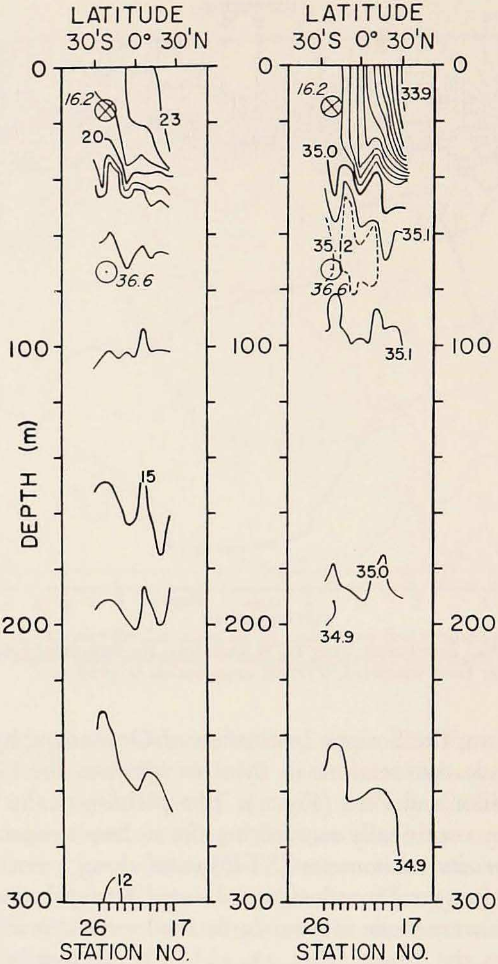

Figure 4. Temperature (°C) and salinity (‰) distributions on southbound recrossing of the Equatorial Front, June 29–30, 1969. The circles represent the location of parachute drogues, with the zonal velocity components (cm sec^{-1}) given by the numbers in italics. The circle with the dot represents motion toward the east, that with the cross, motion toward the west. Vertical exaggeration is 3700:1.

separation of the 15-m and 75-m drogues limited to about six hours the time interval over which they could both be tracked. Best estimates of the relative mean velocities of the drogues were extracted from the displacement trajectories by computer programs (Stevenson 1966); the mean velocities together with attendant water conditions are shown in Table I.

For the time interval preceding, encompassing, and following the drogue measurements, the winds were steady from the south at about 5.5 m sec^{-1}. The

Table I. Mean relative velocity of drogues tracked at 0°22′S, 84°00′W on June 30, 1969. Velocities of the 15-m and 75-m drogues are relative to the 310-m drogue. Vertical shear of the zonal component of velocity ($\partial u/\partial z$) is computed with u positive eastward and z positive upward. Temperature, salinity, and thermosteric anomaly at the location of the drogues was estimated from the STD section (Fig. 4).

Depth (m)	Drogue mean speed (cm sec⁻¹)	Drogue direction (deg)	$\partial u/\partial z$ (10^{-3} sec^{-1})	Temp. (°C)	Salinity (‰)	Thermost. anomaly (cl ton^{-1})
15	58	344	–	20.9	34.94	343
–	–	–	–8.7	–	–	–
75	37	83	–	16.8	35.12	233
–	–	–	1.6	–	–	–
310	0*	–	–	11.9	34.87	152

* The 310-m droque was used for the reference and is shown with zero velocity.

15-m drogue moved in nearly the same direction as the surface wind. The movement of the near-surface drogue toward the southern edge of the Equatorial Front attests to a convergence at the surface near the Front in June–July 1969. Movement of surface water toward the Front was also indicated by GEK measurements in November 1955 (Wooster 1969).

The drogue at 75 m, near the core of high-salinity water, moved almost due east at 37 cm sec^{-1}. Eastward movement of the 75-m drogue suggests that the origin of the high-salinity water in the core at 84°W is the high-salinity water found south of the equator in the Undercurrent west of the Galapagos. Our interpretation of the data is that the high-salinity core at 84°W is evidence that the Undercurrent does extend east of the Galapagos and that there probably is a continuous eastward flow bringing high-salinity water toward the mainland of South America.

The drogue measurements can be used to estimate vertical current shear (Table I). The large vertical shear of the zonal velocity component between 15 m and 75 m reflects the change from weak westward flow to strong eastward flow. The shear between 15 m and 75 m is one-half to one-third the maximum current shear between the sea surface and 30 m found west of the Galapagos in 1968 (Jones 1969). The marked difference in vertical shear on the two sides of the Galapagos shows the attenuation in the strength of the Undercurrent as it passes around the Galapagos.

