CHAPTER 2

EQUATORIAL CIRCULATION IN THE WESTERN PACIFIC* (170°E)

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Abstract. Current measurements taken in the equatorial zone at 170°E aboard R.V. *Coriolis* reveal equatorial dynamics peculiar to the western Pacific. The west equatorial surface current has several speed cores on either side of the equator; the Equatorial Undercurrent has one speed core at 100 m and another at 200 m; the North Equatorial Countercurrent is connected with the Equatorial Undercurrent, which has two deep extensions on either side of the equator; beneath the Equatorial Undercurrent lies a weak west current which appears to reach a depth below 1000 m. The flows of these currents are very variable: the Equatorial Undercurrent may double its flow in 20 days.

INTRODUCTION

In 1967–8, R.V. *Coriolis* of the ORSTOM Centre, Noumea (New Caledonia), undertook a series of cruises in the western Pacific called the "Cyclone" cruises (Fig. 1).

These cruises, which followed the longitude 170°E between 20°S and 4°N, were undertaken primarily for the study of medium- and short-term variations in the hydrological conditions and dynamics of the tropical and equatorial waters of the west Pacific. They were the continuation of a series of 3-monthly cruises, the "Bora" cruises, which followed the same route. These had shown that the changes appearing in the 3 months intervals were so considerable as to make it difficult to relate one cruise to another.

The "Cyclone" programme consisted of five 3-week cruises, "Cyclone" 2, 3, 4, 5 and 6, spaced at 2-week intervals wherever possible; they took place respectively in March, April-May, May-June, July, and August-September 1967. A final cruise, "Cyclone" 7, making three successive equatorial sections in 10 days, took place in April-May 1968.

During each of these cruises, a special study was made of the equatorial zone between 4°S and 4°N: a hydrological station of twenty-four bottles distributed over the first 500-m depth was carried out every 30 miles. Every hydrological station was followed by a current measurement station, with the deepest measurements sometimes reaching a depth of 1800 m.

*This manuscript was written at the end of 1968, before the publication of several studies which have now further defined some of the ideas developed here. Moreover, subsequent studies refer to what is here called the deep equatorial current, as the intermediate equatorial current.

The following study will deal only with the direct measurements of currents carried out between 4°S and 4°N: eight sections of seventeen stations each carried out in 4 days, and several stations on the equator of about 1 day.

Equipment

All the current measurements were made using *in situ* recording current meters by Hydro-Products, model 501 B, which had been modified at the Noumea ORSTOM Centre.

These instruments comprise a speed measuring device with a Savonius rotor, a direction sensor measuring direction relative to the magnetic north, a resistance thermometer for temperature evaluation, and a recording unit enclosed in a cast aluminium sphere, all fixed inside a stainless-steel frame which can be attached by two clamps to the hydrological cable. The retrieval mechanism is a miniaturized Rustrak chart recording microammeter with a cam controlling a $7\frac{1}{2}$-minute measurement cycle, during which the current speed and water temperature are measured alternatively every 4 seconds for $1\frac{1}{2}$ minutes, and then for the next 4 minutes the current speed and direction are measured with the same frequency. The cycle is completed by a halt in the measurements. Two scales can be used in speed measurement, 0–50 cm/s and 0–350 cm/s.

TABLE 1. CORRECTION OF A HYDRO-PRODUCTS CURRENT GRAPH MODEL 501 B

Temp.°C	30°	25°	20°	15°	10°	5°
(a) Temperature correction, °C	0	0	0	+1	+1	+2
(b) Speed correction, cm/s scale 0–350 cm/s	+7	+3.5	0	−3.5	−7	−10.5

(c) speed corrections as a function of the direction of the revolving vane, on the 0–350 cm/s scale.

Direction	340°	250°	180°	100°	50°	10°
Correction, cm/s	0	0	1.5	3.5	6	8.5

(d) Direction corrections as a function of speed

Speed, cm/s	0	25	50	75	150	200
Correction	0	1°	2°	3°	5°	7°

According to the manufacturer, the degree of accuracy of the measurement is ±3% of the speed or temperature indicated, and ±5% for direction. Some trials rapidly revealed that, under the conditions in which the instruments were going to be used, their accuracy would fall far short of the advertized norms. The temperature correction for one of the instruments tested is given in Table 1a; it is considerable in cold water. In speed measurement the influence of temperature is not negligible (Table 1b): although it is nil for water at 20°C, it becomes considerable in very hot or very cold water. Similarly, the measurement of direction affects speed measurement: for a northerly current, the correction is of the order of 10 cm/s

(Table 1c). Speed also has a very marked effect on direction recording (Table 1d). Moreover, it subsequently became clear that all the stainless-steel frames of the current meters were not truly amagnetic, and the effect of the position of the frame relative to the magnetic north could produce an inaccuracy in direction reading of about ±15%.

These current meters are designed by the manufacturer to provide long-term fixed point measurements (a week or a month). During the "Cyclone" cruises they were put to quite different use, being required for rapid profiles ($1\frac{1}{2}$ hours), measured either at fixed depth intervals, or by slow continuous descent of the instruments. For this type of work, the stop required at each level by the $7\frac{1}{2}$-minute cycle was too long. Moreover, the maximum strength of the currents being studied was of the order of 150 cm/s, so that the small scale of 0–50 cm/s was unusable and the scale of 0–350 cm/s too large to allow maximum accuracy of the readings. Also, the influence of the non-amagnetic frame considerably impaired the accuracy of the direction measurements. Lastly, as the current meters were to be used in cold deep waters, the measurement of temperature with the approximation indicated above lost much of its interest.

The current meters were therefore modified in such a way that the strength and direction of current were measured continuously, and temperature measurement eliminated; the scale of current strength measurement was reduced to 0–250 cm/s, and the stainless-steel frames were replaced by brass ones.

On condition that each instrument was calibrated before and after every cruise, and speed and direction corrections similar to those shown in Table 1 were introduced, the accuracy of the recordings was ±5°C for direction and ±2.5 cm/s for speed. Nevertheless, uncertainty about the currents due to instrument performance alone was greater than this, for as will be seen below, currents are relative to a given reference level and are therefore the vectorial difference between two measurements. To this instrumental uncertainty is naturally added the lack of precision inherent in the method of measurement, stemming from the movements of the ship and current meters during recordings, and from the short-term current fluctuations. These causes of errors will be discussed below.

Method of Measurement

R.V. *Coriolis* is not equipped to drop anchor at great depth—4000–5000 m in the zone studied—nor to put down a buoy on the ocean bed without difficulty. There are no landmarks in the selected working zone, the area is not covered by the usual radio navigation systems, and the ship is not equipped for satellite navigation.

With much more time available for each current measurement station, it would doubtless have been possible to introduce a drogue into a deep layer which was presumed motionless; however, the rapid development of equatorial current situations found during the previous cruises made it desirable to work at an accelerated rate, with one station every 6 hours, making a section 4°S–4°N in 4 days.

The measurement technique was adapted to this rhythm of work, and to the natural conditions of the study zone, where steady winds with a strong easterly component generally prevail and there are fairly strong westward surface currents and a relatively calm sea.

Under these conditions a ship drifts westward, so that by steering an easterly course at low speed it is possible to stabilize it directionally, and its speed relative to the ocean bed can become very low. For this purpose, 1000 m of cable were put down before the hydrological station, and during the station, which lasted about an hour, the ship would manoeuvre to obtain the smallest possible constant angle of the cable with the vertical. Once this equilibrium was found, the course and speed of the ship were maintained throughout the current measurement.

This method gave the most stable recordings, and the minimum current strength values at depth (Fig. 2), so that it could be assumed that the drift of the combination of ship and instruments relative to the deep ocean layers was slight and relatively stable. The drift was vectorially subtracted from all the other measurements to obtain the relative currents.

During the "Cyclone" cruises, the conditions of work varied principally as a function of the number of current meters being used. During "Cyclone" 2, 3 and 5, only one instrument was available. During measurements, it was let down at regular intervals to a deep layer: 500 m in the first two cruises, and 1000 m in the other. In cruises 4 and 6, two current meters were available; they were attached 1000 m apart, one operating in the 0–500 m layer, the other in the 1000–1500 m layer, leaving the 500–1000 m layer unexplored. In "Cyclone" 7, three current meters were used; the spacing between these was 200 m and 1000 m respectively, sometimes 200 m and 800 m, and since the uppermost instrument was working in the 0–600 m layer, measurements were distributed between the surface and a maximum depth of 1800 m.

During most of the stations, current measurements were carried out every 20 m from 0 to 300 m, and every 50 m from 300 to 500 m. Each fixed-depth measurement lasted 4 minutes altogether, and each measurement was the average of values recorded every 8 seconds. Apart from some exceptions, 4 minutes was a sufficient time for the cable and current meter to reach their position of equilibrium which had been slightly disturbed by the rapid descent between levels, and to give stable direction and speed recordings. In order to eliminate the possibility of equilibrium being disturbed, and to obtain a more complete description of current gradients, the last section of "Cyclone" 7 was made replacing descent through fixed depth intervals by a continuous descent at a slow speed of 5 m/min.

Accuracy of Measurements

Since the cable was maintained throughout all measurements as close as possible to the vertical, at an angle scarcely ever exceeding 10°, it was assumed that the depth of the current meters was equal to the length of cable let down. The great number of hydrological stations carried out in the same zone and under similar working conditions indicate that this method introduces into depth evaluations an error of overestimate not exceeding 2%.

The relative accuracy of the measurements is a function not only of the performance of the apparatus considered absolutely, but of the conditions under which it is used, which determine the quality of the recordings obtained and the accuracy with which they can be analysed. Thus the stability of the ship, horizontal as well as vertical, directly affects that of the current meter and consequently the stability and clarity of the recording. All short-term fluctuations, whether caused by the swaying of the current meter in the water, by turbulence in the velocity field or by the effect of waves and swell, render the speed and direction recordings indistinct. Moreover, the Savonius rotor responds additively to all currents, whatever their direction.

When a current meter is submerged at depth, the great length of the unreeled cable very effectively dampens all short-term movements originating at the surface of the sea; its

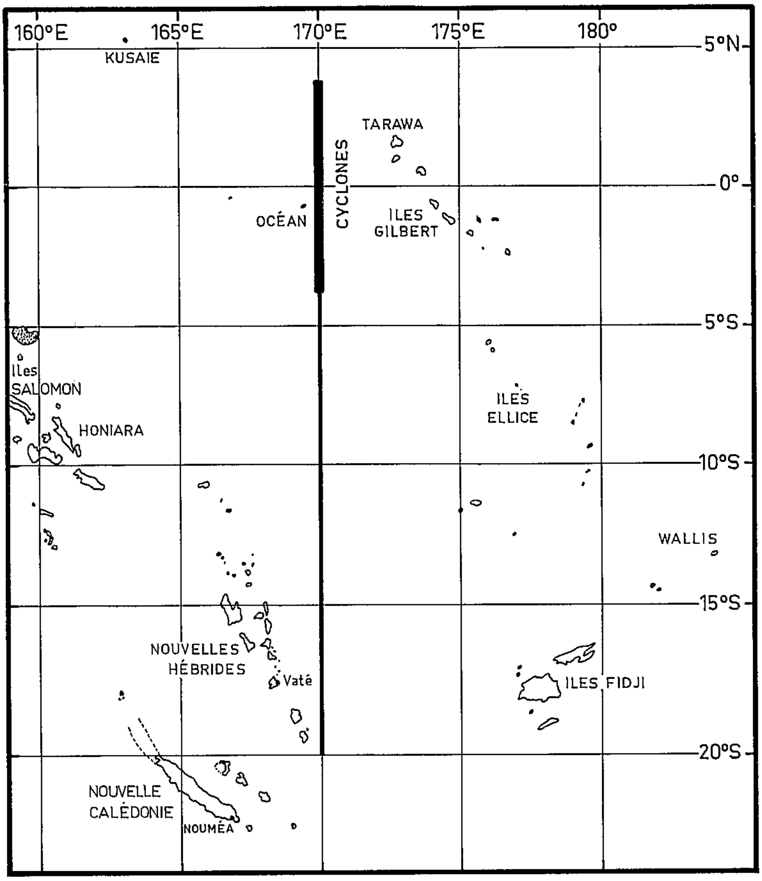

FIG. 1. Map of the region studied during the "Cyclone" and "Bora" cruises of R.V. *Coriolis.*

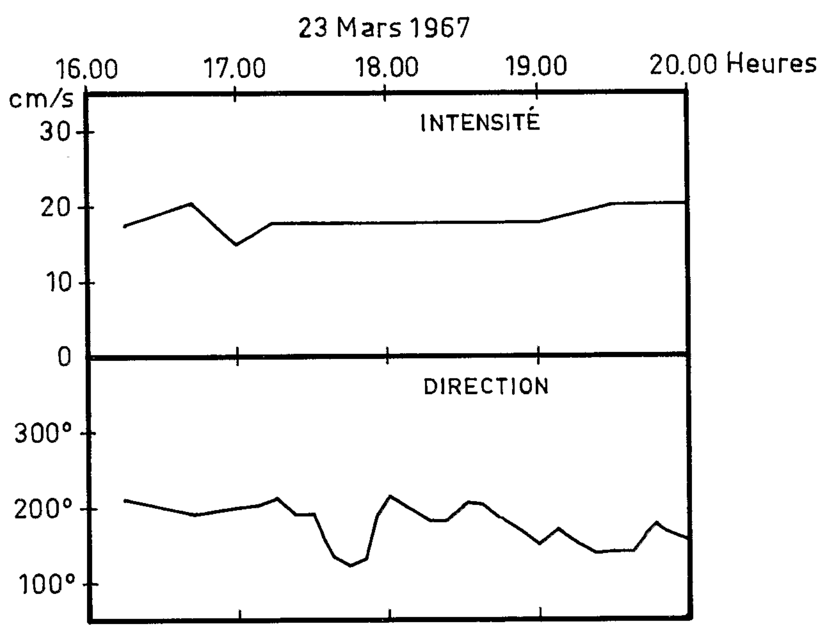

FIG. 2. "Cyclone" cruise 2, 0–169° E, 4-hr recording of the south and east components of the current measured at a depth of 1000 m.

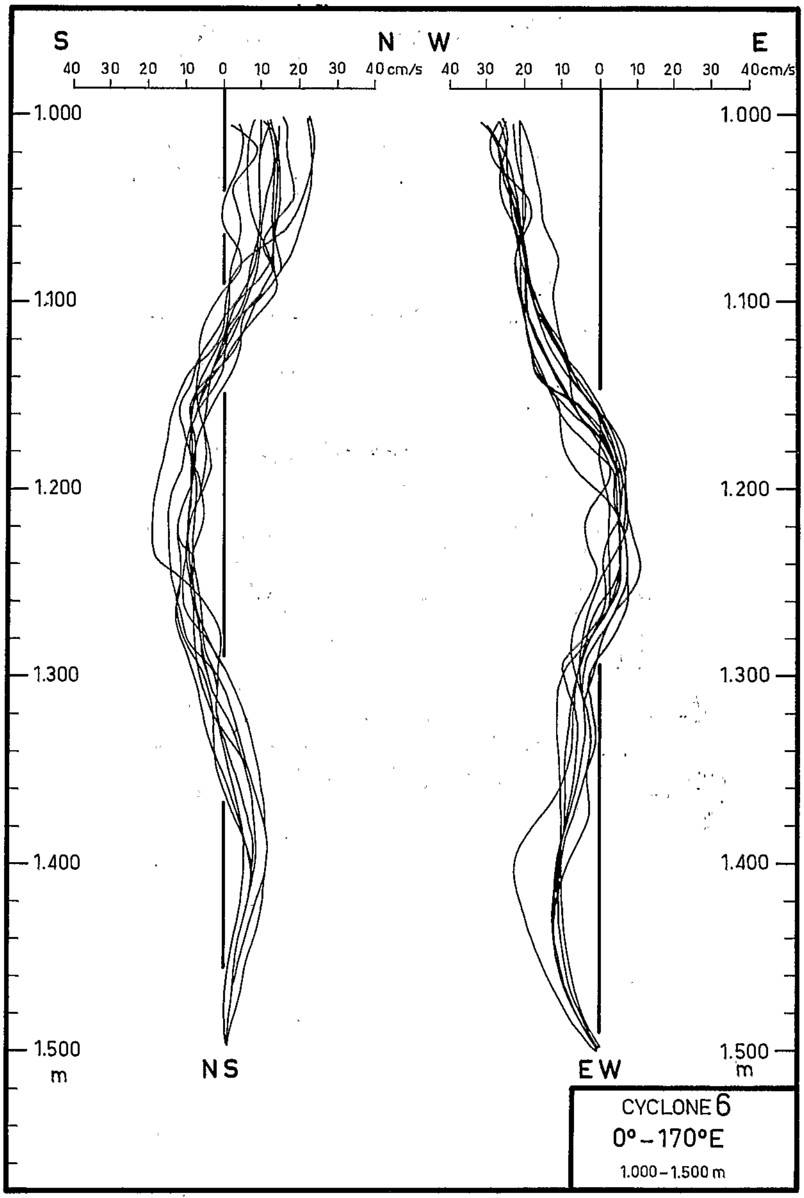

FIG. 3. "Cyclone" cruise 6, 0–170° E, E–W and N–S components of the current between 1000 m and 1500 m relative to 1500 m, determined by twelve profiles extending over a period of 23 hr.

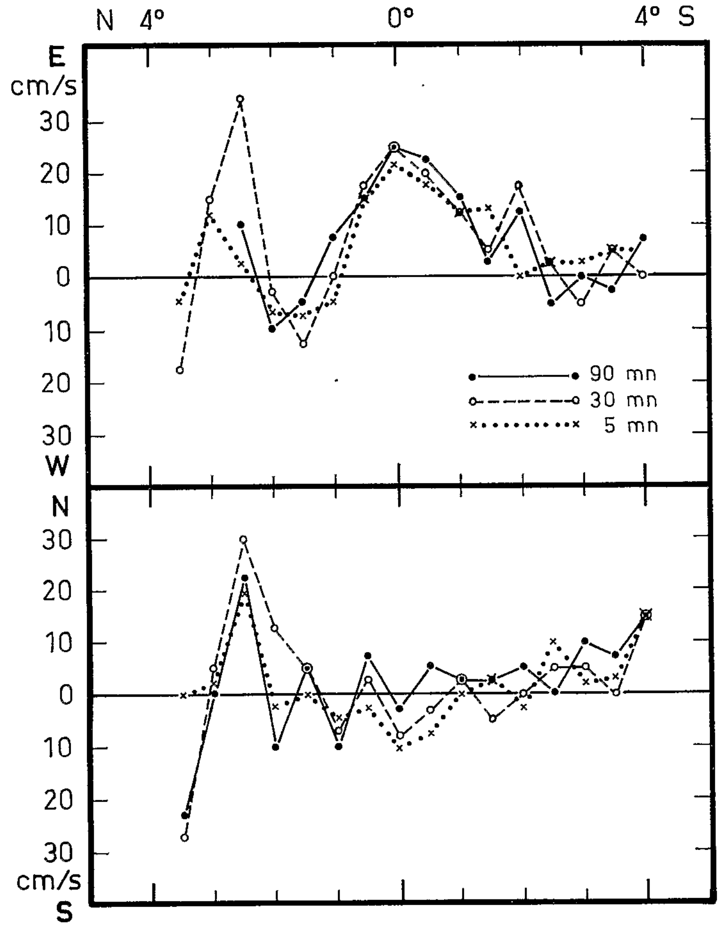

FIG. 4. "Cyclone" cruise 5, distribution from 4° S to 4° N of the E–W and N–S components of the current at 500 m relative to 1000 m; the intervals between the measurements at 500 m and at 1000 m being respectively 90, 30 and 5 min.

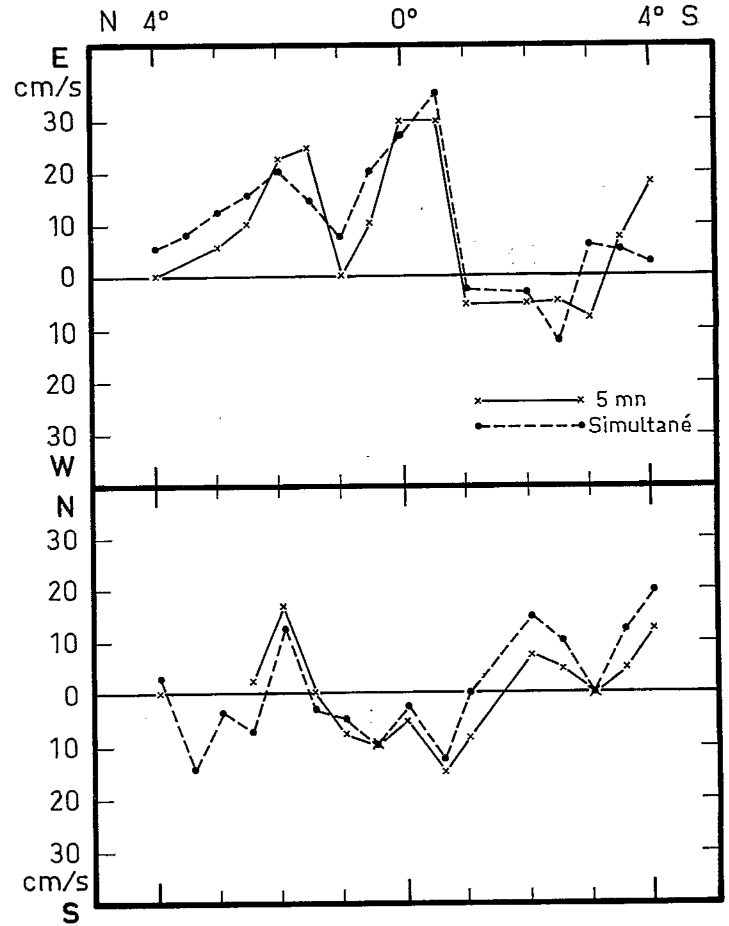

FIG. 5. "Cyclone" cruise 6, distribution from 4° S to 4° N of the E–W and N–S components of the current at 500 m relative to 1000 m, measured either using two instruments submerged simultaneously at the required depths, or with one instrument stopping at 500 m then at 1000 m, with an interval of 5 min.

