Hydrology at 170° E. in the South Pacific

H. ROTSCHI
Centre ORSTOM de Nouméa, New Caledonia

Abstract

Direct current measurements and hydrological studies were made during 11 oceanographic cruises along the meridian 170° E, between 20° S and 4° N. Two hydrological situations are discussed: in the Southern Hemisphere winter, when the trade wind dominates, the equatorial current is westward, and in summer, when the surface wind reverses the current is eastwards. Below the surface westward current in winter there is an eastward current which is the upper core of a two-core Cromwell Current system. In summer the situation is reversed. In and below the thermocline, the currents are not affected by surface conditions. These systems are the second core of the Cromwell Current at about 200 m and from 300 m downwards the westward Equatorial Intermediate Current embedded in an eastward flow. The zonal surface circulation is characterised by the South Equatorial Countercurrent at about 10° S and the South Tropical Countercurrent near 20° S, with little seasonal variation.

In winter, the vertical temperature distribution shows spreading of the isotherms in the thermocline associated with the Cromwell Current, an upward slope of the isotherms near the surface indicating upwelling and in the tropical region, a reversal of the slope of the upper isotherms in the thermocline bound to the two geostrophic countercurrents. In the equatorial region isolated masses of low and high salinity indicate that the Cromwell Current originates west of 170° E. The isohalines suggest convergence in the upper part of the thermocline. There are also indications of upwelling in the upper layers and of downwelling in the lower layers of the thermocline.

In summer, low salinity water from the north of New Guinea flows along the Equator and the equatorial upwelling is replaced by a surface convergence.

INTRODUCTION

For nearly 3 years (November 1965–May 1968), the cruises of the r.v. *Coriolis*, the research vessel of the "Centre ORSTOM de Nouméa" were devoted to the study of the hydrology and dynamics of the western South Pacific. The measurements, concentrated along the meridian 170° E, between 20° S and 4° N, gave a good coverage of the oceanographic conditions in the equatorial and south tropical waters north of New Caledonia. Ten cross sections in tropical waters and 12 in equatorial waters were made at 3-monthly intervals for the first part of the programme (cruises *Bora*) and then at monthly intervals (cruises *Cyclone*), the last three cross sections in the equatorial waters (4° S – 4° N) having been made at weekly intervals. Twenty-four samples were taken in the upper 1000 m at stations 60 to 90 miles apart, in the tropical waters (20° S – 4° S), and in the upper 500 m at stations 30 miles apart, in the equatorial waters (4° S – 4° N). The closer spacing of the reversing bottles in the later region was aimed at a detailed description of the hydrological and dynamical structure of the Equatorial Current system. At every station, classical hydrological studies have been conducted together with determination of nutrient concentration, phosphate, nitrate, nitrite, and oxygen. Direct current measurements from the drifting ship were made only during the cruises *Cyclone*, from 4° S to 4° N, at 20 m intervals from the surface to 300 m and at 50 m or 100 m intervals deeper. Thus, eight cross sections of the currents relative to 500 m have been obtained together with 12 vertical sections of the hydrological properties in equatorial waters.

The purpose of this study, based on the work of the *Coriolis*, is a presentation of the hydrology at 170° E in relation to the general features of the zonal circulation between 20° S and 4° N. Certain features of the equatorial distributions which can be indicators of the meridional circulation will also be discussed in greater detail.

Oceanography of the South Pacific 1972, comp. R. Fraser. New Zealand National Commission for UNESCO, Wellington: 1973.

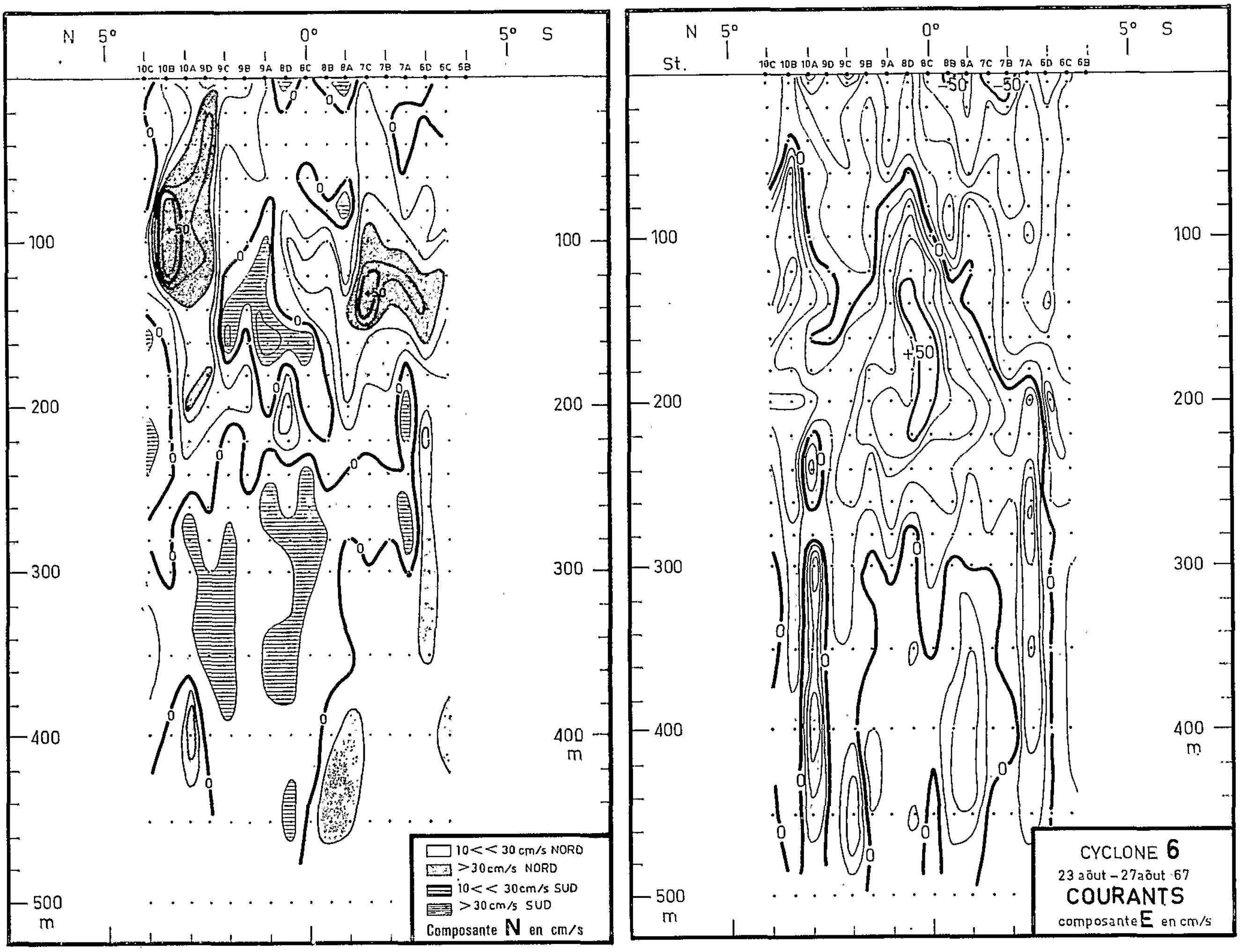

FIG. 1. Currents measured at the Equator. EW and NS components in cm/s, cruise *Cyclone 6,* August 1967. Spacing of the isotachs 10 cm/sec. (After Magnier *et al.*, in press.)

GENERAL FEATURES OF THE CIRCULATION AT 170° E

The method and main results of direct monitoring of the currents have been discussed in detail by Magnier *et al.* (in press), while Merle *et al.* (1969) have described the zonal circulation in tropical waters, 4° S – 20° S, from geostrophic computation.

The detailed features of the equatorial currents and their east-west variations are discussed by Colin *et al.*, (this volume) 1973, so that it is only necessary to recall the principal features of the flows which are wind driven in the upper homogeneous layer and those which belong to the thermohaline circulation in and below the thermocline. In the southern hemisphere winter, when the dominant surface wind is the trade wind, the surface current is westward and occupies, at the equator, only the upper part of the homogeneous layer (fig. 1). In the lower part, there is an eastward current, the upper core of a generally two-core Cromwell Current system, where the two cores are separated at about 150 m by a strong southward component. In and below the thermocline, the thermohaline currents are the lower core of the Cromwell Current at about 200 m, and from 300 m downwards, a westward intermediate current which is embedded in an eastward flow (Hisard and Rual, 1970). In the southern hemisphere summer (December-April) the surface wind blows mainly from the north-west and the surface circulation is reversed. The surface current becomes eastward and the upper core of the Cromwell Current is replaced by a westward flow. The lower core of the Cromwell Current

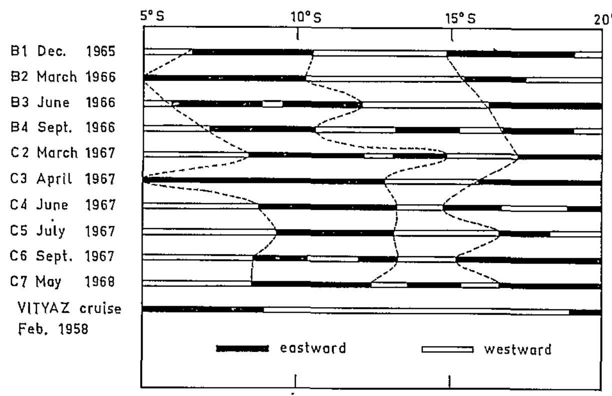

Fig. 2. Geostrophic currents at 170° E, between 20° S and 5° S, during the various cruises of the R.V. *Coriolis* and cruise 25 of R.V. *Vityaz.*

and the Intermediate Equatorial Current are unchanged.

From the geostrophic circulation in the tropical waters (20° S – 4° S), Merle *et al.* (1969) have shown that in a general westward circulation, there are two countercurrents flowing eastward (fig. 2). The South Equatorial Countercurrent has a core near 10° S and the South Tropical Countercurrent is situated close to 20° S. Both transport water mainly from the homogeneous wind-mixed layer. The latter corresponds to a similar current in the northern hemisphere at 20–25° N, the Subtropical Countercurrent (Yoshida and Kidokoro, 1967). The South Equatorial Countercurrent is bound to the atmospheric tropical convergence, which in the western Pacific is close to 10° S. It is very similar to the Equatorial Countercurrent, but its extension eastward is smaller. The existence of both has been confirmed by direct current measurements and by GEK measurements.

GENERAL HYDROLOGICAL FEATURES

The vertical distributions of all the properties which have been studied show a direct dependence upon the movements of the water masses and reflect the principal features of the zonal circulation outlined above. They also suggest some aspects of the meridional and vertical displacements which agree with what is known of these movements as well as with the continuity requirements.