Discussion. Because of the close association between the high-salinity core and the Undercurrent, both east and west of the Galapagos, a comparison of the position and characteristics of the core from cruise to cruise may be used as a measure of the variability in position and strength of the Undercurrent

Table II. Salinity, temperature, depth, and thermosteric anomaly of high-salinity core in the Undercurrent.

Month	Lat.	Long.	Salinity (°/₀₀)	Temp. (°C)	Depth (m)	Thermost. anomaly (cl ton⁻¹)
1967						
June–July†	1°26′S	85°44′W	35.17	16.9	90	232
	0°01′N	82°17′	35.18	17.1	75	235
	2°13′S	81°53′	35.21	17.5	53	242
September††	1°23′S	88°05′	35.08	15.6	56	208
	1°44′S	88°08′	35.07	15.5	50	208
August††	0°40′S	85°04′	35.07	15.9	49	217
	1°03′S	85°04′	35.05	16.0	47	220
	1°26′S	85°04′	35.09	16.3	36	225
August††	1°11′S	82°02′	35.06	16.3	50	226
	1°26′S	82°00′	35.02	15.9	75	219
	1°46′S	81°58′	35.03	16.1	51	224
October†	0°32′S	86°24′	35.06	14.7	74	192
	0°32′S	83°32′	35.15	14.2	73	175
	3°12′S	82°13′	35.12	14.1*	91	175
	2°17′S	81°40′	35.06	14.9	47	196
	1°51′S	81°26′	35.06	14.2	92	181
1969						
July–August**	0°38′S	115°30′	35.46	17.7	56	229
July**	1°02′S	93°30′	35.29	17.4	40	235
July**	2°00′S	86°00′	35.25	17.7	59	244
June–July**	0°25′N	84°00′	35.14	17.3	64	242
	0°05′N	84°00′	35.13	17.3	64	243
	0°25′S	84°00′	35.13	16.8	69	232

† Data from Huayaipe cruises.
†† Data from Rockaway-47 Eastropac Cruise.
** Data from Piquero Expedition.
* Value obtained by interpolation from a temperature-depth diagram.

(Table II). On the June–July 1967 Huayaipe cruise, the salinity and temperature of the core were relatively constant on the three sections. Between 85°44′W and 81°53′W the Undercurrent apparently shoaled from 90 m to 53 m.

The proposal by Knauss (1966) that the Undercurrent deepens east of the Galapagos is not consistent with the observations presented in this paper. The Undercurrent, evidenced by the salinity maximum, was found to lie above 100 m in all cases (Table II). At least a portion of the Undercurrent water appears to be present east of the Galapagos at about the same thermosteric anomaly as Undercurrent water west of the Islands. On Swansong a hydrographic section was made from 5°N to 5°S along 87°W in November 1961. The southern boundary of the Equatorial Front appeared to be between

1°32′S and 2°02′S, so that there were no current measurements made underneath the southern boundary of the Front. It is interesting to look at Knauss' salinity measurements (Anonymous 1965) to see whether there was a salinity maximum at a thermosteric anomaly of about 200 cl/ton. A salinity maximum was present underneath the southern boundary of the Front, with salinities at the maximum of 35.02‰ and a thermosteric anomaly between 190 and 200 cl/ton. This salinity maximum appears to have the same properties as the salinity core we have associated with the Undercurrent east of the Galapagos (Table II). But note that on SWANSONG the salinity maximum was only a maximum in the vertical. It was located in a layer of high salinity in which the salinity monotonically increased to the south so that eastward flow would not be required to maintain the salinity maximum.

Additional evidence of the high-salinity core can be found in the data from the ROCKAWAY EASTROPAC Cruise 47 in August–September 1967 (Table II). The high-salinity core ranged in depth between 36 m and 75 m, with an average depth of 52 m. Salinities decreased to the east by 0.04‰ between 88°W and 82°W, with most of the change occurring between 88°W and 85°W. Temperatures associated with the salinity maximum were approximately equal between 85°W and 82°W, but they were 0.5°C cooler between 88°W and 85°W. Salinities of the core decreased by about 0.12‰ between June–July and August–September 1967. The average temperature within the core for the same time interval also decreased by 1.2°C and signaled the start of an anomalous cold trend.