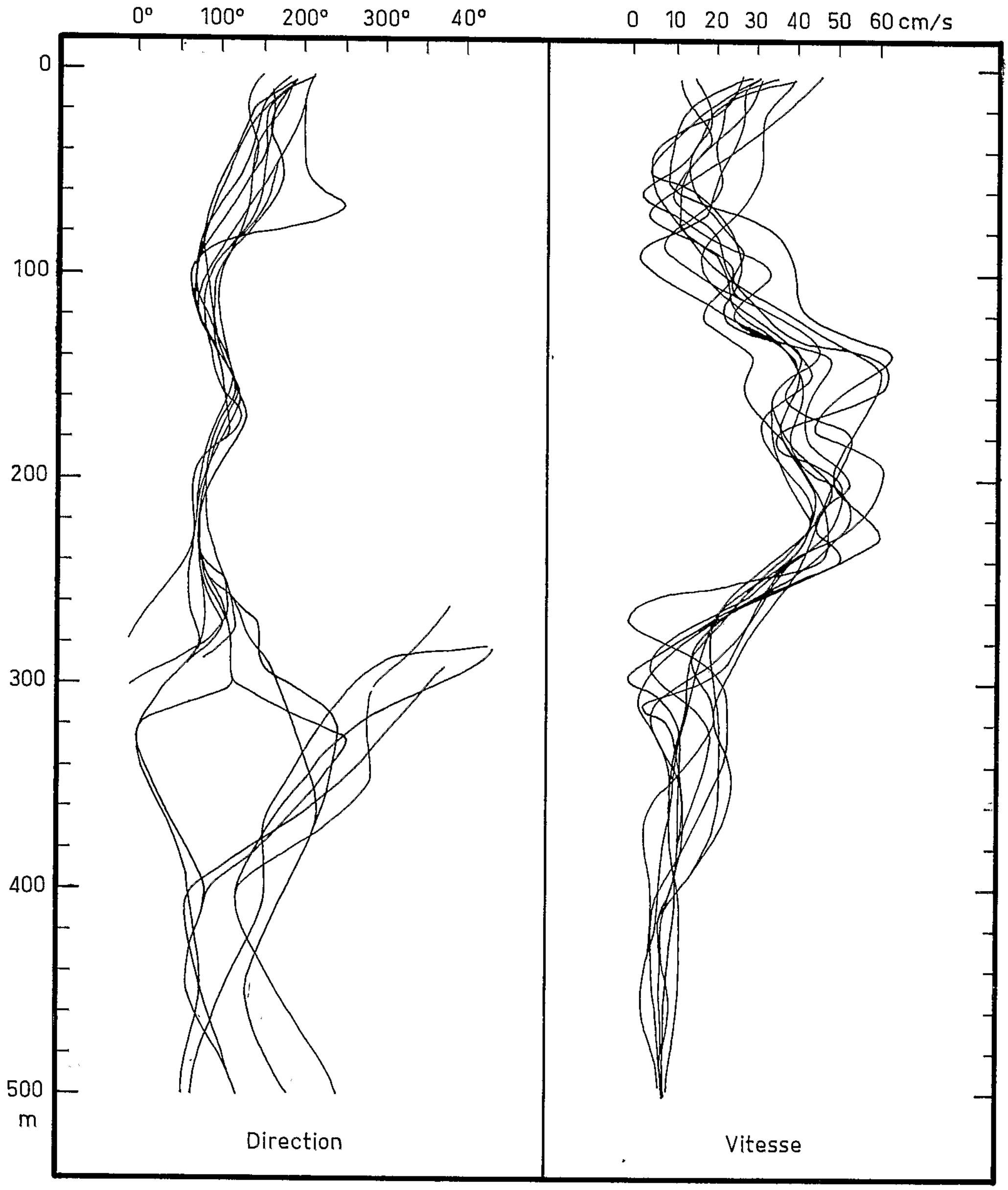

FIG. 6. "Cyclone" cruise 6, 0–170° E, vertical profiles taken in the first 500 m, showing current direction and intensity relative to 1500 m, recorded during a long station of 23 hr.

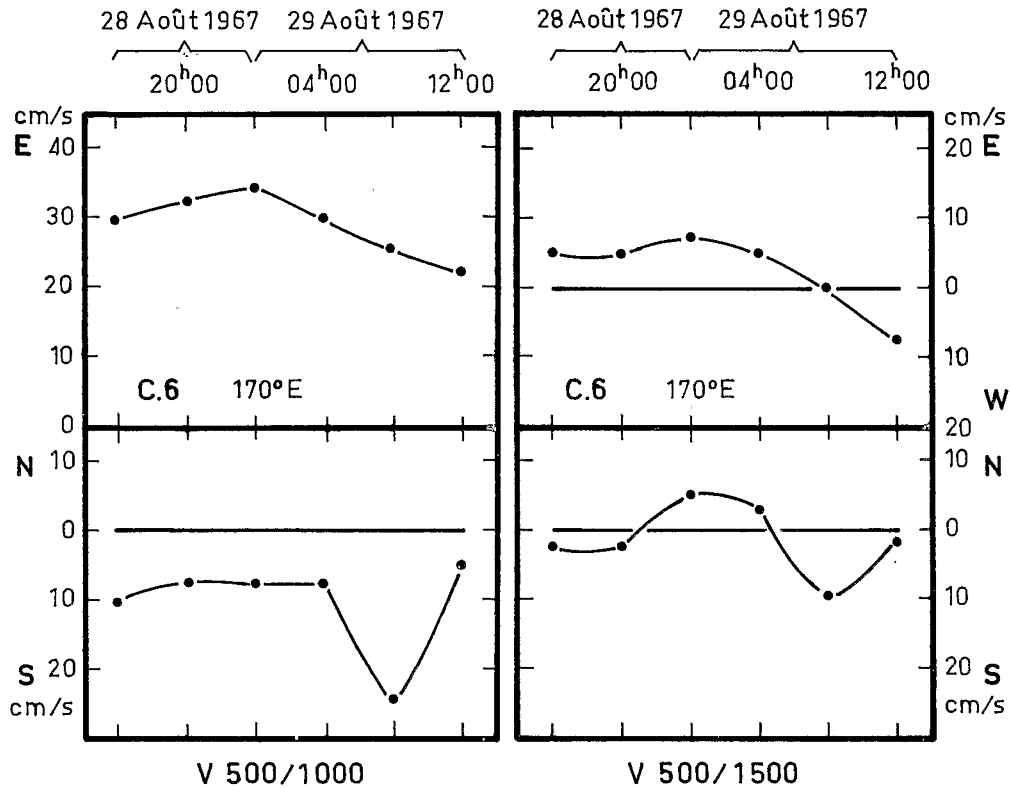

FIG. 7. "Cyclone" cruise 6, 0–170° E, current at 500 m, relative to 1000 m or 1500 m.

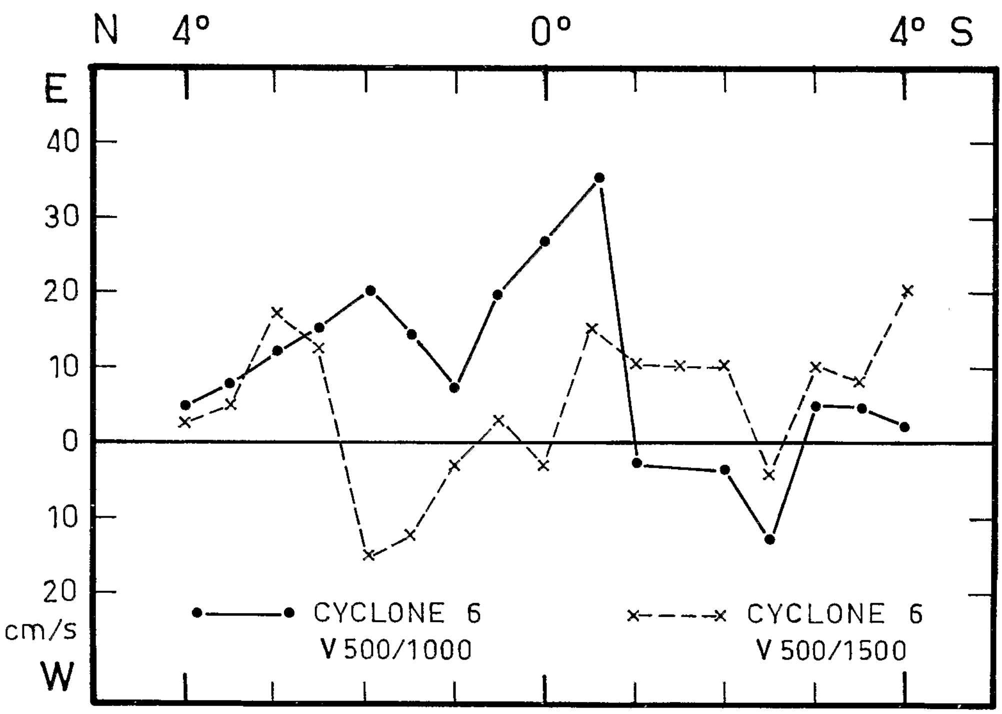

FIG. 8. "Cyclone" cruise 6, E–W component of the current at 500 m relative to a reference level of 1000 m or 1500 m, between 4° S and 4° N at 170° E.

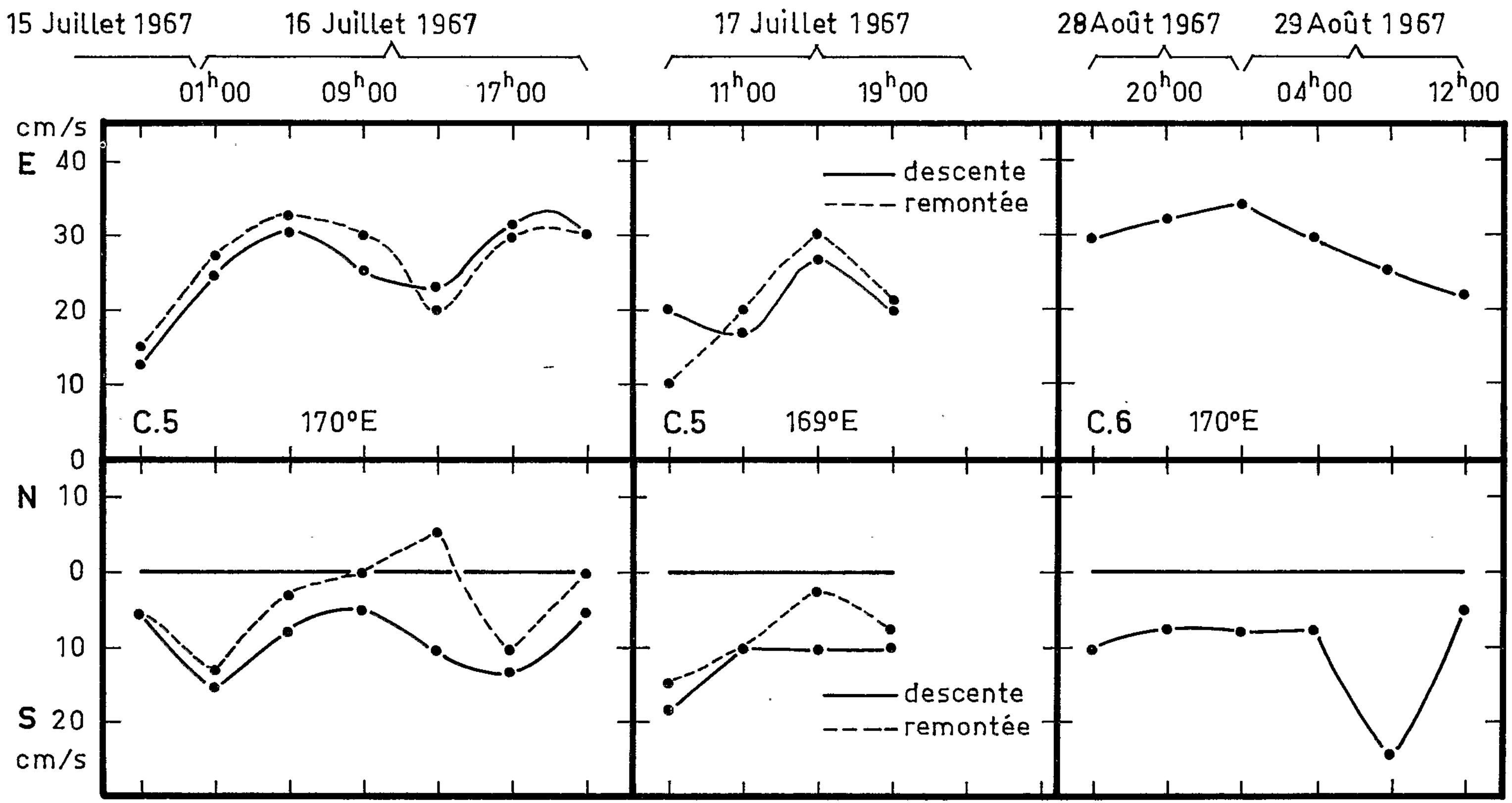

FIG. 9. "Cyclone" cruises 5 and 6, 0–169° E, 0–170° E, variations with time of the E–W and N–S components of the current at 500 m relative to 1000 m.

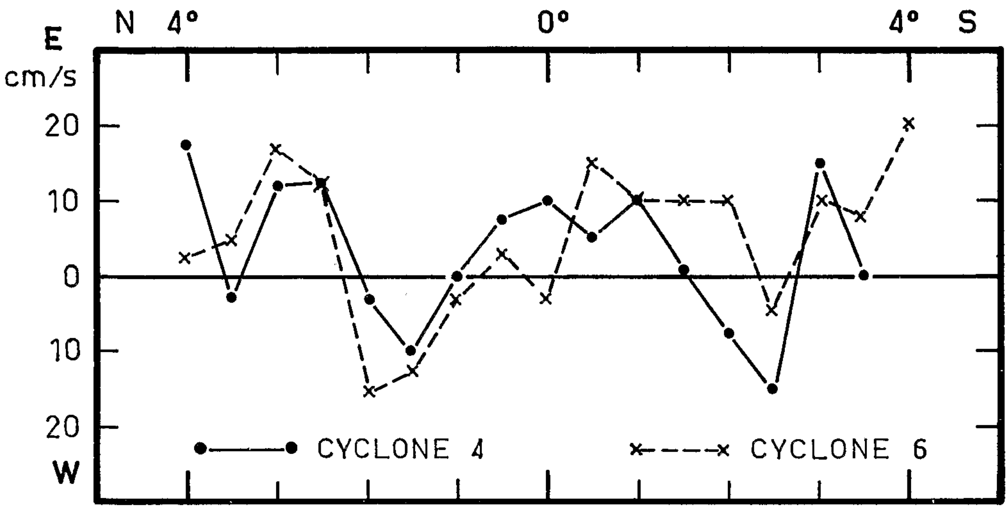

FIG. 10. "Cyclone" cruises 4 and 6, distribution between 4° S and 4° N of the E–W component of the current at 500 m relative to 1500 m.

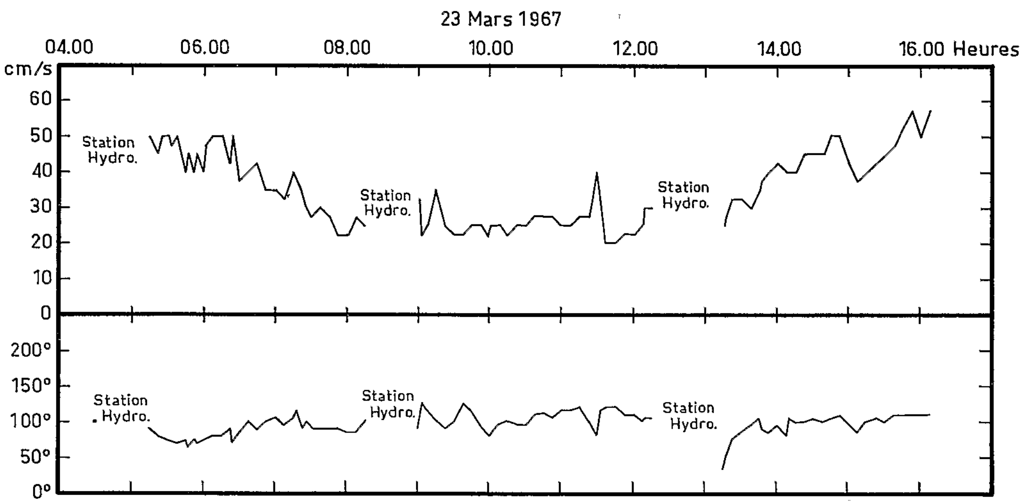

FIG. 11. "Cyclone" cruise 2, 0–169° E, variations with time of the current at 220 m relative to 770 m.

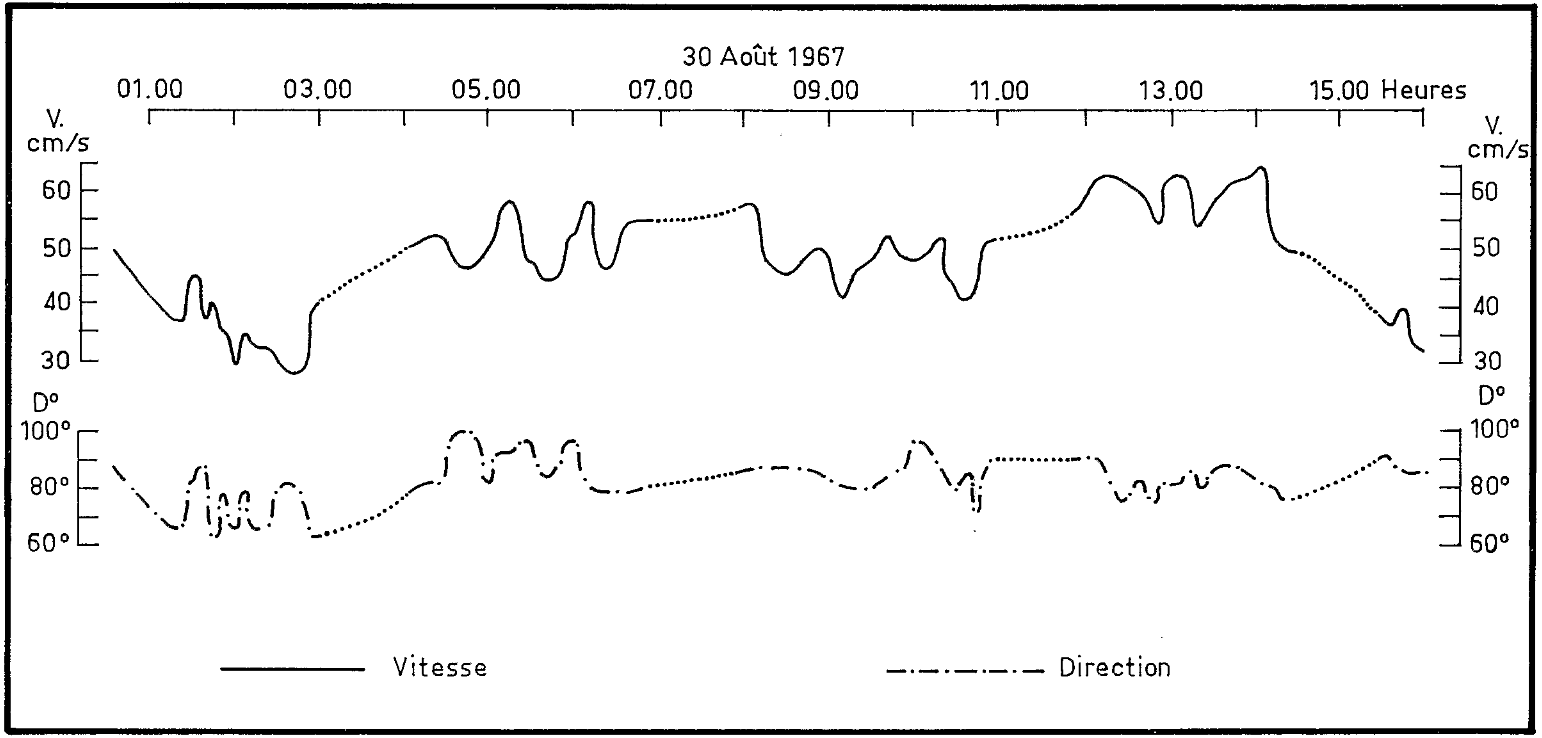

FIG. 12. "Cyclone" cruise 6, 0–169° E, variations with time of the current at 200 m relative to 1000 m.