In the Southern Hemisphere winter (April-December) the vertical temperature distribution (fig. 3) shows the typical equatorial spreading of the isotherms of the thermocline associated in the eastern Pacific by Knauss (1960) with the Cromwell Current or Equatorial Undercurrent. However, this feature is broader, thicker and covers a greater range of temperatures at 170° E than at 140° W. This suggests that the equatorial undercurrent is also broader and thicker, which is the case, as shown by the current measurements (fig. 1). Further, the upward slope of the isotherms near the surface, the 28°c isotherm in the case of the cruise *Cyclone 6*, indicates clearly an equatorial upwelling bringing to the surface water from the lower part of the wind-mixed layer. During this cruise, the upwelling indicated by the vertical temperature structure seemed to be displaced towards the north. Such a situation corresponds to a dominant wind with a northerly

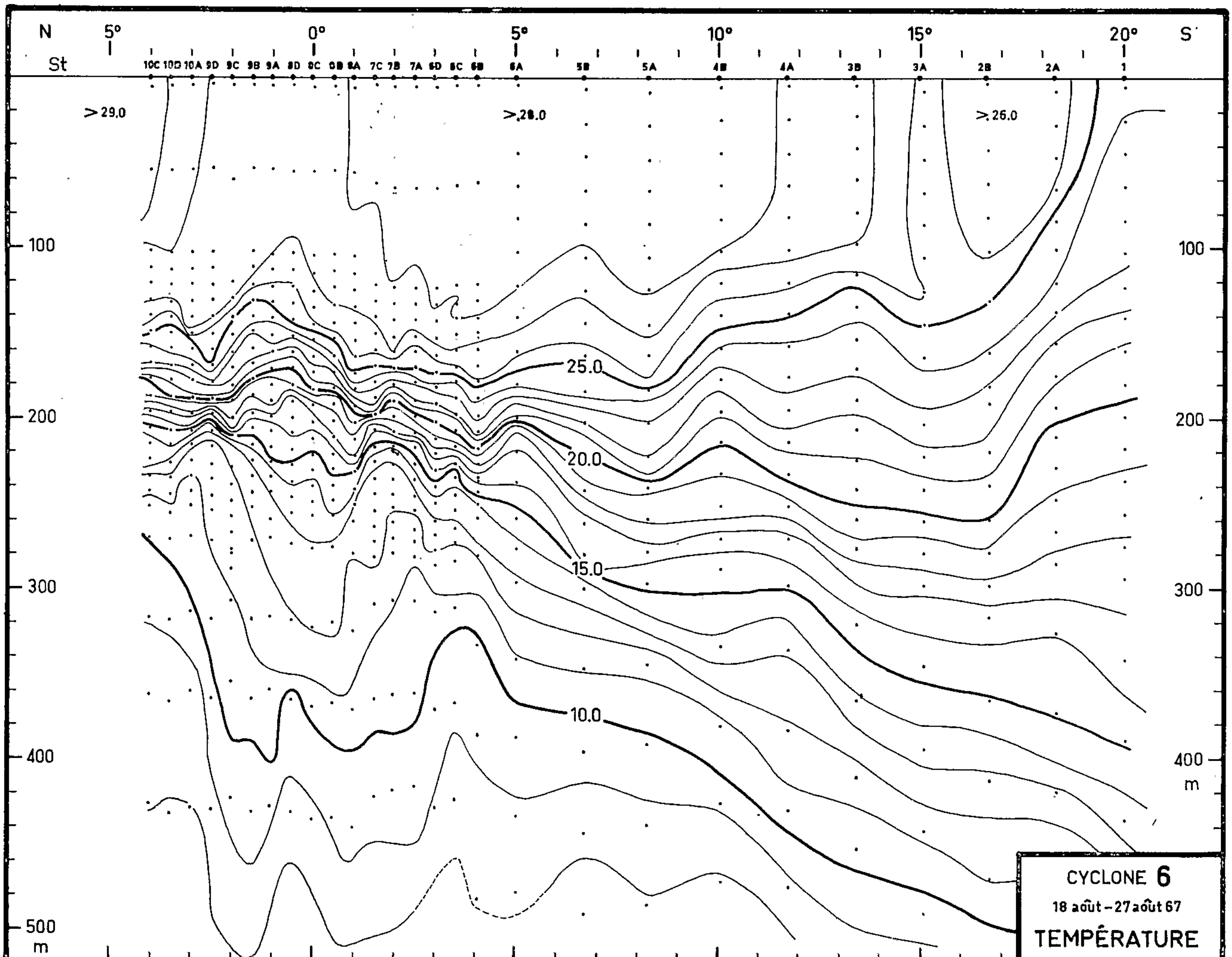

FIG. 3. Vertical distribution of the temperature, in the upper 500 m, at 170° E, between 20° S and 4° N, cruise *Cyclone 6*, August 1967. Spacing of the isotherms 1° c.

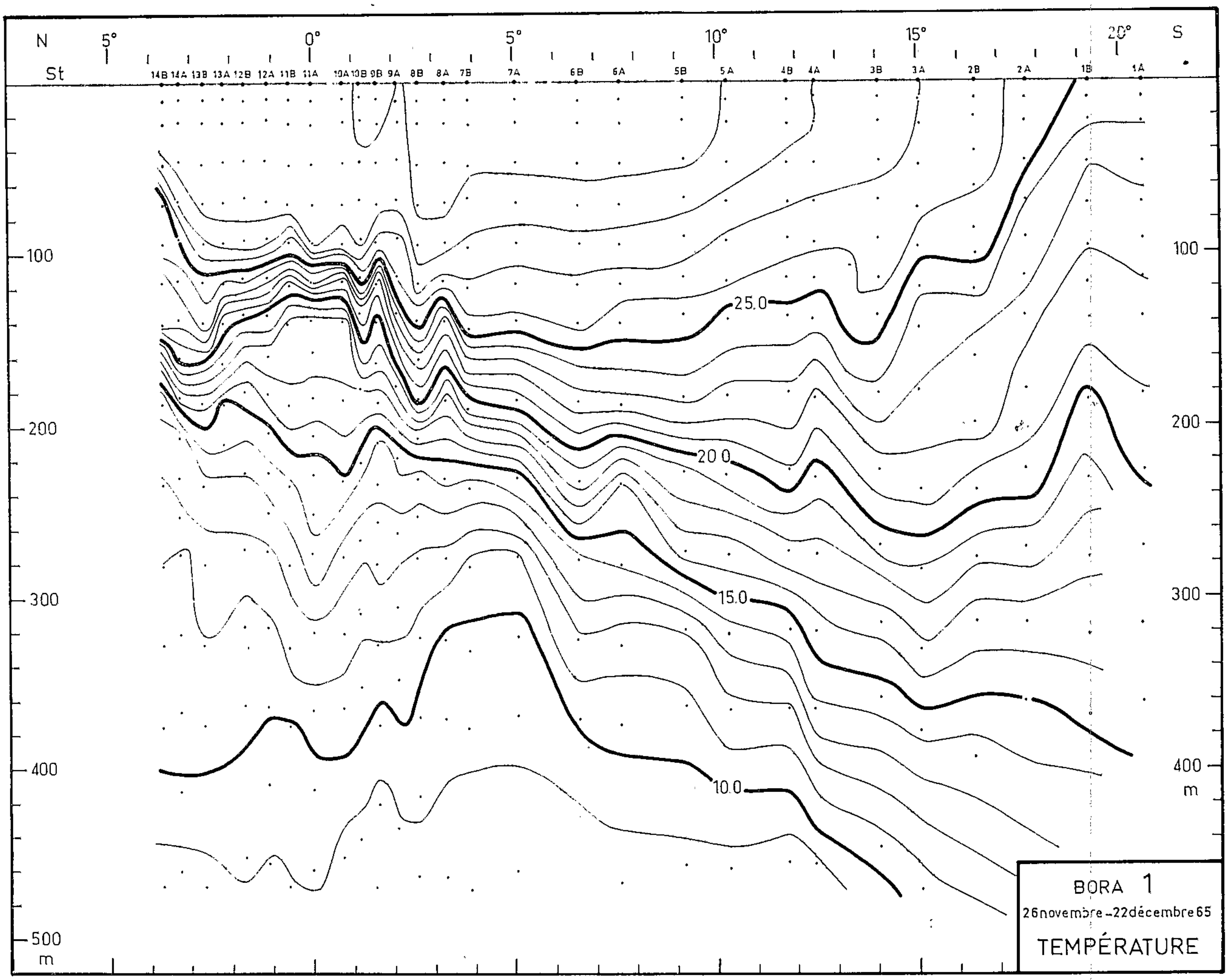

FIG. 4. Vertical distribution of the temperature, in the upper 500 m, at 170° E, between 20° S and 4° N, cruise *Bora 1*, November-December 1965. Spacing of the isotherms 1°C.

component (Cromwell, 1953); and in fact, during the first part of the equatorial studies of the cruise *Cyclone 6*, the wind was ENE. In the deeper water, below the Cromwell Current, whose lower limit is near 300 m (fig. 1), the equatorward slope of the isotherms reverses. In terms of geostrophy, this corresponds to a westward current embedded, on both sides of the Equator, in an eastward flow. Measurements (Magnier *et al.*, in press) and computations (Colin and Rotschi, 1970) show that this is exactly the case. Finally, in the tropical zone south of 5° S, the discontinuity layer becomes thicker and more diffuse southwards. The deeper isotherms slope downwards southwards, whereas the upper ones have clear changes of slope. In the Northern Hemisphere such changes are associated either with the North Equatorial Countercurrent (Kendall, 1966, 1970), or to the North Tropical Countercurrent (Robinson, 1969) which are both eastward geostrophic currents. In the Southern Hemisphere they correspond respectively, near 10° S to the South Equatorial Countercurrent and south of 15° S to the South Tropical Countercurrent, which are also geostrophic and the existence of which, as mentioned above, has been instrumentally verified (Merle *et al.*, 1969).

