Reprinted from
Scientific Exploration of the South Pacific
Standard Book No. 309-01755-6
NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1970

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VARIATIONS OF EQUATORIAL CURRENTS

From October 1965 to May 1968 the research vessel *Coriolis* of the Centre O.R.S.T.O.M. of Nouméa, New Caledonia, made 10 cruises along 170°E, from 20°S to 4°N. On seven of these cruises, direct measurements were made of the equatorial current system. Some of the most significant preliminary results of these cruises are presented in this paper.

CURRENT MEASUREMENTS

Direct current measurements were made with either one or two self-recording Hydro-Products current meters that were attached to the hydrographic cable. The measurements were made immediately after hydrological stations during which the ship was maneuvered to find the proper speed and bearing for keeping the hydrographic cable vertical.

The first current meter was attached to the cable after 1,000 m of it had been paid out. The second meter was attached 1,000 m above the first, and the measurements were made keeping the shallow meter in the depth range of 0–500 m, which put the deep meter in the range of 1,000–1,500 m below the surface. One continuous measurement lasting 4 minutes was made every 20 m in the 0–300-m depth range and every 50 m at depths from 300 to 500 m. Measurements were made again at these intervals while the cable was being retrieved. During the whole series of measurements, the speed and bearing of the ship were kept constant so that the angle of the cable would be minimal. If one current meter was out of order, the same technique was used with the remaining meter, which was sent at regular intervals to depths of 500 or 1,000 m in order to give a deep reference. During the first two cruises, the reference level was 500 m.

In this technique, it is considered that the water in the depth range 1,000–1,500 m is motionless and that the meter in it records the drift of the ship. A vector subtraction gives the true current. In any case, it must be kept in mind that the current velocities in the upper layers are relative to the velocities in the 1,000–1,500-m layer (or at 500 m for the first two cruises). Obviously, there can be no guarantee that the drift of the ship remained constant during the station or that the evaluation of surface drift is reliable.

A study of the current at 500 m relative to that at 1,000 m during two prolonged stations at the equator, at 170°E and 169°E (Figure 1), shows some variation in velocity of both the east–west and the north–south components, but with an average that is the same for both stations: approximately 0.4 knot (positive to the east) for the east–west component, and -0.2 knot (positive to the north) for the north–south component. Similarly, the comparison of the results obtained 5 weeks later at another prolonged station at the equator and 170°E, shows a current at 500 m relative to 1,000 m with the same east–west component of 0.4 knot and a north–south component of -0.2 knot.

Thus, at prolonged stations at two different locations on the equator and at 5-week intervals, the current at 500 m relative to that at 1,000 m was found to be the same. Assuming a stable deep current, evaluation of the drift of the ship by the above method appears to be acceptable. The measurements of the east–west component of the current are computed to within ± 0.1 knot.

Five cruises were made at 5-week intervals, in March, April, June, July, and August 1967. The eastward flux of the Equatorial Undercurrent was computed using the 0 cm sec^{-1} isotach as the northern boundary, 4°S as the southern boundary, 400 m as the lower boundary, and assuming a narrowing of the flow to the east, which has always been found toward 3°N (Figure 2). The flux computed in Figure 2 showed considerable variation over a 3-month period, from April to July, increasing about fourfold; within a 1-month period, from March to April or from July to August, it decreased by about half (Table 1).

