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Study of frontal zones in the Crozet-Kerguelen region

Fronts
Hydrology
Eddy
Indian austral Ocean

Fronts
Hydrologie
Tourbillon
Océan austral Indien

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ABSTRACT

During the March 1977 Antiprod I-MD 12 cruise, hydrological data were collected along 66°30E between 40 and 62°S. These data show a frontal zone between 43 and 46°S which separates the antarctic and subtropical regions and within which is concentrated most of the circumpolar current. The frontal zone is due to the coalescence of the antarctic and subtropical convergences into a single convergence zone, effectively eliminating the subantarctic region. The few observations made previously in the Kerguelen-Crozet area show a similar structure. However, the frontal zone which is located between 43 and 46°S in the Kerguelen region (60°-75°E) is located three degrees further north, between 41 and 43°S, in the Crozet region (50°E). The coalescence of the two fronts was due to the northward translation of the antarctic convergence west of Crozet Islands, a possible effect of the bottom topography.

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RÉSUMÉ

Étude des zones frontales dans la région Crozet-Kerguelen

Des données hydrologiques ont été collectées en mars 1977 au cours de la mission Antiprod I-MD 12, le long du 66°30E et entre 40 et 62°S. Ces données montrent une zone frontale entre 43 et 46°S qui sépare les régions antarctique et subtropicale, et dans laquelle se concentre la quasi-totalité du courant circumpolaire. Cette zone frontale est le résultat d'un resserrement très marqué des convergences antarctique et subtropicale, qui ne permet pas de mettre en évidence de région subantarctique. Les quelques observations faites antérieurement dans la région Kerguelen-Crozet confirment cette structure, mais la zone frontale, qui se situe entre 46 et 43°S, dans la région de Kerguelen (60°-75°E), se situe trois degrés plus au Nord, entre 43 et 41°S, dans la région de Crozet (50°E). Le resserrement des deux fronts serait dû à la déviation vers le Nord de la convergence antarctique, en amont des îles Crozet, par suite d'un effet de la topographie sous-marine.

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HYDROLOGICAL SCHEME OF THE SOUTHERN OCEAN

The large scale hydrological structure of the Southern Ocean is now well-known. Synthetizing all previous works on the subject, Sverdrup *et al.* (1942) and Gordon and Goldberg (1970) have proposed a schematic representation of the currents and water masses in bloc-diagram form, applicable to all three sectors of this ocean: Atlantic, Indian and Pacific.

Between the cold waters of the Antarctic area and the warmer subtropical waters runs a transitional circumpolar zone: the subantarctic region.

This region is bounded by hydrological fronts. To the south, it is separated from the Antarctic region by the Antarctic Convergence (or Polar front zone); to the north, in each of the three oceans, it is separated from the subtropical region by a Subtropical Convergence. The latitudinal extension of the subantarctic region varies from 7 to 13°, depending on the oceanic sector.

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ANALYSIS OF RESULTS OF ANTIPROD I-MD 12 CRUISE

Nota: The Antiprod (ANTarctic PRODuction) I-MD 12 cruise was made in March 1977 by the Mediprod Group. This group was composed of research workers from several laboratories, whose task was to investigate problems connected with the dynamics of pelagic production in the regions of direct nutritional apport: upwelling, divergence zone.

The chief scientist of the Antiprod I cruise was Guy Jacques, Laboratoire Arago, Banyuls-sur-Mer.

The Antiprod I-MD 12 cruise was carried out in March 1977 aboard the supply-ship "Marion Dufresne" by the Mediprod Group. The objective was the study of planctonic production in the Indian Southern Ocean along 66°30E between 40 and 62°S (Fig. 1). All biological and physical data have been published by the Mediprod Group (1978).

On both sides of the Kerguelen Plateau, deep, circumpolar and bottom water masses present an hydrological continuity; only the superficial water masses (Fig. 2, 3, 4) permit differentiation of the following three regions:

– South of 46°S, the Antarctic region: cold and not very salty superficial waters (temperature between 1.5 and 6.6°C and salinities not exceeding $34^0/_{00}$; these waters are characterized during the season in question by a subsuperficial temperature minimum layer whose depth varies from about 75 m in the south to 250 m in the north, the temperature rising from −1.5 to 2.1°C;

– North of 43°S, the subtropical region: warm and salty superficial waters (temperature higher than 12° and salinity exceeding $35^0/_{00}$);

– between these two clearly defined regions: a frontal transitional zone.

In the Antarctic region, the results are consistent with the classical data: presence of three water masses (superficial, circumpolar and bottom waters); we should note the characteristic "scorpion tail" form of the T-S diagram (Fig. 5). More unexpected, however, are the previous data regarding area separating the antarctic and subtropical regions.

In the West Indian Ocean area, the Antarctic and Subtropical Convergences may be generally located respectively around 48 and 41°S (Wyrtki, 1973) i.e. with seven degrees difference in latitude. Along 66°30'E however, only three degrees separate the antarctic and subtropical regions.

Indeed, although the Polar Front is often identified by the northern limit of the 2°C isotherm (at 48°S along the 66°30E), the superficial waters maintain antarctic characteristics as far as 46°S: very similar T-S diagrams and same high amounts of nutrients between 48 and 46°S(stations 7, 6, 5 and 29)

$$(N-NO_3 = 23.0 \pm 0.5 \text{ matg.m}^{-3},$$
$$P-PO_4 = 1.50 \pm 0.05 \text{ matg.m}^{-3});$$

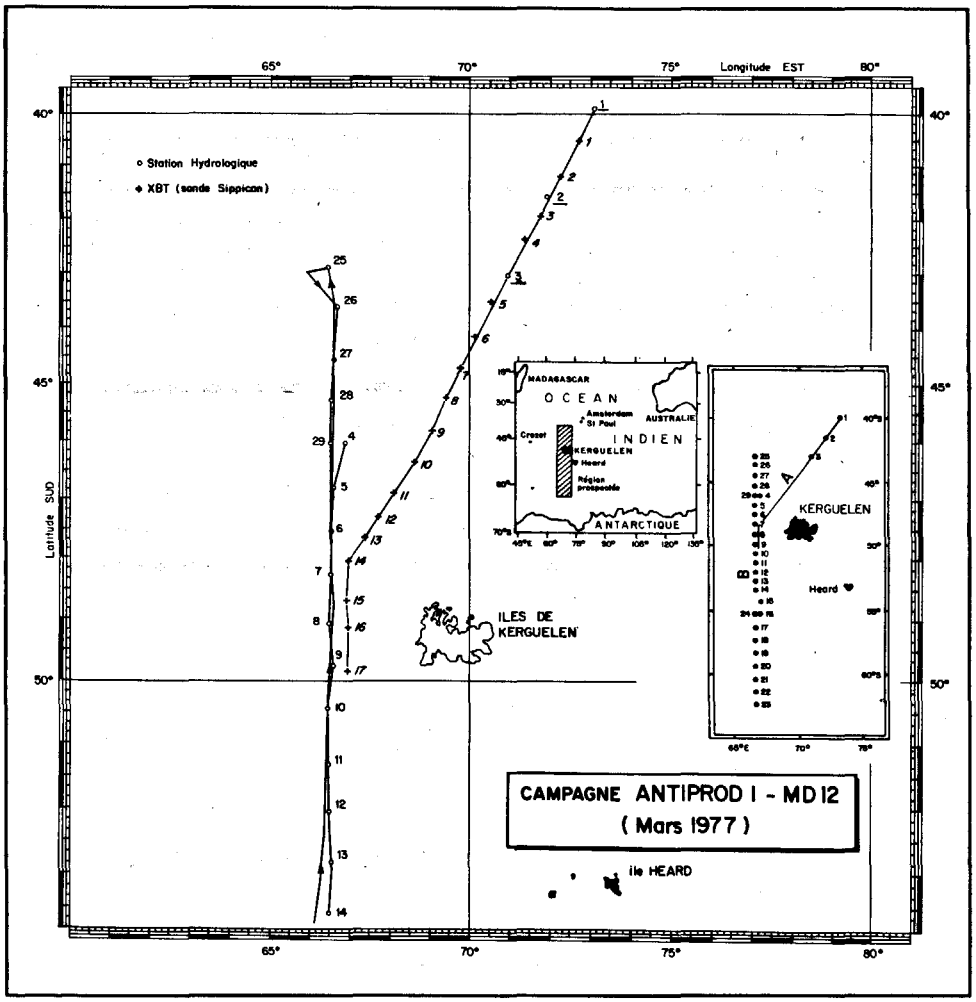


Figure 1

Location of hydrological stations and bathythermograms of the Antiprod I-MD 12 cruise (March 1977).

