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Zonal Circulation in the Tropical Western South Pacific at 170°E*

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Abstract: Recent work made in the Tropical Western South Pacific along 170°E indicates that between 20°S and 5°S there are two permanent eastward countercurrents. One centered at about 9°S is the South Equatorial Countercurrent; it transports low salinity water which has also a minimum oxygen concentration and is nutrient rich. The other is centered near 17°30'S; its water has a low salinity but a high content in oxygen and low nutrient concentrations. The westward flow between them is composed of high salinity, highly oxygenated water. No seasonal variations of the intensity of the meridional extension, of the volume transport of these currents have been observed and it appears clearly that the South Equatorial Countercurrent is distinct from the current observed on the 125 cl/t surface. This zonal circulation can induce vertical displacements of water, the effect of which are seen on the nutrients vertical distributions. Between 9°S and 14°S and near 20°S there should be two zones where the productivity is more or less permanently higher than in the adjacent waters.

1. Introduction

In a recent review of the equatorial circulation of the South Pacific Ocean, TSUCHIYA (1968) has pointed out what he considered to be the main problems still to be solved concerning the zonal fluxes south of the equator. For him the actual knowledges suggest the existence of a permanent South Equatorial Countercurrent.

He questions the zonal continuity of this surface countercurrent through the entire South Pacific since it does not show on certain surface-current charts. Similarly, he raises some doubt as to whether the axis of this current shifts towards the south in the eastern Pacific, as suggested by REID (1959) since it has been observed near 6°S close to 90°W.

Until 1968, only a few direct measurements had been made; BURKOV and OVCHINNIKOV (1960) have measured, between 5°S and 8°S, at 172°E, a shallow countercurrent (less than 200 m deep) with a velocity core of 10 cm/s at the surface; at 176°W KOSHLIAKOV and NEIMAN (1965) have measured between 9°S and 11°S an eastward current extending to a depth of at least 1 000 m, with a velocity core at the surface of 20 cm/s. Further, the first authors indicate that the dynamic method leads to a deep eastward current (more than 2 000 m) at 172°E with a velocity core of 40 cm/s at the surface and approximately the same meridional extension; the other two give on the contrary a geostrophic current at 176°W extending from 7°S to at least 13°S and with a velocity core of 10 cm/s, its depth being not greater than 1 000 m. All the other indirect evidences of the South Equatorial current lead to a maximum speed of about 10 cm/s (TSUCHIYA 1968).

According to TSUCHIYA (1968) there are indications that the two eastward geostrophic currents observed at the surface and on the 125 cl/t isanosteric surface (REID 1961; WOOSTER 1961) can be sometimes distinct from each other and he points out finally that besides this particular aspect of

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the eastward circulation, one interesting question to be studied is the variations with longitude and with season of the South Equatorial Countercurrent.

JARRIGE (1968) has given some interesting details on the strongest geostrophic eastward flow which has been met between December 1965 and August 1967. The latitude of the velocity core ranges from 7°S to 12°S whereas that of the southern border ranges from 10°S to 13°S and that of the northern border between 4°S and 9°S. In most cases, the velocity core is close to the surface and to the northern limit of the countercurrent. The wider the current the more northerly the velocity core and the higher the volume transport the lower the surface salinity which ranges from 34.0 ‰ to 34.8 ‰.

Lastly, it must be stressed that this countercurrent could well not be the only eastward flow in the South Western Pacific. In fact BURKOV and OVCHINNIKOV (1960) have measured between 14°S and 25°S an eastward countercurrent with a velocity maximum of 40 cm/s at 20°S, the geostrophic current showing between 20°S and 28°S with a velocity maximum of 20 cm/s; the later is much shallower than the former.

2. Zonal Circulation at 170°E, between 20°S and 4°S

The nine cruises of the *R. V. Coriolis* referred to by ROTSCHI and LEMASSON (1968) and by JARRIGE (1968) plus an additional cruise along the same itinerary made in April-May 1968 throw some light on the zonal circulation in the Western South Pacific.