It must be pointed out that during all the cruises but one

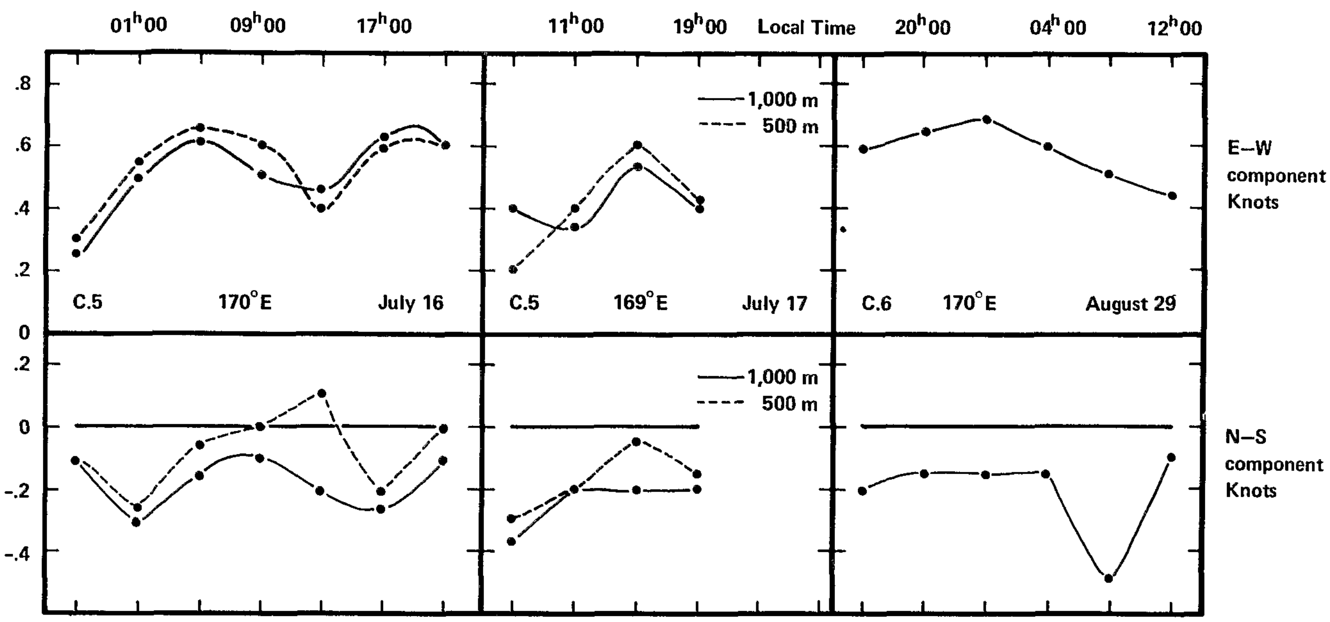

FIGURE 1 East-west and north-south component of the current at 500 m relative to 1,000 m at 0° and 170°E and 169°E, respectively, during cruise Cyclone 5, and at 0° and 170°E 5 weeks later, during cruise Cyclone 6. (Reprinted with permission from B. Warren, ed., *Progress in Oceanography*, vol. 6. Copyright ©1968, Pergamon Press Ltd.)

(cruise Cyclone 3), the Equatorial Undercurrent existed at least between the 500-cl/t and 150-cl/t isanosteric levels (Figure 3); when the flow was at a minimum during this cruise, the undercurrent existed only between the 350-cl/t and 150-cl/t levels.

Another point worth noting is that there is an obvious continuity between the "North Equatorial Countercurrent,"* the Equatorial Undercurrent, and a subsurface flow to the east that extends the undercurrent to the south and to greater depth (Figure 2). The deeper part of this third flow, below the 150-cl/t isanostere shows some stability; between this isanosteric level and the 400-m depth, a flux of about 4×10^6 m^3 sec^{-1} has been measured (Table 2).

Moreover, on three cruises, Cyclone 2, 5, and 6, the eastward flow had two cores, the upper one at the 450–500-cl/t level and the deeper one close to the 150–250-cl/t level (Table 2). The minimum flux is close to the 350–450-cl/t level. It appears also (Figure 3) that the salinity maximum of the Subtropical Lower Water of the South Pacific is distinct from the lower core of the undercurrent. Thus, one can consider that the flow of the undercurrent is vertically stratified, with, from top to bottom, an upper core in which the thermosteric anomaly is greater than 450 cl/t, a layer of

*As suggested by Tsuchiya in this publication, the existence of a pattern of zonal currents more complicated than the classical three-current system (which is actually in use) makes it necessary to revise the terminology. The term "North Equatorial Countercurrent," used here, refers to the so-called Equatorial Countercurrent and allows for the existence of a "South Equatorial Countercurrent," the permanent presence of which has now been demonstrated.

TABLE 1 Variations of the East Flux of the Equatorial Undercurrent Observed during Five Cruises of the Research Vessel *Coriolis* in 1967

Cyclone Cruise	Month	Depth of Reference (m)	Flux (10^6 m^3 sec^{-1})
2	March	500	20
3	April	500	12
4	June	1,000	34
5	July	1,000	54
6	August	1,000	28

TABLE 2 Variations of the Zonal Flux in Various Layers as Observed during Five Cruises of the Research Vessel *Coriolis* in 1967

	Flux (10^6 m^3 sec^{-1})				
Level (cl/t)	Cyclone 2	Cyclone 3	Cyclone 4	Cyclone 5	Cyclone 6
>500	0.1	0	2.0	3.9	1.3
450–500	3.3	0	1.0	8.1	2.8
400–450	0.4	0	2.0	6.1	1.7
350–400	0.7	0	3.3	5.1	1.5
300–350	1.5	0.8	4.9	5.9	1.5
250–300	2.1	2.0	4.8	4.9	2.5
200–250	4.8	2.3	5.4	4.6	5.0
150–200	3.0	3.2	6.8	8.7	7.2
<150	4.4	3.4	4.0	6.1	4.0