Position des stations hydrologiques et des bathythermogrammes de la campagne Antiprod I-MD 12 (mars 1977).

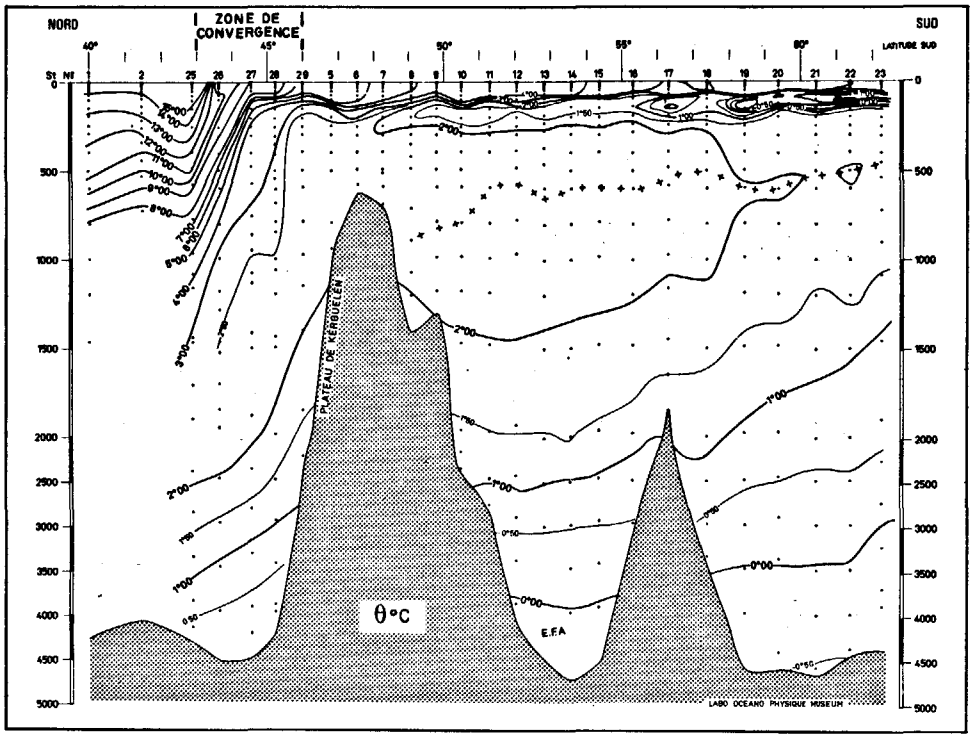


Figure 2
Antiprod I cruise: temperature section.
Campagne Antiprod I : coupe verticale de température.

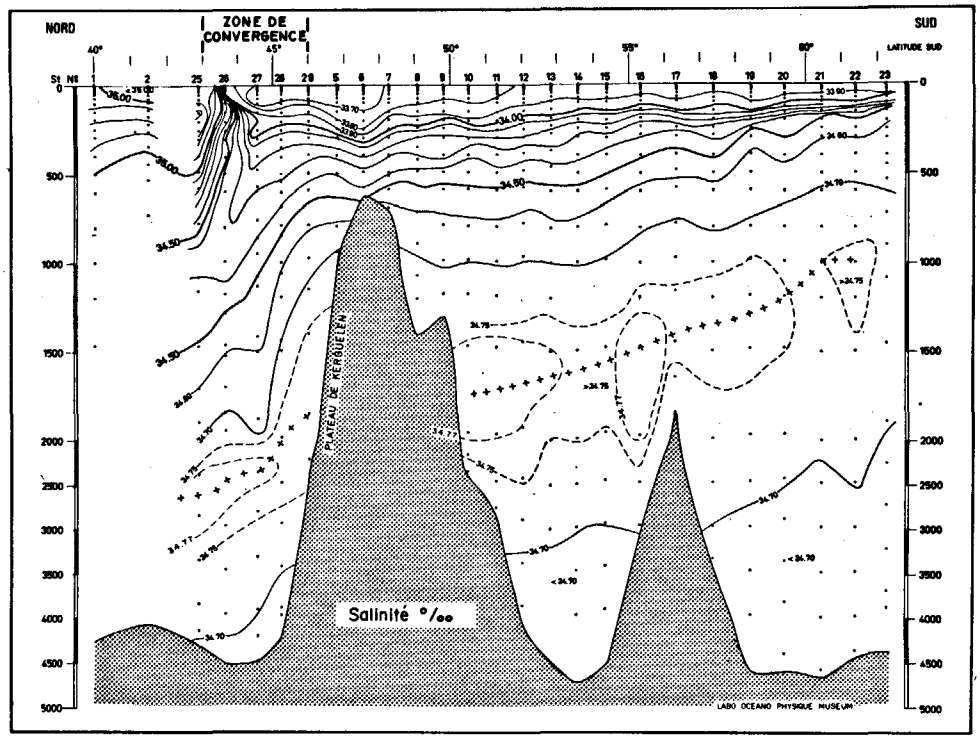


Figure 3
Salinity section.
Coupe verticale de salinité.

northern limit of the thermal minimum ($T < 2.2°C$) at 46°S.

On the other hand, at 43°S (station 25), their characteristics are already subtropical: salinity higher than $35.4^0/_{00}$, presence between 150 and 800 m of the central water mass of the Indian Ocean and low amounts of nutrients ($N-NO_3 < 3.0$ matg.m^{-3}, $P-PO_4 < 0.3$ matg.m^{-3}). Consequently, only three degrees of latitude separate these two regions.

In the transitional zone, between 46 and 43°S, we observe:

– on the surface, on both thermosalinograph records (Fig. 6): south of the zone, from 46 to 45°S a large drop of density (0.3 to 0.5 in σ_t) due to the presence of a thermal front of about 2°C; and north of the zone, around 44-43°S, a very important thermohaline front.

