

# Comparison of the Hydrographic Structure of Equatorial Waters North of New Guinea and at 170° E<sup>1</sup>

Philippe Hisard, Yves Magnier,  
and Bruno Wauthy

Centre O.R.S.T.O.M.  
B.P. 4  
New Caledonia

## ABSTRACT

The Equatorial Undercurrent was observed from March through August 1967 on a transect along 170°E during five cruises of the R.V. CORIOLIS. The velocity structure changed markedly from cruise to cruise. The minimum volume transport,  $15 \times 10^6 \text{ m}^3/\text{sec}$ , was observed in May; the maximum volume transport,  $55 \times 10^6 \text{ m}^3/\text{sec}$ , was observed in July. These changes were accompanied by equally marked changes in other hydrographic features. An attempt is made to compare and relate the observed variations along 170°E with the variations north of New Guinea, particularly in the North Equatorial Countercurrent.

*Introduction.* Tsuchiya (1968) has observed that, in the western Pacific, it is usually difficult to distinguish clearly the Equatorial Undercurrent from the North Equatorial Countercurrent north of it. Throughout the western Pacific Ocean these two currents are connected by a continuous layer of eastward-flowing water, but downstream (eastward) these currents are progressively farther apart (Montgomery 1962). It is of interest, therefore, to compare the hydrographic structure of the waters north of New Guinea with that of the waters at 170°E.

*The Hydrography North of New Guinea.* The pattern and strength of the surface currents north of New Guinea vary markedly during the year (Fig. 1). These variations are induced by meteorological changes associated with the monsoon rhythm. In July, the North Equatorial Countercurrent reaches its maximum strength when it is fed (i) by the Mindanao Current, which originates in the North Equatorial Current, and (ii) by the South Equatorial Current,

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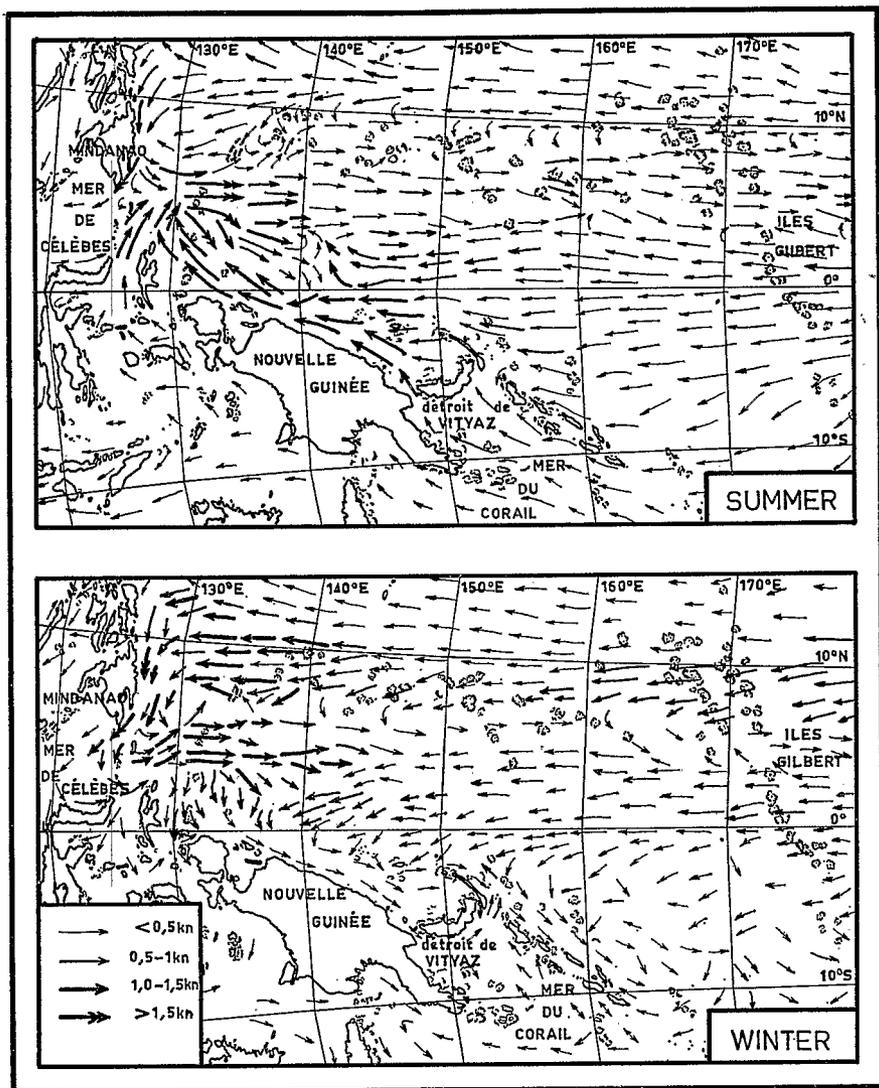


Figure 1. Surface currents north of New Guinea. Upper part: summer; lower part: winter. (From Morskoï Atlas).

which flows along the northern coast of New Guinea up to Halmahera. In January, however, the Countercurrent is minimal in strength, since it receives water from only the north; the South Equatorial Current deteriorates in the face of increasing northwest winds and the Countercurrent loses water to the New Guinea Coastal Current. Thus, in July the North Equatorial Counter-

current is influenced by both northern and southern waters (the latter with relatively high salinity), but in January the Countercurrent is influenced by only the northern water (with decreased salinity along Mindanao and in the Celebes Sea).