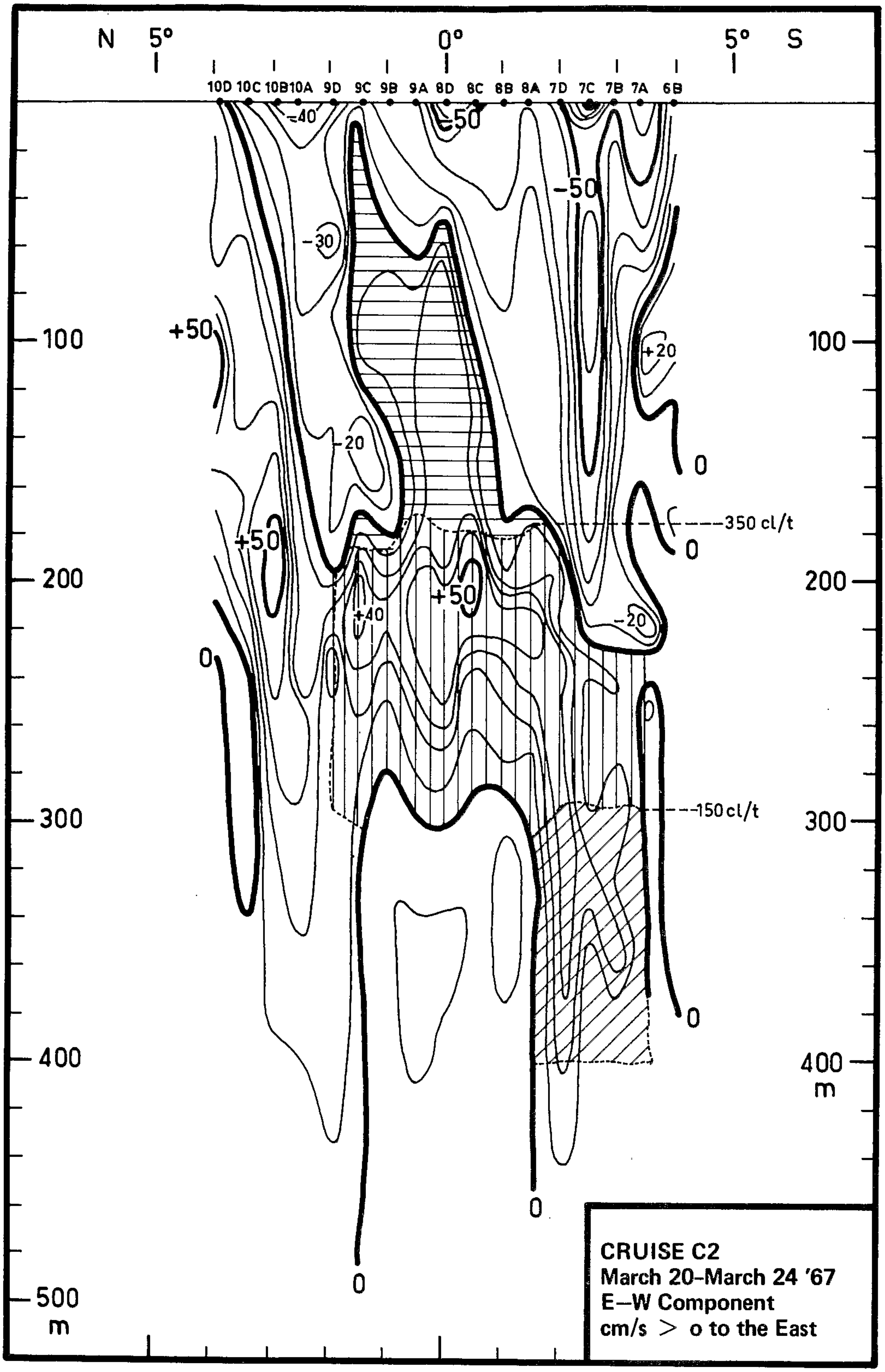

FIGURE 2 Vertical distribution of the east–west component of the currents at 170°E, between 4°S and 4°N, in March 1967, cruise Cyclone 2. (Reprinted with permission from B. Warren, ed., *Progress in Oceanography*, vol. 6. Copyright © 1968, Pergamon Press Ltd.)