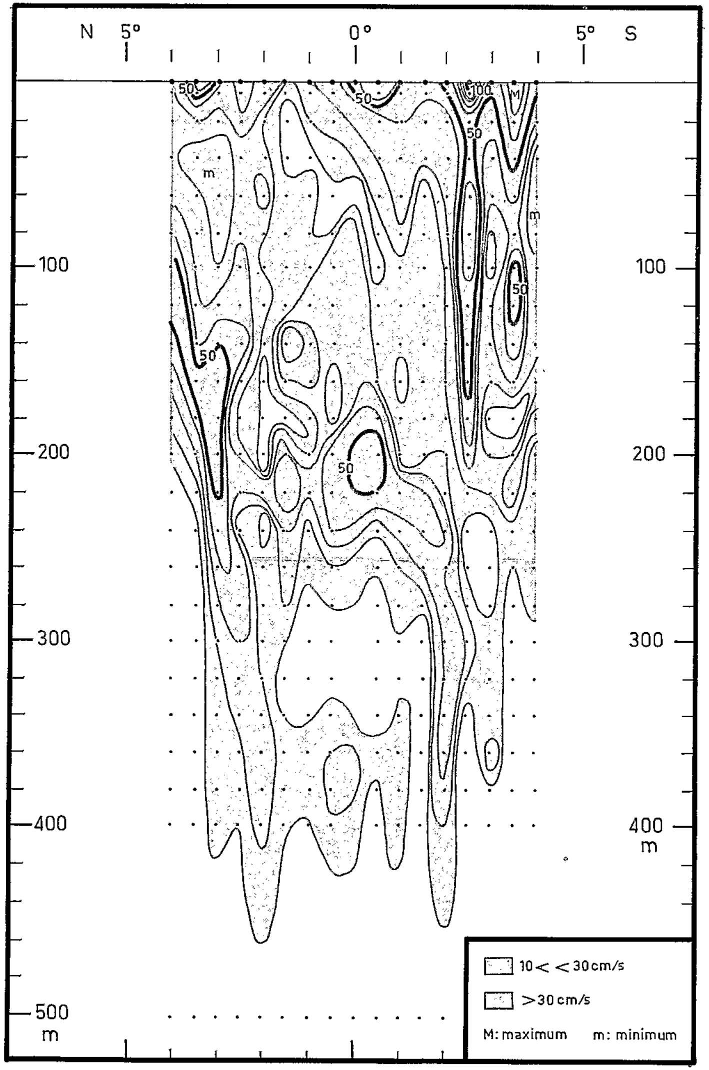

FIG. 13a. Cyclone 2.

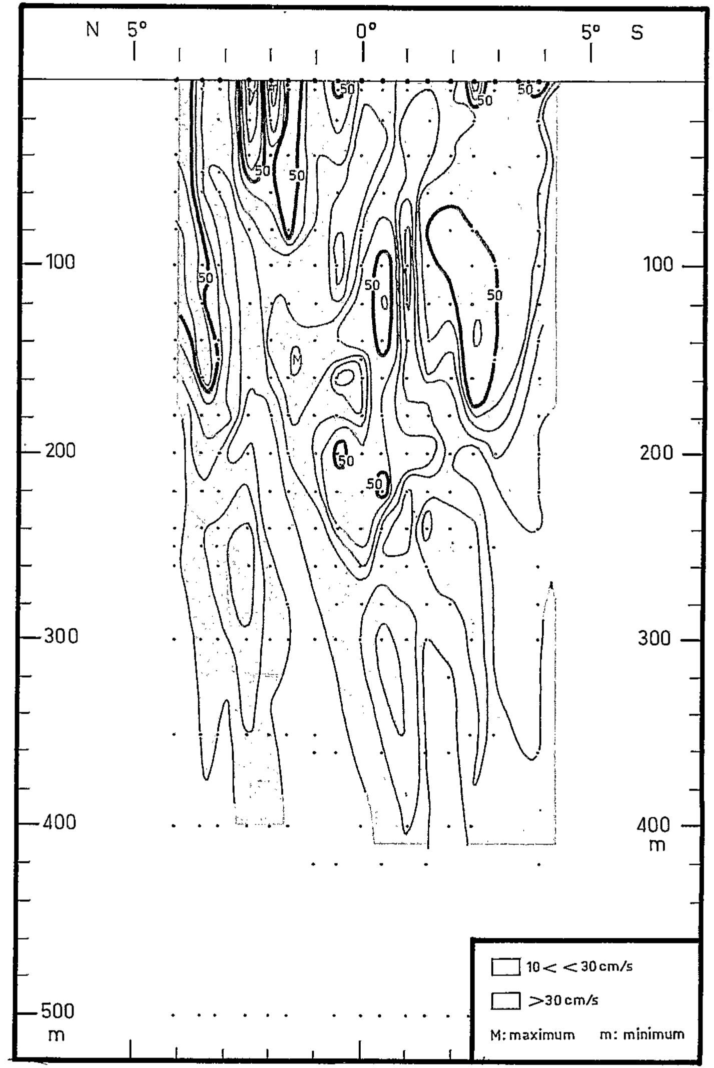

FIG. 13b. Cyclone 3.

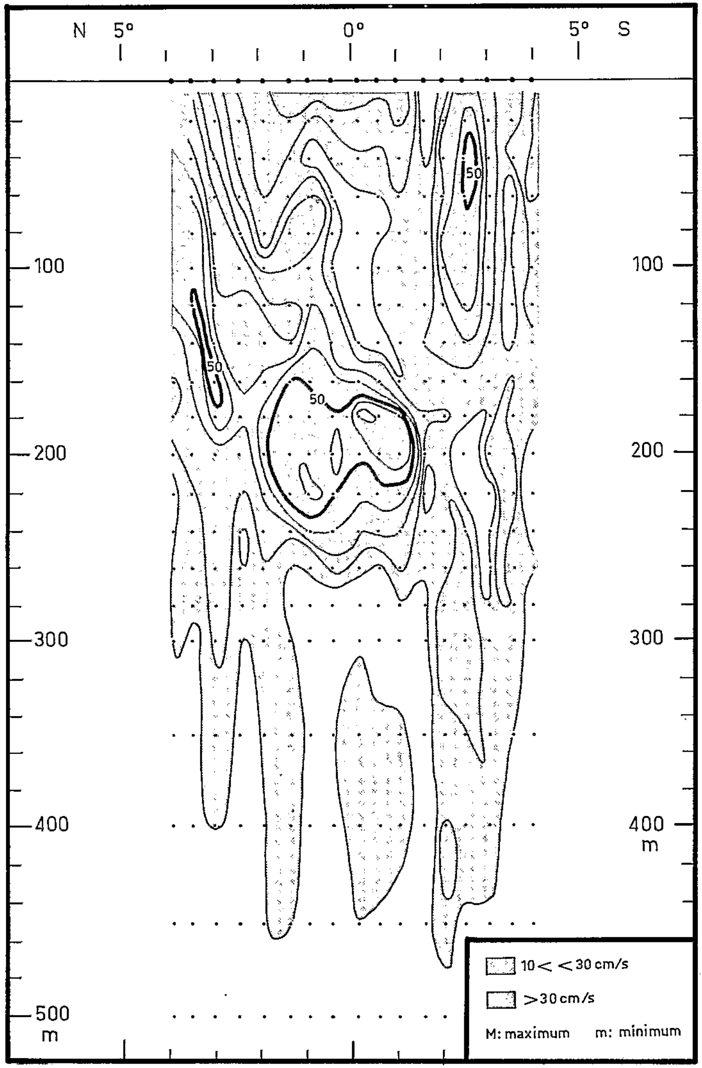

FIG. 13c. Cyclone 4.

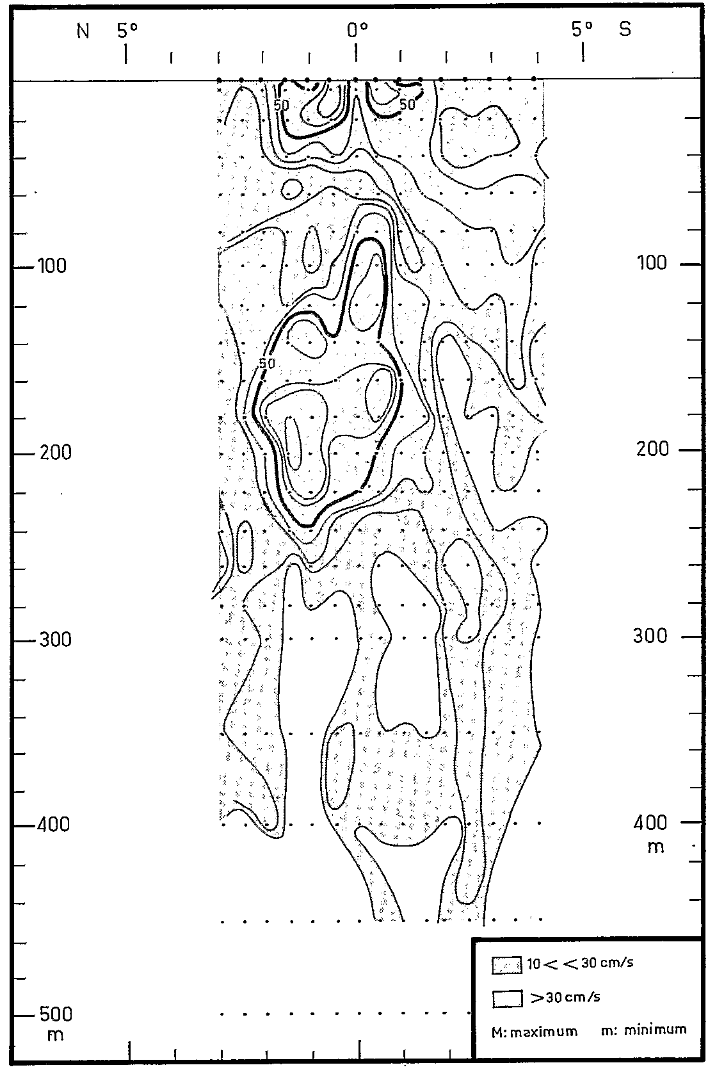

FIG. 13d. Cyclone 5.

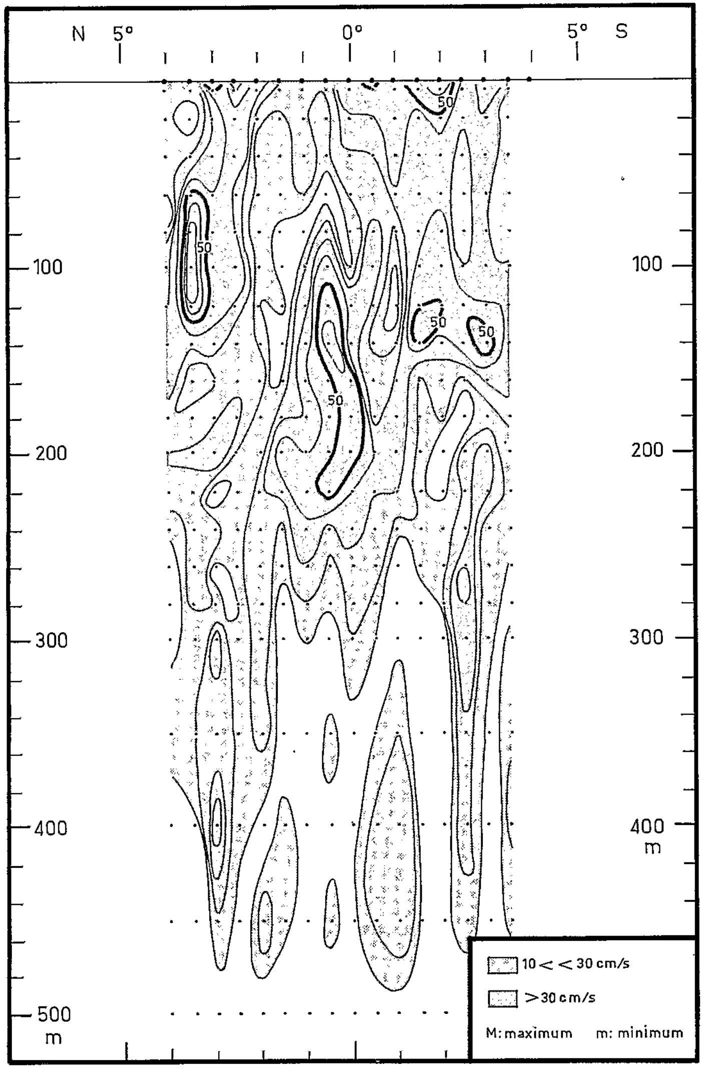

FIG. 13e. Cyclone 6.

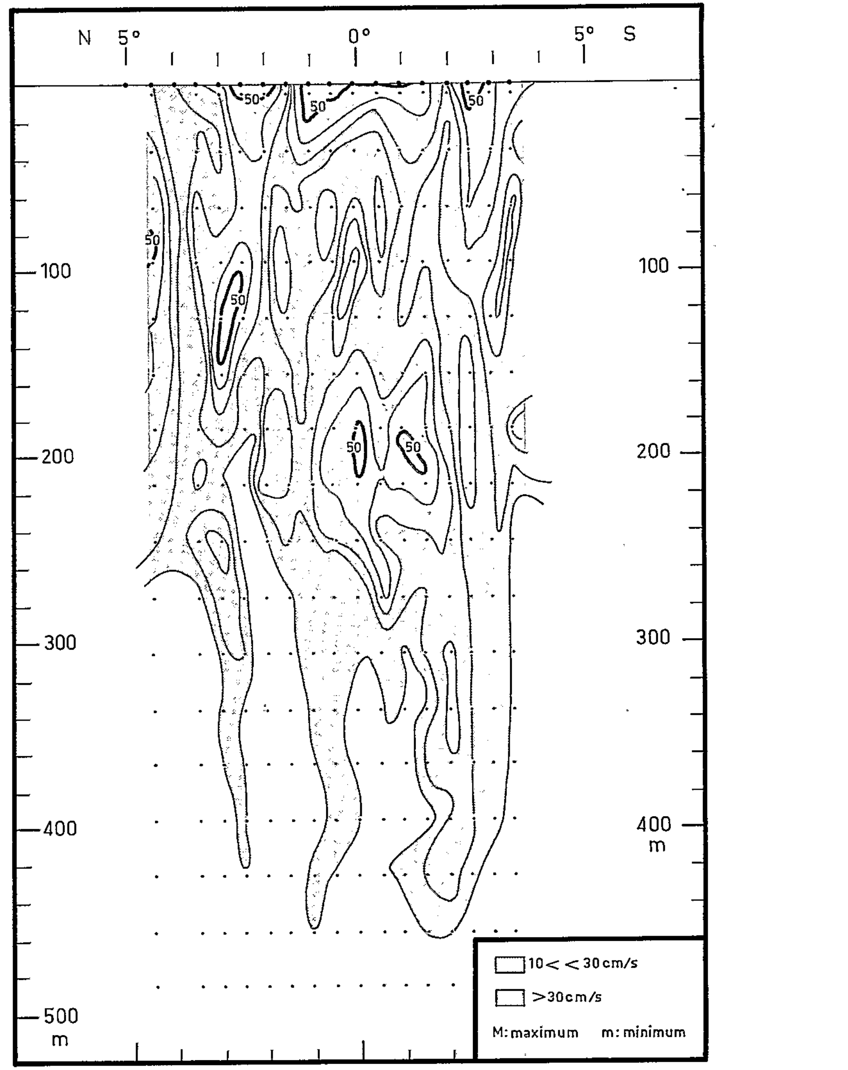

FIG. 13f. Cyclone 7_1.

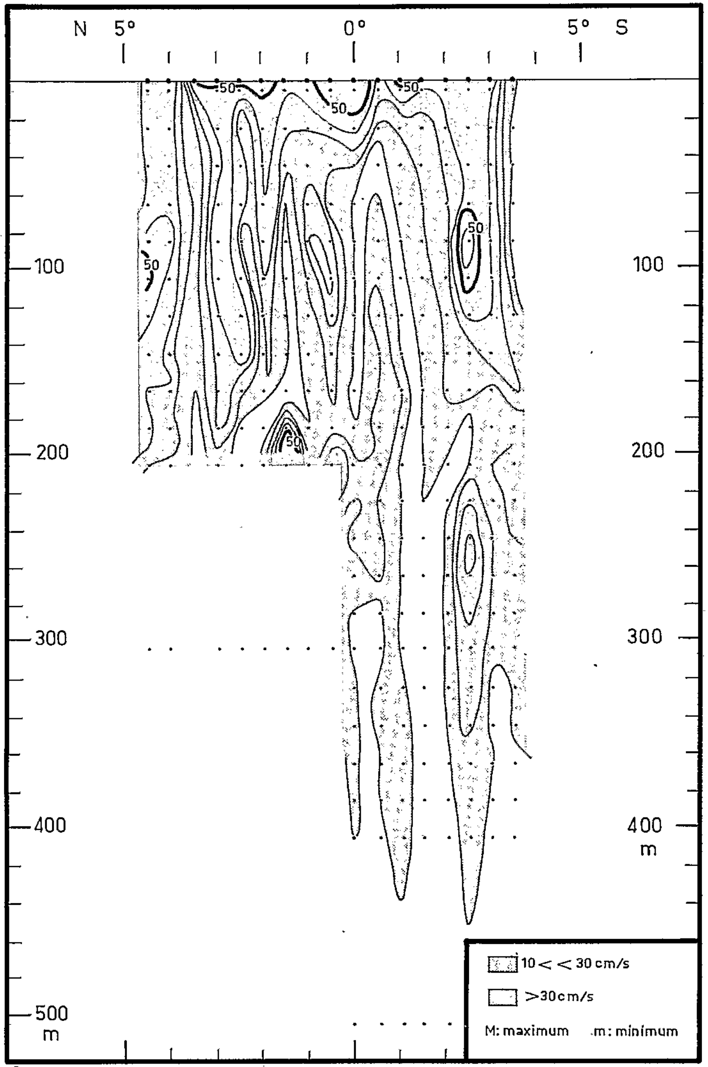

FIG. 13g. Cyclone 7_2.

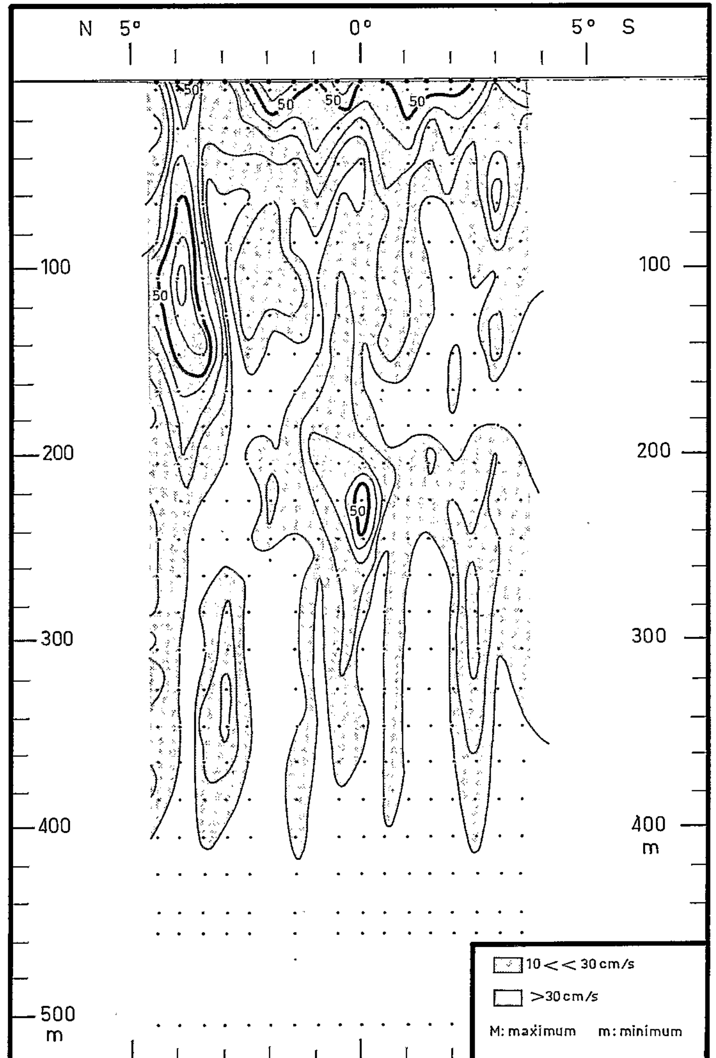

FIG. 13h. Cyclone 7_3.

FIG. 13a–h. "Cyclone" cruises, distribution from 4° S to 4° N of the current intensity: (a) Cyclone 2, (b) Cyclone 3, (c) Cyclone 4, (d) Cyclone 5, (e) Cyclone 6, (f) Cyclone 7_1, (g) Cyclone 7_2, (h) Cyclone 7_3. Isotachs every 10 cm/s.

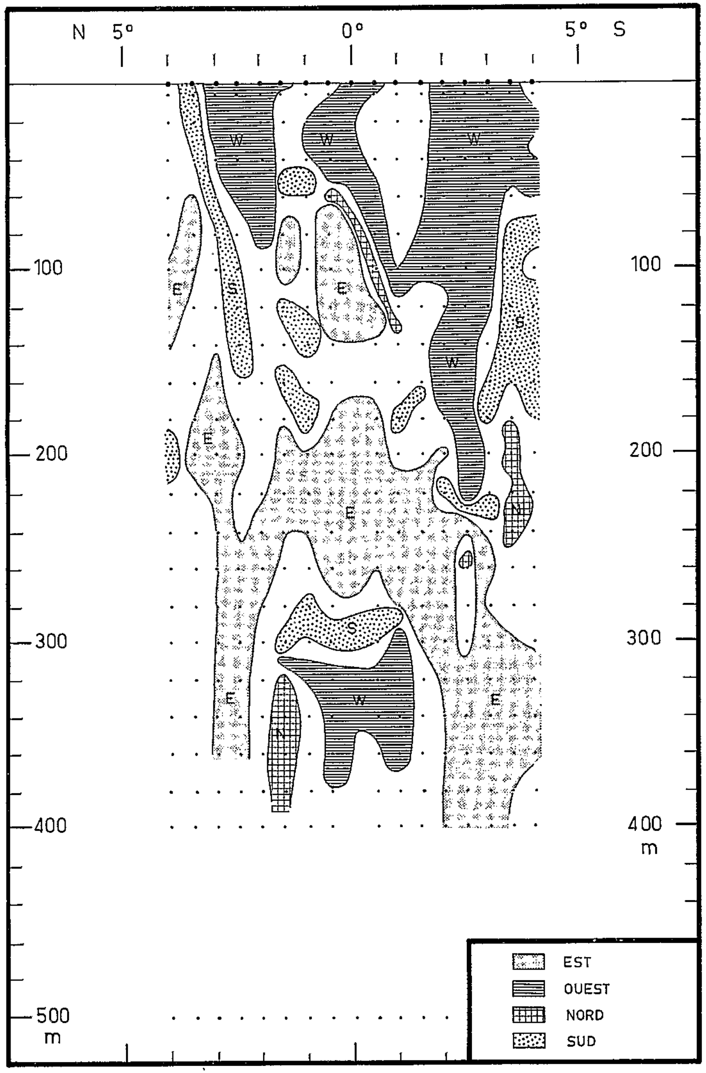

FIG. 14a. Cyclone 2.