At the surface they show not only the permanence, near 10°S, of the South Equatorial Countercurrent, but also the existence further south, between 15°S and 20°S, of a second countercurrent (fig. 1). The existence now proved of a zonal circulation pattern in the Western South Pacific more complicated that the three currents system makes it necessary to pointed out by TSUCHIYA (1968) to revise the names of the equatorial currents. Provisionally in this

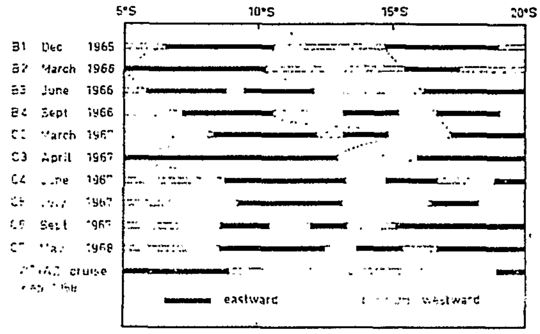

Fig. 1. Meridional extension of the zonal geostrophic currents observed at 170°E by the *R. V. Coriolis* from December 1965 to May 1968. Black line: current to the east; white line: current to the west. For comparison currents observed by the *"Vityaz"* in February 1958 are also given.

paper and in all the studies issued from our laboratory the word "current" applies to westward flowers and the word "countercurrent" to eastward flows. The name Equatorial Current designate the westward current which is at the equator (South Equatorial Current in SVERDRUP). The name South Equatorial Current is reserved to the westward flow south of the equator and which can be divided in several branches.

JARRIGE (1968) has commented the characteristics of the South Equatorial Countercurrent. One can remark that the small westward current which intervenes within the South Equatorial Countercurrent at cruises B3, C2 and C6, has a very low velocity, respectively 2 cm/s, 1 cm/s and 6 cm/s, and can be questioned since no account has been taken of the possible effect of the internal waves. The most northerly extension, beyond 5°S was observed in March 1966 cruise B2, in April 1967 cruise C3 and also by the *Vityaz* in February 1958.

The second countercurrent shown on all the sections, the zonal extension of which is unknown and which could be provisionally called the South Tropical Countercurrent since it is a permanent feature of the zonal circulation in this tropical re-

Table 1. Characteristics of the South Tropical Countercurrent at 170°E.

Cruise	Date	Limits	Maximum depth m	Maximum depth of the 10 cm/s isotach m	Maximum speed cm/s	Volume transport 10^6 m³/s
B 1	Dec. 65	15°S–19°S	200	50	15	4
B 2	March 66	15°30S–17°30S	300	140	20	5
B 3	June 66	16°S–20°S	500	—	4	1
B 4	Sept.-Oct. 66	16°30S–19°S	500	360	35	14
C 2	March 67	17°S–20°S	500	130	20	7
C 3	April 67	16°S–20°S	500	20	10	3
C 4	June 67	15°S–17°S	200	50	17	2
C 5	July 67	16°30S–18°S	100	—	5	0,5
C 6	August 67	15°S–20°S	500	160	17	7
C 7	May 68	17°S–20°S	500	—	9	3

gion, is slower, shallower and has a smaller meridional extension than the South Equatorial Countercurrent (Table 1). Its volume transport is also extremely small, usually below 10×10^6 m³/s. There is no apparent relation between the average latitude, the meridional extension or the volume transport of these two countercurrents. Nevertheless it could well be that the maximum velocity of three permanent currents which have been observed between 20°S and 5°S—the two countercurrents plus a westward current which is a branch of the South Equatorial Current—are bound and vary in the same way, the speedier being the South Equatorial Countercurrent and the slower the South Tropical Countercurrent (fig. 2). Thus, the absence of relation between the volume transport of the two countercurrents could be due only to the inaccuracy of the geostrophic method in the