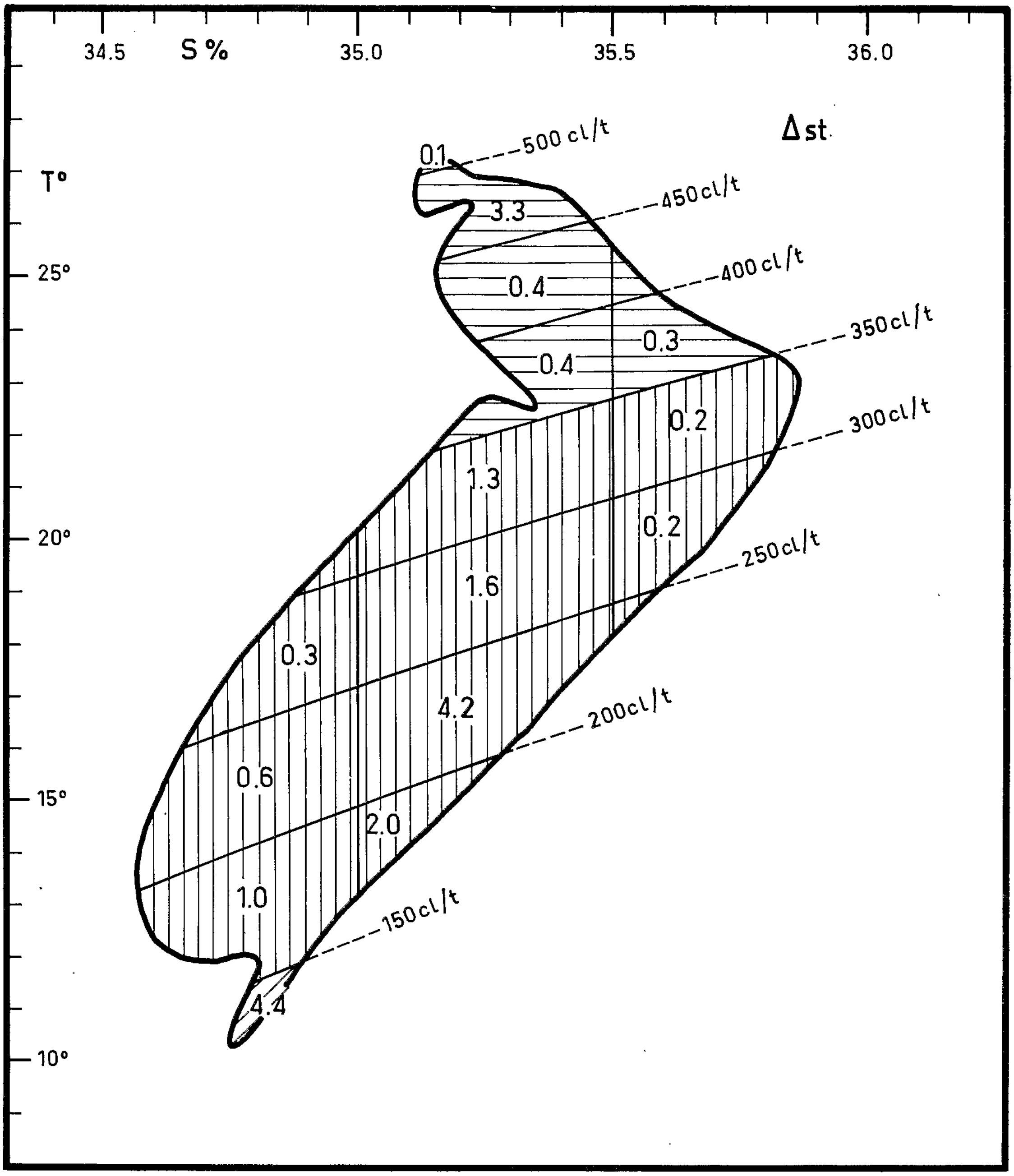

FIGURE 3 Fluxes in the Equatorial Undercurrent for various classes of salinity and thermosteric anomaly, at 170°E, in March 1967, cruise Cyclone 2 (10^6 m^3 sec^{-1}). Total transport = 20.

minimum flux with a thermosteric anomaly between 350 cl/t and 450 cl/t, a salinity maximum with a thermosteric anomaly equal to 250-350 cl/t, a lower core at 150-250 cl/t, and the deep flow mentioned earlier. The most stable part of the flux is the deepest part, which is formed of water originated at intermediate depth in the Southern Hemisphere, and also the lower core, which is a mixture of Equatorial Water and North Equatorial Countercurrent Water. The least stable part is the shallowest, composed of surface and subsurface water of both the Northern and the Southern hemispheres (Table 3).