The October 1967 (HUAYAIPE) salinity at the maximum was 0.03‰ more than in August–September 1967 (ROCKAWAY), but it was still about 0.10‰ less than in June–July 1967 (HUAYAIPE). The average core depth of 75 m in October was a significant increase over the June–July 1967 cruise period. Temperatures associated with the salinity maximum in October were 1.6°C cooler than in August–September and 2.8°C cooler than in June–July. This decrease in temperature at 75 m was coincident with a decrease in surface temperature of 3.5°C, compared with October 1966. The cooling trend extended into February 1968, when surface temperatures were 6–7°C lower than those for February 1967 (Stevenson and Santoro 1968a, 1968b). The anomalous conditions are attributed principally to a stronger-than-normal Peru Current.

Salinity sections at 115.5°W, 93.5°W, and 86°W from PIQUERO show a salinity maximum south of the equator. There was a marked decrease in salinity at the maximum between 115.5°W and 93.5°W but there was almost no change between 93.5°W and 86°W. The temperature and thermosteric anomaly at the maximum are remarkably constant between 115.5°W and 84°W, and the values agree well with the June–July 1967 values. The 35.12‰ isohaline shown in the salinity section at 84°W and present in the sections to the west was separated by adjacent low-salinity values from the higher salinities observed farther north and south. The isolation of the high-salinity core from water to the north and south and the core's persistence from west to east is consistent with the eastward motion of Undercurrent water.

If conditions during August–October 1967 are considered anomalous and if the measurements are not included, the remaining values of the salinity maximum east of the Galapagos show considerable uniformity between 1967 and 1969. The mean salinity is 35.17‰, with a standard deviation of 0.05‰. The thermosteric anomaly of the core is nearly constant, with a mean value of 239 cl/ton and a standard deviation of only 5 cl/ton.

Although the new evidence for the presence of the Equatorial Undercurrent east of the Galapagos and beneath the Equatorial Front is convincing, alternate interpretations of the data should be reviewed.

The suggestion that the eastward flow in the salinity core represents water from the North Equatorial Countercurrent is very unlikely. During the periods of the 1967 and 1969 measurements, the Peru Current was strong and its northern boundary was well defined. In addition, the salinity in the core beneath the Front is considerably greater than the salinity of water in the North Equatorial Countercurrent (Tsuchiya 1968). It is also unlikely that the eastward subsurface current is related to the South Equatorial Countercurrent. Evidence for the existence of the South Equatorial Countercurrent in the eastern tropical Pacific has been recently reviewed by Tsuchiya (1968) and Stevenson et al. (1970). The South Equatorial Countercurrent appears to approach South America near 5°S to 8°S and not near the equator.

The proposal that the high-salinity core observed during the northern summers of 1967 and 1969 represents the Equatorial Undercurrent east of the Galapagos seems best suited to the accumulated evidence. The agreement between the salinity at the maximum and the temperature associated with the salinity maximum beneath the Equatorial Front on the two cruises is strong evidence that the two sets of observations represent the same entity—the Equatorial Undercurrent.

The data available at present suggest that the high-salinity core may not always be present beneath the Front, east of the Galapagos. For example, during the third IATTC-INPE cruise (February 1968) there was no recognizable high-salinity core beneath the Equatorial Front, although the Front was poorly formed and may have been present, primarily to the south of the area of investigation. Salinities between 35.00‰ and 35.10‰ were in fact present south of the Front near 1°22′S, 86°W. Unfortunately, the transect did not extend far enough to the south. The Undercurrent probably remains beneath the Equatorial Front; and when the Front weakens, the Undercurrent probably migrates with the Front to the south during the northern winter.

White (1969) concluded that there was a southern branch of the Undercurrent present during February and March 1967. The current identified by

White was marked by high oxygen values. It is unfortunate that there were no oxygen measurements made on PIQUERO and that the oxygen measurements made on the HUAYAIPE cruises (reported on by Stevenson and Santoro 1967, 1968a, 1968b) were too few to provide a comparison. It is possible that the salinity maximum in Figs. 2, 3, and 4 was also characterized by high oxygen values. Since the Undercurrent west of the Galapagos probably is present throughout the year, it seems unlikely that the eastward extension of the Undercurrent would be only a seasonal phenomenon. The salinity core seems to occur only when the Equatorial Front is well developed, but there may be other tracers of Undercurrent water that will serve to define its position during the periods when the Front is not well developed. It is expected that a thorough analysis of all of the EASTROPAC data will clarify the relationship between the proposed south branch of the Undercurrent described by White and the flow proposed as an eastward extension of the Undercurrent in this paper.