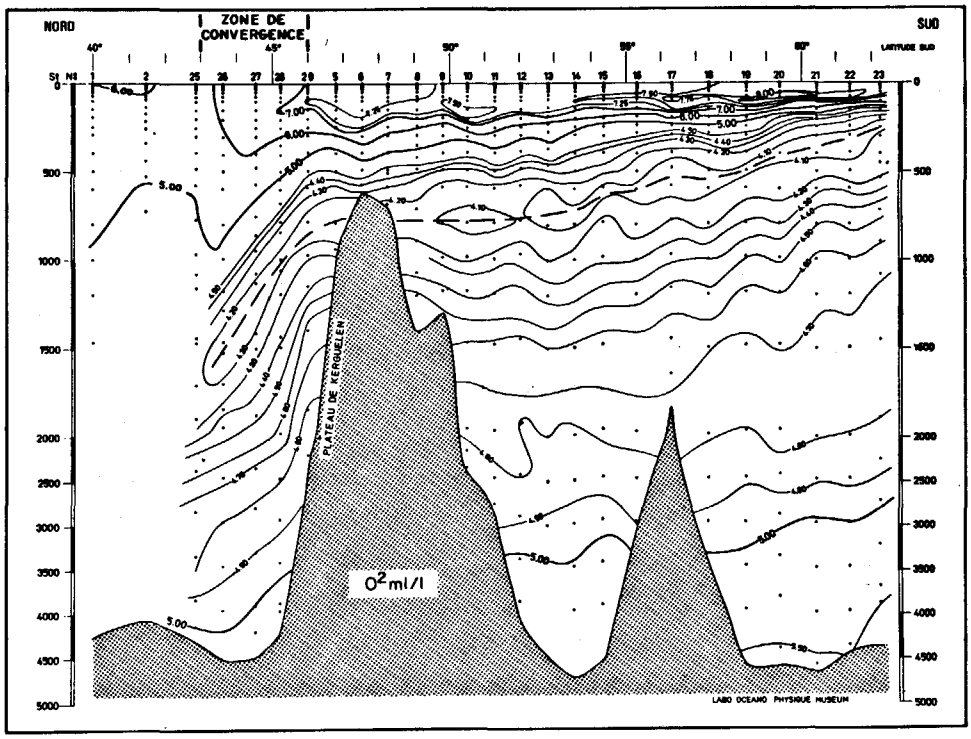
In the upper layers, from south to north (Fig. 2 and 3):

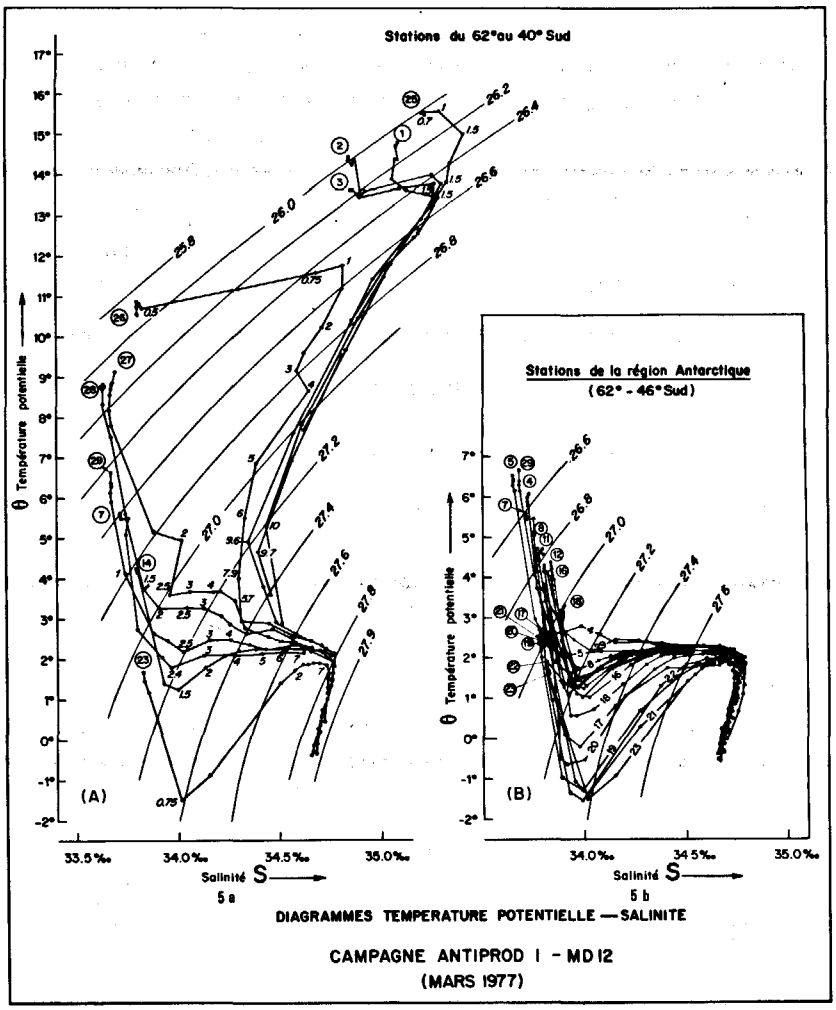
— at 46°S, the limit of the minimum of temperature, followed by a sudden deepening of the 2.5 and 3°C isotherms;

– the emergence at 250 m (station 27) of a salinity minimum which sinks between the 3 and 4°C isotherms to reach 800 and 1 000 m respectively at stations 26 and 25;

— a thermohaline front, from the surface to 800 m, at the northern end of the transition zone (at 200 m, the

Figure 4
Oxygen section.
Coupe verticale d'oxygène.





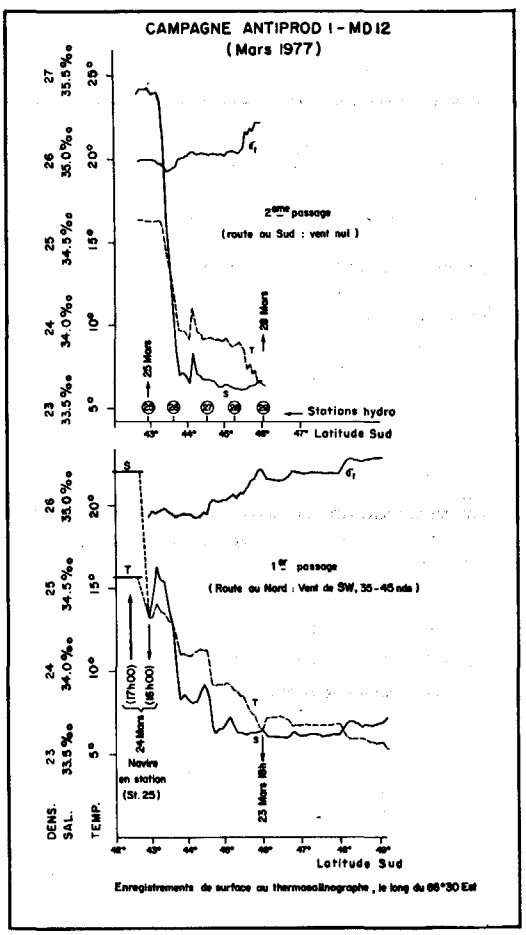
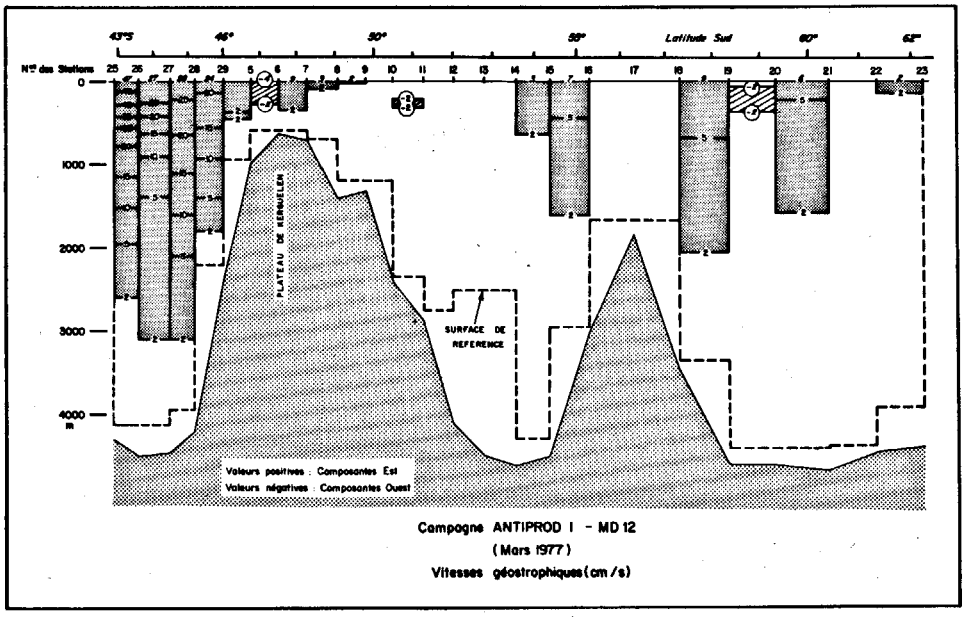