It is interesting to compare these measurements to those made farther east, at 150°W, by Montgomery and Stroup (1962), who computed a flux of 34×10^6 m^3 sec^{-1} relative to 300 dB; this flux is comparable to that found during cruise Cyclone 4 of the research vessel *Coriolis*.

It can be seen from Table 4 that the flux above the 350-cl/t isanosteric surface decreased from west to east; in the

TABLE 3 Variations of the Flux in the Five Main Layers of the Undercurrent

Layer	Thermosteric Anomaly (cl/t)	Flux (10^6 m^3 sec^{-1}) Cyclone 2	Cyclone 3	Cyclone 4	Cyclone 5	Cyclone 6
Upper core	>450	3.4	0	3.0	12.0	4.1
Minimum of flux	350–450	1.1	0	5.3	11.1	3.2
Salinity maximum	250–350	3.6	2.8	9.7	10.8	4.0
Lower core	150–250	7.8	5.5	12.2	13.3	12.2
Deep flux	<150	4.4	3.4	4.0	6.1	4.0

TABLE 4 Comparison of the Fluxes at 150°W and 170°E (10^6 m^3 sec^{-1})

	Layer (cl/t)	Increase to the East		Unchanged		Decrease to the East			
Longitude	150	150–200	200–250	250–300	300–350	350–400	400–450	450–500	500–550
150°W	1.9	9.4	7.8	4.9	5.0	2.8	1.9	0.7	0.0
170°E	4.0	6.8	5.4	4.8	4.9	3.9	2.0	1.0	2.0

layer of the salinity maximum, the east and west fluxes were the same, and in the core layer and below there was an increase from west to east. The difference between the east and west fluxes below 150 cl/t is probably due to the fact that the flux obtained from data of cruise Cyclone 4 has been evaluated to 400 m. Finally, it seems that the undercurrent cools as it moves to the east.

EQUATORIAL UPWELLING

In the western part of the Pacific Ocean, cooling of the equatorial surface waters by upwelling has seldom been observed, except at 150°E at the beginning of the year. Nevertheless, the atlases of temperature distribution at the surface indicate that there could be an extension to 170°E of the equatorial upwelling, but at the beginning of the year only. Thus, it could be considered that enrichment of the upper layers of this region of the Pacific is unlikely, in spite of the fact that the average wind has a noticeable westward component.

During all the cruises of the research vessel *Coriolis* along 170°E, the wind observed in the equatorial region had a westward component stronger than 2 m sec^{-1}, except in December 1965 and in June 1966, when it blew for short periods from the west. The Ekman transport, as observed from the drift of the ship and from the direct current measurements, was in the direction of the wind, except in April 1967, when, as observed during cruise Cyclone 3, the surface current flowed toward the east, in spite of a rather strong westward wind. During June and September 1966, a tendency for a surface divergence to exist at the equator has been noted.

Thus, in most places and at most times, conditions were such as to induce a surface divergence, and a divergence was indeed observed during most of the cruises (Figure 4). The vertical distribution of temperature in the upper 100 m, between 4°S and 4°N, gives a good picture of the surface circulation; it indicates that there was upwelling during all cruises except those of December 1965 (cruise Bora 1) and of April 1967 (cruise Cyclone 3). During these two cruises, on the contrary, the eastward surface current induced a convergence, which was responsible for the low flux of the undercurrent measured during cruise Cyclone 3.

The vertical distribution of the nutrients phosphate and nitrate confirms that there is effectively an upwelling, with enrichment of the upper layer at the equator. During the two intervals when there was a convergence, the surface waters were poorer in nutrients and no enrichment at the equator relative to the adjacent waters was observed.

The flux minimum of the Equatorial Undercurrent, observed during cruise Cyclone 3 in April 1967, is directly bound to the particular structure of the currents during this period. On all the other cruises, the direct measurements indicated that the westward flow at the surface is very shallow and does not extend, at the equator, deeper than 60 m.