In the Southern Hemisphere summer, when the equatorial wind is blowing from the northwest, and when the westward current is replaced by an eastward flow, the equatorial divergence which induces the upwelling is replaced by a convergence accompanied by a descending movement of the surface water (fig. 4). The isothermal surface layer becomes thicker and there is no upward spreading of the upper isotherms of the thermocline. But the meteorological conditions affect only the upper layer. The downward spreading of the lower isotherms of the thermocline

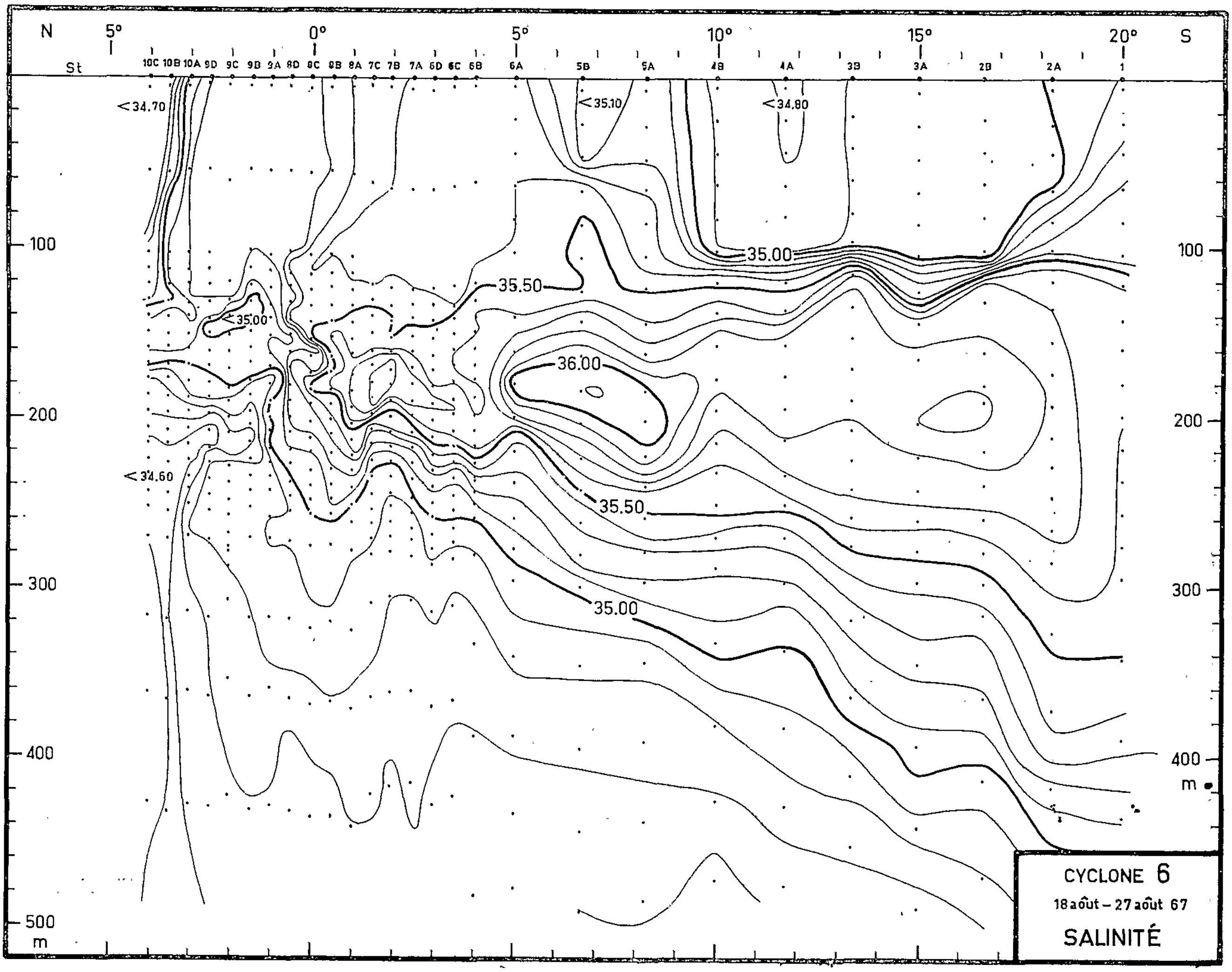

FIG. 5. Vertical distribution of the salinity, in the upper 500 m, at 170° E, between 20° S and 4° N, cruise *Cyclone 6,* August 1967. Spacing of the isohalines 0, 10‰.

is unchanged, as well as the thermal structure associated to the intermediate equatorial current. Similarly, the geostrophic countercurrents show weakly between 5° S and 10° S and more strongly south of 15° S.

The more complicated salinity structure gives some other details on the circulation. According to Wyrtki (1967a) the water with a salinity lower than 35‰ entrained in the central and eastern Pacific by the southern part of the North Equatorial Countercurrent and the northern part of the Equatorial Current, and which he observed at 156° W (Wyrtki, 1967b), is equatorial water formed mostly by the advection of the upwelled Peru and equatorial water. At 170° E (fig. 5) this water appears north of 3° N, very near the northern limit of the westward Equatorial Current and is very likely to be bound to the North Equatorial Countercurrent. The surface salinity distribution north of New Guinea (Panfilova, 1968) shows that this water comes from the extreme western end of the equatorial Pacific where the annual average rainfall is very high. The subtropical surface water of the South Pacific with a salinity greater than 35‰ (Wyrtki, 1967a) extends from 3° N to about 10° S; it is separated from the equatorial surface water by a well marked salinity front. The isohalines 35.20‰ and 35.30‰ suggest an equatorial upwelling slightly north of the Equator. South of 10° S, entrained partly by the South Equatorial Countercurrent, there is another low salinity water mass, the origin of which is also in the western equatorial Pacific, near New Guinea. At about 9° S a salinity front separates it from the subtropical water of the South Pacific and is quite close to the northern limit of the South Equatorial Countercurrent. These salinity fronts are bound to the meridional circulation and mark the probable location of surface convergences.

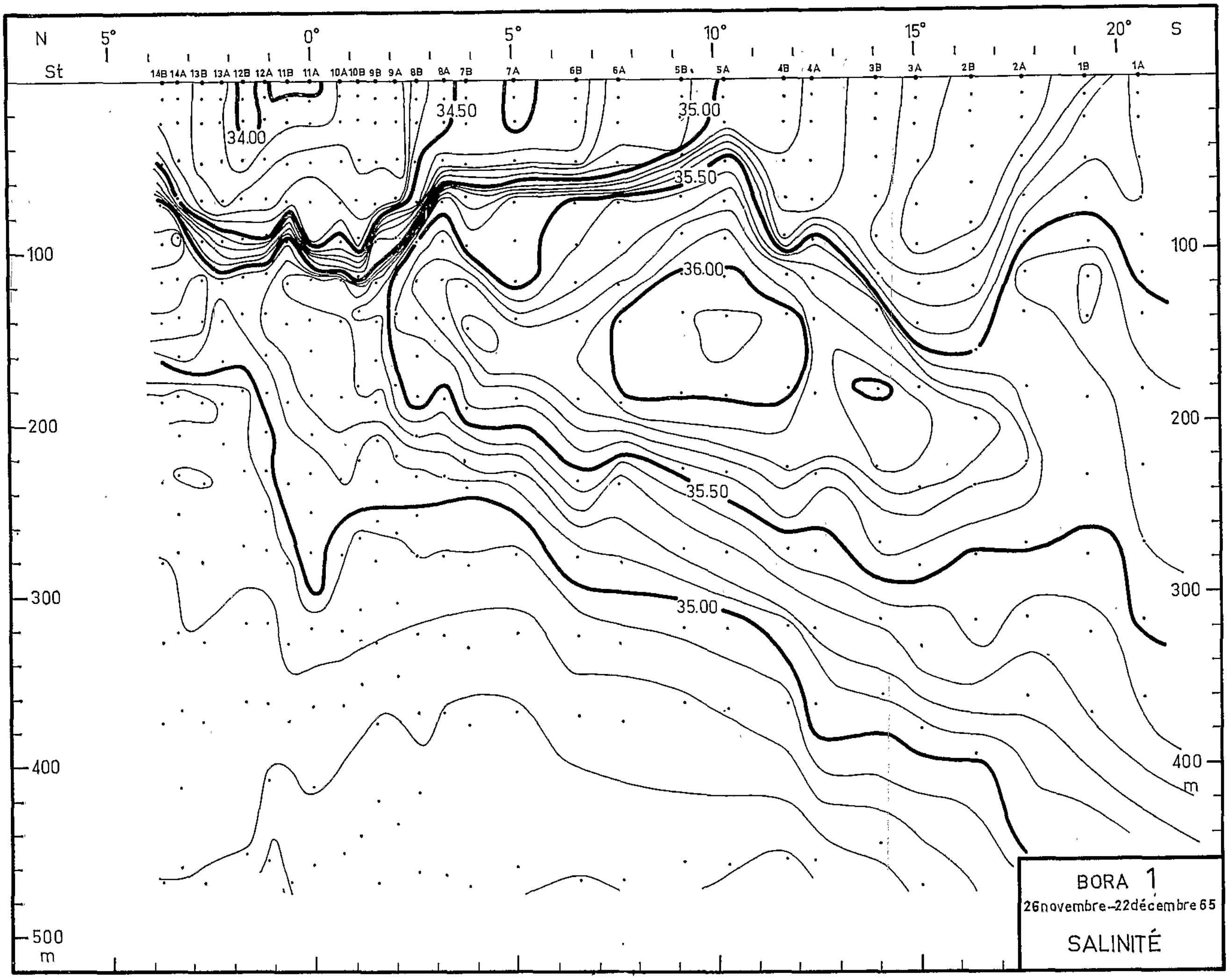

FIG. 6. Vertical distribution of the salinity in the upper 500 m, at 170° E, between 20° S and 4° N, cruise *Bora 1*, November-December 1965. Spacing of the isohaline 0, 10‰.

Below the surface, the most interesting feature of the salinity distribution is the saline subtropical water of the South Pacific with a core near 7° S, at a depth of about 200 m. This water is formed in the central Pacific, south of 20° S, between 110° W and 140° W and extends westwards and northwards, following several paths as indicated by the secondary maximum at 16° S. This highly saline water crosses the Equator in the western Pacific resulting in a core of high salinity isolated near the Equator but south of it in the central and eastern Pacific (Montgomery and Stroup 1962, Knauss 1966, Wyrtki 1967b). The core at 1° 30′ S–2° S (fig. 5) could be the result of such a mechanism or the trace of another path of the subtropical South Pacific water. The salinity distribution in December 1965 (fig. 6) indicates that it is more likely the northernmost extension of a highly saline tongue. At the Equator (fig. 5) the core of the high salinity water is slightly above the velocity core of the Cromwell Current and it is clear that the subtropical South Pacific water participates in the formation of its southern upper part. Thus, the longitude of 170° E is near the eastern limit of the direct participation of water of southern origin in the Cromwell Current. North of the Equator, at 200 m depth, there is low salinity water, salinity less than 34.60‰, which is the North Pacific intermediate water; it extends southwards and almost reaches the Equator where it forms, with the saline water of southern origin, a well-marked salinity front. Thus, there is at the Equator strong indication of a convergence of the subsurface water masses and of weak horizontal mixing. The isolated core at 2° N, salinity below 35.00‰, could result from strong turbulence north of New Guinea, having isolated either some surface equatorial water or some North Pacific intermediate water. The distribution of