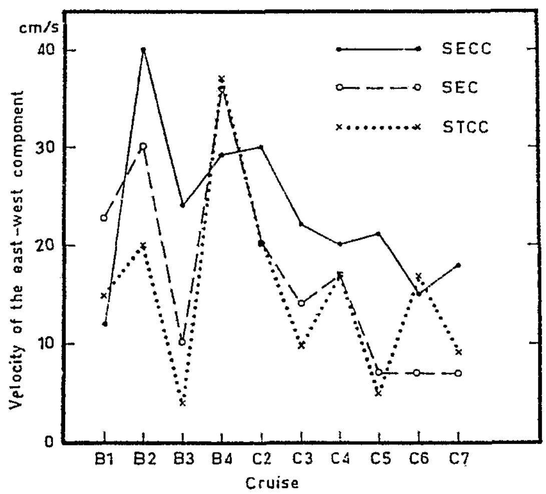

Fig. 2. Variation from cruise to cruise of the intensity of the east-west component of the permanent geostrophic currents observed between 20°S and 5°S. The three currents are: the South Equatorial Countercurrent, the South Equatorial Current and the South Tropical Countercurrent.

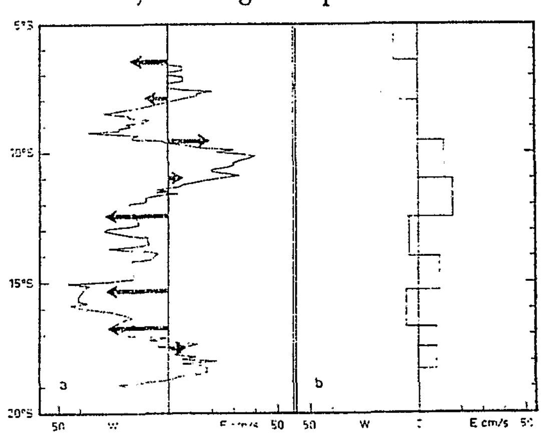

Fig. 3. Meridional distribution of the east-west component of the currents measured in April-May 1968 during the cruise C 7 of the *R. V. Coriolis.* (a)—G.E.K. measurements, b)—geostrophic currents. Arrows: measures with current meters.

evaluation of the true meridional extension and of the thickness of the currents.

This zonal geostrophic circulation which is supported by the direct measurements of BURKOV and OVCHINNIKOV (1960) has been confirmed by direct measurements of April 1968 during cruise C7 of the *R. V. Coriolis.* Measurements were made both with G. E. K. and with three Hydro-Product self-recording currentmeters according to the method described by MAGNIER, ROTSCHI, RUAL and COLIN (1969). The G. E. K. (Fig. 3) shows an eastward current between 9°30'S and 11°20'S, with a maximum velocity of 40 cm/s and another eastward current between 17°S and 18°45'S with a maximum velocity of 15 cm/s; the velocity core seems to be near the northern limit of the northernmost countercurrent and near the southern limit of the southernmost. In between, there is a westward current with a velocity maximum of 40 cm/s in the southern half of the current. North of the South Equatorial Countercurrent there is, between 8°S and 9°30'S, a westward current which can be seen also on all the vertical sections of the geotrophic currents of the *R. V. Coriolis.* Another weak eastward current has been measured between 6°30'S and 8°S.

The geostrophic circulation is slacker but the meridional distribution of the zonal component of the currents is quite similar. The South Equatorial Countercurrent shows at the same latitude but with a greater meridional extension both north and south and the South Tropical Countercurrent has the same extension but is displaced towards the north by half a degree. The South Equatorial Current appears as two bands separated by an eastward current, at about the same location where the G. E. K. measurements show a minimum of westward current at 14°S which at all events can be due to the fact that the westward drift of the ship under southeasterly wind with a speed of 7 m/s was compensated by an eastward geostrophic current. But the northernmost eastward current is replaced by a westward one. The direct measurements with currentmeters which were made at the same location as the hydrological station give an east-west component which is in good agreement with other measurements.