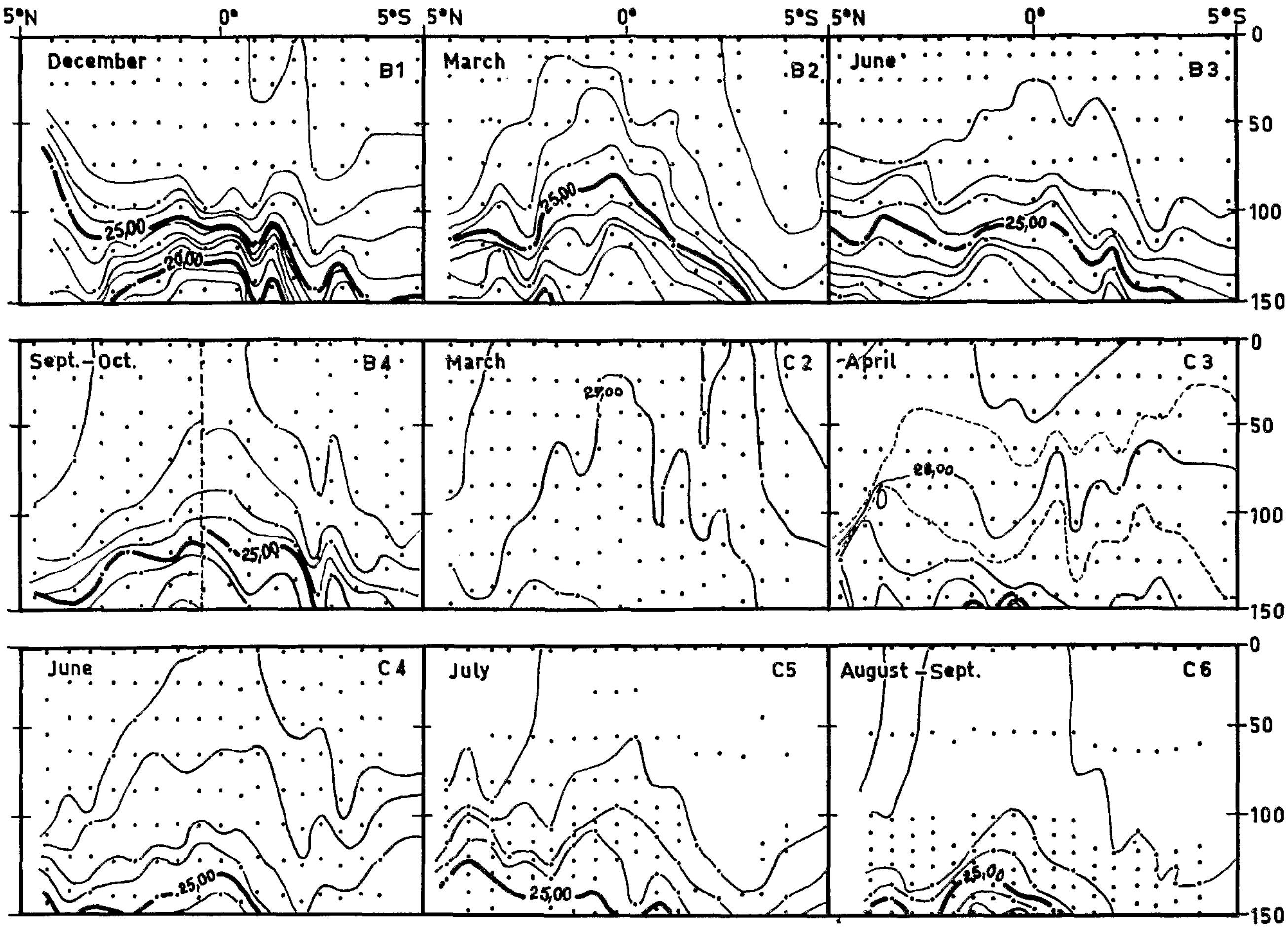

FIGURE 4 Vertical distribution of temperature (°C) in the upper 150 m, at 170°E, during various cruises of the research vessel *Coriolis*. (Reprinted with permission from Rotschi, 1968.)

Below this depth, there is a continuous flow to the east down to a depth of at least 300 m. Farther north and south, the eastward current extends much deeper. During cruise Cyclone 3, when the flux of the undercurrent was smallest, the vertical structure at the equator was different: The Equatorial Undercurrent proper existed only between 200 m and 300 m; in the upper 100 m, between 2°N and 2°S, there was a flow to the east; in the intermediate layer (100–200 m), the flow was to the west. Thus, in the presence of a surface convergence, the undercurrent was deprived of its shallower part, which is composed of warm and less saline water; this loss, added to the obvious slackening of the speed at the core, was responsible for the considerable decrease of the flux.

SOUTH EQUATORIAL COUNTERCURRENT

Jarrige (1968), in a preliminary study of the data of all the cruises of the research vessel *Coriolis* from the point of view of the geostrophic circulation, found a permanent eastward component of the surface current relative to 1,000 dB. This flow, located near 10°S, corresponds to the South Equatorial Countercurrent, shown in various atlases of the surface circulation and reported by Reid (1959).