Tsuchiya (1967) believes that the water mass north of New Guinea is the northern boundary of the Coral Sea water that passes through the Vityaz Strait. However, the lack of data from a southern station in July makes it impossible to determine whether the South Equatorial Current along the northern coast of New Guinea helps in the spreading of Coral Sea water.

According to Yamanaka et al. (1965), the major seasonal and long-term variations in the Countercurrent, in addition to the variations in transport, are the geographical positions of the Countercurrent's northern and southern edges; between  $130^{\circ}\text{E}$  and  $140^{\circ}\text{E}$ , the southern edge fluctuates between  $2^{\circ}\text{N}$  and  $4^{\circ}30'\text{N}$ . Yamanaka et al. (1965) in determining that the Countercurrent reaches its maximum transport in June–July, has confirmed Wyrski's (1961) observations and has provided evidence of the relative regularity in the annual variation in the volume transport. Burkov et al. (1960) have shown that the southern edge of the Countercurrent plays an important part in the interaction of the Countercurrent and the Undercurrent as the edge of the former sinks equatorward. These workers have also noted that the eastward flow of the Countercurrent is 700 km wide at the surface and 1200 km wide at 500 m; the interaction of these two currents, which are strengthened by their relative positions with depth, is not limited to the western Pacific but must be significant across the entire ocean because of the convergence observed at the surface along the southern edge of the Countercurrent across the entire ocean (Burkov 1963, 1966).

By considering the two equatorial sections occupied by the VITYAZ along  $142^{\circ}\text{E}$  in April 1958 and along  $140^{\circ}\text{E}$  in July 1957 (cruises 27 and 25; Burkov and Ovchinnikov 1960a), it is possible to demonstrate the variations previously described. During April and July, which represent opposite seasons, the surface circulation is different and typical. In both April and July (Figs. 2 and 3, respectively), the salinity distributions show the extension of a high-salinity tongue of South Pacific subtropical water across the equator to the north at 150 m. The northern boundary of this tongue constitutes a strong salinity gradient enclosed approximately by the 35‰ isohaline. In April, at 150 m, this boundary extends to  $3^{\circ}\text{N}$  whereas at 250 m it is close to the equator. However, in July, at a depth of about 120 m, the high-salinity tongue reaches to only  $2^{\circ}\text{N}$ ; but farther north, between  $5^{\circ}\text{N}$  and  $6^{\circ}\text{N}$ , at 120 m, there is an isolated high-salinity core that provides a higher salinity in the Countercurrent waters.

Figs. 2 and 3 also show the oxygen distributions, which illustrate the mixing processes at the southern edge of the Countercurrent. North of the equator, in April, when the convergence is weak due to the lesser flow of the Counter-