Neither the direct measurements, nor the indirect evaluations of the circulation give

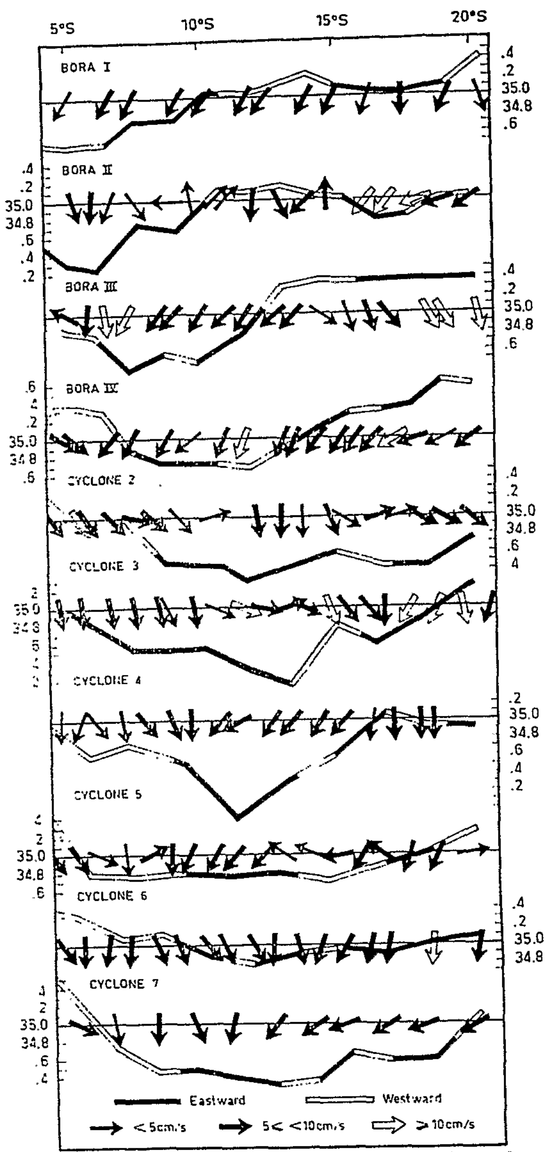

Fig. 4. Surface salinity observed during the cruises of the *R. V. Coriolis* along 170°E, in the westward currents and the eastward countercurrents. The arrows indicate the direction and strength of the observed winds.

any evidence of a shift of the countercurrent, in the direction of the equator, in the deep water. Thus, it seems now quite obvious that the surface South Equatorial Countercurrent is different from the subsurface one which has been observed on the 125 cl/t isanosteric surface at 5°S in the Western South Pacific (REID 1959, 1965). Direct measurements between 4°S and 4°N show a deep extension to the south of the Equatorial Undercurrent (MAGNIER, ROTSCHI, RUAL and COLIN, 1969), and this extension could well be the deep countercurrent met by REID (1959).

3. Hydrological Properties Associated to the Zonal Circulation

JARRIGE (1968) has pointed out that the South Equatorial Countercurrent is associated to a low salinity ranging from 34.0 ‰ to 34.8 ‰. The comparison of the surface salinity and of the geostrophic currents shows that the so-called South Tropical Countercurrent is also associated to a low salinity (fig. 4) and that, generally speaking, the meridional alternation of high and low salinity reflects the alternation of the westward currents and of the eastward countercurrents. Our actual knowledge of the oceanography of the Western South Pacific indicates that there is only one possible source of low salinity water, the Solomons region.