Figure 5
θ. *S diagrams. a) antarctic, transitional and subtropical regions* (62°*S*-40°*S*); *b) antarctic region* (62°*S*-46°*S*).
Diagramme température potentielle-salinité : *a*) région antarctique, région de transition et région subtropicale (du 62°S au 40°S); *b*) région antarctique (du 62 au 46°S).

Figure 6
Surface temperature, salinity and density along 66°30′*E in the transition region* (46-43°*S*).
Profils de surface de la température, de la salinité et de la densité, le long du 66°30′E, dans la région de transition (46-43°S).

Figure 7
Geostrophic current section along 66° 30′E between 62°S and 43°S.
Coupe verticale des vitesses géostrophiques, le long du 66°30′E, entre les latitudes 62 et 43°S.



temperature increases from 4 to 14°C and salinity from 34.0 to 35.3‰ over a distance of only about 100 miles.

South of the zone, therefore, and identified on the surface by the thermal front, the Antarctic Convergence is marked by the sinking of isotherms and the deepening of the salinity minimum, i. e. the formation of Antarctic Intermediate Water. Since station 25 (43°S) is in the subtropical region, both the Antarctic and the Subtropical Convergences are effectively located between 46 and 43°S. Along this meridian, it is difficult to individualize a subantarctic region which would be characterized, between 200 and 600 m, by a relatively homogeneous water mass with an average temperature of about 9°C and an average salinity of about 34.5‰ (never exceeding 35‰): there would consequently appear to exist a juxtaposition of the two convergences.

The profile of geostrophic speeds (Fig. 7) shows a high current vein between 43 and 46°S, i. e. in the transitional zone: on the surface, speeds exceed 25 cm. sec.$^{-1}$, and may even attain 50 cm. sec.$^{-1}$ between stations 25 and 26; speeds superior or equal to 5 cm. sec.$^{-1}$ are noticeable to a depth of 2000 m.

The global geostrophic flow (43-62°S) is 118 SV (1 SV = 10^6 m^3. sec^{-1}). Ninety-eight per cent of the flow passes north of the shelf, between 46 and 43°S (one and a half times the Gulf Stream transport off Cape Hatteras). These results underline the importance of this "convergence zone", in which most of the circumpolar current is concentrated.

STUDY OF CONVERGENCES IN THE CROZET-KERGUELEN REGION

Since effect of bottom topography on currents west of the Kerguelen Islands may account for the closeness of two convergences, the location of fronts in the Crozet-Kerguelen sector will be examined on the basis of some of the previous observations.

Region north of the Kerguelen Islands, between 60 and 75°E

Vertical temperature profiles (XBT)

These are bathythermogram (XBT) readings, made during the Antiprod I Cruise and during the cruises aboard the "Gallieni" and "Marion Dufresne" by Murail (unpublished manuscript) and by Delepine *et al.* (1971; 1973; 1976) (profiles A, C, D and E:Fig. 8, 9, 10, 11 and 12).

On the four profiles drawn up virtually at the same period of the year (austral summer and early autumn), we may observe at 46°S the sudden sinking of the 3°C isotherm which marks the beginning of the 10°C thermal front. We may then identify either a single front running from 46 down to 44°S, i. e. 120 miles (profiles A and E) or a more extensive frontal zone from 46 to 43°S (profiles C and D) composed of two fronts separated by an intermediary zone (9°C on the surface, 7-8°C at 200 m).

On these profiles, the northern part of the frontal zone is characterized at the surface by strong haline gradient (salinity superior to 35.0‰, north of the fronts).

We may also observe the presence, a few degrees north of the fronts, of important cyclonic eddies characterized by a sharp rise of the isotherms (profiles A, D and E); on profile E, for instance, the 12°C isotherm rises from 650 to 250 m within two degrees of latitude: at 650 m, the horizontal thermal gradient is 1.5°C per degree of latitude.

These eddies, which are encountered over a depth range of 800 m (profile E) and have zonal extension of about 3 degrees, are characterized at the surface by a drop in salinity (some 0.7‰ in the case of profile E), the centre of the eddy being under the salinity minimum.

According to some authors, these features constitute the subtropical convergence. Thus, Copin-Montegut and Copin-Montegut (1978), in their study of the Reunion-Kerguelen route (profile E), have located the subtropical convergence between 38°15′ and 39°56′S, i. e. on the northern side of the eddy. It is also very