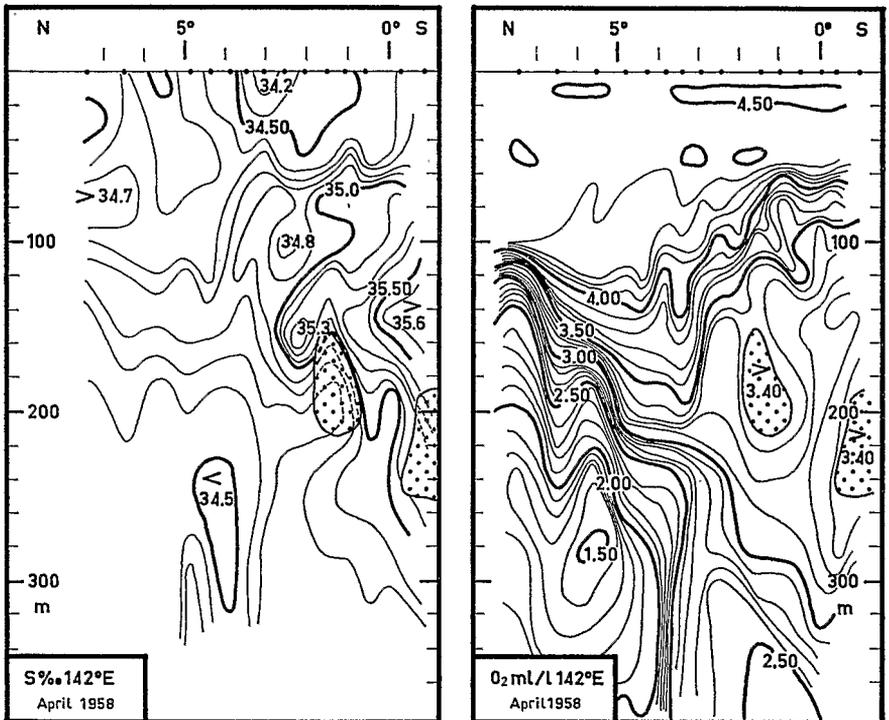


Figure 2. Salinity distribution (left) and oxygen distribution (right) along 142°E, April 1958. (VIRYAZ: cruise 27). Dotted areas indicate the 3.40 ml/l oxygen-content cores.

current, water of high oxygen content does not sink but forms a single core that remains at the same latitude as the salinity front; this oxygen core, with a salinity lower than 35.0‰, appears to originate from Countercurrent water. South of the equator, in April, at a depth of 200 m to 250 m, there is another core of high oxygen content that is richer than 3.40 ml/l; this core contains water having a salinity higher than 35.0‰. In July, at about 2°N, it is obvious that the subsurface oxygen isopleths slope downward and southward.

Fig. 4 shows the current-velocity structure obtained by direct measurements during April along 142°E; this permits clear identification of the Undercurrent, whose core has a velocity up to 20 cm/sec at a depth of 200 m. At this time, the North Equatorial Countercurrent, extending north to 2°N, flowed at speeds as high as 30 cm/sec at depths between 100 m and 200 m. Evidence for the existence of convergence between the two currents has been presented by Burkov and Ovchinnikov (1960b).

The eastward-flowing Undercurrent, with speeds greater than 10 cm/sec, has salinity values that range from 34.70 to 35.30‰, and the upper part of

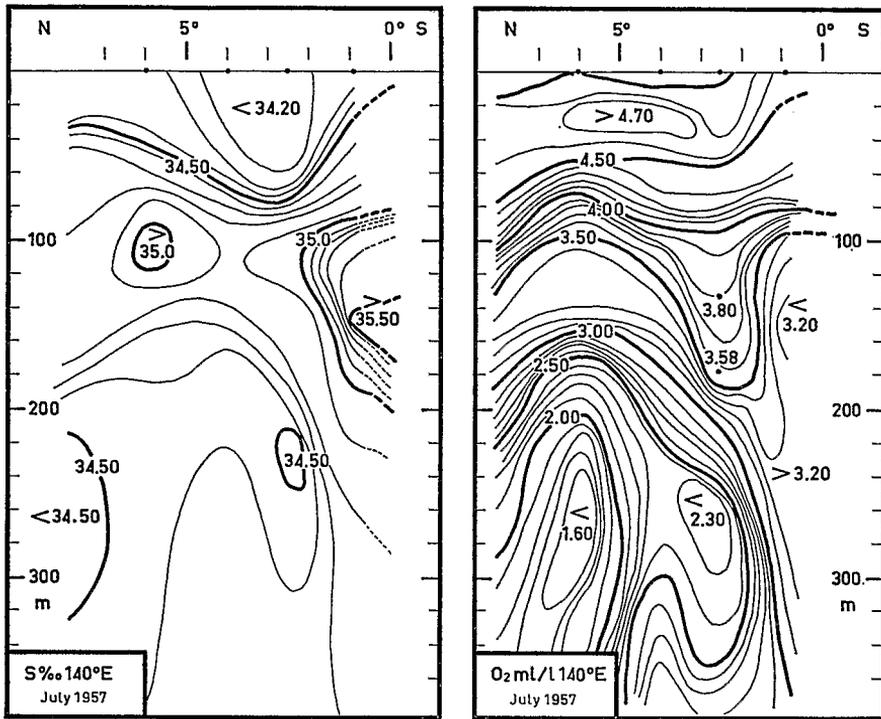


Figure 3. Salinity distribution (left) and oxygen distribution (right) along 140°E, July 1957. (VITYAZ: cruise 25).

the Undercurrent is associated with the northern core of oxygen at 2°N while the lower part is associated with the deep southern oxygen core. Thus, although the oxygen content of these two cores is the same, about 3.40 ml/l, their salinities are very different. It is possible that these two oxygen sources, with different origins but with the same value, could account for the oxygen homogeneity of the Undercurrent described by Knauss (1960).

In summary, it appears that the Undercurrent in the vicinity of 140°E, north of New Guinea, is composed of two different water masses as judged by the oxygen and salinity values. On the one hand, the Undercurrent is associated with the Countercurrent water in July when this mass is more oxygenated by mixing processes along the convergence at the southern edge of the Countercurrent. On the other hand, at the same time, the Undercurrent is associated with Coral Sea water that reaches the equatorial zone north of New Guinea. It is possible that the seasonal hydrographic variations that determine changes in the Countercurrent water have an effect upon the oxygen distribution in the upper northern part of the Undercurrent, with this variation in oxygen content being related to changes in the volume transport.