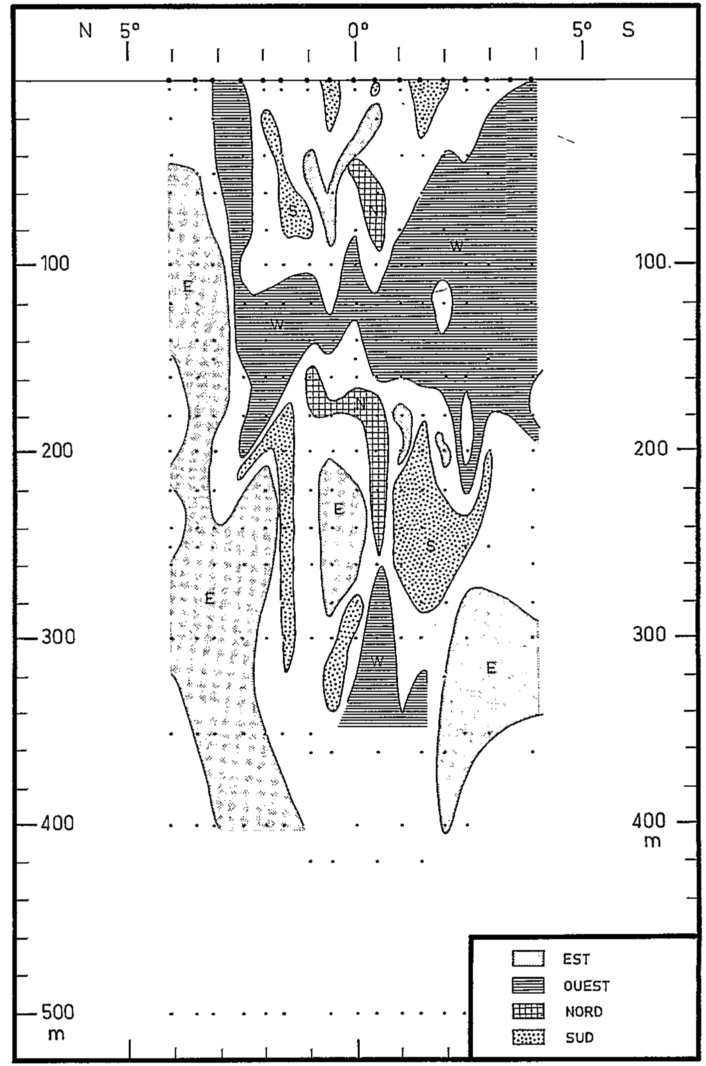

FIG. 14b. Cyclone 3.

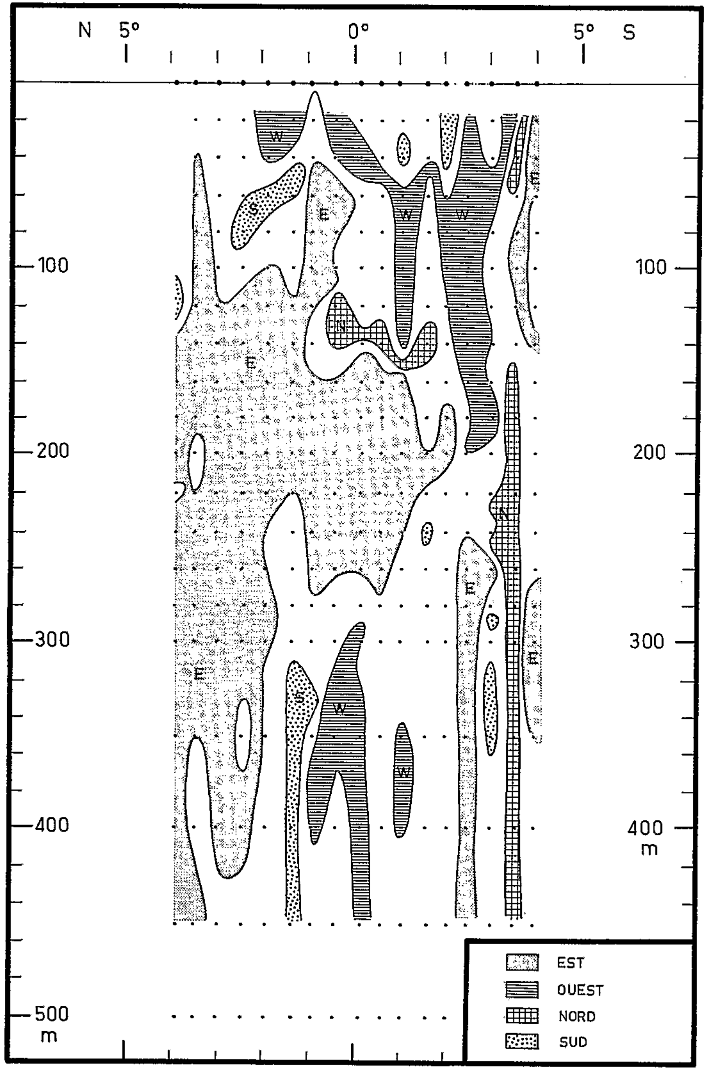

FIG. 14c Cyclone 4.

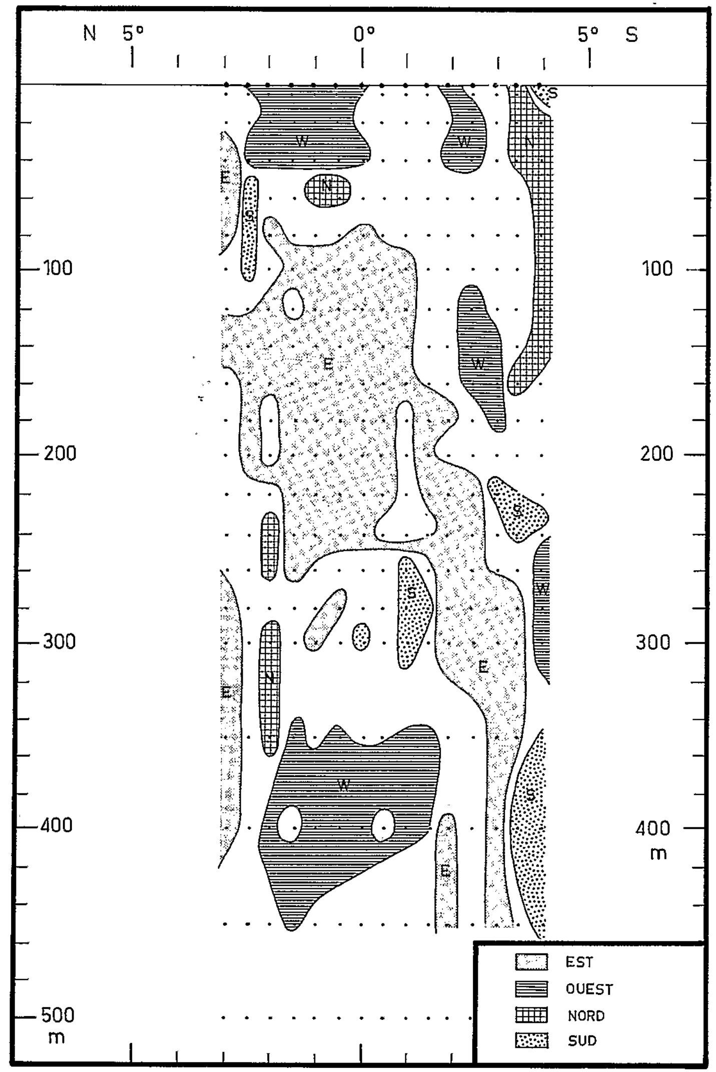

FIG. 14d. Cyclone 5.

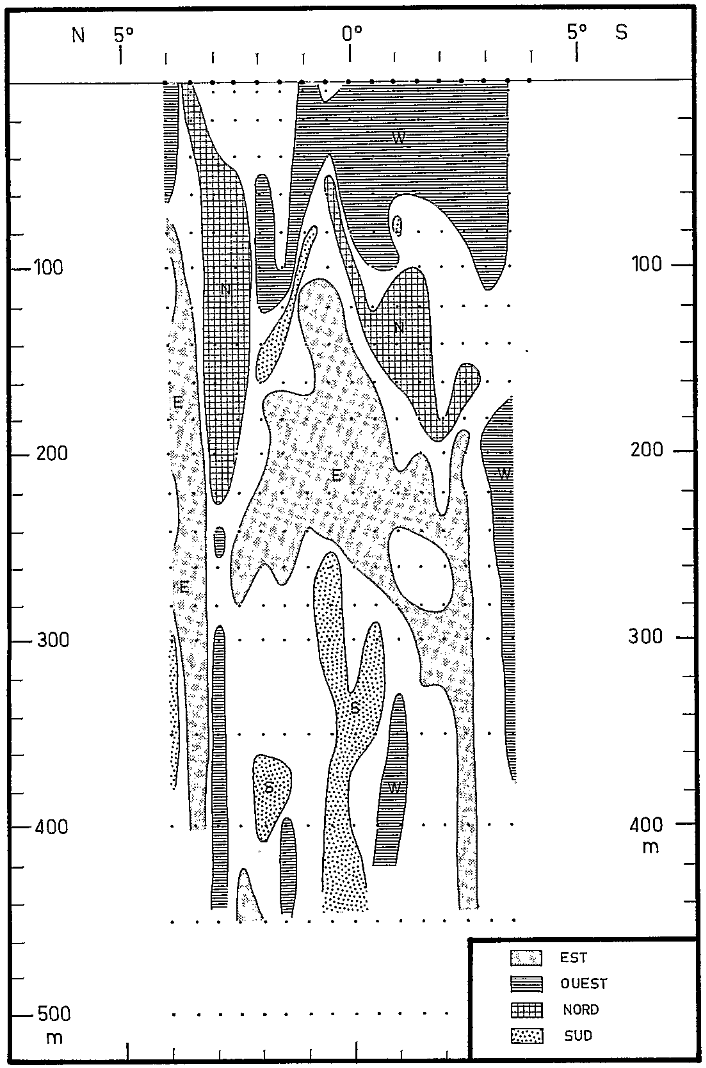

FIG. 14e. Cyclone 6.

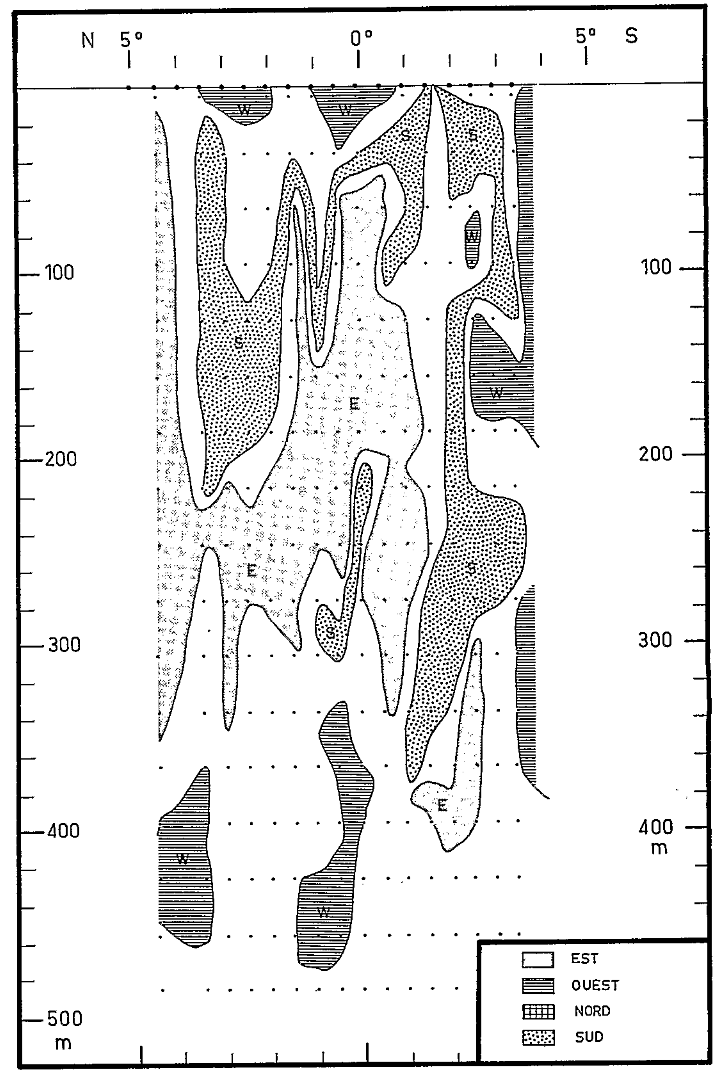

FIG. 14f. Cyclone 7_1.

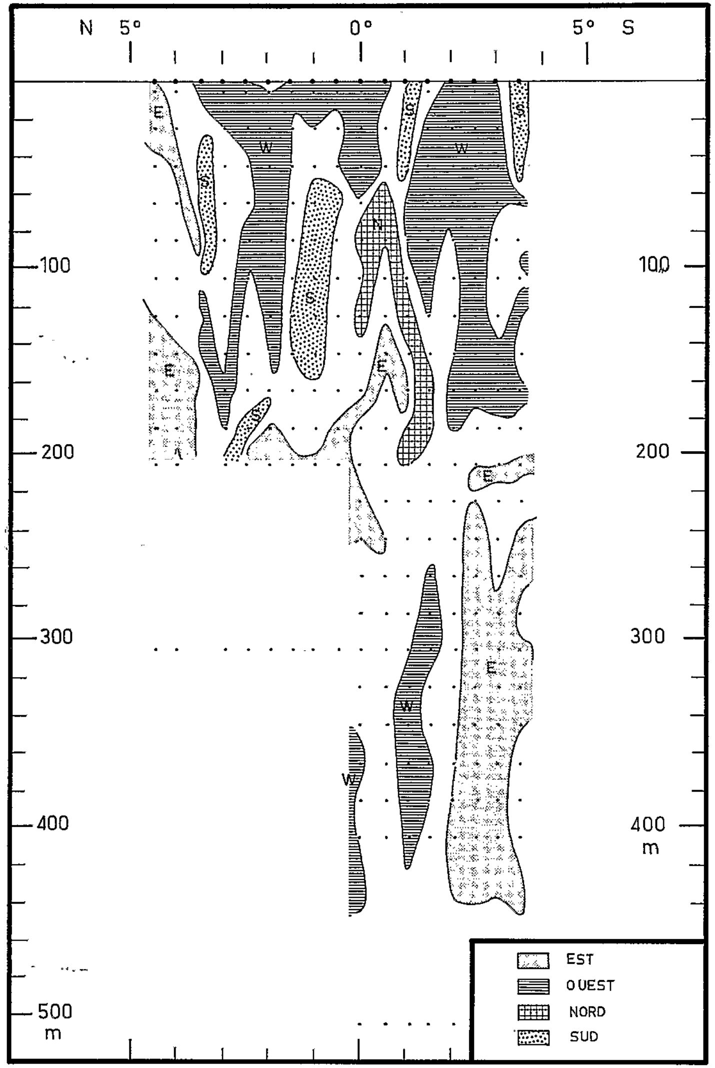

FIG. 14g. Cyclone 7_2.

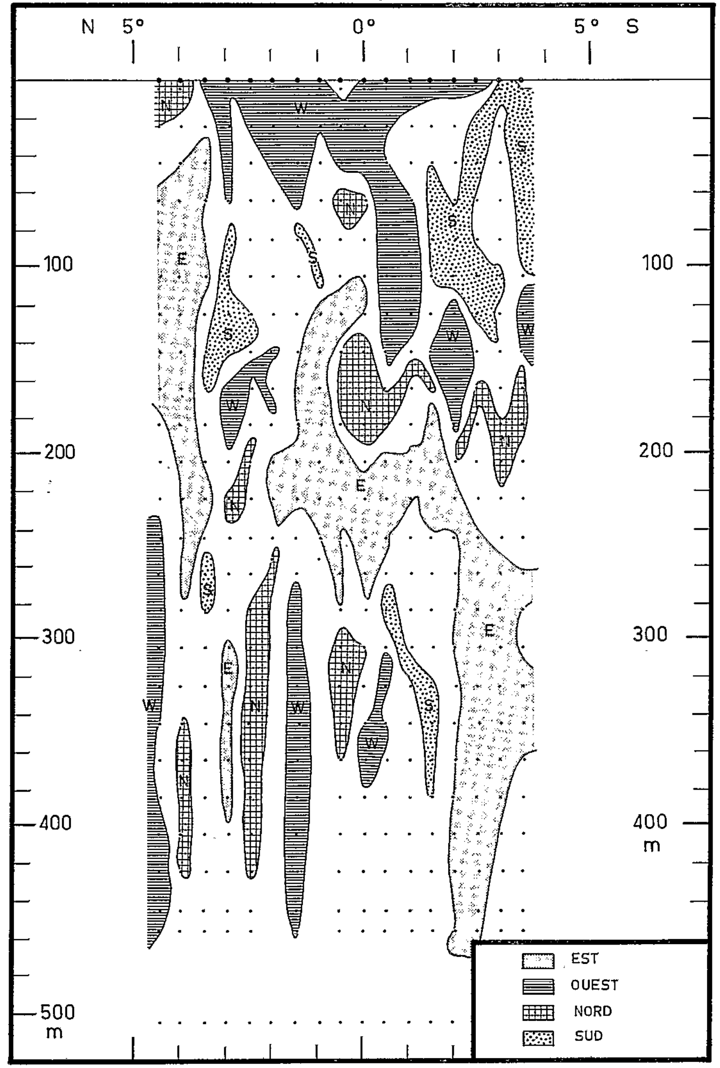

FIG. 14h. Cyclone 7_3.

FIG. 14a–h. "Cyclone" cruises, distribution from 4° S to 4° N of current direction: (a) Cyclone 2, (b) Cyclone 3, (c) Cyclone 4, (d) Cyclone 5, (e) Cyclone 6, (f) Cyclone 7_1, (g) Cyclone 7_2, (h) Cyclone 7_3. Each sector is ±22.5° around the cardinal points.

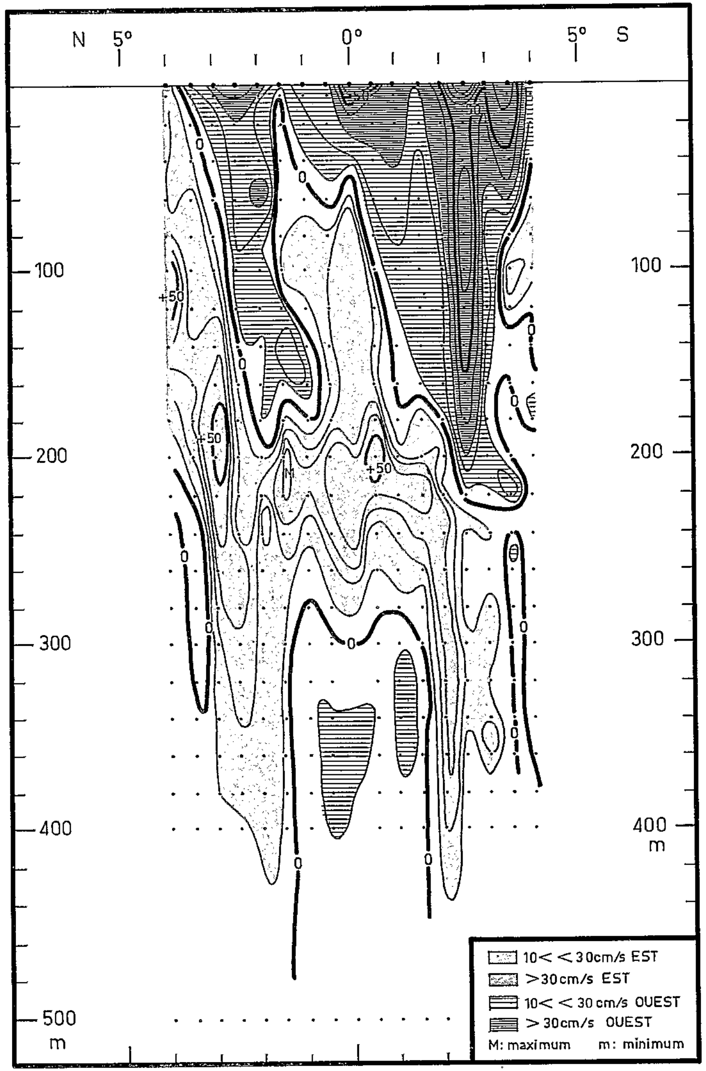

FIG. 15a. Cyclone 2.