The characteristics of this flow are highly variable (Table 5). Its depth was found to be near 200 m on one cruise, 300 m on two others, and greater than 500 m on all others. Nevertheless, the velocity core, with a velocity of 10–30 cm sec^{-1}, has always been very close to the surface. The average width of this eastward component of the surface current is 560 km, varying between 330 km and 620 km; the southern boundary, which is bound to a permanent lessening of the westward component of the wind, does not vary much in latitude, whereas the northern boundary varies much more. Moreover, the upper 100 m of the current is always associated with a salinity minimum having salinity values between 34.00‰ and 34.80‰.

The existence of this current has been confirmed by the capture at 10°S, 170°E, of *Euphausia fallax*, which origi-

TABLE 5 Characteristics of the South Equatorial Countercurrent at 170°E (after Jarrige, 1968)

Cruise	Date	Extreme Latitude	Depth (m)	Maximum Velocity (cm/sec)	Latitude of the Velocity Maximum	Width (km)	Volume Transport (10^6 m^3 sec^{-1})	Salinity Minimum (‰)	Drift of the Ship
Bora 1	Dec. 1965	7°00′ S–12°15′ S	160	12	9°45′ S	580	2.2	34.6	–
Bora 2	March 1966	4°00′ S–10°15′ S	>500	31	7°50′ S	695	19.6	34.3	6°00′ S–5°00′S 1 knot–ENE
Bora 3	June 1966	5°50′ S–12°05′ S	>500	24	6°50′ S	685	9.6	34.5	
Bora 4	Sept.-Oct. 1966	7°30′ S–10°25′ S	>500	29	8°00′ S	330	8.8	34.7	9°00′S 0.2 knot–E
Cyclone 2	March 1967	8°20′ S–12°10′ S	>500	31	9°40′ S	410	18.6	34.8	10° 30′ S–9° 00′S 0.8–1.0knot–E
Cyclone 3	April 1967	5°00′ S–12°45′ S	>500	22	6°00′ S	930	14.7	34.2	9°00′S 1.5–2.0 knot–SE
Cyclone 4	June 1967	8°45′ S–13°05′ S	>500	20	12°00′ S	480	12.4	34.0	
Cyclone 5	July 1967	9°20′ S–13°00′ S	280	21	12°00′ S	410	6.6	34.8	11°30′S–11°00′S 1.0 knot–E
Cyclone 6	August 1967	8°25′ S–13°10′ S	220	15	9°00′ S	540	3.4	34.8	–

nates north of New Guinea, and by the capture at about the same location of very young stomatopod larvae that could have originated only in the northern part of the New Hebrides archipelago. Recent GEK measurements indicate that in May 1968 there was an eastward drift at the latitude of the geostrophic South Equatorial Countercurrent. Finally, star fixes and dead reckoning always indicated an eastward drift of the ship at the latitude where the geostrophic eastward current exists.

THE HYDROLOGICAL STRUCTURE OF THE EQUATORIAL UNDERCURRENT

Knauss (1960) has noted that in the core of the Equatorial Undercurrent oxygen content did not vary and that this homogeneity can be considered to be an indication of a fairly strong vertical mixing process within the core of the undercurrent.

A close examination of the measurements made along the equator from the research vessel *Coriolis* during its Alize cruise (Rotschi *et al.*, 1967), however, shows that the core of the undercurrent is not really homogeneous in oxygen content; on the contrary, there is an oxygen minimum at the upper boundary of this layer and a maximum at its lower boundary, the increase from the minimum to the maximum amounting to about 0.10 ml/l (Figure 5). It seems somewhat surprising that a mechanism of vertical mixing could create such a distribution. A further detailed study of the hydrological structure of the undercurrent has shown that in the same layer, where the oxygen content is apparently constant, the concentrations of nitrate and of phosphate increase substantially with depth. In fact, it was observed at 170° in July 1967 (Pickard and Rotschi, 1968), that in the core, where the speed was higher than 50 cm sec^{-1}, there was a chemical two-layer system. In the upper layer, a little less than 100 m thick (between 100 m and 200 m in depth) and lying between two thermal inversions, the oxygen decreased with depth (Figure 6). In the lower layer, at depths between 200 m and 300 m, oxygen increased slightly with depth. In both layers, nitrate and phosphate increased with depth, but in the deeper one, the gradient was greater.