This alternation is again found in subsurface and particularly at the depth of the salinity maximum of the subtropical lower water of the south Pacific, extending westward and northward along the 340 cl/t

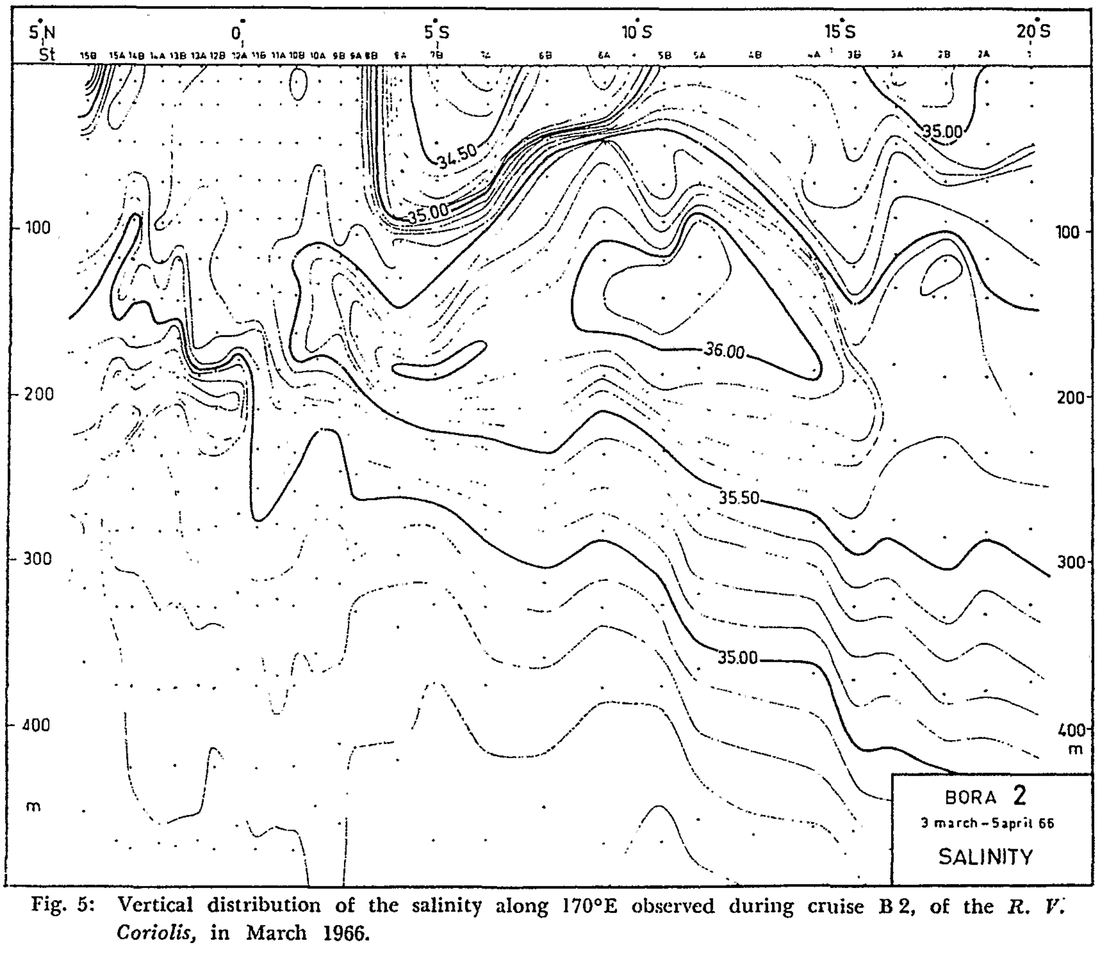

Fig. 5: Vertical distribution of the salinity along 170°E observed during cruise B 2, of the *R. V. Coriolis*, in March 1966.