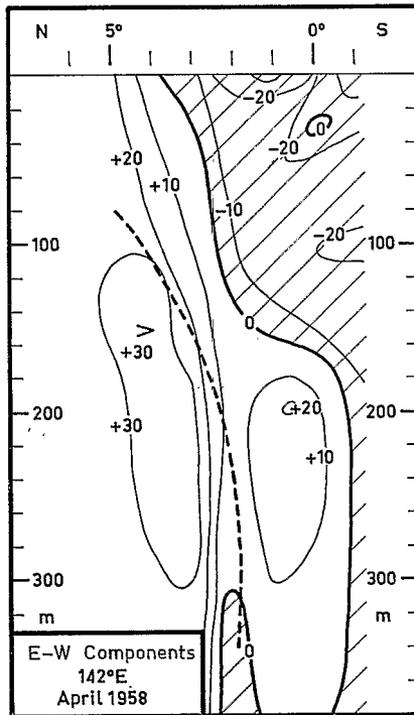


Figure 4. East-west velocity cross section at  $142^{\circ}\text{E}$  in April 1958. After Burkov 1960. Plus values are eastward velocities. Dotted line indicates an axis of convergence.

*The Hydrography along  $170^{\circ}\text{E}$ .* In 1966 and 1967, respectively, the R.V. CORIOLIS made four cruises in the "Bora" series and five cruises in the "Cyclone" series along transects at  $170^{\circ}\text{E}$ . The hydrographic data collected on these cruises have been published (Lemasson et al. 1967a and b, Magnier et al. 1967, Rotschi et al. 1967, Hisard et al. 1968, Jarrige et al. 1968, Magnier et al. 1968, Rotschi et al. 1968). The results from current meters will be published by the O.R.S.T.O.M. Centre of Noumea. On each cruise, the vessel occupied 10 hydrographic stations from  $20^{\circ}\text{S}$  to  $4^{\circ}\text{S}$  and 17 stations from  $4^{\circ}\text{S}$  to  $4^{\circ}\text{N}$ . The sections between  $4^{\circ}\text{S}$  and  $4^{\circ}\text{N}$  were completed in eight days in 1966 and in only four days in 1967 to minimize time variations; the equatorial stations were occupied on 11 March, 26 April, 6 June, 12 July, and 25 August.

At each hydrographic station, 24 samples from 0 to 500 m were collected and the 24 bottles were spaced to obtain close samples of the characteristic bathythermic structure. Temperature, salinity, oxygen, phosphate, nitrate and nitrite content were measured at each depth. In 1967, between  $4^{\circ}\text{S}$  and  $4^{\circ}\text{N}$ , direct current measurements were obtained with two current meters having Savonius rotors. These meters were spaced 1000 m apart on the same wire,

the wire angle being kept minimal at the surface. The current was then calculated as the vector difference between the reading on the upper meter (between 0 and 500 m) and the reading on the lower meter (assumed to be located in a region of relatively small current).

Fig. 5 shows the east-west velocity fields on the five 1967 sections. The Undercurrent is clearly identified; it is connected to the Countercurrent by the continuous layer of eastward-flowing water during all the pertinent months. The velocity at the core was 50 cm/sec in March, 40 cm/sec in April, 70 cm/sec in June, 90 cm/sec in July, and 60 cm/sec in August. On each cruise the maximum velocity was found near the equator at about 200 m. The volume transport of the Undercurrent fluctuated noticeably. The transport has been calculated down to a depth of 400 m and to a southern limit of 4°S. Northward the limit of integration was the constriction between the Undercurrent and the Countercurrent. The eastward transport within these limits was:  $20 \times 10^6 \text{ m}^3/\text{sec}$  in March,  $15 \times 10^6 \text{ m}^3/\text{sec}$  in April,  $40 \times 10^6 \text{ m}^3/\text{sec}$  in June,  $55 \times 10^6 \text{ m}^3/\text{sec}$  in July, and  $25 \times 10^6 \text{ m}^3/\text{sec}$  in August. Knauss (1960, 1966), at 140°W, obtained an Undercurrent transport of  $40 \times 10^6 \text{ m}^3/\text{sec}$  in April 1958 and of  $22 \times 10^6 \text{ m}^3/\text{sec}$  in September 1961. Yosida et al. (1959) have given an eastward transport evaluation of  $71 \times 10^6 \text{ m}^3/\text{sec}$  for January 1958 at 150°E, but it is not clear whether this was for only the Undercurrent eastward flux.