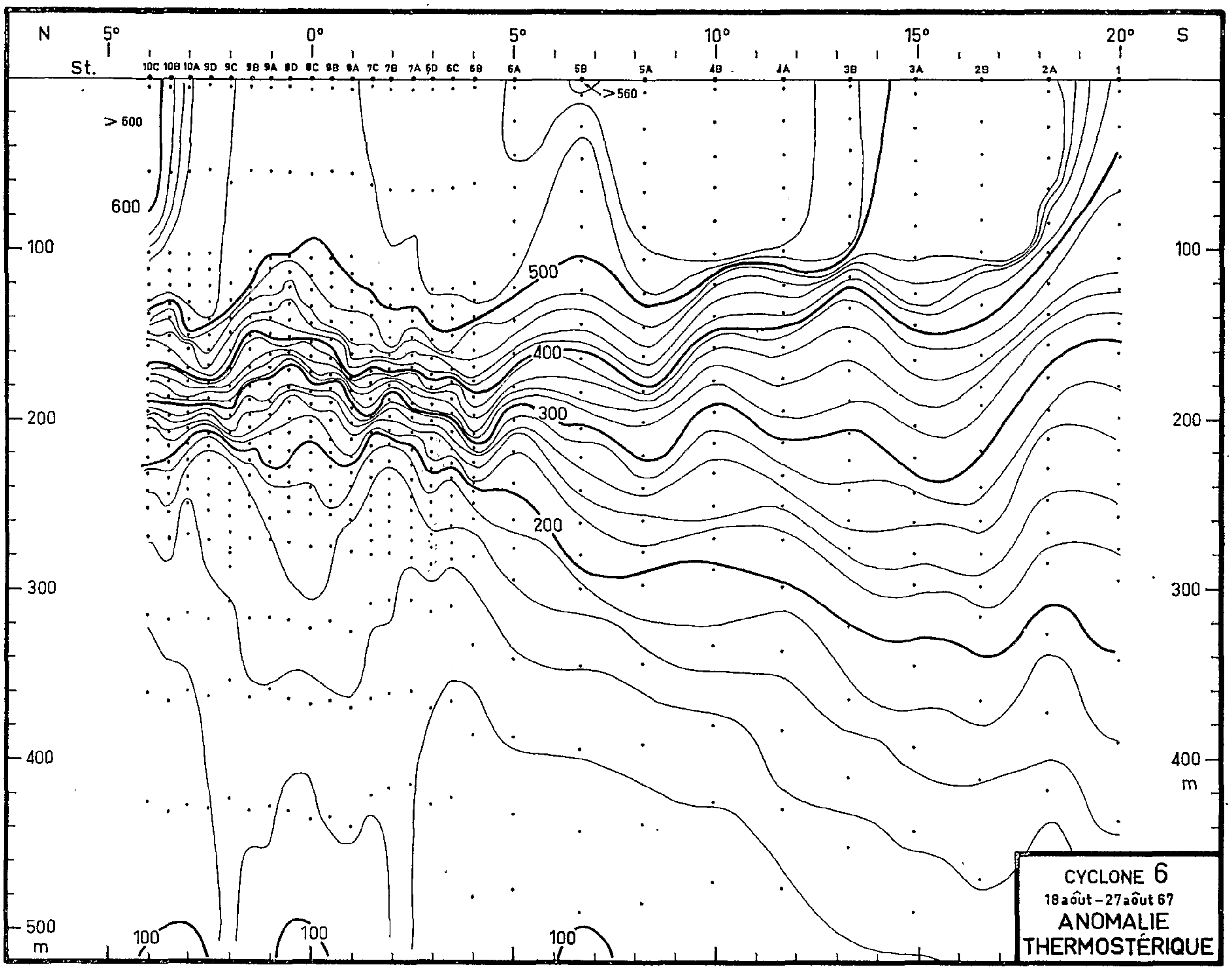

FIG. 7. Vertical distribution of the thermosteric anomaly, in the upper 500 m, at 170° E, between 20° S and 4° N, cruise *Cyclone 6*, August 1967. Spacing of the isanosteres 20 cl/t.

phosphate shows that it is likely to be equatorial surface water. Masuzawa (1967) has observed at 137° E, north of New Guinea, such low salinity cores isolated in water of southern origin and has shown that they can derive from the southern part of the North Equatorial Current.

The salinity distribution in summer (fig. 6) differs mainly in the surface conditions. The wind-driven equatorial surface current is eastward and the equatorial winter surface divergence is replaced by a convergence. The eastward current entrains low salinity water from the New Guinean region, and the upper homogeneous layer covers a vast region. This low salinity water extends south of 10° S, and since it flows above a westward subsurface current entraining subtropical surface water with a salinity higher than 35‰, a well-marked halocline develops in the equatorial region. Between 15° S and 20° S, the low salinity water associated with the South Tropical Countercurrent is also easy to identify. The salinity maximum of the subtropical water of the South Pacific appears with three cores and does not extend as far north as in winter. Similarly, the low salinity north Pacific intermediate water does not extend as far south. The convergence towards the Equator at intermediate depth of water masses of both hemispheres is weaker, and results in a weak meridional salinity gradient at the Equator and an apparently more homogeneous Cromwell Current. The weakening of the southward extension of the Northern Hemisphere water is bound to the weakening of the North Equatorial Countercurrent which, during this season, is composed mostly of North Equatorial Current Water.

The density distribution (fig. 7) represented by the thermosteric anomaly (Montgomery and Wooster, 1954) reflects that of the temperature (fig. 3). The

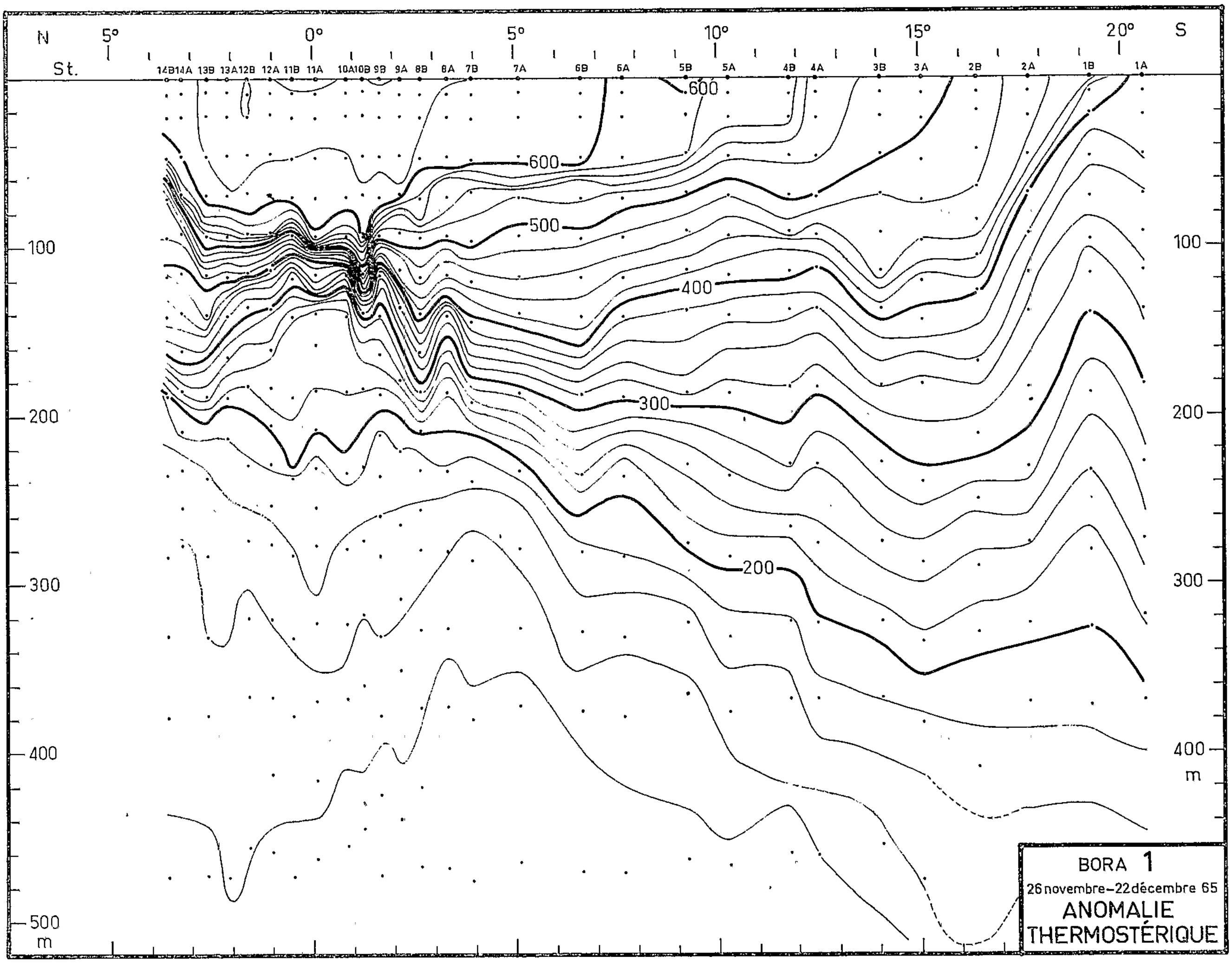

FIG. 8. Vertical distribution of the thermosteric anomaly in the upper 500 m, at 170° E, between 20° S and 4° N, cruise *Bora 1*, November-December 1965. Spacing of the isanosteres 20 cl/t.

vertical spreading of the isanosteres locates the Cromwell Current, and confirms that it is wider and thicker at 170° E than at 140° W. For the hypothesis of a geostrophic current, the vertical shear of the zonal current both sides of the equator is given by

$$f \frac{\partial u}{\partial z} = - \rho g \frac{\partial \delta}{\partial y} \qquad (1)$$

whereas at the Equator it is given by

$$\frac{\partial u}{\partial z} = - \rho g \frac{\partial^2 \delta}{\partial y^2} \Big/ \beta \qquad (2)$$

in which g is gravity, δ anomaly of specific volume, f Coriolis force and $\beta = df/dy$. Both equations indicate that the zonal component of the current is a maximum at the level where an isanosteric surface is horizontal (Montgomery and Stroup, 1962). During the cruise *Cyclone 6* the horizontal isanostere was located close to 200 m, with a thermosteric anomaly of the order of 200 cl/t. Since at 150° W the core of the current is close to the 300 cl/t isanostere at a depth of 125 m (Montgomery and Stroup, 1962) it is obvious that, flowing eastward, the Cromwell Current gets lighter and closer to the surface. Its lower limit is close to 300 m since on the 140 cl/t isanostere surface there is a reversal of the equatorward slope of the isanostere. This reversal is due to the westward Equatorial Intermediate Current flowing below the Cromwell Current (Hisard and Rual, 1970). The upper limit of the latter is not clear, but the density distribution below the surface indicates an equatorial upwelling displaced slightly northwards. Similarly the spreading of the isanosteres is not quite symmetrical about the equator, which confirms the direct current measurements. In the tropical region the upward slope