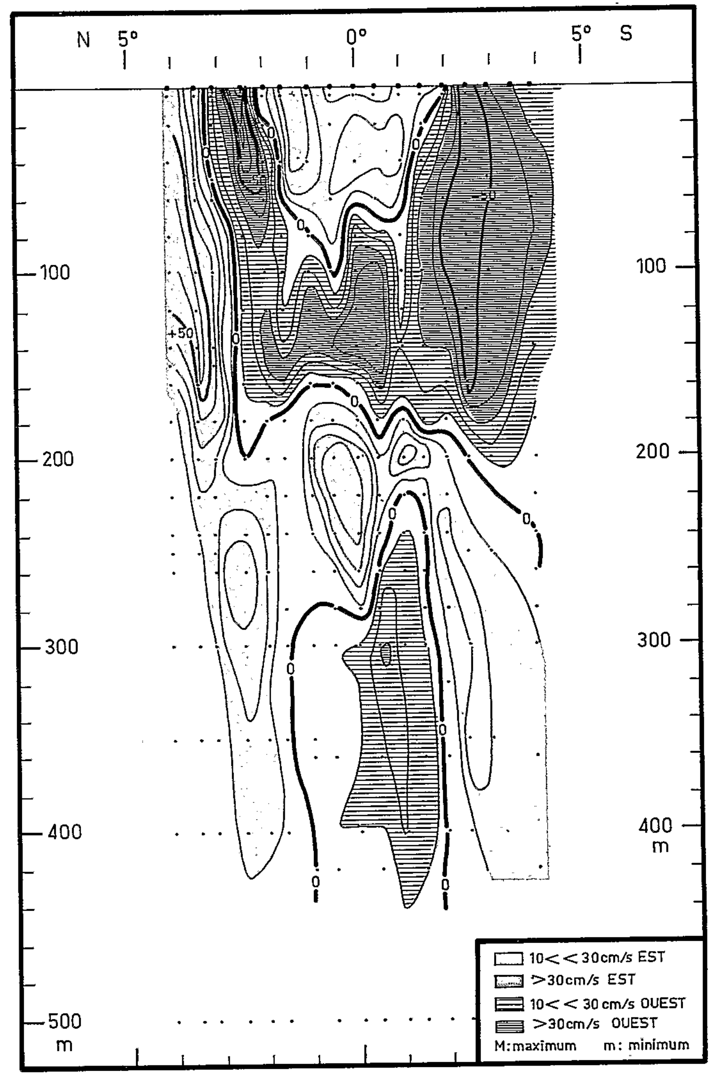

FIG. 15b. Cyclone 3.

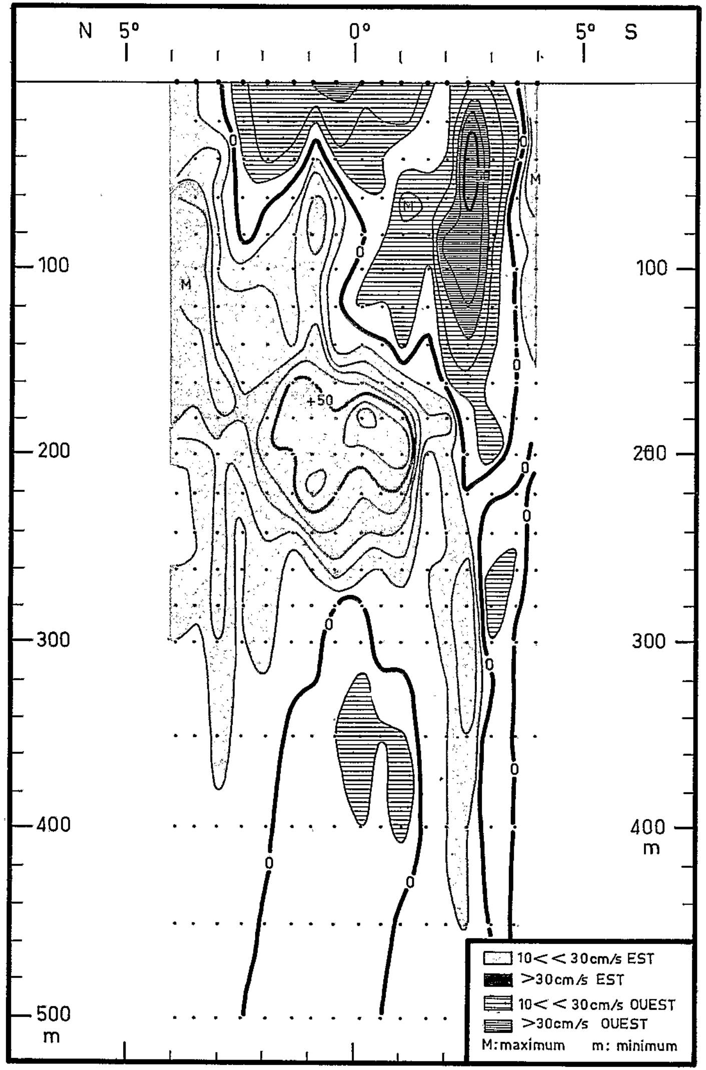

FIG. 15c. Cyclone 4.

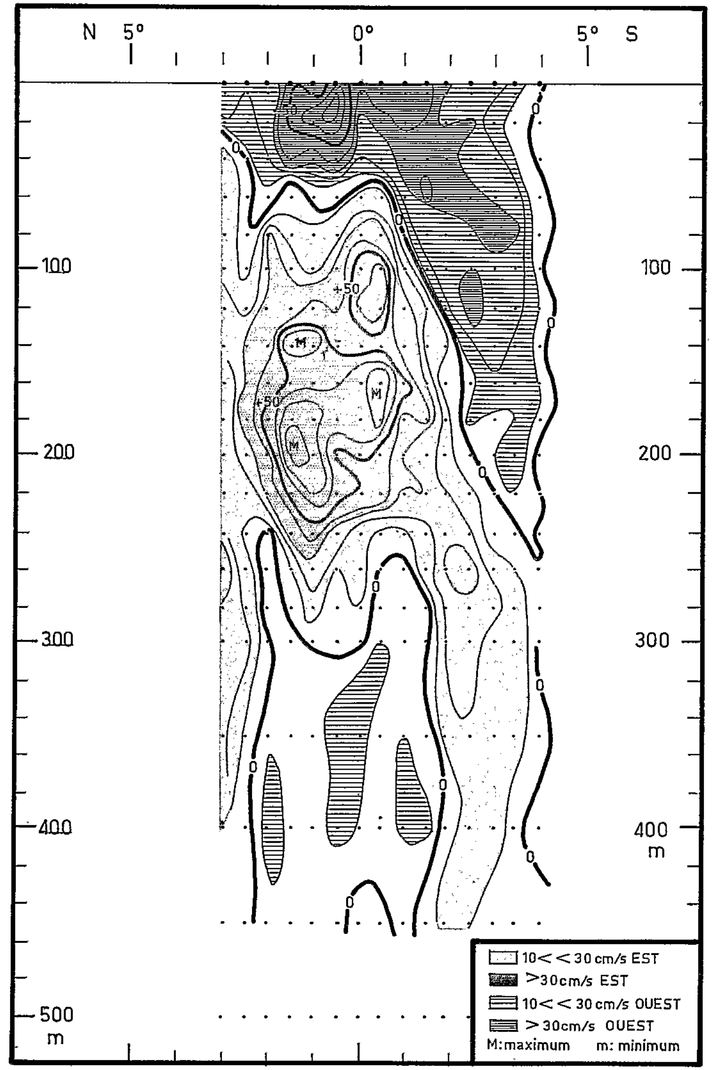

FIG. 15d. Cyclone 5.

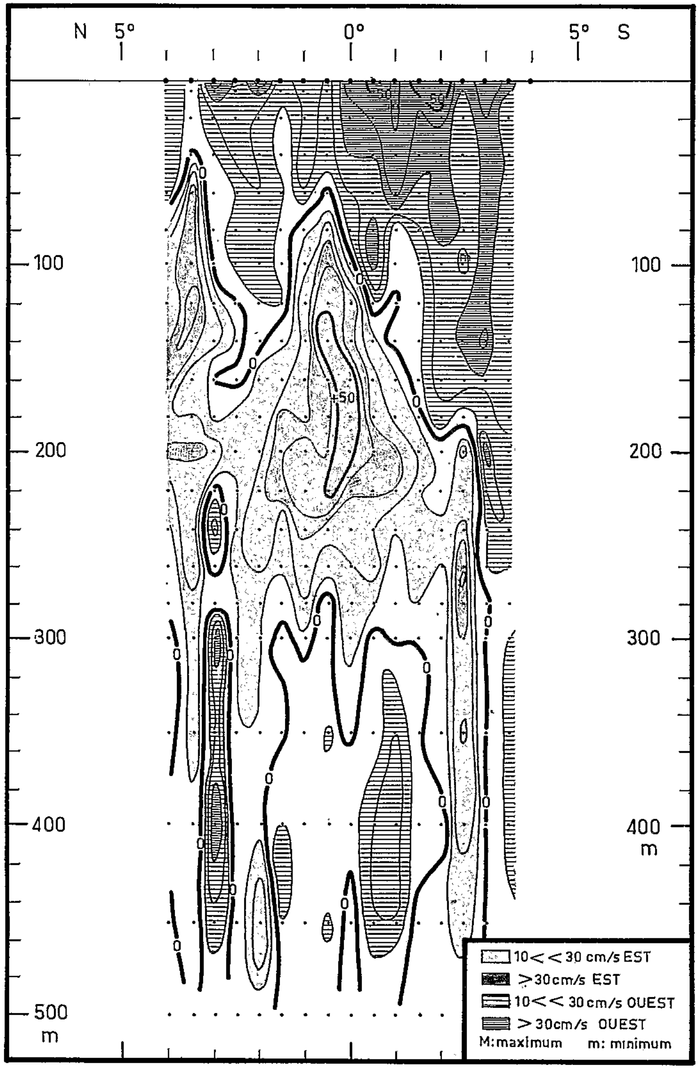

FIG. 15e. Cyclone 6.

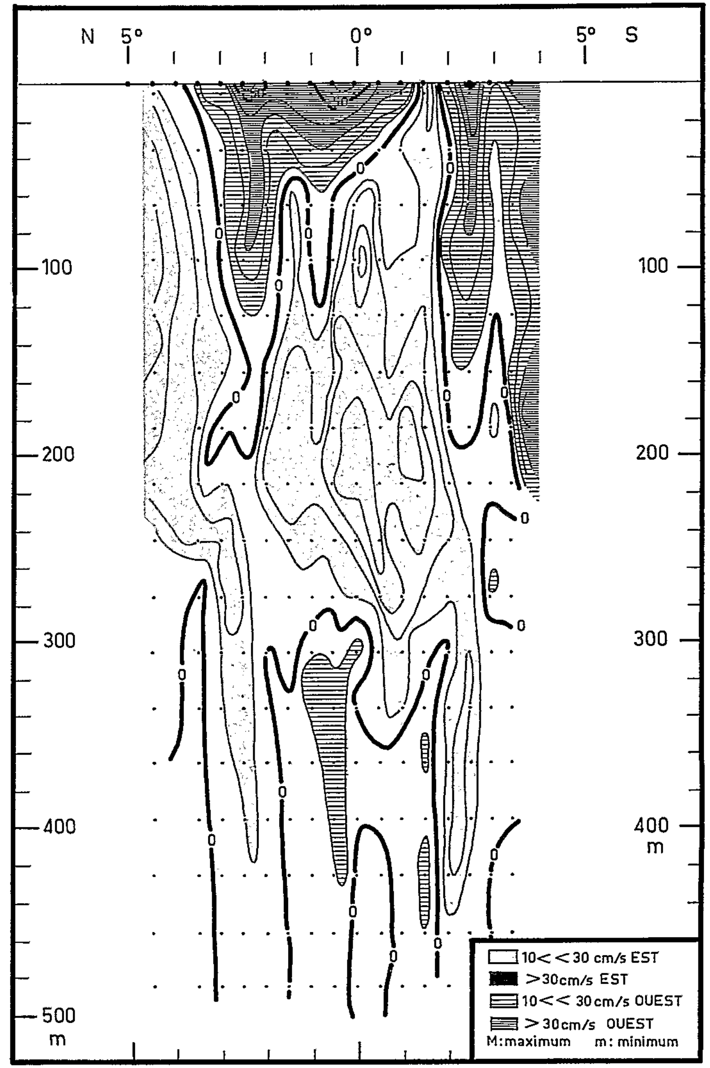

FIG. 15f. Cyclone 7_1.

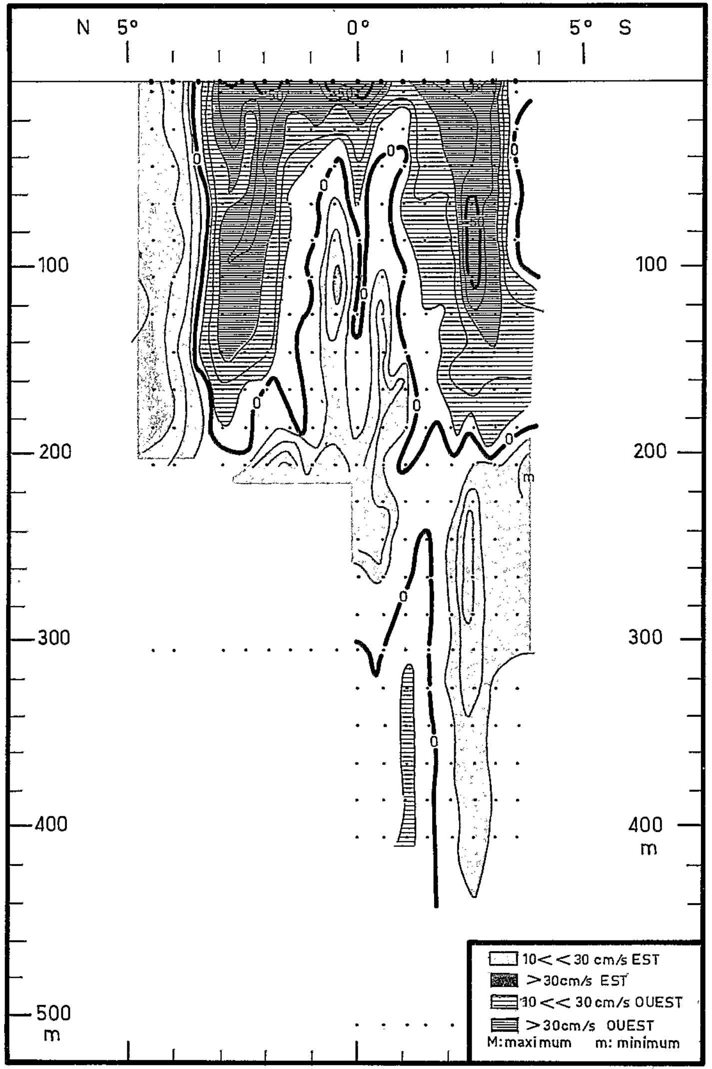

FIG. 15g. Cyclone 7_2.

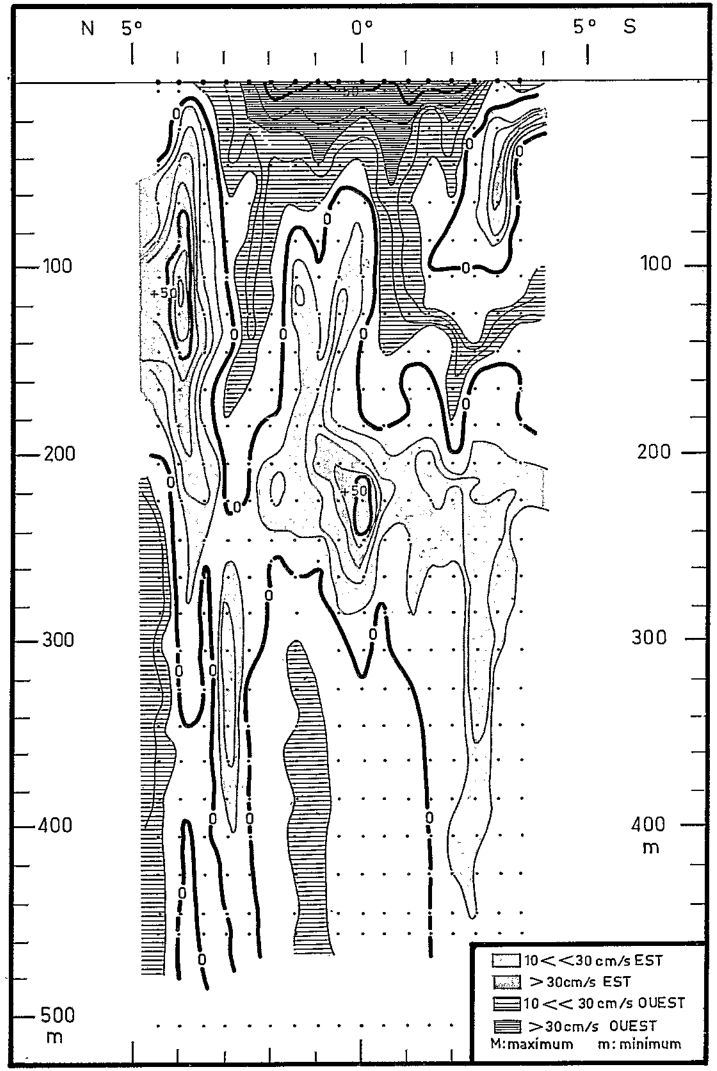

FIG. 15h. Cyclone 7_3.

FIG. 15a–h. "Cyclone" cruises, distribution from 4° S to 4° N of the zonal speed component: (a) Cyclone 2, (b) Cyclone 3, (c) Cyclone 4, (d) Cyclone 5, (e) Cyclone 6, (f) Cyclone 7_1, (g) Cyclone 7_2, (h) Cyclone 7_3. Isotachs every 10 cm/s.

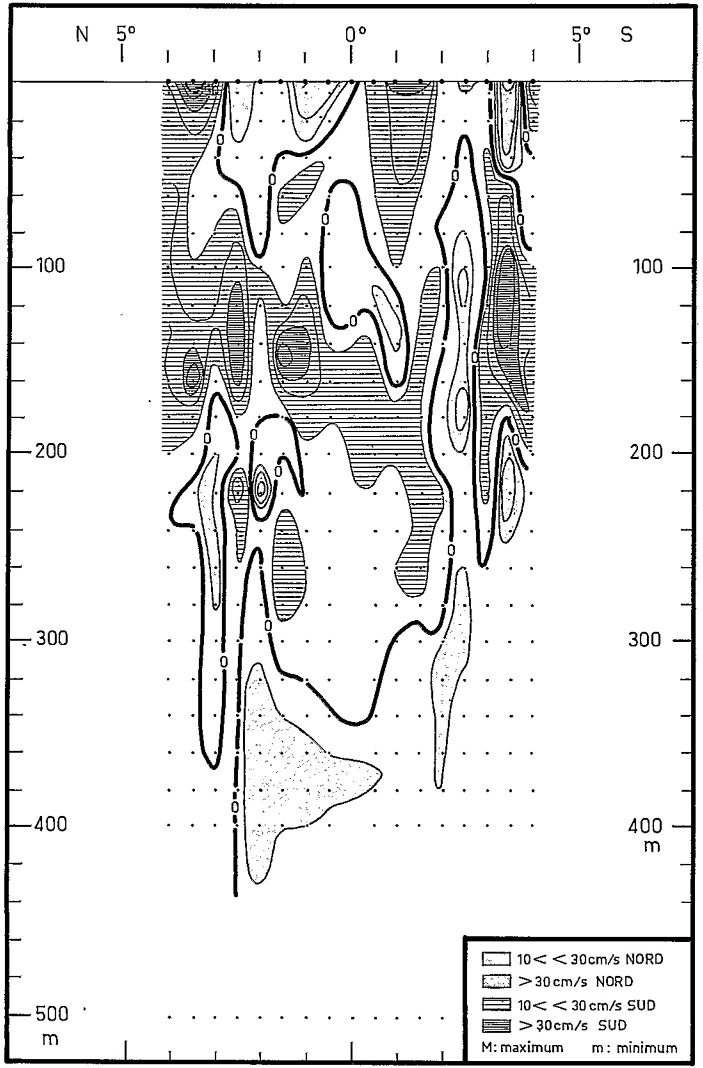

FIG. 16a. Cyclone 2.

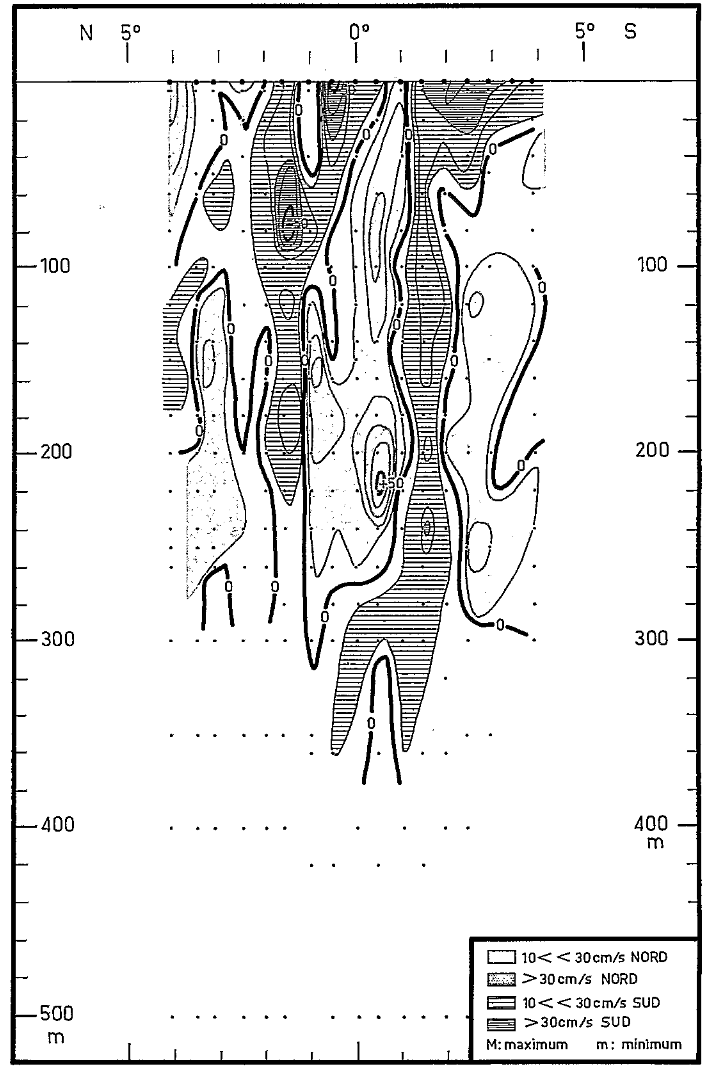

FIG. 16b. Cyclone 3.