Wyrski (1961) has observed that the Countercurrent transport is maximum between June and September. Since we did not extend our measurements far enough to the north, we have little information about the Countercurrent at 170°E. However, we might note that, within the limits of our measurements along 170°E, the Undercurrent from March through August 1967 showed important transport variations, with a sharp maximum in July, and that these variations are similar to those of the Countercurrent north of New Guinea.

The eastward flow that connects the two currents is always associated with a zone of divergence for the north-south velocity component. At 170°E, the waters of the two currents would therefore tend to spread farther apart rather than mix. Consequently, the identifiable common hydrographic features of these two currents at 170°E cannot result from exchanges but must develop farther west where there is more interaction between the currents. The permanence of this divergence at 170°E at the level where the currents are connected does not agree with Burkov's hypothesis (1963) of continuous exchange all along the equator.

A salinity front associated with the 35‰ isohaline is a permanent feature of the area from 0° to 4°N. This front may be considered as a boundary between the low salinities of the Countercurrent and the higher salinities of the South Pacific subtropical water that extends across the equator. These features are similar to those observed at 140°E.

In Fig. 6, the superimposed cross sections of salinity and density show that the general trend of the isanosteres is usually normal to the frontal zone. This

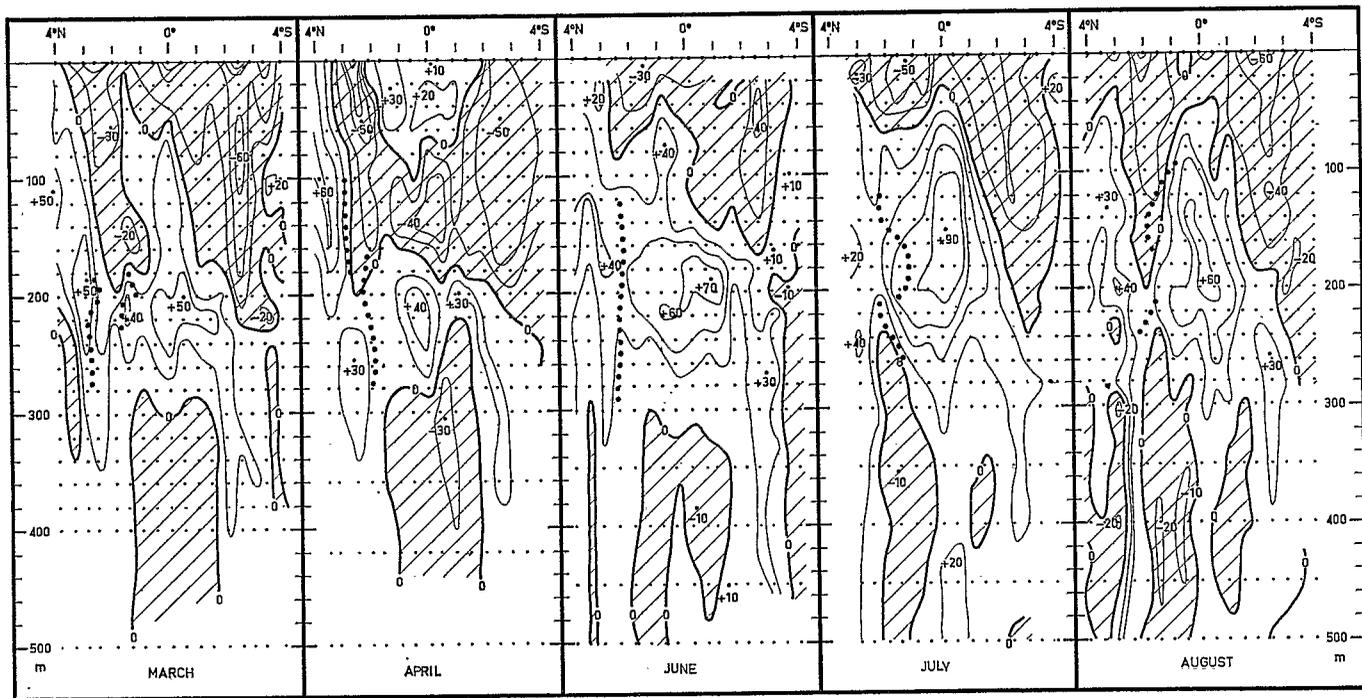


Figure 5. East-west velocity cross sections for the five cruises in March, April, June, July, and August 1967 at  $170^{\circ}\text{E}$ . Unit is cm/sec. Plus values are eastward velocities. Dotted lines indicate north-south divergences in the zone of connection.