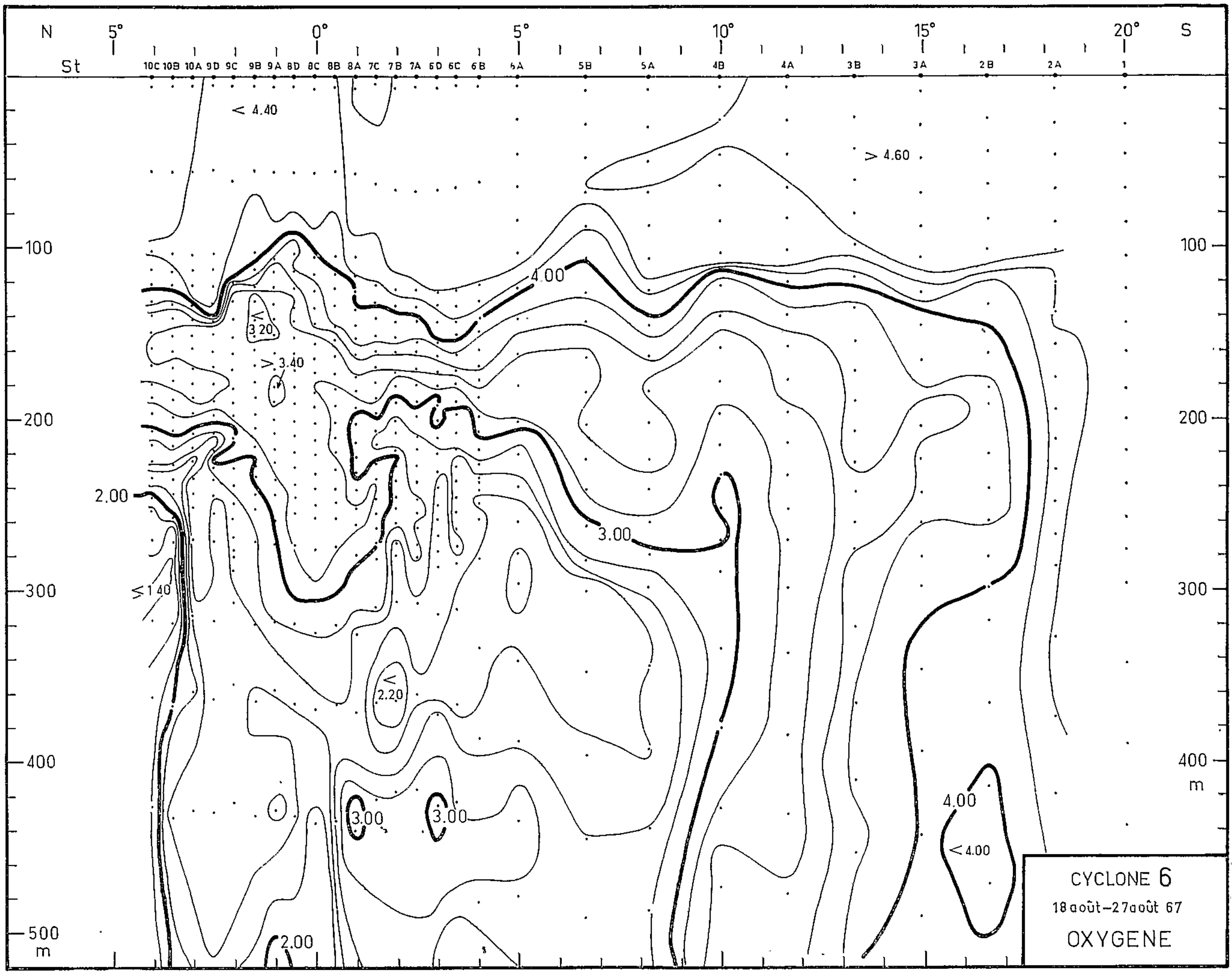

FIG. 9. Vertical distribution of the concentration of oxygen in the upper 500 m, at 170° E, between 20° S and 4° N, cruise *Cyclone 6*, August 1967. Spacing of the isolines 0, 20 ml/l.

polewards of the upper isanosteres of the pycnocline points to the geostrophic South Equatorial Countercurrent between 8° S and 13° S and the South Tropical Countercurrent south of 15° S.

In summer (Fig. 8) the equatorial spreading of the isanosteric surfaces is limited, because of the surface convergence induced by an eastward surface current, to the lower part of the pycnocline. Here the level isanostere is again found at a depth of 200 m and corresponds to a thermosteric anomaly close to 200 cl/t. The lower limit of the Cromwell Current does not show as clearly as in August, but its location is between 300 m and 400 m. At the surface, because of the convergence, the equatorial water is lighter than that found to the north and south. In the tropical zone, the slope of the isanosteres implies a very weak eastward current between 5° S and 12° S and a stronger one south of 15° S.

The tropical surface waters are oversaturated in oxygen and homogeneous over a great thickness (fig. 9). At the equator, there is an upwelling displaced slightly northwards. The core of the Cromwell Current is homogeneous as in the central Pacific (Knauss, 1960), but as has been shown previously (Rotschi and Wauthy, 1969), this homogeneity is not the result of an intense vertical mixing within the swiftest part of the current, but of the superposition of different water masses having very similar oxygen content. The upper water is a mixture of subtropical water of the South Pacific and water of the North Equatorial Countercurrent. The lower water is from the Coral Sea. Within the core of the Cromwell Current the slight isolated maximum is the trace of Coral Sea water integrated into the eastward flow further west and not entirely mixed with the surrounding waters. The small minimum, associated

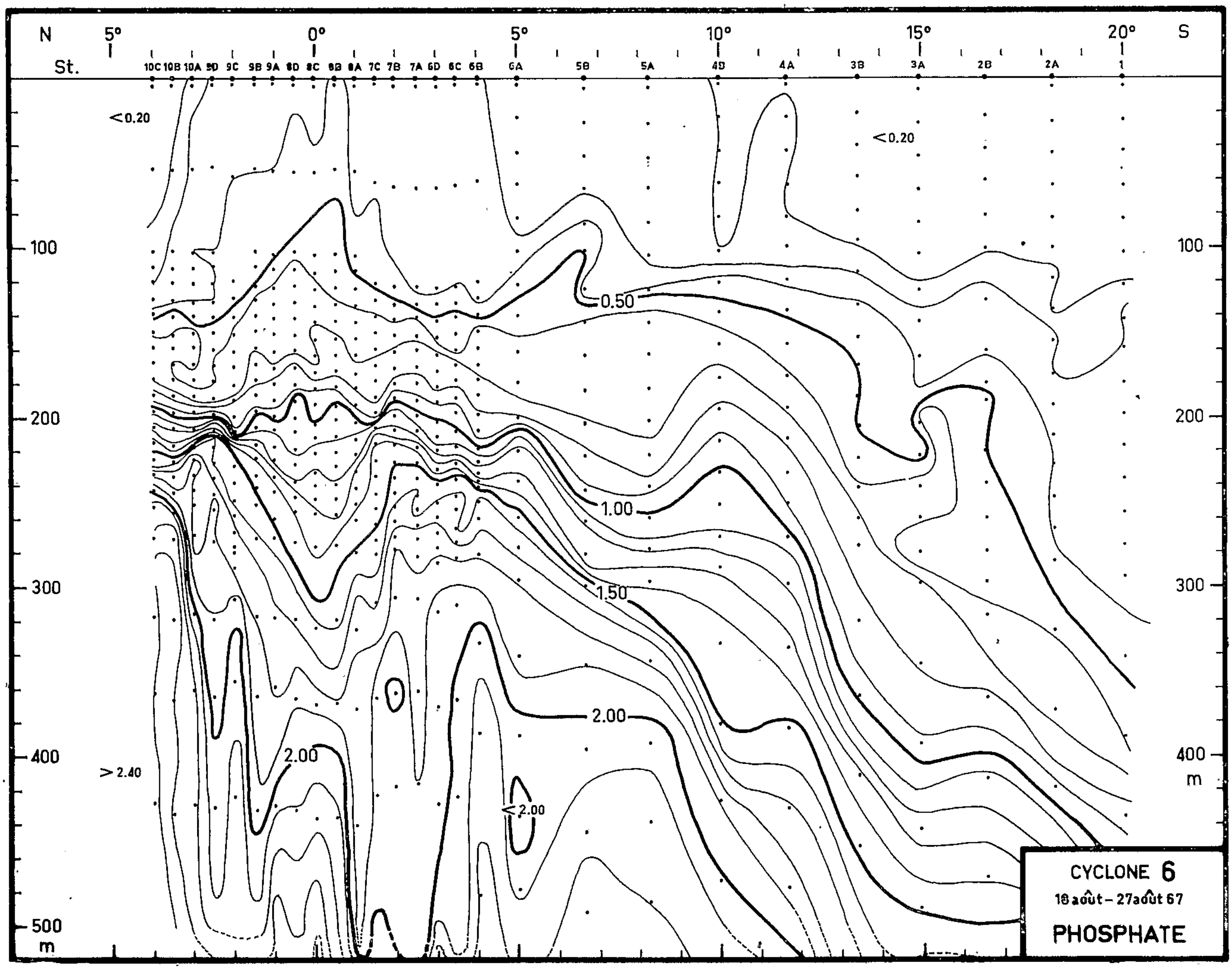

FIG. 10. Vertical distribution of the concentration of phosphate in the upper 500 m, at 170 E, between 20° S and 4° N, cruise *Cyclone 6*, August 1967. Spacing of the isolines 0, 10 mat.g/m³.

with a low salinity, is the trace of water of the North Equatorial Countercurrent. Below the Cromwell Current the equatorial intermediate flow transports water with a relatively small concentration of oxygen reflecting the oxygen minimum formed along the coast of Peru. On both sides of this oxygen minimum, deeper than 400 m, there is oxygenated water which, south of the equator, is from the Coral Sea (Hisard and Rual, 1970). Further poleward another oxygen minimum is the trace, south of the equator, of the Peru minimum, and north of the equator of the Central America minimum (Reid, 1965). At 10° S – 15° S the subsurface water of the intertropical zone is a transition between the Antarctic Intermediate Water with a high oxygen content and the poorly oxygenated equatorial system.

The distribution in December has the same general features. It must be pointed out nevertheless that at the equator there is no trace of upwelling. Further, the low oxygen content from the Central American coast does not appear at 4° N. This confirms the indication, from the salinity, of a lesser equatorward subsurface extension of the northern hemisphere water. Similarly, the low oxygen water of Peruvian origin does not extend as far north. Finally, the Antarctic Intermediate Water with an oxygen content higher than 4 ml/l is barely observable at 20° S.