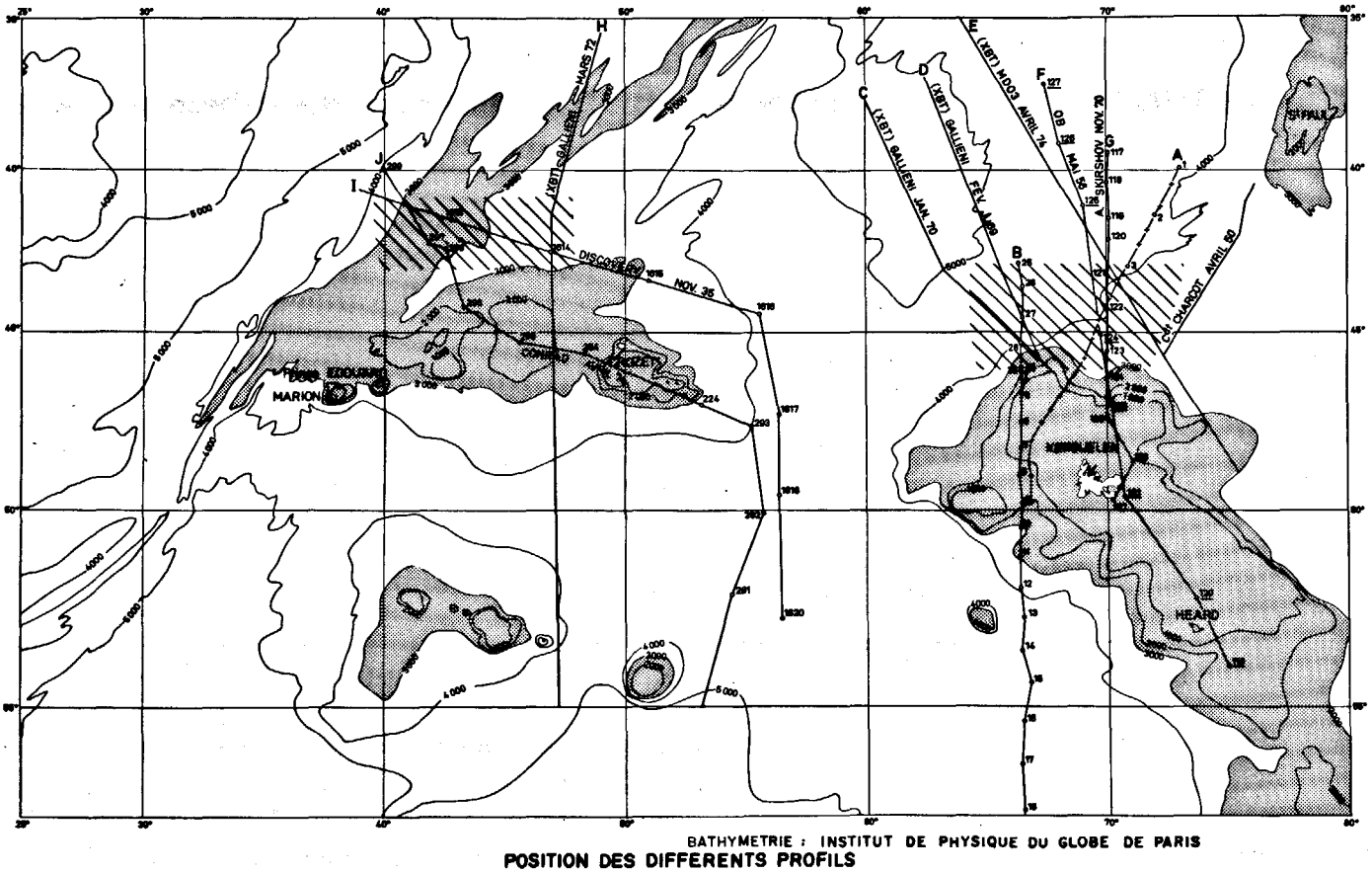
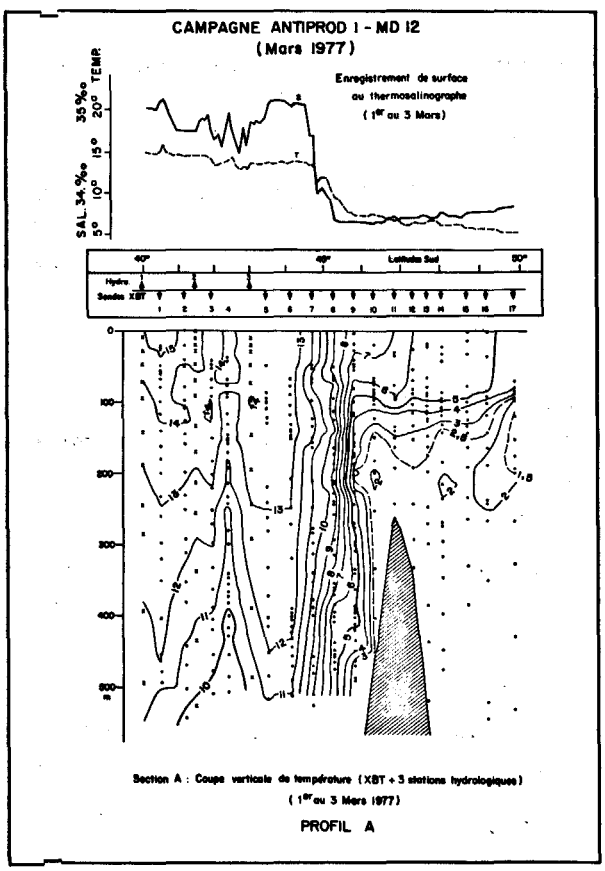


Figure 8

Situation of the eight legs C to J, and of legs A and B of the Antiprod I cruise. Location of the convergence zone (hatched zone).

Position des huit profils C à J et des profils A et B de la campagne Antiprod I. Localisation de la zone de convergence (zone hachurée).



likely that the salinity anomaly observed at the surface at 41°30'S during the Kerguelen-St-Paul leg (Tchernia, 1951) and interpreted in the absence of deep observations as a sign of the subtropical convergence, is in fact merely the surface manifestation of such an eddy. In this case, the surface thermohaline front located between the 46 and 44°S would correspond to a convergence zone uniting the two fronts, i. e. a situation similar to that identified on profiles E and A (April 1974 and March 1977).

The velocities obtained by comparing the slope of the isotherms of these profiles with those of profile B, between stations 25 and 26, are about 20 cm . sec. $^{-1}$ for the eddy of profile A and about 40 cm . sec. $^{-1}$ for the eddy of profile E. On profile C, in contrast with the three other profiles, no clearly individualized eddy may be observed; however, we may note, very close to the front at 42°30'S, the beginning of such an eddy, with an important drop in salinity at the surface.

The presence of these eddies appears to be a fairly common phenomenon in the Kerguelen region. Thus, the trajectories of drifting "Marisonde" buoys n° 1030

Figure 9

Temperature sections (XBT) and hydrological stations, and surface temperature and salinity records along leg A (Antiprod I, March 1977).

Coupe verticale de température (XBT et stations hydrologiques) et enregistrement de surface de la température et de la salinité, le long du profil A (Antiprod I, mars 1977).

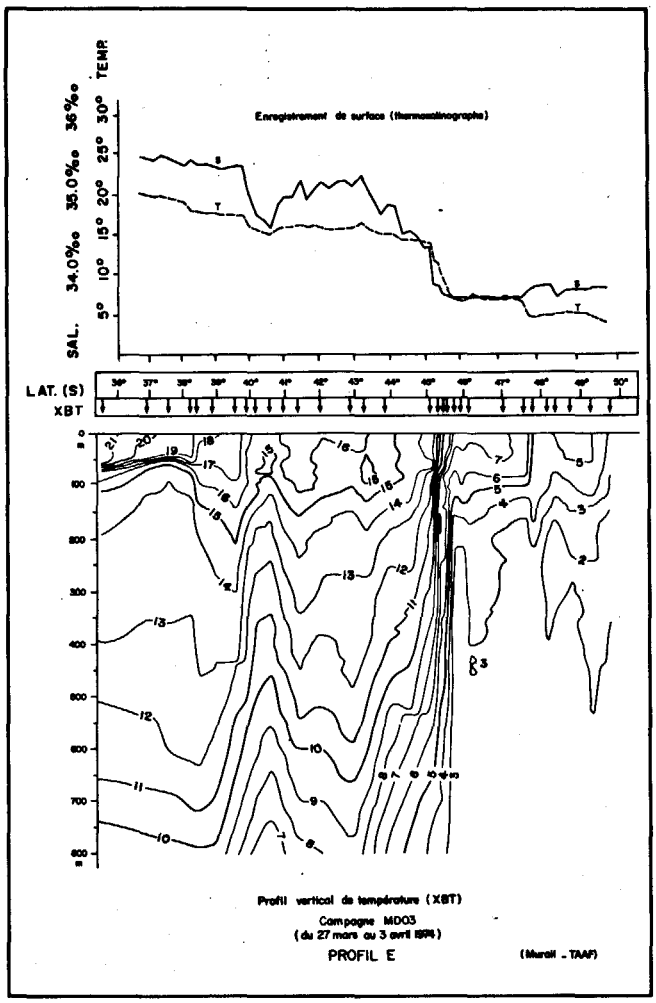


Figure 10

Temperature section (XBT) and surface temperature and salinity records along leg E (MD 03, April 1974).

Coupe verticale de température (XBT) et enregistrements de surface de la température et de la salinité, le long du profil E (MD 03, avril 1974).