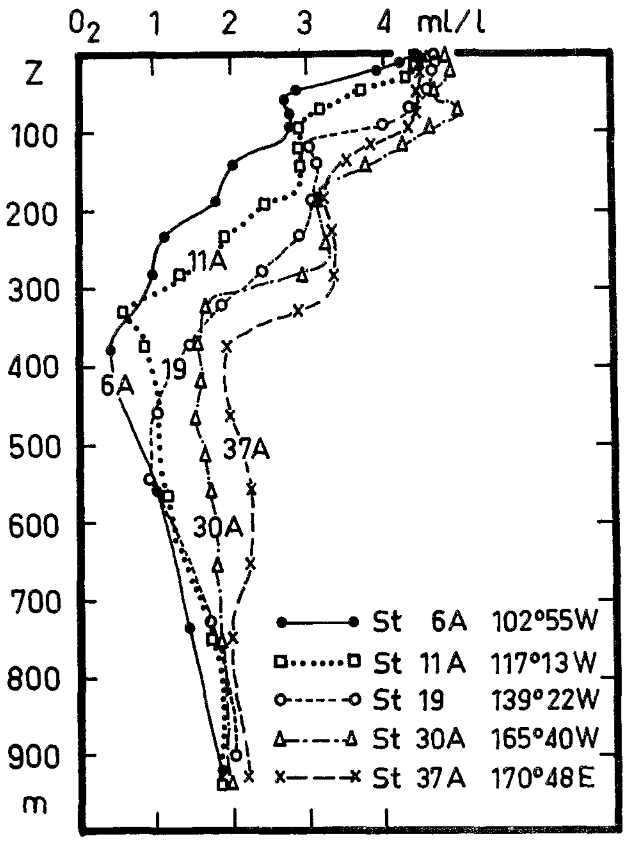

FIGURE 5 Vertical distribution of oxygen along the equator. (Reprinted with permission from Rotschi and Wauthy, 1969.)

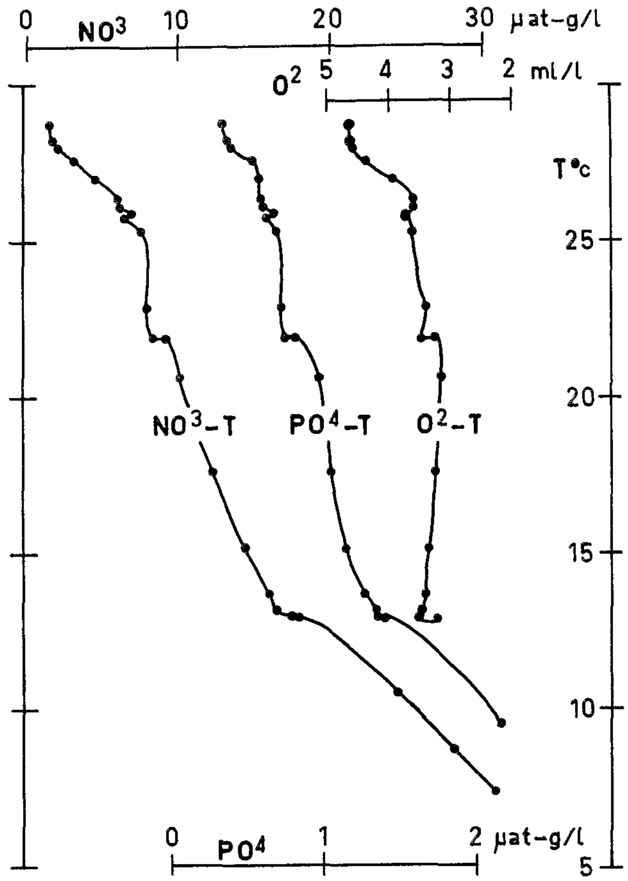

FIGURE 6 Oxygen-temperature, phosphate-temperature, and nitrate-temperature diagrams at the equator and 170°E in July 1967. (Reprinted with permission from Pickard and Rotschi, 1968.)

Such a stratification and such different depth variations of the concentrations of variables that are bound to each other do not support belief in strong vertical mixing. They suggest, on the contrary, that in the western Pacific, at least, the water of the core of the Equatorial Undercurrent is stratified and that the stratification is favored by stable, quasipermanent thermal inversions.

Thus, it could well be that the apparent oxygen homogeneity of the undercurrent water is due to the formation of this current from different water sources at different depths that have approximately the same oxygen content purely by chance. This view is supported by Tsuchiya (1967) and by his analysis of oxygen distributions on the 160-cl/t isanosteric surface. Recent studies undertaken at the Centre O.R.S.T.O.M. of Nouméa have shown that the undercurrent can be formed in its upper part by Tropical and Subtropical Water of the south Pacific, crossing the equator north of New Guinea, and by water of the North Equatorial Countercurrent. As for the lower part, the same studies confirm Tsuchiya's suggestion that the Coral Sea is a likely source region.

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