The phosphate distribution is similar in many aspects to that of the oxygen. In the equatorial region it is easy to identify (fig. 10) an equatorial upwelling, which contrary to what is observed with all the other properties, is displaced southwards. The Cromwell Current is associated with a spreading of the isolines and within its core the vertical gradient of the phosphate concentration is not negligible, the phosphate increasing downwards whereas the oxygen

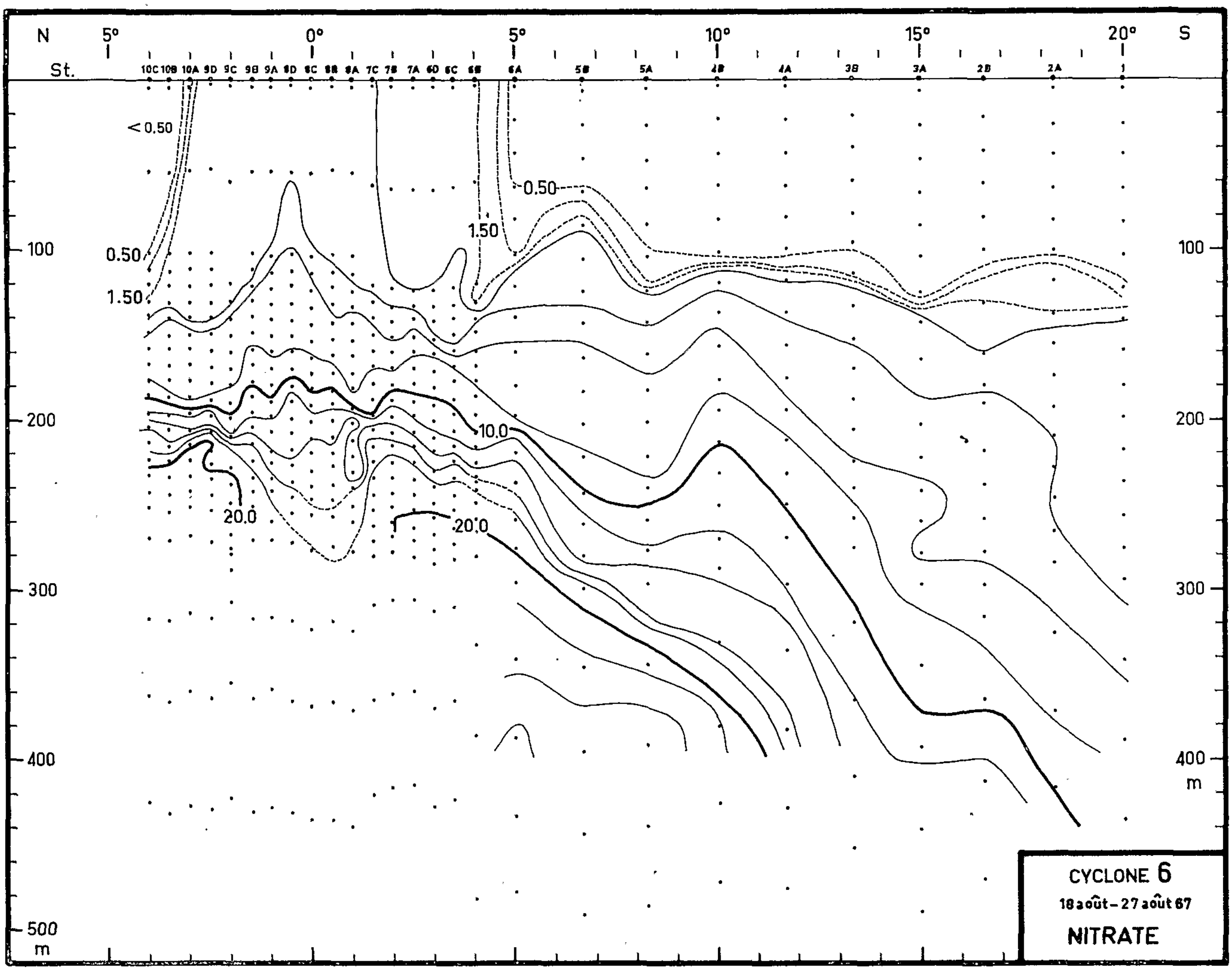

FIG. 11. Vertical distribution of the concentration of nitrate in the upper 500 m, at 170° E, between 20° S and 4° N, cruise *Cyclone 6*, August 1967. Spacing of the isolines 2 mat.g/m^3.

is constant. This confirms that the homogeneity of the oxygen concentration is not due to an intense vertical mixing. Just below the Cromwell Current, the Equatorial Intermediate Current is associated with a phosphate maximum. The water which surrounds it is relatively rich in oxygen and poor in phosphate; this shows very clearly in the Coral Sea water where the oxygen content is higher than 2.80 ml/l and where the phosphate concentration is minimum and smaller than 2.00 mat. g/m^3. The oxygen minima of the Central American coast and of the coast of Peru correspond to high phosphate concentration. In the tropical région, between 10° S and 15° S, there is, at middle depth a strong meridional phosphate gradient having the same significance as the corresponding oxygen gradient and marking the limit of the direct northward extension of the Antarctic Intermediate Water. The ridge of the discontinuity layer at 6° 30′ S is at the southern limit of an eastward current. In permanent zonal currents with no space acceleration the continuity equation implies, in the southern hemisphere, an ascending motion at the southern limit of an eastward current. The phosphate distribution confirms this hypothesis. The upward movement of the upper layer of the thermocline enriches the lower water of homogeneous layer.

The nitrate distribution (fig. 11) has similar characteristics: in particular the equatorial upwelling displaced slightly northwards, the spreading of the isolines in the Cromwell Current confirming the absence of intense vertical turbulence within its core, the strong horizontal gradient at intermediate depth south of 10° S and the ridge of the discontinuity layer at 6° 30′ S. In summer, the fundamental difference is the absence of equatorial upwelling (fig. 12). The two ridges in the discontinuity layer

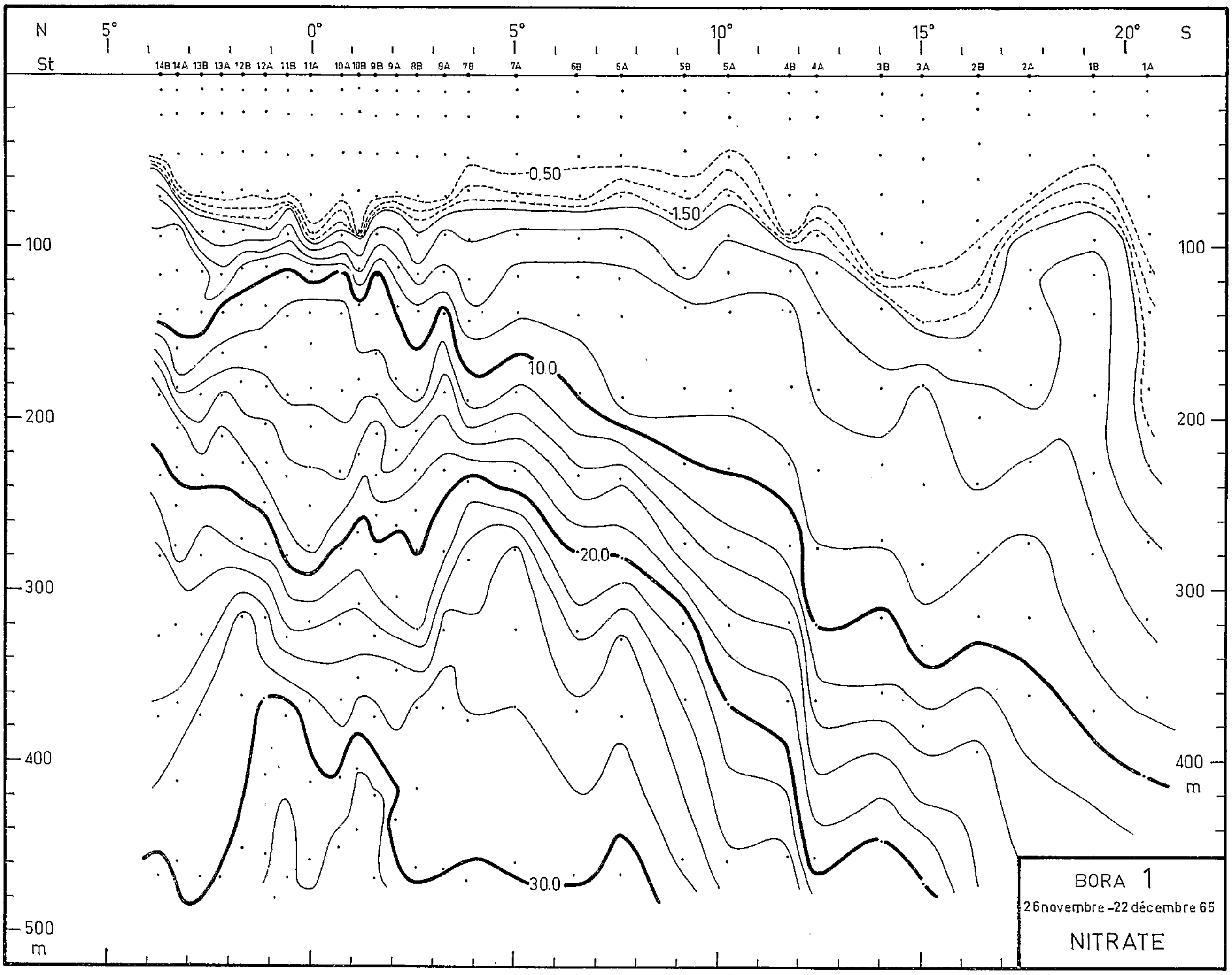

FIG. 12. Vertical distribution of the concentration of nitrate in the upper 500 m, at 170 E, between 20° S and 4° N, cruise *Bora 1*, November-December 1965. Spacing of the isolines 2 mat.g/m³.

at 10° S and 19° S are located at the southern limit of an eastward countercurrent. They confirm that in the tropical waters the zonal circulation can induce an enrichment of the base of the wind-mixed homogeneous layer. This mechanism has been called ridging by Cromwell (1958).

CONCLUSIONS

Taking into account the currents both measured and computed, the study of the hydrology at 170° E, between 20° S and 4° N shows that the circulation strongly determines the various properties of the water masses. On the vertical distributions, it is easy to identify:

- an equatorial upwelling the axis of which seems to depend on the meridional component of the wind. It disappears when the surface current reverses;
- the Cromwell current broader and thicker than in the central Pacific and with a lower limit clear enough to be located near 300 m depth;
- the Westward Equatorial Intermediate Current embedded in the deep northern and southern extensions of the Cromwell Current;
- the South Equatorial and South Tropical Countercurrents;
- the subtropical water mass of the South Pacific, which converges equatorwards from the south, whereas the North Pacific intermediate water flows southwards;
- the northward direct extension of the Antarctic Intermediate Water limited at about 15° S;
- the water with an oxygen minimum formed along the Peruvian coast in the southern hemisphere and along the Central American coast in the northern hemisphere.

The vertical distributions also show that:

- some hydrological characteristics of the Cromwell Current are gained further to the West, north of New Guinea;
- the core of the Cromwell Current is homogeneous in oxygen because of its formation by the superposition of different water masses with the same original oxygen content and not by vertical mixing;
- there is an upward movement of the upper water in the discontinuity layer at the southern limit of the eastward countercurrents.