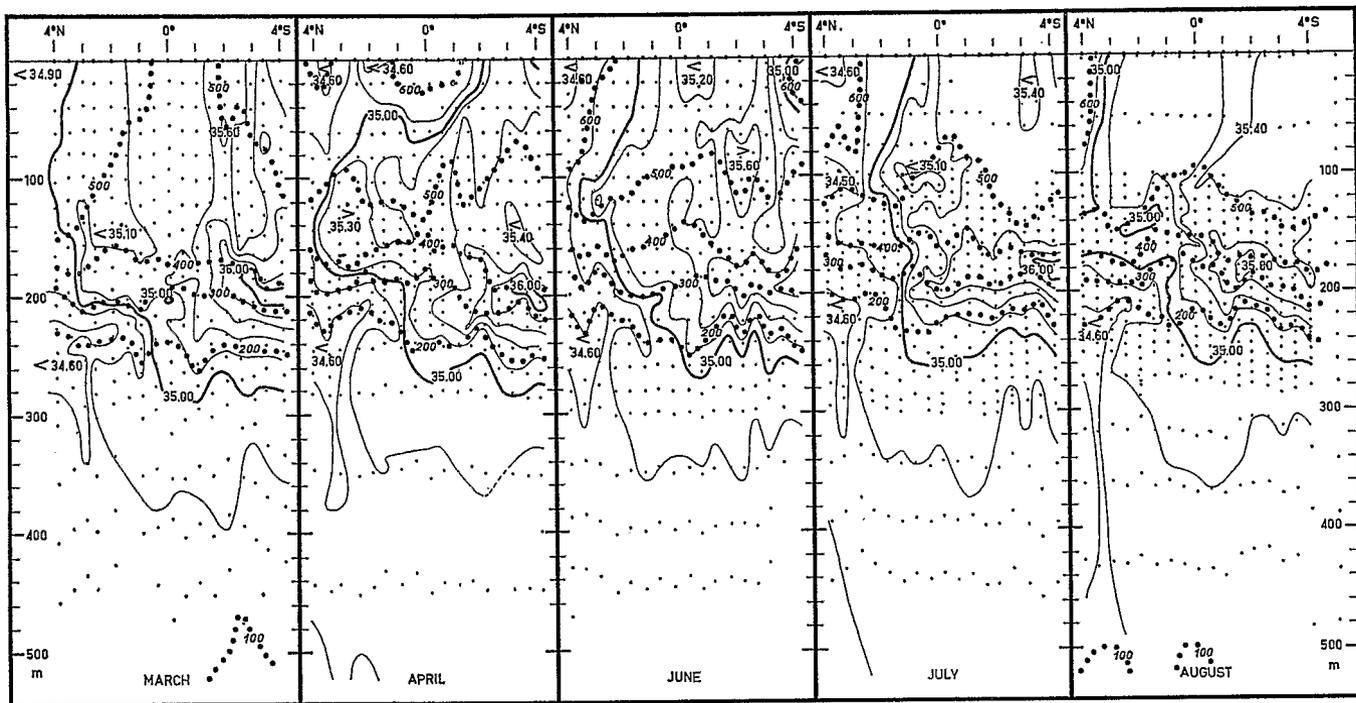


Figure 6. Salinity distributions for the five cruises in March, April, June, July, and August 1967 at  $170^{\circ}\text{E}$ . Isohalines every  $0.20\text{‰}$ . Dotted lines are isanosteres for every 100 cl/t.