Table 2. Hydrological Identification of the Various Zonal Currents between

	Northern Westward Current					South Equatorial Countercurrent Average latitude 9°S				
	Surface Salinity Maximum	Salinity Maximum on 450 cl/t	0_2 Maximum ml/l	Phosphate Minimum μgat/l	Nitrate Minimum μgat/l	Surface Salinity Minimum	Salinity Minimum on 340 cl/t	0_2 Minimum ml/l	Phosphate Maximum μgat/l	Nitrate Maximum μgat/l
B 1	34.55	35.90	3.20	0.60	3.0	34.50	35.85	3.15	0.80	6.0
B 2	35.40	36.02	3.52	0.90	6.0	34.25	35.92	3.20	0.99	8.0
B 3	35.44	36.11	3.60	—	6.5	34.45	35.96	3.10	—	8.9
B 4	35.52	36.15	3.62	—	6.0	34.70	36.00	3.20	—	8.9
C 2	35.59	36.14	3.50	0.65	—	34.25	35.83	3.15	0.78	—
C 3	35.32	36.10	3.60	0.68	4.9	34.15	35.85	3.15	0.78	—
C 4	35.50	36.09	3.10	—	4.4	33.95	35.79	3.15	—	5.5
C 5	35.49	36.11	3.35	0.70	7.0	34.70	35.83	3.25	0.72	9.0
C 6	35.42	36.12	3.70	0.64	6.0	34.77	35.87	3.10	0.70	7.8
C 7	35.44	36.08	3.45	0.70	7.0	34.33	35.71	3.15	—	9.2

isanosteric surface. At most of the cruises, as noted by TSUCHIYA (1968) two cores of high salinity are revealed (fig. 5) and on the 340 cl/t isanosteric surface salinity maxima and minima are associated to westward and eastward geostrophic currents. Further, at least as far as the South Equatorial Countercurrent and the adjoining northern westward current are concerned, oxygen and nutrient (phosphate and nitrate) concentrations are such that when the salinity is maximum, the oxygen concentration is also maximum, the nutrients one being minimum and vice versa (fig. 6). In the South Tropical Countercurrent, to a low salinity correspond an oxygen maximum and nutrients minima.

Thus, the various zonal currents are relatively easy to identify, both at the surface and on the 340 cl/t isanosteric surface, and their characteristics have been summarized, Table 2.

In a steady zonal circulation in the southern hemisphere, the continuity equation implies that there is a divergence at the northern border of a westward current and a convergence at its southern border which is the northern border of the adjoining eastward flow. Such a vertical circulation should affect the distribution of the nutrients.

This appears mainly on the form of the discontinuity layer, below the surface homogeneous layer, in the distribution of phosphate (fig. 7) and of nitrate (fig. 8). Thus the subsurface waters seem effectively to be enriched by upward movements which do not reach the surface. But, as suggested by CROMWELL (1958) such a doming can have a great biological importance in the case of an euphotic zone deep enough to have its lower water affected by the water brought up in the direction of the surface.

The intensity of the doming does depend on the intensity of the zonal circulation; when the later is sluggish, the doming can be unnoticeable and such conditions have been met at several occasions.

HISARD and PITON (1968) have shown that at the northern limit of the South

20°S and 5°S.

South Equatorial Current Average latitude 13°30S		South Tropical Counter-current
Surface Salinity Maximum	Salinity Maximum on 340 cl/t	Surface Salinity Minimum
35.25	36.12	35.05
35.29	36.16	34.79
35.37	35.87	no minimum
no maximum		no minimum
34.61	35.96	34.44
34.79	35.96	34.61
35.08	35.86	no minimum
no maximum	35.90	no minimum
34.96	35.90	34.91
34.67	35.83	34.60