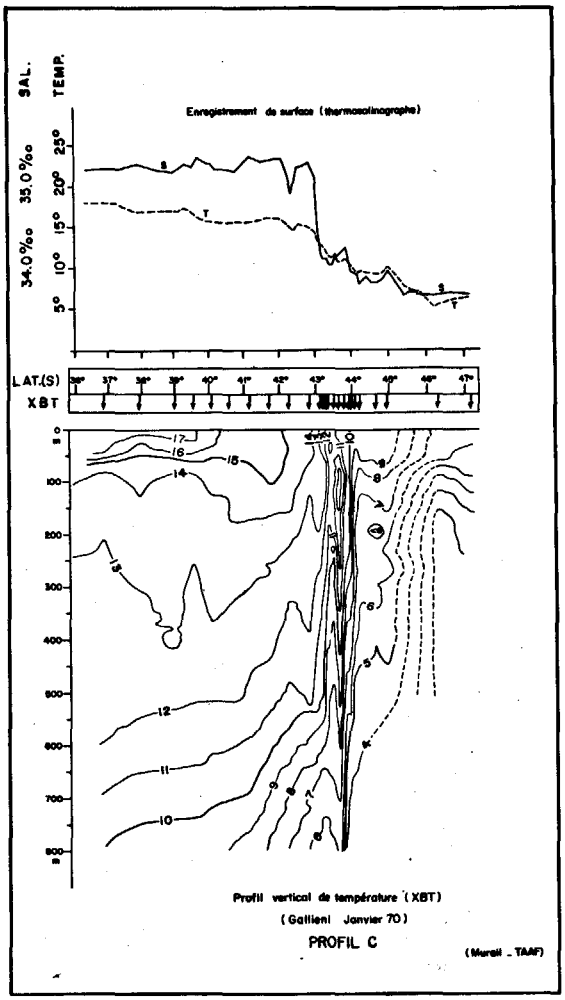


Figure 11

Temperature sections (XBT) and surface temperature and salinity records along leg C (" Gallieni ", January 1969).

Coupe verticale de température (XBT) et enregistrement de surface de la température et de la salinité, le long du profil C (« Gallieni », janvier 1970).

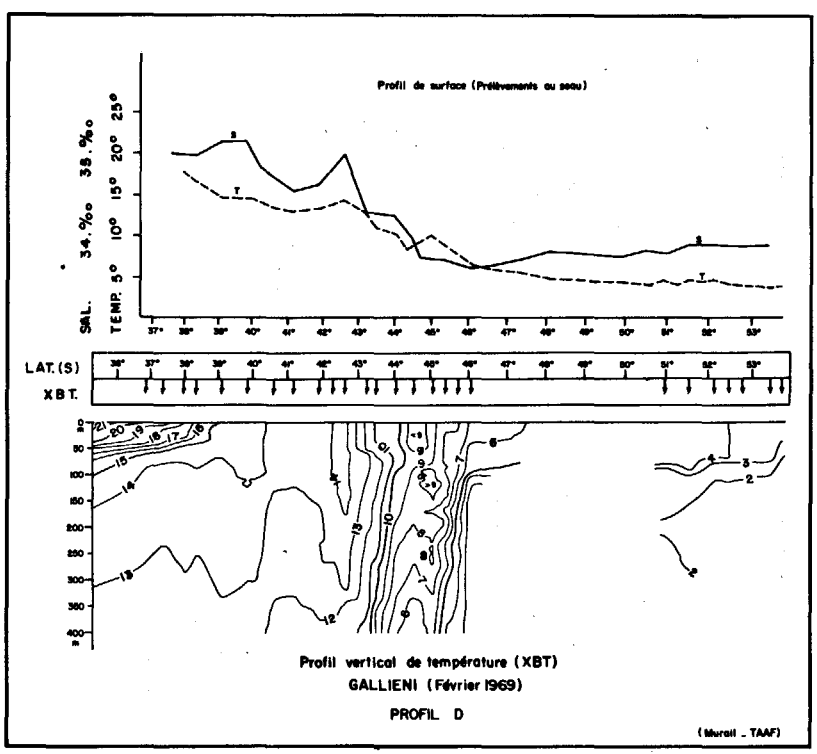


Figure 12

Temperature sections (XBT) and surface temperature and salinity records along leg D (" Gallieni ", February 1969).

Coupe verticale de température (XBT) et enregistrements de surface de la température et de la salinité, le long du profil D (« Galliéni », février 1969).

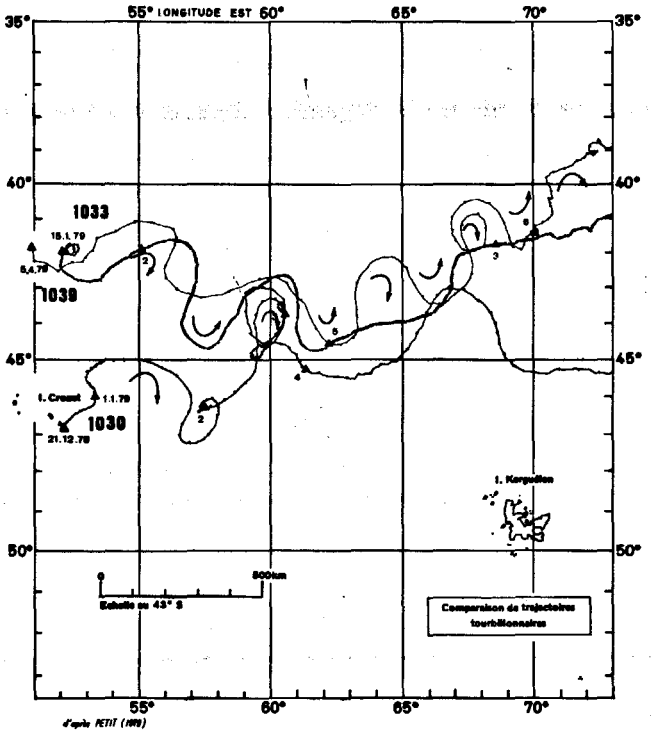


Figure 13
Trajectories of Marisonde buoys n^{os} 1030, 1033 *and* 1039, *respectively launched in the Crozet region in December* 1978, *January* 1979, *and April* 1979.
Trajectoire des bouées Marisonde n^{os} 1030, 1033 et 1039 mises respectivement à l'eau dans la région de Crozet en décembre 1978, janvier 1979 et avril 1979.

and 1039 (Fig. 13) launched in the Indian Ocean as part of the first world-wide GARP experiment (Global Atmospheric Research Program), show cyclonic eddies at 44°S-60°E (buoy 1030) and at 42°S-67°E (buoy 1039) (Petit, 1979).

Hydrological section of the R/V "OB" (May 1956, *profile F)*

On this hydrological section represented in the Indian Ocean atlas (Wyrtki *et al.*, 1971) we also observe, north of the thermal minimum ($t < 2$°C), near 46°S, the sinking of the 3°C isotherm and the deepening of the 27.2-27.4 isopycnals between which the salinity of the Antarctic Intermediate Water is found (Wyrtki *et al.*, 1971). The Antarctic Convergence, deepening of the Antarctic Superficial Water, would therefore be located at 46°S, and not at 56°S as Ivanenkov and Gubin (1960) have supposed. At this latitude (56°S), we note a discontinuity in the slope which concerns mainly the 27.6-27.7 isopycnals and which is due to the rising of deep water (the 27.2 isopycnal, situated at 50 m at 56°S, reaches only 250 m at 47°S). Since the stations are at a relatively large distance from each other (four degrees of latitude separate stations "OB" 124 and "OB" 125), the northern limit of the convergence zone in this section cannot be accurately located.

Profile G-R/V "Akademik Skirshov" (November 1972) *(Fig.* 14)

The hydrological stations established in spring (November 1972) along 70°E reveal at 46°S the northern limit of the 2°C isotherm and the presence of two fronts at 46 and 43°S, separated, from the surface to 300 m, by a relatively homogeneous water (temperature about 9°C, salinity about 34.5‰) beneath which we may observe the appearance of Antarctic Intermediate Water from 45°30 S (station 123).