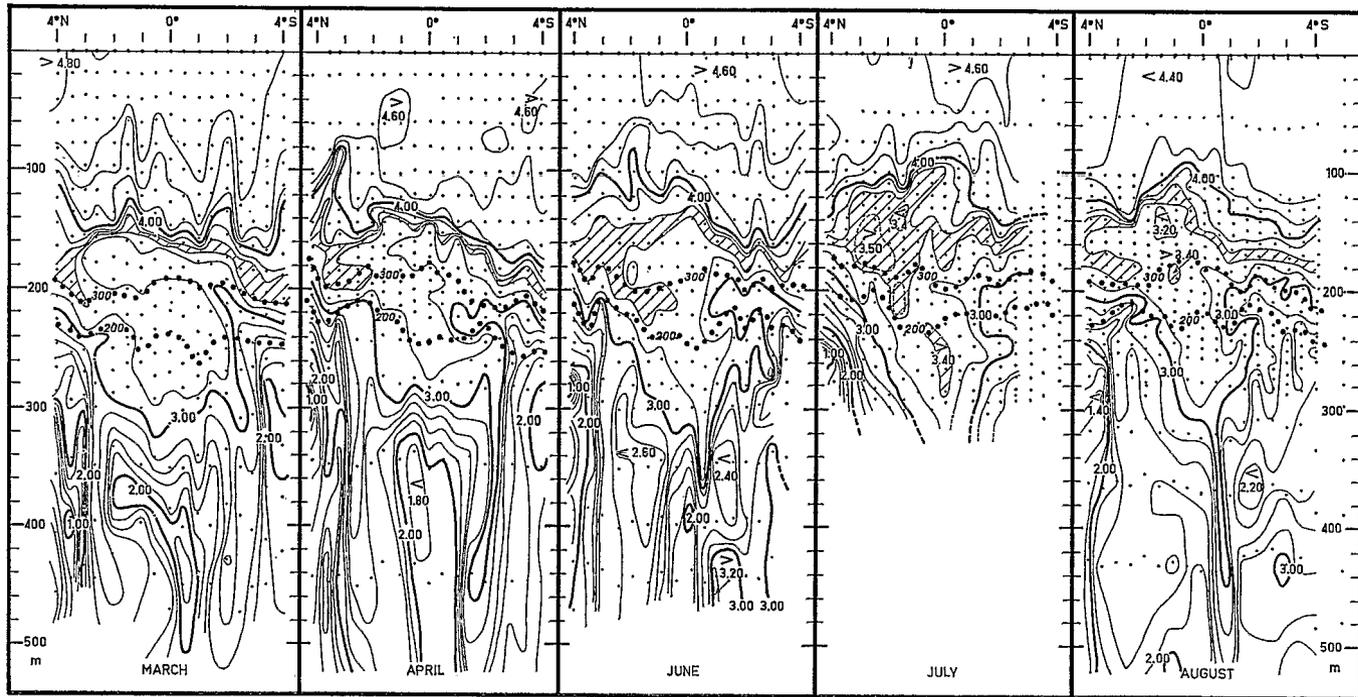


Figure 7. Oxygen distribution for the five cruises in March, April, June, July, and August 1967 at 170°E. Isohalines every 0.20 ml/l. Hatched areas indicate the 3.40-3.60 ml/l oxygen-content layer. Dotted lines indicate the isanosteres for 200 and 300 cl/t.

structure may represent the isentropic northward extent of the subtropical water mass. From March to July, the salinity front moves equatorward, and low-salinity water is then preponderant north of  $0^{\circ}$ , reflecting the greatest extent of the water of Countercurrent origin.

It is difficult to determine an average value for the Undercurrent salinity, which varies considerably. In March the velocity core coincided with an isolated core that had a salinity of less than  $35.0\text{‰}$  whereas in July the core was associated with the high-salinity tongue that was moving northward. Thus the salinity in the velocity core rose from  $35.0\text{‰}$  to about  $35.70\text{‰}$  between March and July; this increase is parallel to the increase in velocity and transport that is associated with the Countercurrent evolution north of New Guinea, where we have noted a maximum of transport and a salinity increase due to the contribution from the South Equatorial Current in July.

Fig. 7 shows that in March an oxygen area richer than  $3.40\text{ ml/l}$  appeared at a depth of about  $200\text{ m}$  near  $4^{\circ}\text{N}$  at  $170^{\circ}\text{E}$ ; this area lay along the salinity front in a manner similar to that noted at  $140^{\circ}\text{E}$ . From March to July, this oxygen core extended equatorward, and in July it covered most of the zone between  $0^{\circ}$  and  $4^{\circ}\text{N}$  at depths between  $100\text{ m}$  and  $200\text{ m}$ . This spreading occurred along the  $300\text{ cl/t}$  isanostere.

In summary, some relatively important variations have been observed in the hydrographic features of the Undercurrent along  $170^{\circ}\text{E}$  from March through August 1967. These variations are associated with strong variation in eastward transport and they may be associated with the Countercurrent variations north of New Guinea.

*Composition of the Equatorial Water Mass.* The equatorial zone is bounded on the south and north by characteristic water masses. (i) That on the south is the "Western Central South Pacific" water mass (Sverdrup et al. 1942), with a temperature-salinity curve that is essentially a straight line between the salinity maximum of South Pacific Subtropical water and the salinity minimum of the Antarctic Intermediate Water. (ii) That on the north characterizes an Equatorial Countercurrent water mass with an almost linear and isohaline T-S curve and with a uniform salinity of  $34.6\text{‰}$  to  $34.9\text{‰}$ . The T-S curve for the Countercurrent water mass can be modified in the downstream direction by the salinity maximum of the subtropical water mass.

In the westernmost part of the Pacific, instead of the Western Central South Pacific water mass there is the Coral Sea water mass (Rotschi and Lemasson 1967) which, at depth, is more saline and has a higher and more uniform oxygen content than the western South Pacific mass.

Along  $170^{\circ}\text{E}$  in the equatorial zone, the T-S curve is intermediate between the T-S curve of the Western Central South Pacific mass and that of the Countercurrent water mass. The change with latitude from one to the other is very striking as it is shown on Fig. 8.