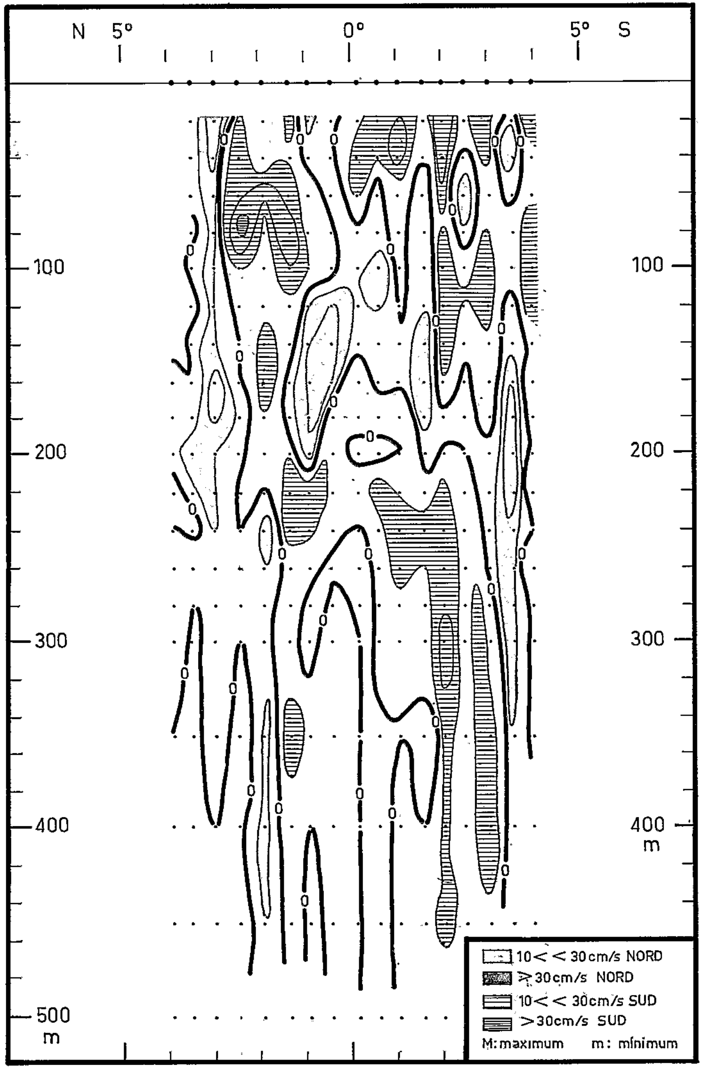

FIG. 16c. Cyclone 4.

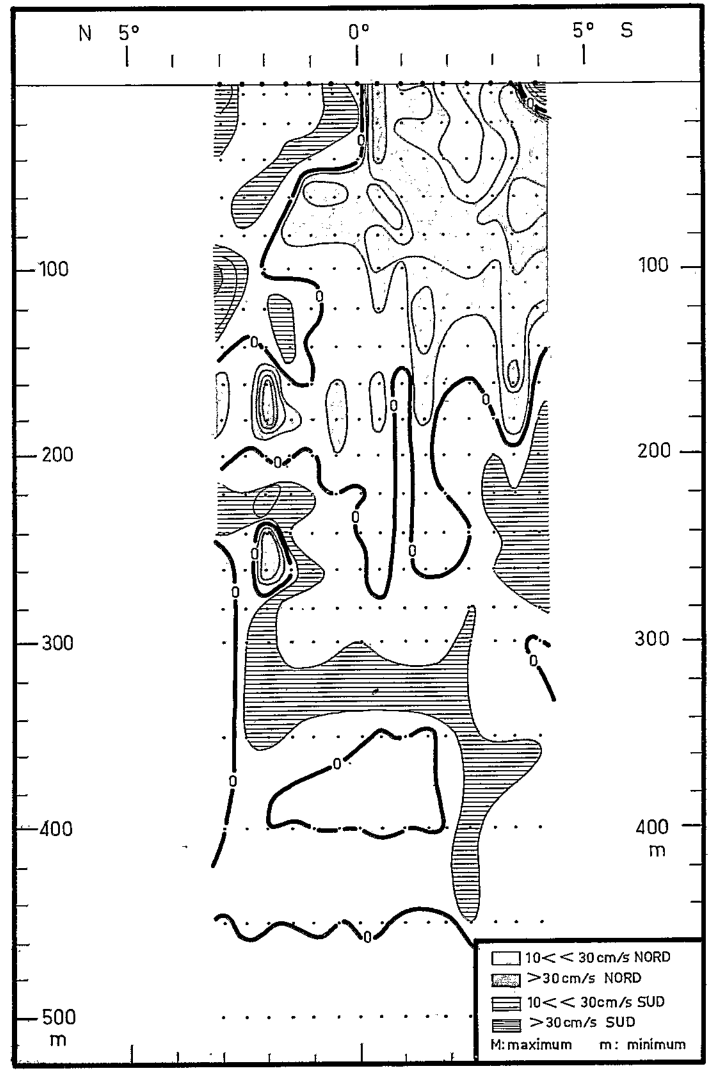

FIG. 16d. Cyclone 5.

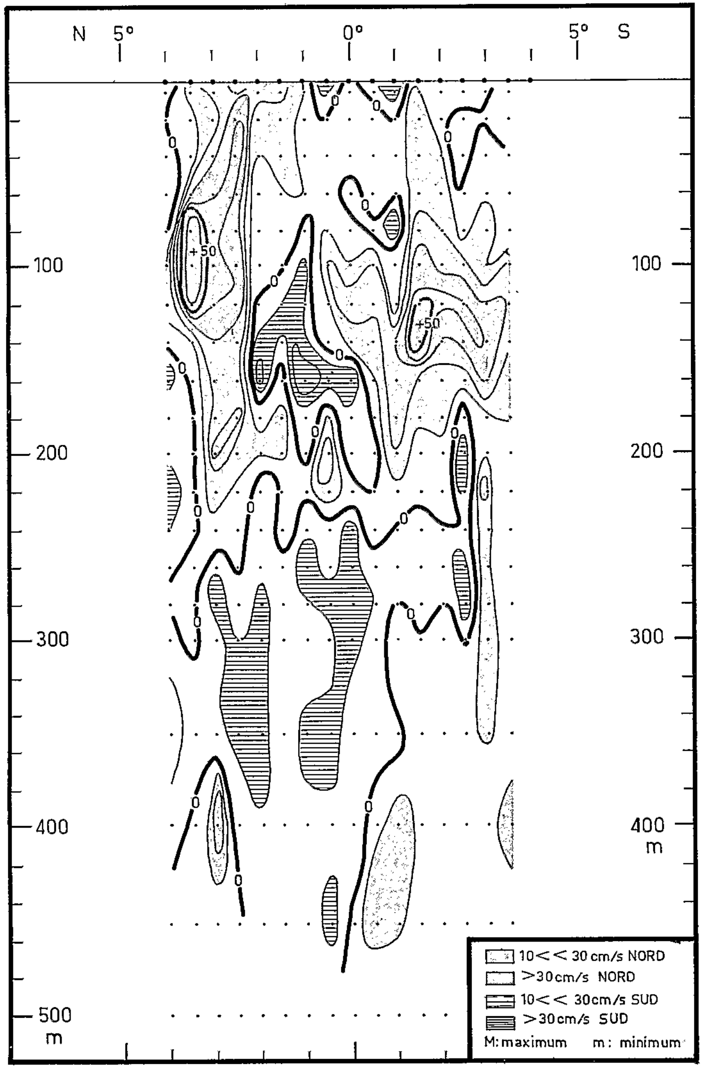

FIG. 16e. Cyclone 6.

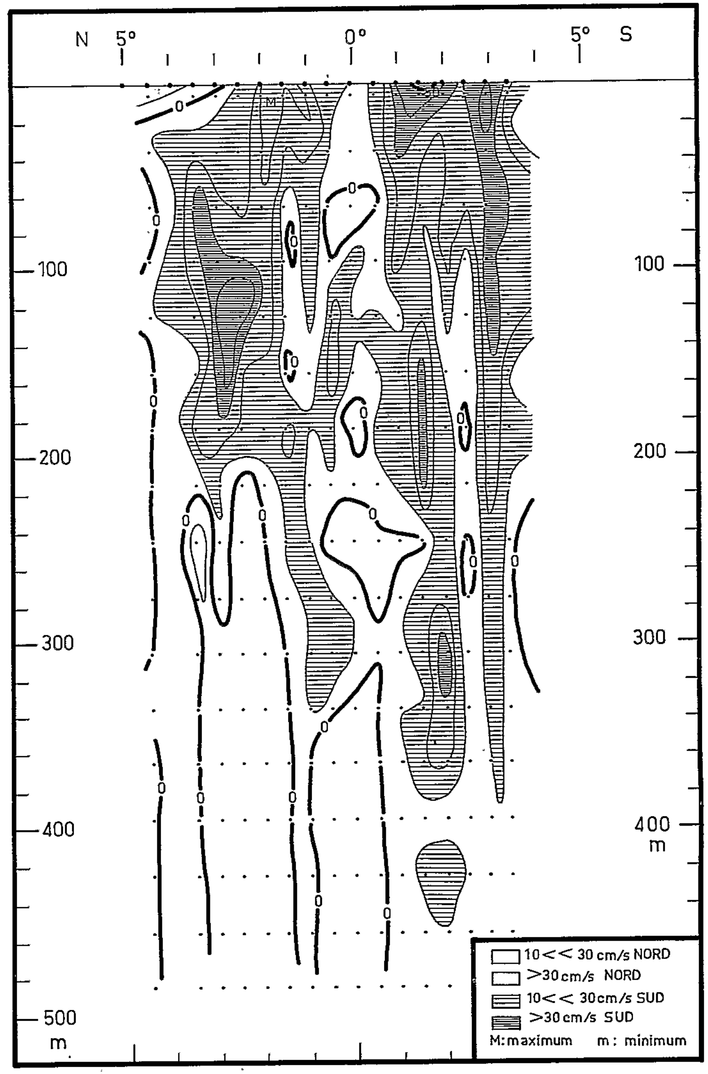

FIG. 16f. Cyclone 7_1.

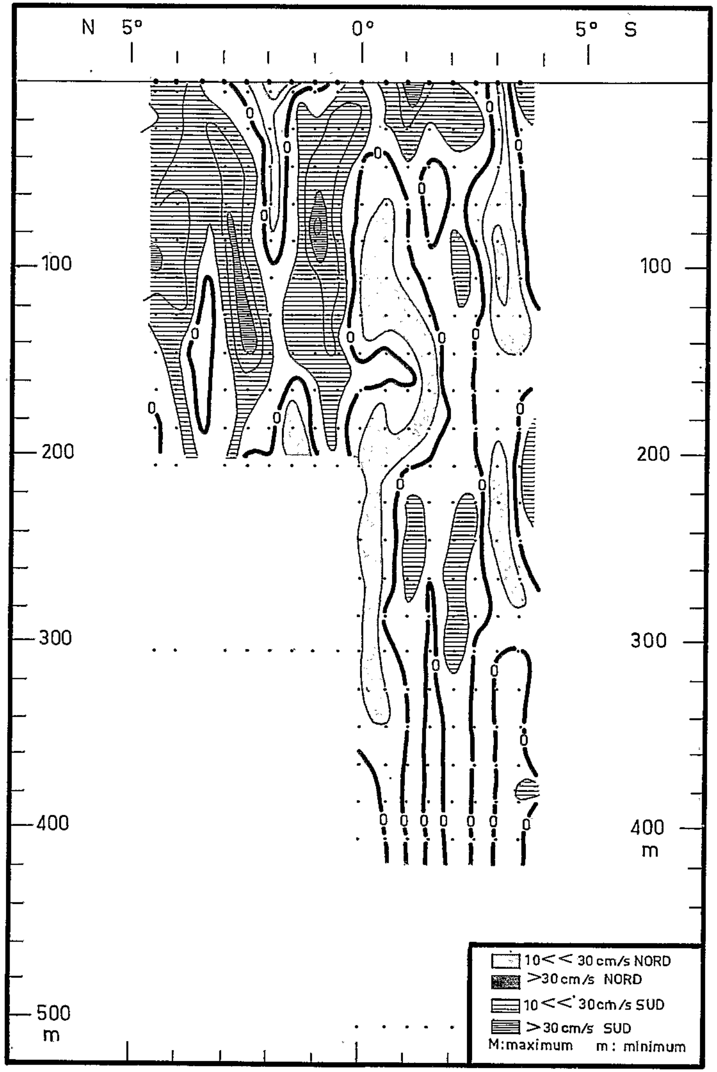

FIG. 16g. Cyclone 7_2.

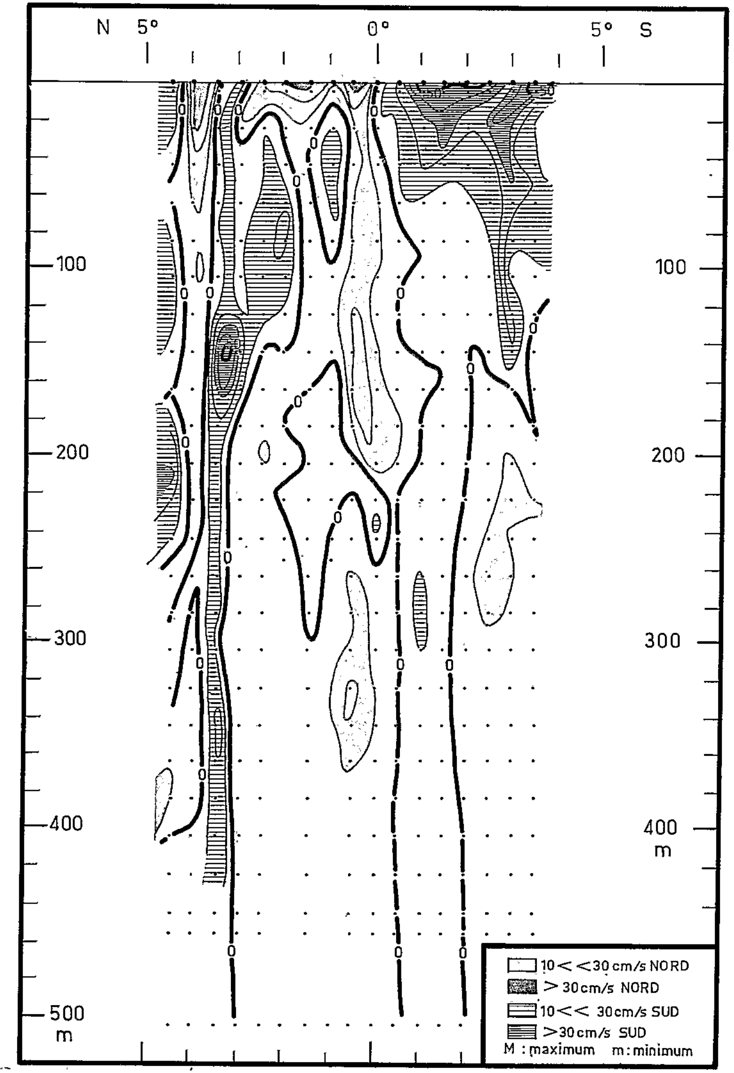

FIG. 16h. Cyclone 7_3.

FIG. 16a–h. "Cyclone" cruises, distribution from 4° S to 4° N of the meridional speed component: (a) Cyclone 2, (b) Cyclone 3, (c) Cyclone 4, (d) Cyclone 5, (e) Cyclone 6, (f) Cyclone 7_1, (g) Cyclone 7_2, (h) Cyclone 7_3. Isotachs every 10 cm/s.

recordings are thus more stable, and consequently give a more accurate reading than when the apparatus is submerged close to the surface.

The effect of the magnetic mass of the ship upon the direction measurements was reduced by the fact that the current meter was let down amidships on the starboard side of the vessel, which was generally on an easterly course. Thus the mass of the ship was to the north of the compass of the direction sensor, and was balanced in relation to it. The slight effect that it may have under these conditions disappears in any case as soon as the instrument is more than 30 m below the surface (TAFT and KNAUSS, 1967).

In the best of cases, a deep recording can be read to an accuracy greater than $\pm 5°$ for direction, and ± 7 cm/s for speed. A recording nearer the surface gives an accuracy of $\pm 10°$ for direction and the same degree of uncertainty for speed. However, the meteorological situation did not always favour the application of this method and sometimes, when the ship was very unstable and the currents perhaps varying very rapidly, the recordings were indistinct and their interpretation difficult. In these cases, errors in direction might approach or even exceed $\pm 35°$.

It thus appears difficult to evaluate the absolute accuracy of recording for individual measurements; values become significant only when inserted into a vertical sequence which allows us to follow the variations of the current with depth. It is the repetition of the same profile which gives an indication of the degree of confidence to be placed in measurements.

It is the deep measurements, unaffected by the movements of the ship and giving stable recordings of currents probably little subject to variation, which afford the best means of evaluating maximum relative accuracy. For a series of twelve vertical profiles carried out on the equator at 170°E at depths between 1000 m and 1500 m during "Cyclone" 6, it is about ± 5 cm/s for each of the E–W and N–S components (Fig. 3) (RUAL, 1969). This accuracy is limited by the variations in the drift of the ship during measurements; the current recorded at a depth of 1000 m for 6 hours on the equator at 169°E indicates in fact that, assuming a stable flow at 1000 m, the movements of the ship may give rise to inaccuracy of ± 5 cm/s for the E–W and N–S components (Fig. 2). Accuracy of the same order is evidenced by the stability in time of the distribution between 4°S and 4°N of the zonal and meridional components of the current at 500 m relative to 1000 m, observed during "Cyclone" 5 (Fig. 4); these measurements also show a considerable meridional gradient of the deep currents; a meridional section of currents relative to a fixed reference depth thus gives a distorted image of reality.

The degree of accuracy mentioned above applies to measurements carried out with one instrument submerged successively at the required depths; when two instruments are submerged simultaneously at the measurement depth and the reference depth, no change in accuracy is observed (Fig. 5); if one considers the current vectors themselves, the errors in direction are $\pm 10°$.

In the waters of the 0–500 m layer, vertical profiles measured at a fixed point on the equator reveal the existence of layers where only one of the two current parameters—direction or speed—is stable in time (Fig. 6). From this may be deduced an evaluation of the accuracy of measurements in the subsurface zone, of the same magnitude as previously (Table 2). The magnitude of the differences in measurements taken simultaneously is proof of the variability of current in these zones.

In conclusion, it seems reasonable to allow a relative error for the measurements of ± 10 cm/s for each of the E–W and N–S components. To the degree of accuracy thus defined are added the influence of the choice of reference layer, and the intrinsic variability of currents.

TABLE 2. AVERAGE VARIATIONS IN INTENSITY AND SPEED OF THE CURRENTS MEASURED DURING FIXED STATIONS AT THE EQUATOR

Cruises	CYCLONES							
	C_2		C_{5_1}		C_{5_2}		C_6	
Duration of measurements in hours	21		28		15		23	
	ΔV cm/s	$\Delta D°$	ΔV cm/s	$\Delta D°$	ΔV cm/s	$\Delta D°$	ΔV cm/s	$\Delta D°$
West surface current	±25	±12	±10	±20	±2	±20	±15	±35
Equatorial undercurrent: Secondary core	±4	±10	±18	±8	±10	±8	±15	±8
Equatorial undercurrent: Intermediary minimum	±8	+35	±10	±10	±8	±10	±8	±18
Equatorial undercurrent: Main core	±8	±10	±18	±8	±9	±5	±10	±7
Minimum below the Equatorial Undercurrent	±4	±90	±2	±30	0	±80	±5	±160
Deep equatorial current	±8	±25	±11	±10	±5	±25	±2	±40
Average over whole profile	±6	±20	±13	±15	±6	±20	±10	±25

The choice of reference layer is very important. All deep measurements between 500 m and 1500 m show a not negligible vertical speed gradient; for example, at a depth of 500 m on the equator the current is quite different according to whether the reference level adopted is 1000 m or 1500 m (Fig. 7); similarly, the E–W component of the current at 500 m varies between 4°S and 4°N (Fig. 8). Thus a vertical meridional section of the distribution of currents will differ according to the reference level; the comparison of measurements taken during "Cyclone" 7 referred to 500 m (Fig. 16f–h) and to 1400 m (Fig. 25a–c) shows that the differences relate to the geographical extent of the principal currents, the intensity at the

TABLE 3. EAST FLOW OF THE EQUATORIAL UNDERCURRENT AND WESTWARD FLOW OF THE EQUATORIAL CURRENT BETWEEN 4°N AND 4°S REFERRED TO 500 m AND 1000 m ($10^6 m^3/s$)

Cruises	CYCLONES		
	C_4	C_5	C_6
Flow E/500	28	45	23
Flow E/1000	34	54	28*
Flow W/500	14	20	26
Flow W/1000	10	18	23*

*Reference varying between 1000 m and 1500 m.

core and the nature of the deep circulation, which is very slow; nevertheless, regarding the general pattern and distribution of the principal surface and subsurface currents, the differences are negligible. The easterly and westerly flows calculated are evidently affected by the choice of reference level: the flow of the Equatorial Undercurrent referred to 500 m is weaker than if it is referred to 1000 m; the opposite is true of the westerly surface current (Table 3). For the former, the difference is of the order of 20 %.