These data permit us to state that in the Kerguelen region, the "Polar Front", northern limit of the Antarctic Surface Water, is located at 46°S and corresponds to the beginning of a frontal transition of three degrees in latitude (46-43°S) situated between the antarctic and subtropical regions. In this area, the two fronts (Antarctic Convergence and Subtropical Convergence) are always very close: certain observations (profiles A, E) do not permit the identification of a subantarctic region; others may reveal an intermediate region between the two fronts.

Lacombe (1951), who studied the circulation in the austral Indian Basin, pointed out the influence of the Prince Edward and Crozet Islands on superficial circulation: the dynamic isobaths bend to the left approaching the ridge, and beyond it, to the right.

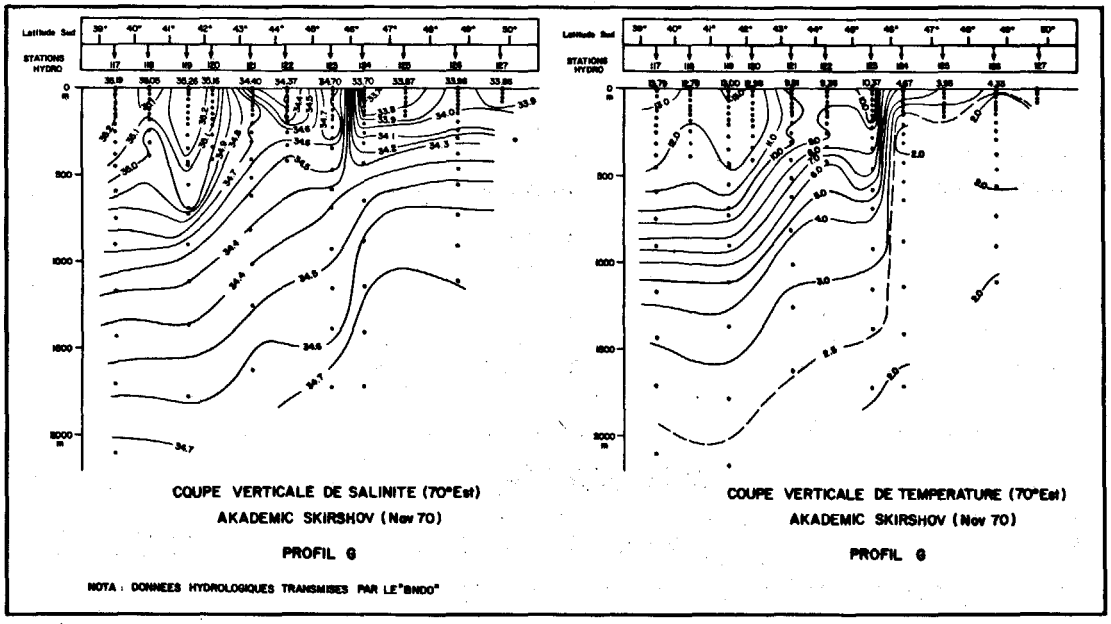


Figure 14
Temperature and salinity sections along 70°*E, "Akademik Skirshov" stations-November* 1970 *(leg G).*
Coupes verticales de salinité et de température, le long du 70°E : stations de l'« Akademic Skirshov », novembre 1970 (profil G).

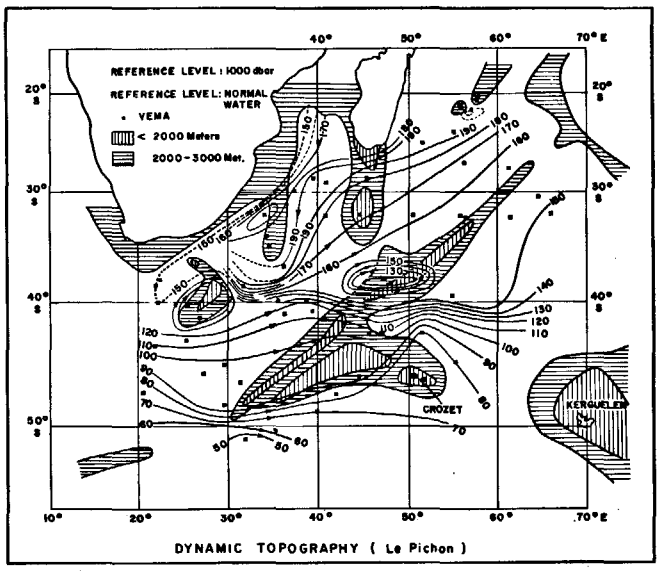


Figure 15
Surface dynamic topography relative to 1 000 *db, in dynamic centimeters.*
Topographie dynamique de la surface par rapport à 1 000 db en centimètres dynamiques.

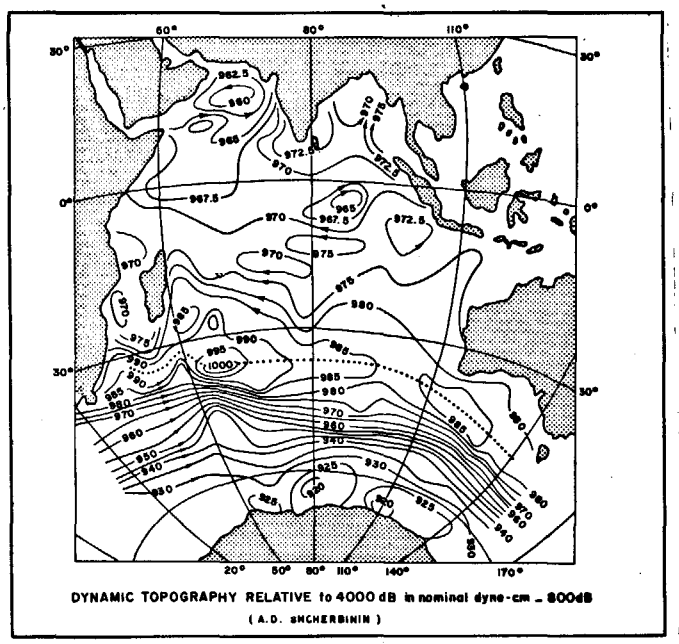


Figure 16
800 *db dynamic topography relative to* 4 000 *db, in dynamic centimetres.*
Topographie dynamique de la surface 800 db par rapport à la surface 4 000 db en centimètres dynamiques.

The surface dynamic topography map of the South West region of the Indian Ocean (Le Pichon, 1960) (Fig. 15) shows that the two current branches, which may be considered as Antarctic and Subtropical convergences, are separated along 30°E by a region (subantarctic region) of weak current; they then form a single strong current vein, centered along 42°S, north of Crozet, as a consequence of the deflection to the north of the southern current vein.

The deflection of current veins occurs not only at the surface but also at depth, as shown on the 800 db dynamic topography map (Scherbinin, 1973; Fig. 16).

More recent analysis of the Southern Ocean Circulation (Fig. 17) (Gordon *et al.*, 1978) confirms these observations: the main vein of circumpolar current, centered along 48-49°S between 20 and 40°E, is then deflected to the north and joins the return branch of the Agulha current at a location east of 50°E, 40°S.

Crozet Islands Region

We observe, along 47°E, on the temperature profile established by Murail in March 1972 (profile H, Fig. 18) a thermal front identical to those of profiles A and E, but shifted three degrees to the north (43-41°S).