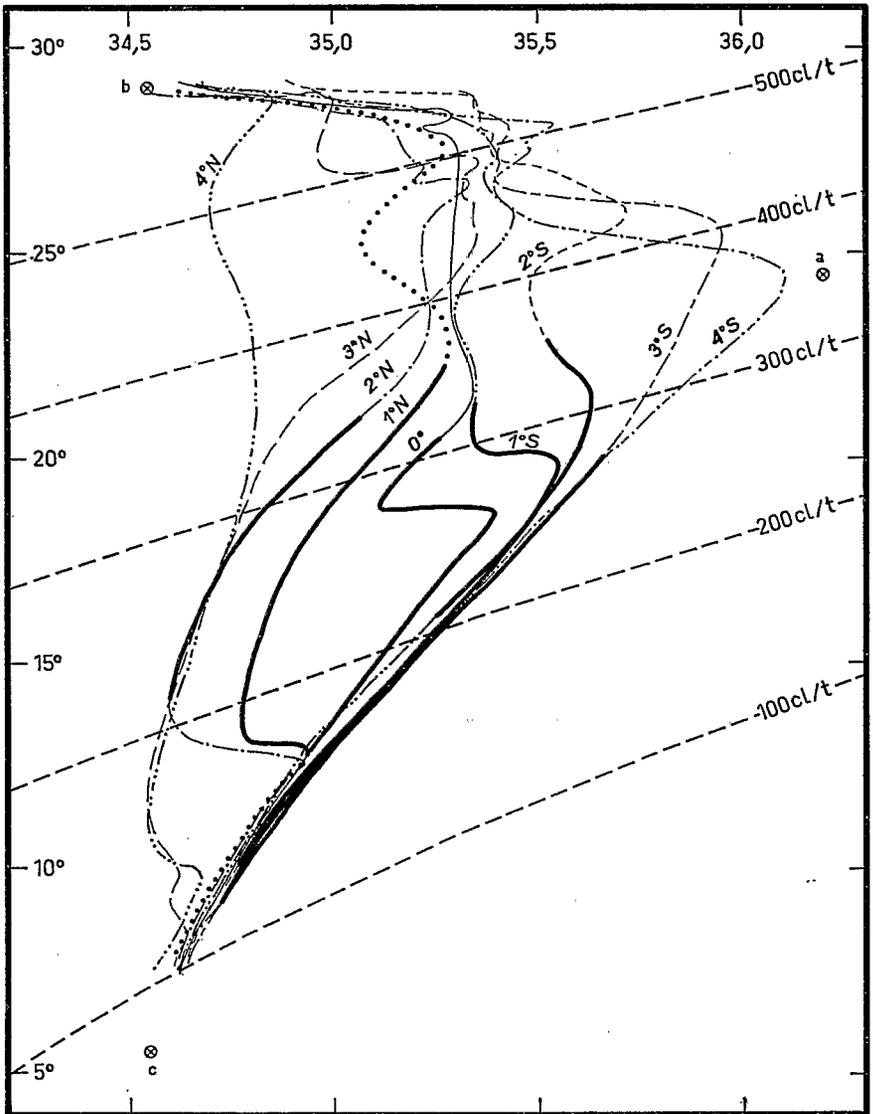


Figure 8. The temperature-salinity diagrams from  $4^{\circ}\text{S}$  to  $4^{\circ}\text{N}$ , at  $170^{\circ}\text{E}$  in April 1967. The portions of lines related to the Cromwell Current are thickened. a = South Pacific water, b = Countercurrent surface water, c = modified Antarctic Intermediate water.

*Conclusions.* In 1967, during cruises of the R.V. CORIOLIS, it was observed that the Equatorial Undercurrent was present at  $170^{\circ}\text{E}$  and that it evidenced strong variations in both eastward volume transport and hydrographic structure.

In March, the salinity in the velocity core was lower than 35.0‰ and the volume transport was  $20 \times 10^6 \text{ m}^3 \text{ sec}$ . In July, the salinity in the core was 35.70‰, the volume transport was about  $55 \times 10^6 \text{ m}^3 \text{ sec}$  (nearly three times that in March), and the velocity reached 90 cm/sec. Simultaneously, oxygenated water richer than 3.40 ml/l was spreading progressively equatorward at a depth of about 200 m. By July this spreading had reached its maximal extent, and a secondary core, highly oxygenated, was present at the equator at a depth of 250 m.

The variations at 170°E can be related to the mean change in the North Equatorial Countercurrent, the transport of which, in the northern hemisphere, is minimal in the winter and maximal in the summer. Furthermore, in the winter the Countercurrent consists mainly of water from the North Equatorial Current, the salinity of which is lowered along the course of the Countercurrent through the Celebes Sea. In the summer, on the other hand, the salinity of the Countercurrent is increased by contributions from the South Equatorial Current.

*Acknowledgments.* This paper presents the preliminary results of research on the equatorial current system carried out by the O.R.S.T.O.M. Centre of Noumea, under the direction of Mr. H. Rotschi. It is based on the results of five cruises representing nearly five months working at sea for all our colleagues. We are also indebted to Dr. George L. Pickard, University of British Columbia, who took part in one of these cruises and was also most helpful in subsequent discussions.

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