The occurrence of the high-salinity core (Undercurrent) beneath the Equatorial Front on a number of occasions raises the question as to whether there is an interaction or coupling between the Undercurrent and the Front. Although the present information is far from complete, it appears that the north-northwest transport of surface water, representing the Peru Coastal Current, forms a convergence with attendant subsidence along the Front. After the Undercurrent swings to the south around the Galapagos, the Undercurrent veers toward the equator and comes into proximity with the Equatorial Front. Detailed current measurements need to be made along the Front in order to provide a basis for understanding the possible coupling between the position of the Front and the location of the Undercurrent.

Conclusions. The measurements discussed in this paper have led us to the following conclusions regarding the presence of the Undercurrent east of the Galapagos Islands during the northern summer.

(i) The Undercurrent extends eastward of the Galapagos and may be found within 110 km of the coast of Ecuador and northern Peru.

(ii) The Undercurrent is found beneath the southern edge of the Equatorial Front. It is possible that all of the Undercurrent water is not found underneath the Front. Some portion of the Undercurrent water may be found farther south of the equator, as proposed by White (1969).

(iii) The high-salinity core of the Undercurrent is characterized by a salinity maximum of 35.13–36.17 ‰, a temperature of 17.2°C, and a thermosteric anomaly of 239 cl/ton; it is most frequently found at a depth of 68 m.

(iv) The Undercurrent may retain eastward velocities of up to 37 cm sec^{-1}.

Acknowledgments. We thank the captain and crew of the THOMAS WASHINGTON for their close cooperation during the PIQUERO Expedition. We also acknowledge the good fortune of being able to make use of the findings of Jose Santoro and his associates at the National Fisheries Institute of Ecuador. The sections made on their cruises were of great help in interpreting the PIQUERO measurements near the Equatorial Front in 1969.

The work of one of the authors (Taft) was supported by the Office of Naval Research and the Marine Life Research Program of the Scripps Institution of Oceanography.

REFERENCES

ANONYMOUS

1965. Physical, chemical, current measurement and biological data. SWANSONG Expedition. SIO Ref. 66–1; 125 pp.

CROMWELL, TOWNSEND, R. B. MONTGOMERY, and E. D. STROUP

1954. Equatorial Undercurrent in Pacific Ocean revealed by new methods. Science, *119*: 648–649.

KNAUSS, J. A.

1960. Measurements of the Cromwell Current. Deep-sea Res., *6*: 265–286.

1966. Further measurements and observations on the Cromwell Current. J. mar. Res., *24*: 205–240.

JONES, J. H.

1969. Surfacing of the Pacific Equatorial Undercurrent: direct observation. Science, *163*: 1449–1450.

MONTGOMERY, R. B., and E. D. STROUP

1962. Equatorial waters and currents at 150°W in July–August 1952. Johns Hopkins Oceanogr. Stud., *1*: 68 pp.

STEVENSON, M. R.

1966. Subsurface currents off the Oregon Coast. Ph. D. Thesis, Oregon State University; 140 pp.

STEVENSON, M. R., and JOSÉ SANTORO Y.

1967. Preliminary results and data report from EASTROPAC-1 Cruise. Inter-Amer. Trop. Tuna Comm., La Jolla; 83 pp. (Spanish and English).

1968a. Preliminary results and data report from EASTROPAC-2 Cruise. Inter-Amer. Trop. Tuna Comm., Ja Jolla; 77 pp. (Spanish and English).

1968b. Preliminary results and data report from EASTROPAC-3 Cruise. Inter-Amer. Trop. Tuna Comm., La Jolla; 85 pp. (Spanish and English).

STEVENSON, M. R., OSCAR GUILLEN G., and JOSÉ SANTORO Y.

1970. Marine atlas of the Pacific coastal waters of South America. Univ. of California Press, Berkeley. 23 pp. + 99 charts. (English and Spanish).

TSUCHIYA, Mizuki

1968. Upper waters of the Intertropical Pacific Ocean. Johns Hopkins Oceanogr. Stud. *4*; 50 pp.

WHITE, W. B.
1969. The Equatorial Undercurrent, the South Equatorial Countercurrent, and their extensions in the South Pacific Ocean east of the Galapagos Islands during February-March, 1967. Texas A & M University Ref. 69-4-T; 74 pp.

WOOSTER, W. S.
1969. Equatorial front between Peru and Galapagos. Deep-sea Res., *16* (Supplement): 407–419.

WYRTKI, KLAUS
1965. Surface currents of the eastern tropical Pacific Ocean. Inter-Amer. Trop. Tuna Comm. Bull., *9*: 271–304. (English and Spanish).