The choice of 500 m as reference level is justified by the fact that on the equator the current at 500 m related to 1000 m proved to be stable in time and space (Fig. 9). Moreover, the distribution of the E–W component of the current at 500 m relative to 1500 m between 4°S and 4°N appears to have varied little over a fairly long period (Fig. 10). Consequently, even if 500 m is not a depth where no movement takes place, movement there seems to be slight and above all stable enough to allow comparison of one section with another when referred to this depth, which is also the maximum depth common to all the sections.

However, the study of vertical profiles measured at a point on the equator has shown, as previously indicated, that there are layers where the current is extremely variable with time. Since the measurements covered a zone about 900 km wide in 4 days on each cruise, instability of the phenomenon studied, and its variations over more or less lengthy periods relative to the duration of each individual measurement, may seriously affect the representativeness of the meridional sections. Some measurements carried out continuously at fixed depth afford a description of the nature of fluctuations in the maximum speed layer of the Equatorial Undercurrent. On the equator at 169°E, at a depth of 220 m in March 1967 and at 200 m in August, short-term fluctuations of the order of 10 minutes to 1 hour, and long-term fluctuations of the order of 6 to 12 hours, sometimes varying by more than ± 15 cm/s, were observed (Figs. 11 and 12). Measurements made using an Ekman current meter during a fixed station of 6 days at 170°E and 0°36S, taken at about 1000 and 1700 local time respectively, indicated possible periods of the order of 12 hours on the one hand and over 6 days on the other (NOEL and MERLE, 1969). Since the amplitude of the variations observed was greater in all cases than the margin of error estimated for the measurements, it is virtually certain that they are evidence of real variations in the strength and direction of the currents.

In practice, short-term variations deform each individual profile, for which the measurements take 2 hours, and long-term ones deform the sections. In order at least to moderate the effect of short-term fluctuations, it would be possible to prolong the individual measurements, and this has been done elsewhere (KNAUSS, 1966; KORT *et al.*, 1966); but if each station had lasted a day, a section would have taken 17 days, which in view of the long-term evolution would have been much too long, as is fully proved by comparing three sections from the cruise "Cyclone" 7, made at intervals of about 10 days (Figs. 15f–h and 16f–h).

Thus the only way to obtain a precise description of the equatorial circulation would be to submerge a great number of current meters simultaneously for a sufficient period of time. This solution was not feasible with the equipment available. The measurement technique adopted thus represents a compromise tending to reduce the influence of long-term variations while accepting a certain degree of inaccuracy due to the shorter term variations.

Although the sections 4°N–4°S are thus distorted by a lack of simultaneity, there is virtual simultaneity between the hydrological and dynamic measurements at each station. The body of simultaneously collected information, including data on nutrient salts and dissolved oxygen, has facilitated a thorough study of the hydrological nature of the equatorial currents of the Pacific (HISARD *et al.*, 1969; HISARD and RUAL, 1970; HISARD *et al.*, 1970; OUDOT *et al.*, 1969; ROTSCHI and WAUTHY, 1969).

RESULTS

In the following discussions terminology will be used to describe the surface currents of the equatorial system which is not that of SVERDRUP *et al.* (1942), and which it would be appropriate to define. The term "Equatorial Current" denotes the westerly surface current which straddles the equator (Sverdrup's "south equatorial current"); this current is bounded to the north by the North Equatorial Countercurrent (Sverdrup's "equatorial countercurrent"), and to the south by the South Equatorial Countercurrent discovered by REID (1959).

The system of currents whose fluctuations are shown in the sections is composed of three flows, from top to bottom:

the Equatorial Current flowing west, bounded at about 3°N by the North Equatorial Countercurrent, and whose southern limit does not always come north of 4°S;

beneath the Equatorial Current, a group of eastward currents whose centre is constituted by the Equatorial Undercurrent (Cromwell current);

beneath the Equatorial Undercurrent, a westward current which is weak (10–20 cm/s) but seems to be present all the year round at a depth of about 300–400 m.

The Equatorial Current is usually divided into two branches, often completed by a surface vein at the equator (Figs. 13a–h and 14a–h). The first branch, with its centre at about 2°30′S, has a thickness of 200 m and a maximum strength of the order of 50 cm/s; the other with its centre at about 2°30′N, has a thickness varying between 50 and 200 m, and is generally less strong than the southern branch.

Between these two branches and beneath the equatorial vein slides an eastward current, centred almost on the equator, with its upper limit usually at a depth of about 50 m. This current is one of the group of eastward subsurface currents; it is the upper core of the Equatorial Undercurrent; in fact, at 170°E the Equatorial Undercurrent generally has two cores which are not always centred on the equator, at depths of 100 and 200 m respectively (NOEL and MERLE, 1969). The average speed at the lower core is of the order of 50 cm/s, and in the upper core 30 to 40 cm/s (Fig. 13a–h).

To the north and south, the Equatorial Undercurrent is connected with two other eastward currents (Figs. 14a–h and 15a–h): to the north, the North Equatorial Countercurrent and to the south, a current centred around 2°S with a core at about 200–300 m and a maximum strength of the order of 30 cm/s (Fig. 13a–h). This current appears very stable, and runs very deep, to a depth of at least 1500 m (RUAL, 1969). It may be that this is the current described by REID (1965) between 3°S and 7°S on 125 cl/t. Only the southern border of the North Equatorial Countercurrent appears in the measurements. It slopes down towards the equator and a deep extension of eastward flow is formed which goes down to at least 500 m. A "bridge" of variable strength and dimensions, situated 200 m deep at about 2°30N, joins it to the Equatorial Undercurrent (HISARD *et al.*, 1969).

All these currents have a substantial meridional component (Fig. 16a–h) but this is very variable with time, as much over a period of 24 hours as from one cruise to another; it is possible nevertheless to distinguish some main characteristics. The eastward currents are generally zonal, while the westward currents often have a stronger meridional component; the maximum values of the north–south component are often in the zones of the minimum values of the east–west component, giving a rotating current vector of constant magnitude. This leads to the zero isotachs of the north–south and east–west components being out of phase. For example, in June 1967 the core of the south component at a depth of 80 m at

TABLE 4. CRUISES 4°S–4°N

Current	Branch	Average characteristics	CYCLONE 2 20–24 Mar. 1967 4°S–4°N	CYCLONE 3 24–28 Apr. 1967 4°S–4°N	CYCLONE 4 4–8 June 1967 4°S–4°N	CYCLONE 5 10–14 July 1967 4°S–3°N	CYCLONE 6 23–27 Aug. 1967 3°30'S–4°N	CYCLONE 7–1 17–21 Apr. 1968 3°30'S–4°30'N	CYCLONE 7–2 27 Apr.–2 May 1968 3°30'S–4°30'N	CYCLONE 7–3 6–10 May 1968 3°30'S–4°30'N	Remarks
Equatorial Current	South branch	Core: Position	80 m 2°30'S	80 m 2°30'S	50 m 2°30'S	10 m 0°30'S	0 m 130 m 2°00'S 2°30'S	0 m 2°30'S	80 m 2°30'S	0 m 1°00'S	Cyclone 5—sloping axis 0 m–1°S to 200 m–3°30'S
		Core: Speed	70 cm/s	60 cm/s	50 cm/s	40 cm/s	60 cm/s 50 cm/s	40 cm/s	60 cm/s	60 cm/s	
		Extent	0–220 m 1°30'S–3°30'S	0–200 m 1°00'S–4°00'S	0–200 m 1°30'S–3°30'S	0–50 m(0°)—0–220 m(4°00S) 0°00'–4°00'S	0–50 m(0°)—0–180 m(4°S) 0°–4°S	0–160 m 2°S–3°30'S	0–180 m 1°S–3°30'S	0–140 m 0°30'S–1°30'S	
		Direction	W	SW (0–50 m) W (50–200 m)	W	NW	W (0–100 m) NW (100–180 m)	SW–S	W	W	
	Equatorial vein	Core: Position	0 m 0°	120 m 0°30'S	0 m 0°30'N	Mingled with the South branch	Mingled with the North branch	0 m 0°15'N	0 m 0°	0 m 0°	Not always separable from the north or south branches
		Core: Speed	80 cm/s	60 cm/s	30 cm/s			60 cm/s	70 cm/s	50 cm/s	
		Extent	0–80 m 1°30'S–1°30'N	80–180 m 1°S–1°30'N	0–50 m 1°30'S–1°N			0–50 m 1°30'S–1°30'N	0–40 m 1°S–1°N	0–40 m 0°30'S–1°N	
		Direction	SW (1°30'S–1°S) W (1°S–0°) NW (0°–1°30'N)	W (80–140 m) NW (140–180 m)	SW (1°30'S–0°) W (0°–1°N)			W	W	W	
	North branch	Core: Position	0 m 2°30'N	0 m 2°30'N	0 m 2°N	20 m 0°30'N	0 m 2°N	0 m 2°30'N	0 m 2°30'N	0 m 2°N	Less stable than the south branch
		Core: Speed	40 cm/s	80 cm/s	30 cm/s	70 cm/s	30 cm/s	50 cm/s	50 cm/s	50 cm/s	
		Extent	0–180 m 1°30'N–3°N	0–170 m 1°30'N–3°N	0–60 m 1°N–2°30'N	0–60 m 0°–3°N	0–120 m 0°30'N–3°30'N	0–150 m 1°30'N–3°N	0–180 m 1°N–3°30'N	0–180 m 1°30'N–3°N	
		Direction	W (0–100 m) S (100–180 m)	S (1°30'N—20–80 m) W	W (0–40 m) S (40–60 m)	W	NW	SW (0–100 m) S (100–150 m)	W	W (0–50 m) SW (50–180 m)	
Equatorial Undercurrent	Secondary core	Core: Position	120 m 0°	40 m 1°30'N	80 m 1°N	110 m 0°30'S	140 m 0°30'N	120 m 0°	100 m 120 m 0°30'N 0°30'S	120 m 0°30'N	Not always very apparent as a core of maximum speed
		Core: Speed	30 cm/s	50 cm/s	40 cm/s	60 cm/s	50 cm/s	40 cm/s	40 cm/s 30 cm/s	20 cm/s	
		Extent	60–160 m 0°30'S–1°N	0–80 m 1°30'S–2°S	40–120 m 0°30'N–1°30'N	60–140 m 1°S–0°30'N	70–170 m 0°30'S–1°N	80–160 m 0°30'S–0°30'N	60–180 m 100–180 m 0°–1°N 0°15'S–1°S	80–170 m 0°–1°N	
		Direction	E	S (0–20 m) E (20–80 m)	E	E	E	E	SE NE	NE	
	Main core	Core: Position	200 m 0°30'S	210 m 0°30'N	190 m 0°30'S	170 m 1°N	210 m 0°30'S	210 m 0°30'N		130 m 0°	
		Core: Speed	60 cm/s	50 cm/s	70 cm/s	80 cm/s	50 cm/s	50 cm/s		60 cm/s	
		Extent	180–280 m 1°30'S–2°N	170–280 m 0°30'S–1°30'N	140–270 m 1°30'S–2°30'N	130–280 m 1°30'S–2°30'N	180–300 m 2°S–2°N	160–300 m 2°S–2°30'N	180–300 m 1°S–2°30'N	180–270 m 1°30'S–2°30'N	
		Direction	E	E	E	E	E (180–260 m) S (260–300 m)	E	E	E	
Deep east current at 2°30S		Core: Position	300–350 m 2°S	350 m 2°30'S	300 m 2°30'S	260 m 2°15'S	270 m 2°30'S	300 m 2°30'S	250 m 2°30'S	280 m 2°30'S	Extremely stable current probably extending much deeper than 500 m
		Core: Speed	30 cm/s	30 cm/s	30 cm/s	30 cm/s	40 cm/s	30 cm/s	40 cm/s	30 cm/s	
		Extent	240–500 m 1°45'S–3°S	220–500 m 1°30'S–4°S	200–500 m 1°30'S–3°S	230–500 m 1°30'S–3°30'S	200–500 m 2°S–3°S	280–500 m 2°S–3°15'S	210–500 m 2°S–3°30'S	200–500 m 2°S–3°30'S	
		Direction	E	S (220–260 m) E (260–500 m)	SE (200–240 m) E (240–500 m)	E	E	E	E	E	
North Equatorial Countercurrent	Surface part (limited to 4°N)	Core: Position	100 m 4°N	100 m 4°N	100 m 4°N	100 m 3°N	120 m 3°30'N	90 m 4°30'N	100 m 4°30'N	110 m 4°N	These characteristics only represent the portion measured, that is, the margin of the NECC
		Core: Speed	50 cm/s	60 cm/s	50 cm/s	30 cm/s	80 cm/s	50 cm/s	50 cm/s	70 cm/s	
		Extent	0–150 m 3°N–4°N	0–220 m 2°45'N–4°N	0–200 m 2°30'N–4°N	30–160 m 2°30'N–3°N	40–180 m 3°N–4°N	0–230 m 3°N–4°30'N	0–200 m 3°45'N–4°30'N	10–280 m 3°N–4°30'N	
		Direction	E	E	E	E (30–100 m) SE (100–160 m)	N (3°N–3°30'N) E (3°30'N–4°N)	S (3°N–3°30'N) E (4°N–4°30'N)	E (0–40 m) SE (40–120 m) E (120–200 m)	E	
	Deep branch	Core: Position	200 m 3°N	260 m 2°45'N	200–300 m 3°N	260 m 3°N	200 m 3°30'N	250 m 3°N		330 m 3°N	Current probably extending much deeper than 500 m
		Core: Speed	60 cm/s	30 cm/s	20 cm/s	30 cm/s	40 cm/s	30 cm/s		30 cm/s	
		Extent	120–500 m 2°N–3°30'N	220–500 m 2°N–3°30'N	200–400 m 2°30'N–4°N	160–500 m 2°30'N–3°N	180–500 m 180–400 m 1°30'N–2°30'N 3°15'N–3°45'N	220–500 m 2°N–3°N		240–500 m 2°45'N–3°30'N	
		Direction	E	E	E	SE (160–260 m) E (260–500 m)	SE E	E		NE (240–300 m) E (300–500 m)	
Bridge between the North Equatorial Countercurrent and the Equatorial Undercurrent		Core: Position	220 m 2°N	210 m 1°30'N	180 m 2°30'N	140 m 2°30'N	200 m 2°30'N	230 m 2°30'N	3°N	250 m 2°30'N	
		Core: Speed	25 cm/s	85 cm/s	30 cm/s	80 cm/s	10 cm/s				
		Extent	200–280 m	200–230 m	100–240 m	100–240 m	180–210 m				
		Direction	E	S	E	E	NE				
Deep west current		Core: Position									Weak current whose extent and intensity are very dependent upon choice of reference layer
		Core: Speed	20 cm/s	30 cm/s	20 cm/s	20 cm/s	30 cm/s	20 cm/s	10 cm/s	10 cm/s	
		Extent	300–500 m 1°30'S–1°30'N	240–500 m 2°S–1°30'N	300–500 m 1°30'S–2°N	300–500 m 2°S–2°N	300–500 m 2°S–2°N	300–500 m 2°S–2°N	300–500 m 2°S–2°N	280–500 m 1°30'S–2°30'N	
		Direction	W	W	W	SW (300–350 m) W (350–500 m)	W (1°S) S (0°) W (2°N)	N (2°S) W (0°) N (2°N)	W	W (1°30S) N (0°) W (1°30N)	
Remarks			No station on equator	East current at surface		Exceptionally strong currents	Deep branch of NECC—forked by a west current	Station 11D eliminated	No measurements in the 200–500 m zone, between 0° and 4°30N		

2°30′ N (Fig. 16c) is exactly on the zero isotachs of the east–west component (Fig. 15c), and the vertical distribution of the total speed does not show any minimum (Fig. 13c). On the other hand, the zone separating the south branch of the Equatorial Current from the east flowing currents is a zone of weak meridional movement.

Particular aspects

All the characteristics of the various elements of the sections of currents are described in Table 4; however, some remarkable findings need to be underlined:

The most unexpected feature appeared in April 1967 (Fig. 15b). At the surface, on the equator, the current is eastward and the upper core of the Equatorial Undercurrent is replaced by a westward current core, connected to the two branches of the Equatorial Current. A current travelling eastwards at the surface had already been noted at 170°E (NOEL and MERLE, 1969), as well as farther to the west, at 140–150°E (MONTGOMERY, 1962), at 130°E and 140–150°E (KORT *et al.*, 1966).

Of all the cruises, "Cyclone" 5 (July 1967) (Fig. 15d) presents the maximum intensity and geographical extent of the eastward currents. By "Cyclone" 6 (August 1967), 5 weeks later, this exceptional situation had disappeared but the two cores of the Equatorial Undercurrent were connected to each other without any sign of an intermediary minimum (Fig. 15e).

It appears that at 170°E one approaches the zone where the Equatorial Undercurrent separates from the North Equatorial Countercurrent; the bridge connecting them is very variable in thickness and speed: in June and July 1967 it was 150 m thick and had a maximum strength of 30 cm/s, but in April of the same year it was only 30 m thick and had a maximum strength of 5 cm/s. Moreover, the meridional component shows a tendency to diverge there (HISARD *et al.*, 1969) which was detected in 1958 at 172°E in the section presented by BURKOV and OYCHINNIKÓV (1960).

The three sections of "Cyclone" 7 (Fig. 13f–h) were carried out at intervals of 10 days; they reveal the rapid evolution of currents: the displacement of the lower core of the Equatorial Undercurrent from one section to another, the geographical extension of the north branch of the Equatorial Current in section II (Fig. 15g) and the sudden appearance of a current of speed 40 cm/s flowing east at 3°S at 50 m in Section III (Fig. 15f). Lastly, the rise to the surface of the eastward current apparent in the first section has disappeared in the second.

One important characteristic of the cruises in July and August 1967 (Fig. 16d–e) is the importance of the meridional component. In July, from 4°S to the equator and from the surface to a depth of 150 m (Fig. 16d) the waters were shifting with a northward component reaching 50 cm/s at 4°S. In August (Fig. 16e), centred on 1°30′S and at 130 m, a northward component core was also reaching a speed of 50 cm/s; another at 3°30′N and a depth of 100 m was exceeding 60 cm/s. All these cores were centred on zero isotachs of the east–west component.

In conclusion, we should emphasize the constant presence of various elements of each group of currents, despite the variability of their extent and flow.

Flow

In order to calculate the transport of the Equatorial Undercurrent and of the surface Equatorial Current through a meridional section 4°S to 4°N limits of integration have been selected, some of them arbitrarily.

For the Equatorial Undercurrent, these are: to the north, the constriction line of the bridge connecting the North Equatorial Countercurrent with the Equatorial Undercurrent; everywhere else, the zero isotachs of the zonal component, and where these isotachs are not in the section studied, the 400 m isopleth and the parallel 4°S (or 3°30′S for "Cyclone" 7).

For the equatorial surface current, we have considered the section between the surface and the zero isotachs. In all cases where these do not cut the surface, the limit chosen is the highest latitude of the section.

For each meridional section, the interior of the domains thus defined was divided up into units measuring 25 miles by 10 m deep. To each of these was assigned a mean value of the zonal component in m/s, according to the distribution of the isotachs in Figs. 16a–h.

TABLE 5. FLOW OF EQUATORIAL CURRENT, REFERENCE 500 m ($10^6 m^3/s$)

Range of thermosteric anomaly in cl/t	C_2	C_3	C_4	C_5	C_6	C_{7_1}	C_{7_2}	C_{7_3}
550–600	0.2	5.6	4.7	4.5				
500–550	7.5	12.8	6.2	13.6	21.0	10.6	19.5	10.8
450–500	11.7	13.3	2.7	0.8	1.6	4.2	4.8	4.8
400–450	1.0	1.4	0.2	0.4	0.7	0.2	0.6	0.5
350–400	0.7	0.7	0.1	0.2	0.4	0.1	0.1	0.1
300–350	0.5	0.6	0.1	0.2	0.2			
250–300	0.3	0.1	0.1	0.1	0.2			
200–250				0.1	0.3			
150–200				0.1	0.5			
100–150					0.8			
Total Flow	21.9	34.5	14.1	20.0	25.7	15.1	25.0	16.2

On these numbered grids were superimposed isanosteres of every 50 cl/t, and isohalines of 0.50‰. For each quadrangle bounded by two isanosteres and two isohalines (or by one of the boundaries defined above) the average speeds for the squares included in it were added. These totals, multiplied by 4.63×10^5 m^2, the area of one square, give the values in cubic metres per second of the transport of water of given characteristics.

The presentation of these results in Figs. 17a–h is similar to that used by MONTGOMERY and STROUP (1962). The exterior contours which have been added represent in terms of temperature–salinity the boundaries of the currents as defined at the beginning of this sub-section. The interior contours of Figs. 18a–h are the T–S limits of the Equatorial Under-current where the speed measured exceeds 30 cm/s. For each class of thermosteric anomaly the sums of the flows are given in Tables 5, 6 and 7, as well as the total easterly and westerly flows for each cruise.