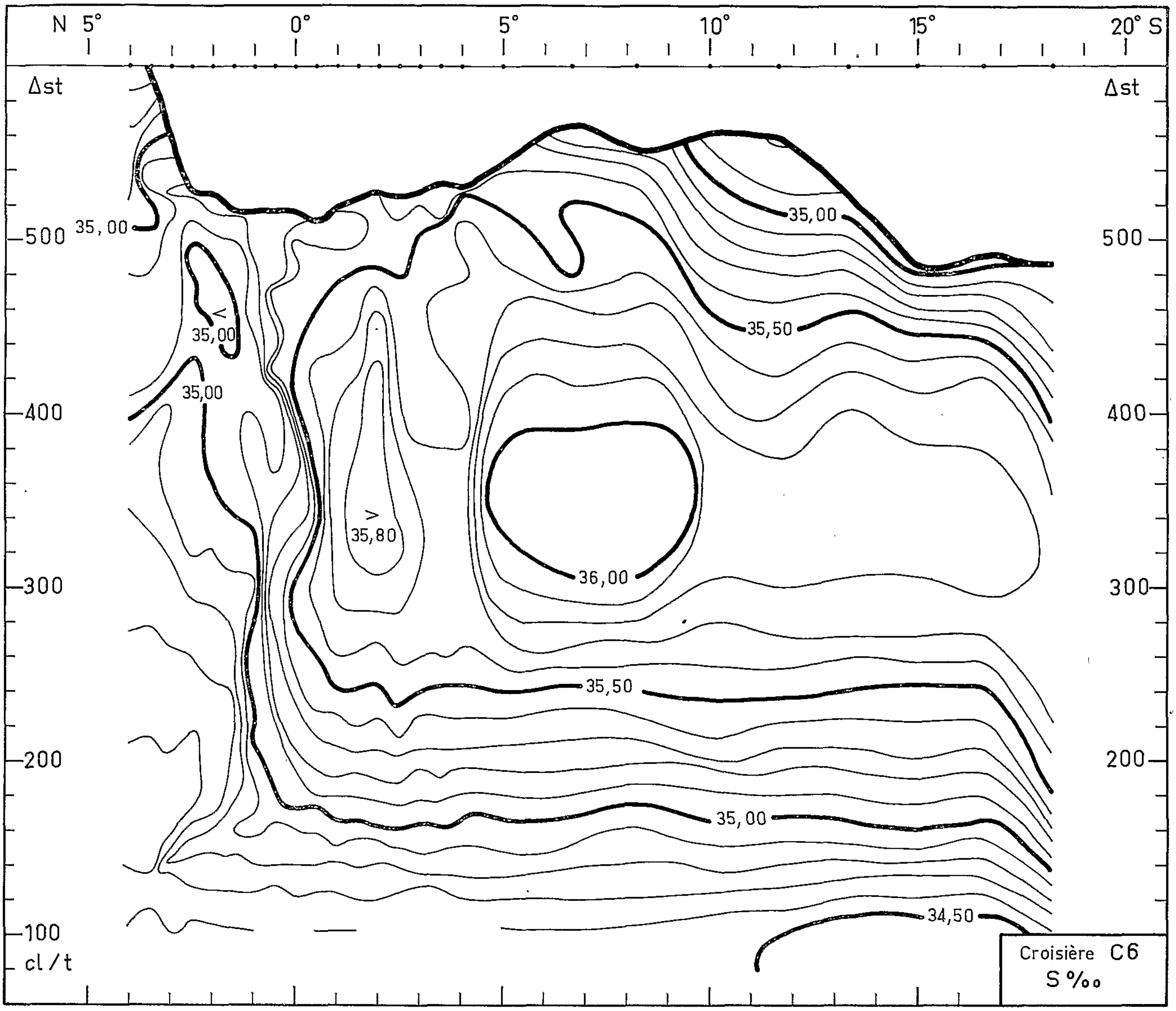

FIG. 13. Distribution with thermosteric anomaly of the salinity at 170° E, between 20° S and 4° N, cruise *Cyclone 6*, August 1967. Spacing of the isohalines 0, 10‰.

EQUATORIAL DISTRIBUTIONS

Most of the models of meridional circulation which take into account the Cromwell Current (Cromwell, 1953; Fofonoff and Montgomery, 1955) include a divergence at the surface at the equator with ascending water from the core of the Cromwell Current. Thus, in the surface layer there is a flow away from the equator and within the thermocline the flow is towards the equator, from both sides. The question can be raised whether this converging water towards the equator only ascends or whether part of it descends, and in case of a descending motion whether there is at some depth a flow away from the equator.

All the vertical distributions (fig. 3 – fig. 12) show a typical bulging downwards of the lower isolines of the discontinuity layer. Interpreted in the same manner as the bulging upwards of the upper isolines, it means a descending motion of part of the water converging equatorwards within the thermocline which, at the equator covers a range of thermosteric anomaly from 500 cl/t to 200 cl/t. Colin and Rotschi (1970) have shown that below the surface layer the flow is likely to be isentropic, consequently a study of the distribution of the properties with density could give good indications of the converging and diverging movements at intermediate depth.

The salinity distribution versus thermosteric anomaly (fig. 13) suggests a northward movement, away from the equator, from 1° N to 3° 30′ N, at the thermosteric anomaly level 160–140 cl/t. There are also clues for an equatorward convergence from 3° N to the equator in the layer 500–300 cl/t and south of the equator on the 420 cl/t isanosteric surface. The oxygen distribution shows water which could move away from the equator between 2° N and 3° N on one side and between 1° S and 2° 30′ S on the other side, at the thermosteric level 160 cl/t. The phosphate distribution confirms these features.

Since Hisard and Rual (1970) have shown that the limit between the Cromwell Current and the Equatorial Intermediate Current is at 160 cl/t, a movement away from the equator on the 160 cl/t isanosteric surface and slightly below is in perfect agreement with a vertical circulation which includes an equatorward convergence in the thermocline, a descending movement in its lower part and a poleward divergence below the thermocline.

The direct current measurements (fig. 14) confirm the equatorward divergence with a northward component between 2° N and 3° 30′ N on the 180-140 cl/t isanosteric surfaces and a southward component, south of the equator on the 160 cl/t isanosteric surface. In the layer 500-300 cl/t, there is an equatorward component both sides of the equator. Nevertheless, the southward movement does not show north of 2° N, where there is a northward movement.

A detailed study of the variation with latitude of the T-S characteristics illustrates in another manner

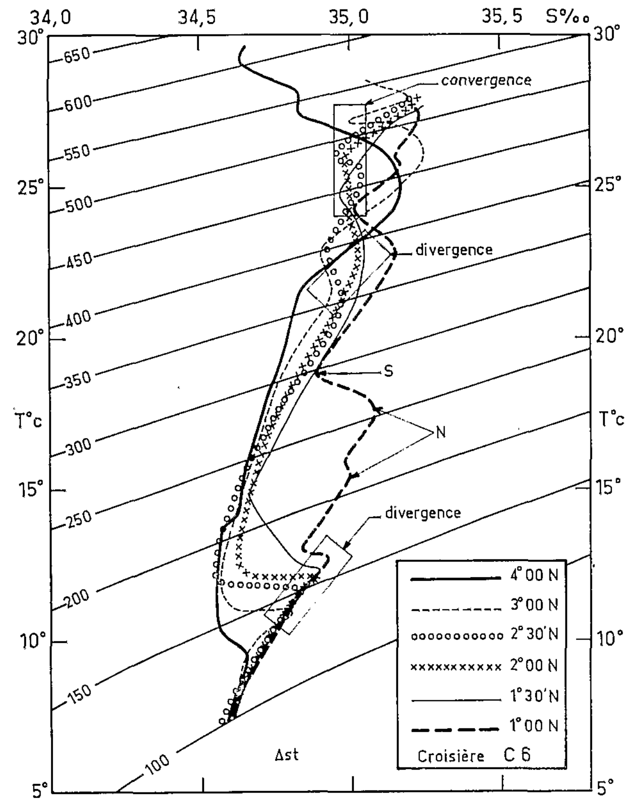

FIG. 15. T-S diagrams at the stations north of 1° N at 170° E, cruise *Cyclone 6*, August 1967. The background lines are lines of equal thermosteric anomaly in cl/t. Divergence: northward component, convergence: southward component.

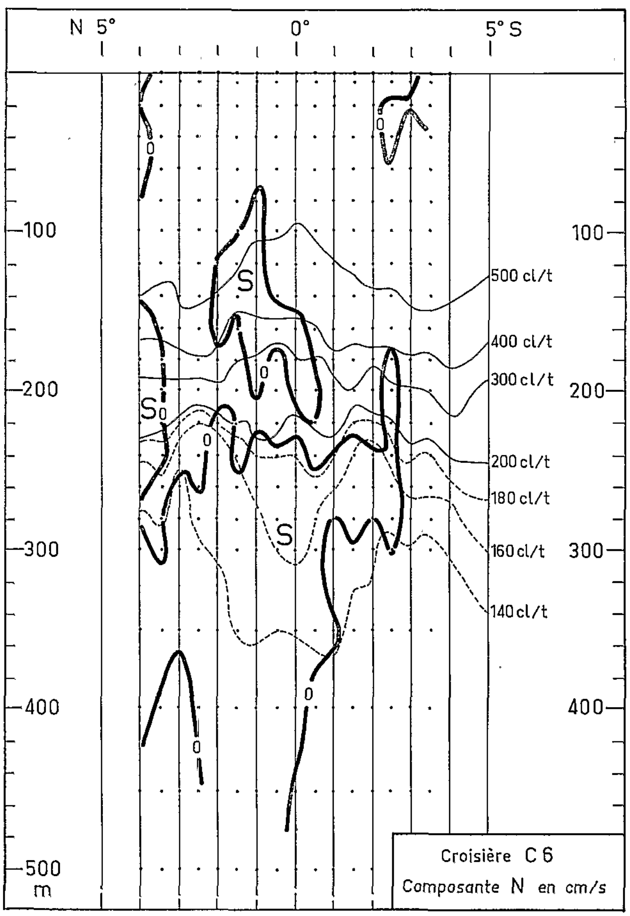

FIG. 14. North-south component of the current measured relative to 500 m, between 4° S and 4° N at 170° E, cruise *Cyclone 6*, August 1967. The thick contour is the isotach zero; the thin and dotted lines are isanosteric surfaces.

the movements of the various water masses. North of the equator, from 3° N to 1°30′ N (fig. 15), the salinity minimum of the North Pacific Intermediate Water occurs between two maxima which are traces of the subtropical water of the South Pacific at a level where the component of the current is northward, away from the equator. The upper minimum, the source of which can only be north of the equator, is in a layer of southward, equatorward movement. Between 1° S and 1° N (fig. 16) there is an obvious transition zone. Here the low salinity water from the north and the high salinity from the south meet without intense lateral mixing. The resulting T-S diagrams have numerous extrema, many of which are located at levels where the north-south components of the current are strong. The salinity maxima are associated with a northward component, implying that they are formed of water coming from the southern hemisphere. The salinity minima are associated with a southward component, implying that low salinity water from the northern hemisphere is transported equatorwards; in some instances it even crosses the equator. In the tropical region the T-S diagrams (fig. 16) are typical of the western South Pacific central water mass according to Sverdrup *et al.* (1942). Nevertheless, it can be seen that there are two sources of Antarctic Intermediate Water; one which flows directly northwards with a salinity close to 34.45‰ and does not extend further north than 10° S, and one which flows along the South American coast before reaching the equatorial region, where it has a salinity greater than 34.50‰.