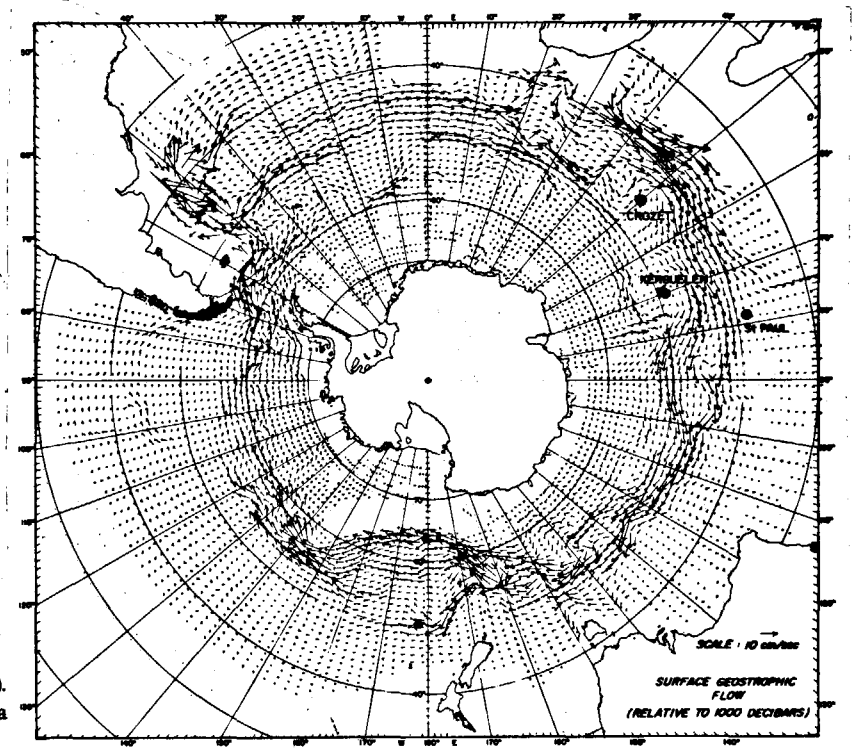


Figure 17
Surface geostrophic current relative to 1 000 *db (cm/sec.).*
Courant géostrophique de la surface par rapport à la surface 1 000 db (cm/s).

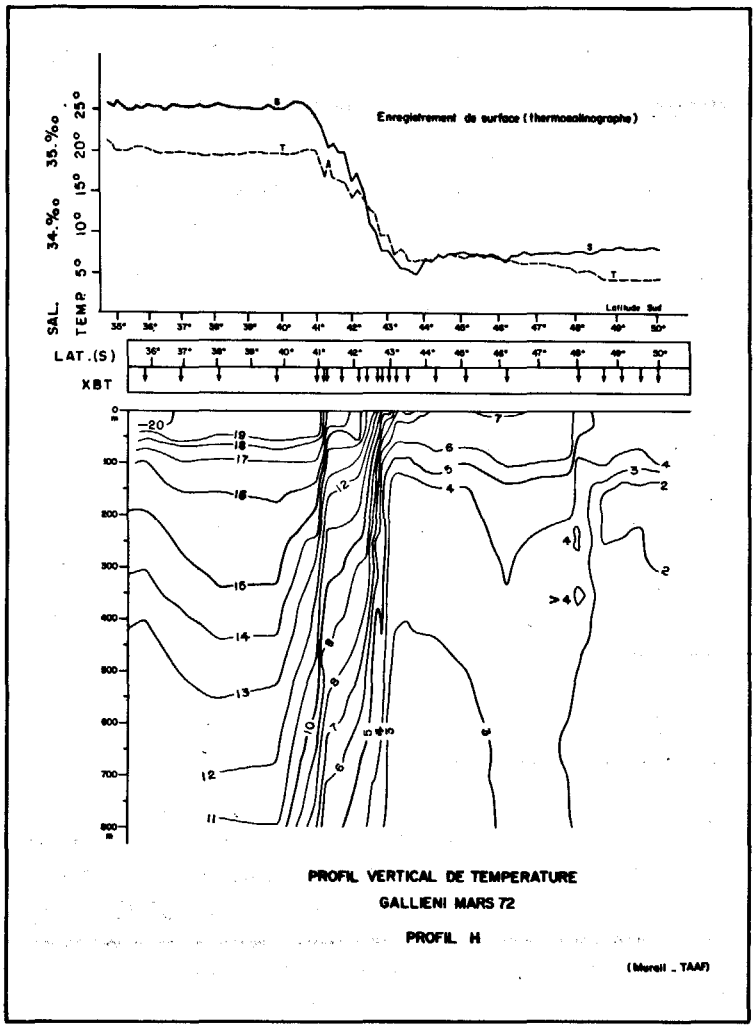


Figure 18

Temperature section (XBT) and surface temperature and salinity along leg H (" Gallieni ", March 1972).

Coupe verticale de température (XBT) et enregistrement de surface de la température et de la salinité, le long du profil H (« Gallieni », mars 1972).

The low salinities (lower than $33.8^0/_{00}$) at the surface, south of 43°S, and the very important haline front ($33.6\text{-}35.5^0/_{00}$), associated with the thermal front on the surface, appear to confirm the hypothesis of the deviation to the north of the Antarctic Convergence. On the other hand, the end of the thermal minimum ($t<2$°C) is situated around 49-48°S, i. e. at not very different latitude from that in the Kerguelen region.

This thermal structure is confirmed by the "Discovery" stations [November 1935 (Discovery Reports, 1944; profile 1)]; We also note, at 49°S, the northern limit of the thermal minimum waters ($t<2$°C). The deepening of the 3 and 4°C isotherms, showing the beginning of the front, extends between stations 1614 and 1615, i. e. about 43°S. The salinities of the superficial waters (0-200 m) are below $34.0^0/_{00}$, south of station 1614 (43°35' S). Between stations 1615 and 1614 begins the deepening of the superficial waters, i. e. the formation of Antarctic Intermediate Water perceptible at 700 m-station 1613; the Antarctic Convergence should therefore be situated in reality at 43°S.

We also find the same hydrological structure along profile J (R/V Conrad, April 1974; Jacobs, Georgi, 1977): northern limit of the 2°C isotherm about 50-51°S, convergence zone between 43 and 41°S and superficial salinities (0-200 m), lower than $34^0/_{00}$, south of the convergence. The salinity minimum, a feature of Antarctic Intermediate Water, appears at 43°S.

Assuming a deflection to the north of the Antarctic Convergence, the frontal zone (43-41°S) observed in the Crozet Islands region would be, as along 66°E, a consequence of the closeness of the two convergences. Being located three degrees further north, a large area separates the northern limit of the 2°C isotherm, marking, for some authors, the position of the "Polar Front" (Jacobs, Georgi, 1977) and the beginning of the "convergence zone", which we identify as the Antarctic Convergence. In this zone, between 50/49° and 43°S, the surface waters have a temperature which increases gradualy with latitude (from 4° to 8-9°C) but, as the influence of the high subtropical salinities is absent to the south of the "convergence zone", they maintain very low salinities (precipitation). This zone presents very similar hydrological characteristics (T-S diagrams) to that which has been called the "Antarctic Polar Frontal Zone" (Gordon *et al.*, 1977; Emery, 1977; Savchenko *et al.*, 1978).

CONCLUSION

According to the observations of MD 12 cruise, and in agreement with the few available studies of this oceanic Crozet-Kerguelen sector, there is a merging of the fronts which results in a convergence zone of about three degrees latitude.

This structure might be due to the northwards deflection of the Antarctic convergence as a result of the bottom topography west of the Crozet Islands.

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