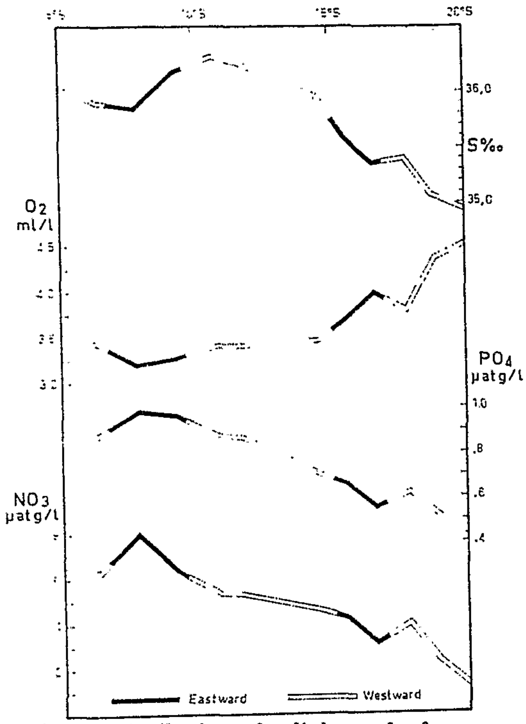

Fig. 6. Distribution of salinity and of oxygen, phosphate and nitrate concentrations on the 340 cl/t isanosteric surface during cruise B 2 of the *R. V. Coriolis* in March 1966.

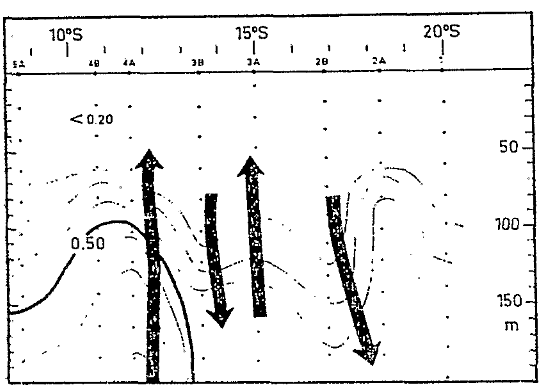

Fig. 7. Vertical distribution of phosphate in the subsurface layer, in March 1967, cruise C 2 of the *R. V. Coriolis*. The arrows indicating the convergence or the divergence of the waters follow the limits between eastward and westward flow.

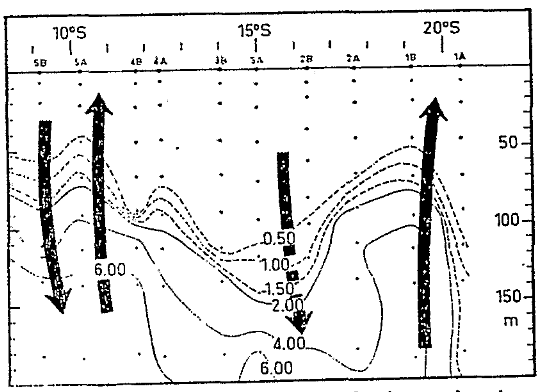

Fig. 8. Vertical distribution of nitrate in the subsurface layer, in December 1965, cruise B 1 of the *R. V. Coriolis*. The arrows have the same meaning as in Figure 7.

Equatorial Countercurrent there is, at the basis of the surface homogeneous layer, a nitrite maximum extending at least to 180° and obviously due to a convergence.

4. Summary and Conclusions

It appears that the zonal circulation between 20°S and 5°S, in the Western South

Pacific is more complicated than believed until now. Besides the South Equatorial Countercurrent with a core at about 9°S, the existence of which is no more questionable and which in its swiftest part transports low salinity, low oxygen and nutrient rich water, there is, centered at about 17°30'S a second permanent, shallower and less meridionally extended countercurrent. This later current is composed of low salinity water, rich in oxygen and poor in nutrients. Between those two currents a branch of the South Equatorial Current with a core at about 13°30'S flows westward and is composed of high salinity water.

This surface and subsurface circulation is entirely distinct from the circulation which has been observed on the 125 cl/t isanosteric surface.

No apparent seasonal variation in the intensity, the volume transport, the meridional extension and the thickness of the various currents has been found.

This circulation has an effect on the vertical distribution of nutrients, and it can be expected that between 9°S and 13°30'S and near 20°S there is a more or less permanent enrichment of the deepest layer of the euphotic zone with a possible increase of the productivity of the upper layer. The total biomass collected with a 10 feet Isaac Kidd Midwater Trawl during the cruises BORA is maximum between 10°S and 15°S and this is a confirmation of the existence near these latitudes of a mechanism of enrichment.

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