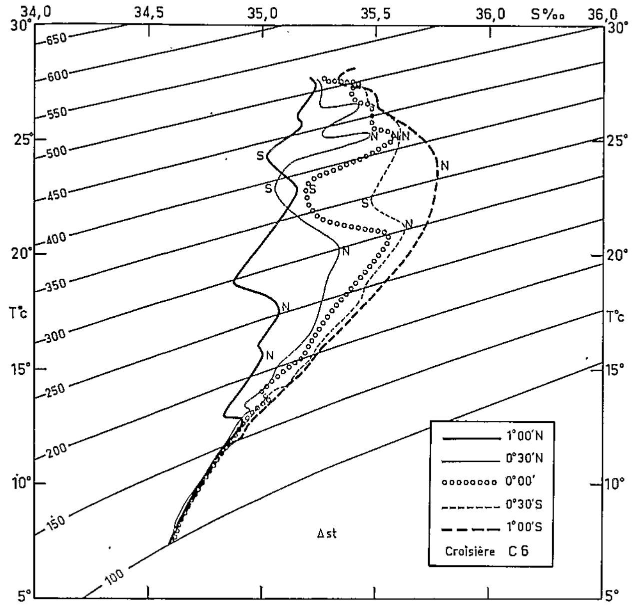

FIG. 16A. T-S diagrams at the stations between 1° S and 1° N at 170° E, cruise *Cyclone 6,* August 1967. The background lines are lines of equal thermosteric anomaly in cl/t. N means that at this latitude and at this level the current has a northward component; S indicates a southward component.

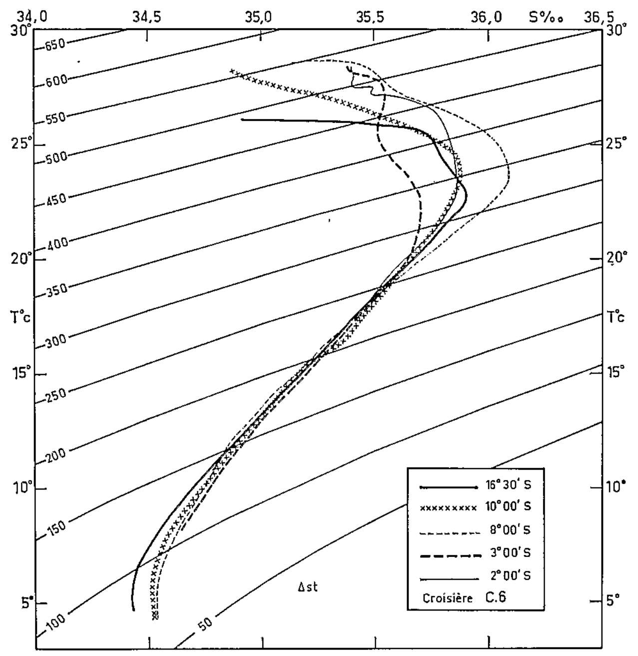

FIG. 16B. T-S diagrams at the tropical stations, cruise *Cyclone 6,* August 1967. The background lines are lines of equal thermosteric anomaly in cl/t.

CONCLUSIONS

There exist important clues for a well defined type of circulation in the vertical plane at 170° E. With a wind blowing from the east, an equatorial upwelling is very probable. Rotschi (1968), Rotschi *et al.* (1968), Hisard *et al.* (1971) have shown that under such conditions the upwelling is present. In some cases, a divergence away from the equator has been observed, and numerous data confirm that in the thermocline there is an equatorward convergence. A thorough examination of the vertical distributions in the light of the current measurements suggests that below the Cromwell Current there is a divergence away from the equator. There is also strong evidence for a descending movement in the lower part of the discontinuity layer. Gathering of all these facts leads to a schematic circulation in the vertical plane (fig. 17), taking also into account the two convergences on either side of the equator which have occasionally been observed (Rotschi *et al.,* 1968). To this picture should be added the ascending and descending motions located respectively at the northern and southern border of each of the eastward counter-currents in the tropical waters. It appears thus that the wind-mixed layer can be locally enriched and then exhausted in nutrient salts according to a mechanism similar to that proposed by Vinogradov *et al.* (1970).

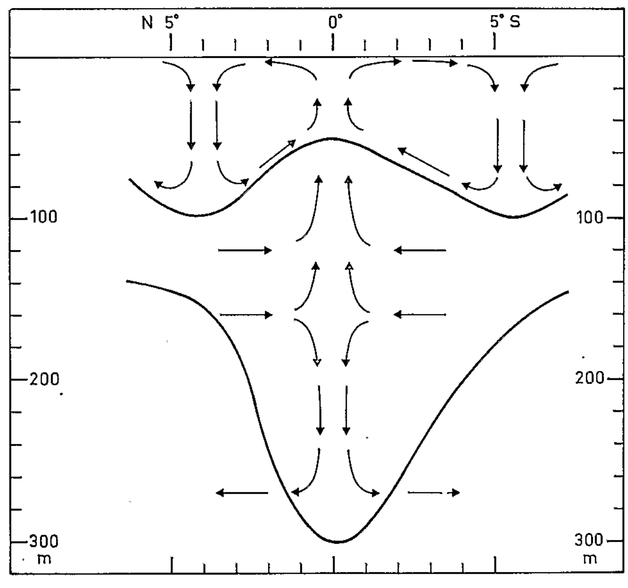

FIG. 17. Proposed scheme for the circulation in a vertical plane through the equator, at 170° E, when the wind is blowing from the east.

REFERENCES

COLIN, C.; ROTSCHI, H. 1970: Aspects géostrophiques de la circulation est-ouest dans l'Océan Pacifique équatorial occidental. *C.R. Acad. Sci. Paris, 271:* 929-932.

COLIN, C.; HISARD, P.; RUAL P. 1973: Currents at the equator in the western Pacific Ocean. Evolution between 140° W and 140° E. Wind influence. "South Pacific Oceanography 1972". comp. R. Fraser, National Commission for UNESCO, Wellington.

CROMWELL, T. S. 1953: Circulation in a meridional plane in the central equatorial Pacific. *J. Mar. Res., 12:* 196-213.

——— 1958: Thermocline topography, horizontal currents and ridging in the eastern tropical Pacific. *Bull. Inter-Am. Trop. Tuna Comm 3:* 135-152.

FOFONOFF, N. P.; MONTGOMERY, R. B. 1955: The equatorial undercurrent in the light of the vorticity equation. *Tellus, 7:* 518-521.

HISARD, P.; RUAL, P. 1970: Courant équatorial intermédiaire de l'Océan Pacifique et contre-courants adjacents. *Cah. ORSTOM, sér. Océanogr. 8, (1):* 21-45.

HISARD, P.; JARRIGE, P.; ROTSCHI. H. 1971: Circulation in the western and south tropical Pacific Ocean in relation to enrichment processes. *Rec. Proc. 12th Pac. Sci. Cong.*, Canberra, Australia, *1:* 146-147.

KENDALL, T. R. 1966: Transports in the Pacific Equatorial Countercurrent. M.S. Thesis, University of Hawaii, Honolulu, 40 pp.

——— 1970: The Pacific Equatorial Countercurrent. Int. Centre Environm. Res., Laguna Beach, 72 pp.

KNAUSS, J. 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.

MAGNIER, Y.; ROTSCHI, H.; RUAL, P.; COLIN, C. (in press): Circulation équatoriale dans le Pacifique occidental (170° E). *in* Progress in Oceanography, vol. 6, B. Warren ed.: Pergamon Press.

MASUZAWA, J. 1967: An oceanographic section from Japan to New Guinea at 137° E, in January 1967. *Oceanogrl. Mag., 19:* 95-118.

MERLE, J.; ROTSCHI, H.; VOITURIEZ, B. 1969: Zonal circulation in the tropical western Pacific at 170° E. *Bull. Japan Soc. Fish. Oceanogr., Special Number,* (Prof. Uda's commemorative papers): 91–98.

MONTGOMERY, R. B.; WOOSTER, W. S. 1954: Thermosteric anomaly and the analysis of serial oceanographic data. *Deep Sea Res., 2:* 63-70.

MONTGOMERY, R. B.; STROUP, E. D. 1962: Equatorial waters and currents at 150° west, in July-August 1952. Johns Hopkins Oceanogr. Stud., No. 1, The Johns Hopkins Press, Baltimore, 68 pp.

PANFILOVA, S. G. 1968: Water salinity of the Pacific Ocean. *in* Hydrology of the Pacific Ocean: Nauka, Moscow, 524 pp. (in Russian).

REID, J. L. 1965: Intermediate waters of the Pacific Ocean. Johns Hopkins Oceanogr. Stud., No. 2, The Johns Hopkins Press, Baltimore, 85 pp.

ROBINSON, M. K. 1969: Theoretical predictions of subtropical countercurrent confirmed by bathythermograph data. *Bull. Japan Soc. Fish. Oceanogr., Special Number* (Prof. Uda's commemorative papers): 115-122.

ROTSCHI, H. 1968: Remontée d'eau froide et convergence à l'équateur dans le Pacifique occidental. *C.R. Acad. Sci. Paris, 167:* 1459-1462.

ROTSCHI, H.; HISARD, P.; RUAL, P. 1968: Observations de deux fronts thermiques dans le Pacifique équatorial occidental. *C. R. Acad. Sci. Paris, 266:* 1465-1468.

ROTSCHI, H.; WAUTHY, B. 1969: Remarques sur le courant de Cromwell. *Cahier ORSTOM ser. Oceanogr., III, 2:* 27-43.

SVERDRUP, H. W.; JOHNSON, M. W.; FLEMING, R. H. 1942: The oceans; their physics, chemistry and general biology. Prentice-Hall, New York, 1087 pp.

VINOGRADOV, M. E.; GITELZON, I. I.. SOROKIN, YU. I. 1970: The vertical structure of a pelagic community in the tropical ocean. *Mar. Biol., 6:* 187-194.

WYRTKI, K. 1967a: Circulation and water masses in the eastern equatorial Pacific Ocean. *Int. J. Oceanol. Limnol., 1:* 117-147.

——— 1967b: Oceanographic observations during the Line Islands expedition, February-March 1967. Hawaii Institute of Geophysica, HIG 67-17, 35 pp.

YOSHIDA, K.; KIDOKORO, T. 1967: A subtropical countercurrent (II)—A prediction of eastward flows at lower subtropical latitudes. *J. Oceanogr. Soc. Japan, 23:* 231–246.