Comments on the flow of the Equatorial Current

The mean flow of this current is 20 million m^3/s with extreme values of 14 and 35 million m^3/s (Table 5). More than three-quarters of the water thus transported has a thermosteric anomaly between 450 and 550 cl/t and usually a salinity between 35.0 and 35.5‰.

TABLE 6. EQUATORIAL UNDERCURRENT, TOTAL FLOW, REFERENCE 500 m ($10^6 m^3/s$)

Thermosteric anomaly	C_2	C_3	C_4	C_5	C_6	C_{7_1}	C_{7_2}	C_{7_3}	Average	Standard deviation
550–600				0.1					0	
500–550	0.1	0	1.9	2.8	0.4	0.6			0.7	1.0
450–500	3.3	0	1.0	6.4	2.1	6.4	2.5	1.3	2.9	2.4
400–450	0.4	0	2.1	4.9	1.5	2.9	0.8	0.3	1.6	1.7
350–400	0.7	0	3.3	4.4	1.6	3.3	1.3	0.7	1.9	1.6
300–350	1.5	0.8	4.4	6.1	1.3	2.6	2.2	0.9	2.5	1.9
250–300	2.1	2.0	4.5	3.8	2.2	3.0	2.3	2.6	2.8	0.9
200–250	4.8	2.3	4.7	3.2	4.1	3.5	3.1	2.7	3.5	0.9
150–200	3.0	3.2	4.3	5.9	7.1	4.5	6.7	3.4	4.8	1.6
100–150	4.4	3.4	2.0	5.7	3.0	3.9	3.8	2.3	3.6	1.2
Total Flow	20.3	11.7	28.2	43.3	23.3	30.9	22.7	14.2	24.3	10

Comments on the flow of the Equatorial Undercurrent

In the second to last column of Table 6 are given the mean values of the flows of the Equatorial Undercurrent for each density layer. Two maximum flow values stand out, one in the 450–500 cl/t layer, the other in the 150–200 cl/t layer; the 400–450 cl/t layer, on the other hand, is characterized by a minimum flow. The layers correspond respectively to the upper core of the Equatorial Undercurrent, the base of its lower core, and the intermediary minimum.

The 200–300 cl/t layer, the upper part of the lower core, is noticeable in having both the highest speeds and the most stable flows from one cruise to another (Table 6, last column).

If the composition of the flow calculated by MONTGOMERY and STROUP (1962) at 150°W is compared with the mean flow measured at 170°E (Table 8) it is found that, in terms of

TABLE 7. EQUATORIAL UNDERCURRENT, FLOW AT MORE THAN 30 cm/s (10^6 m^3/s)

Thermosteric anomaly in cl/t	C_2	C_3	C_4	C_5	C_6	C_{7_1}	C_{7_2}	C_{7_3}
500–550				1.4				
450–500				5.5	1.1	1.9		
400–450			0.5	4.4	0.9	1.9		
350–400	0.1		2.6	3.9	0.9	2.3		
300–350	0.3		4.3	4.8	0.6	2.3	0.3	
250–300	1.1	0.4	4.3	3.1	1.4	2.1	0.9	1.1
200–250	1.9	0.8	4.0	3.3	3.6	1.4	1.0	1.0
150–200	0.8	0.1	1.0	1.1	1.1		0.5	0.5
100–150								
Total transport at more than 30 cm/s	4.2	1.3	16.7	27.5	9.6	11.9	2.7	2.6
% of total flow	21.0	11.0	59.0	63.0	41.0	40.0	12.0	18.0

percentage, there is more water with a thermosteric anomaly of less than 350 cl/t in the east than in the west; in the east the lightest water has disappeared. Thus if the secondary core of the Equatorial Undercurrent continues to exist in the central Pacific, its hydrological characteristics have entirely changed. Moreover, since only one core was measured there, there must have been fusion of the two cores by isentropic ascent of the main core.

Table 7 shows waters travelling eastwards in the Equatorial Undercurrent at more than 30 cm/s. The bottom row of Table 7 gives the percentage carried relative to the total flow of the Equatorial Undercurrent. Figure 19 shows that the evolution of this percentage in the course of the "Cyclone" cruises accompanies that of the total flow—in other words, increases in strength of the Equatorial Undercurrent occur principally through reinforcement of the rapid core.

The total flow of the Equatorial Undercurrent showed great variability during the eight sections. In particular, between "Cyclone" 5 and 6 it decreased by 20×10^6 m^3/s in 5 weeks, and during "Cyclone" 7, by 17×10^6 m^3/s in 20 days, or by approximately 50% of the initial flow in both cases.

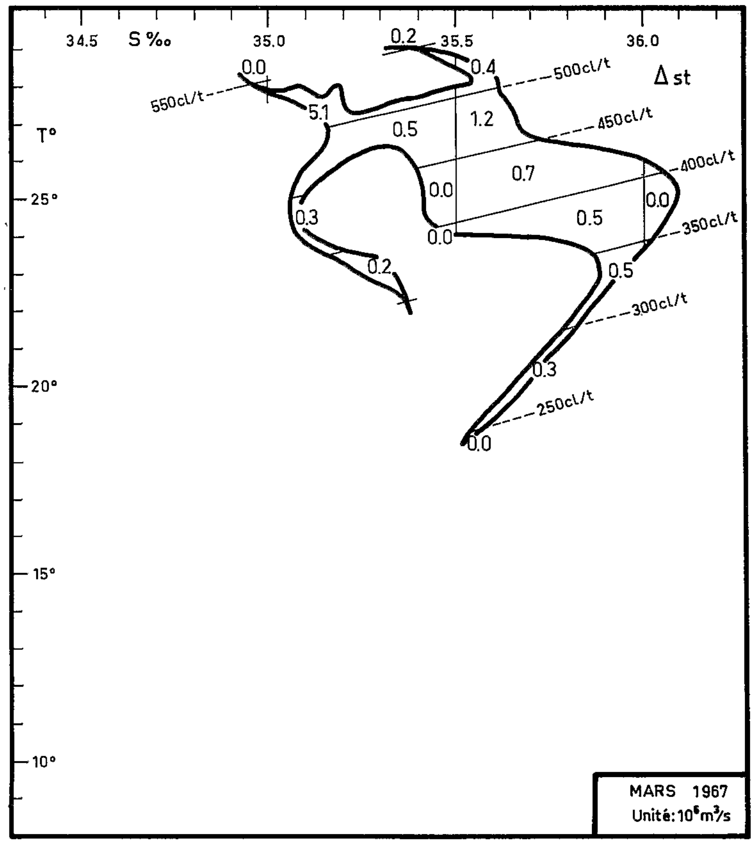

FIG. 17a. Cyclone 2.

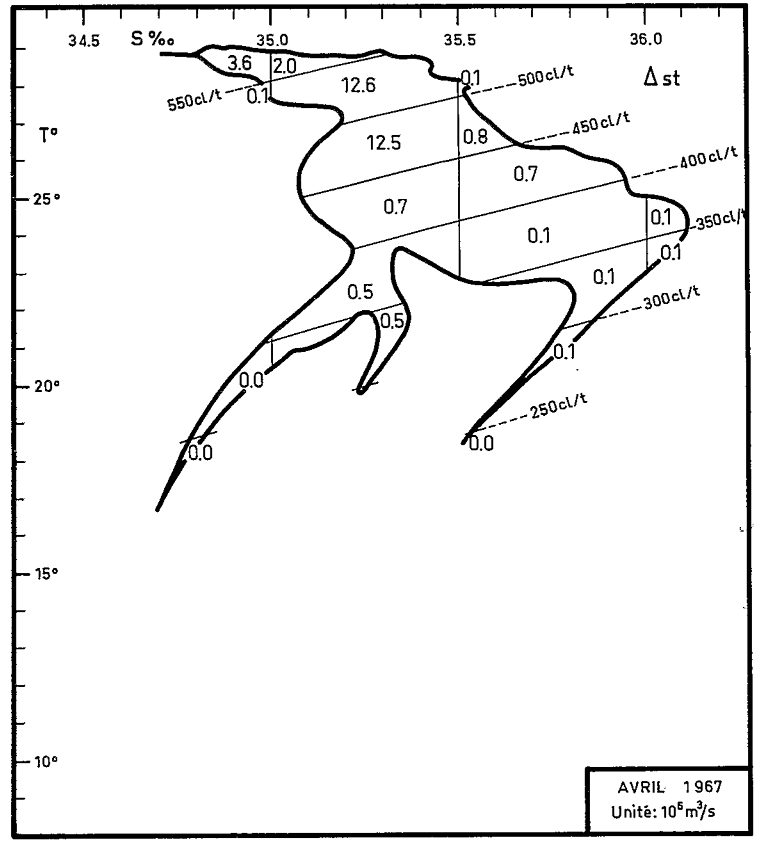

FIG. 17b. Cyclone 3.

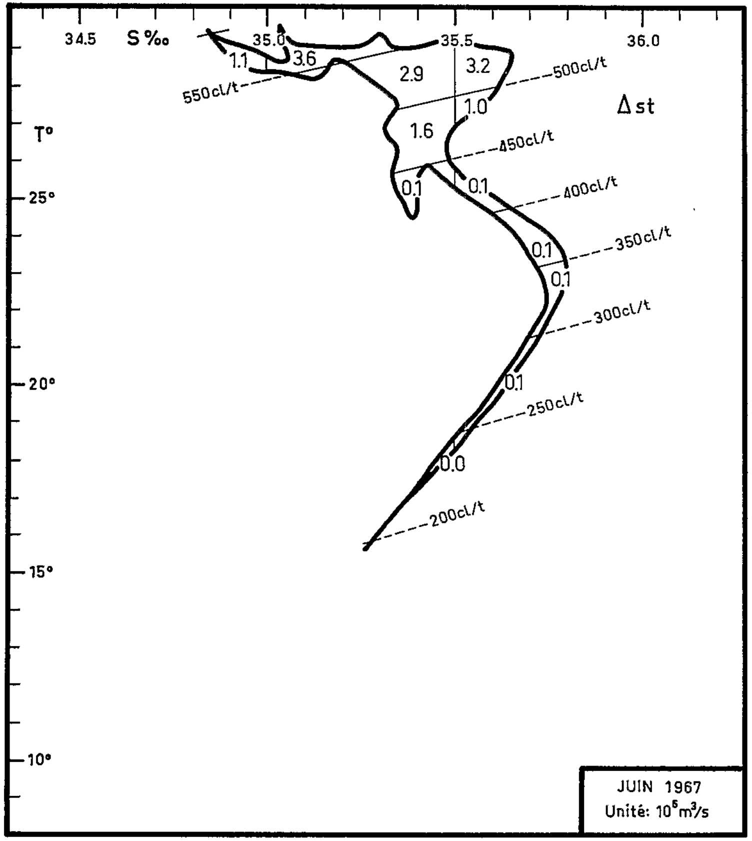

FIG. 17c. Cyclone 4.

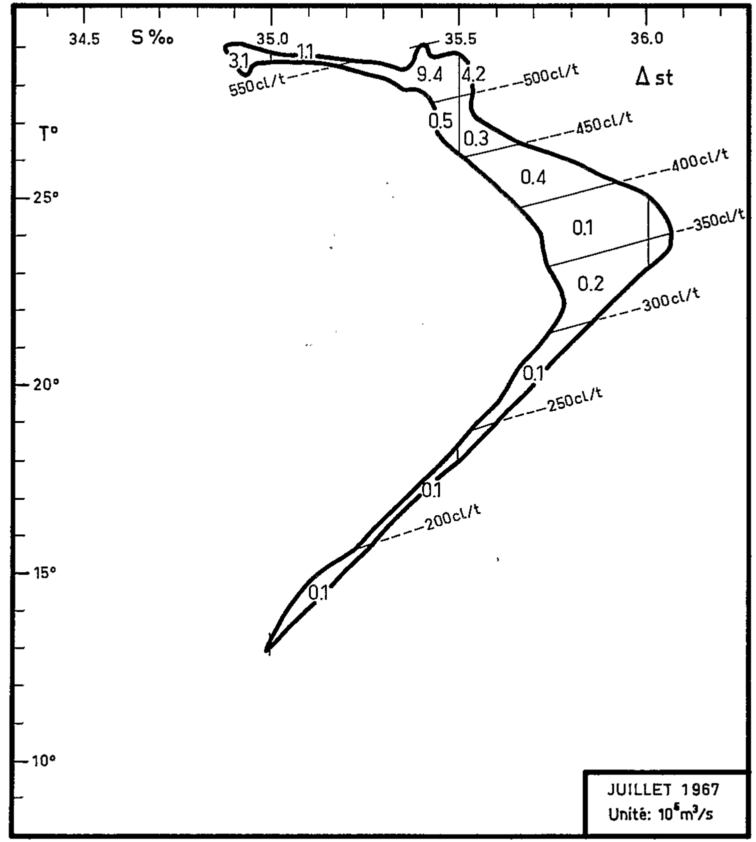

FIG. 17d. Cyclone 5.

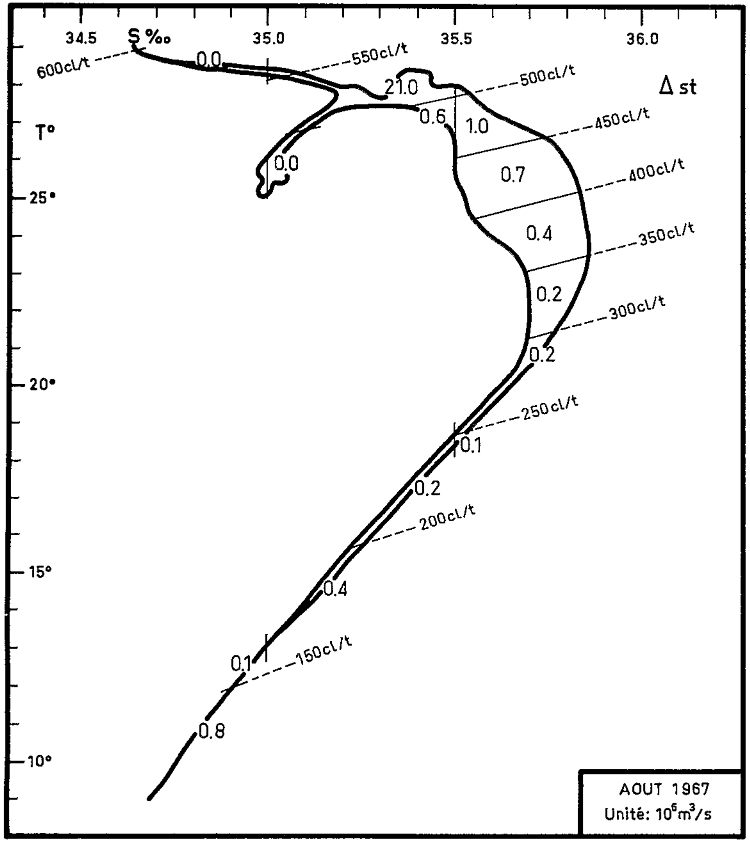

FIG. 17e. Cyclone 6.

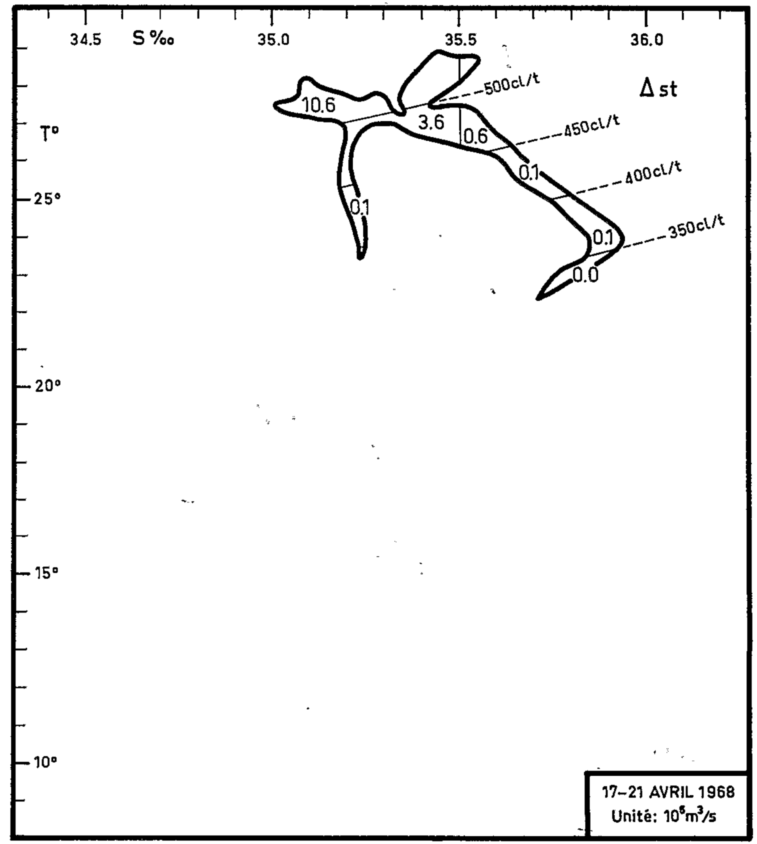

FIG. 17f. Cyclone 7_1.

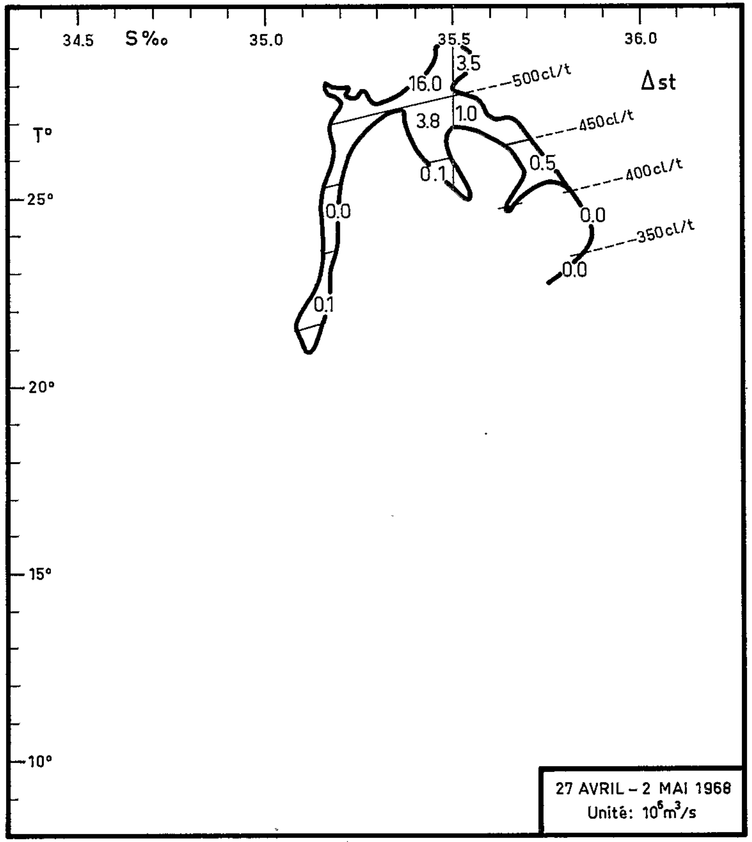

FIG. 17g. Cyclone 7_2.

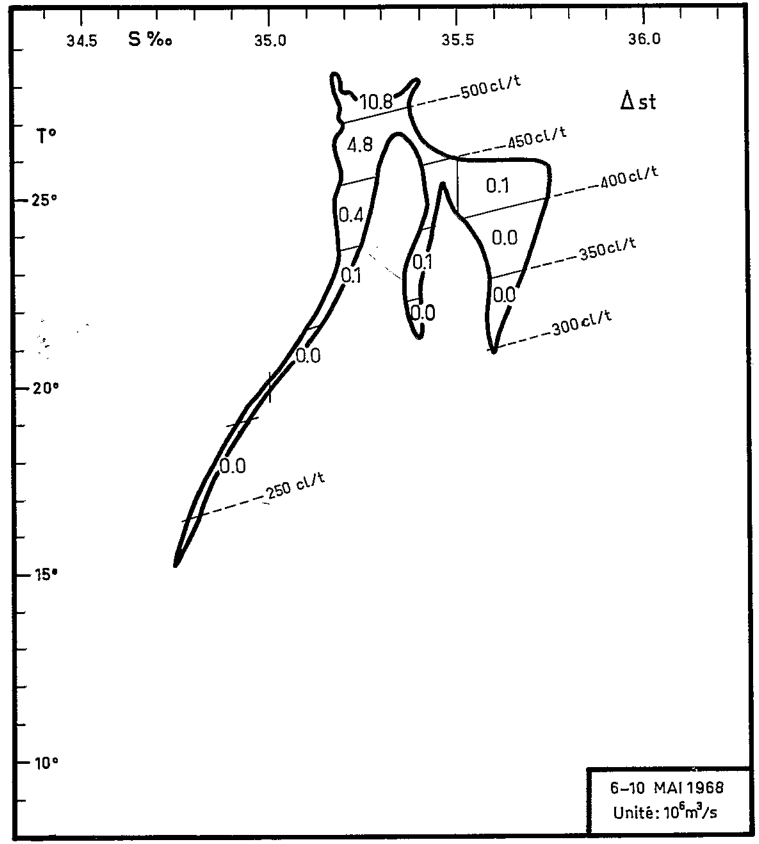

FIG. 17h. Cyclone 7_3.

FIG. 17a–h. "Cyclone" cruises, flow of Equatorial Current. Division according to thermosteric anomaly and salinity: (a) Cyclone 2, (b) Cyclone 3, (c) Cyclone 4, (d) Cyclone 5, (e) Cyclone 6, (f) Cyclone 7_1, (g) Cyclone 7_2, (h) Cyclone 7_3.

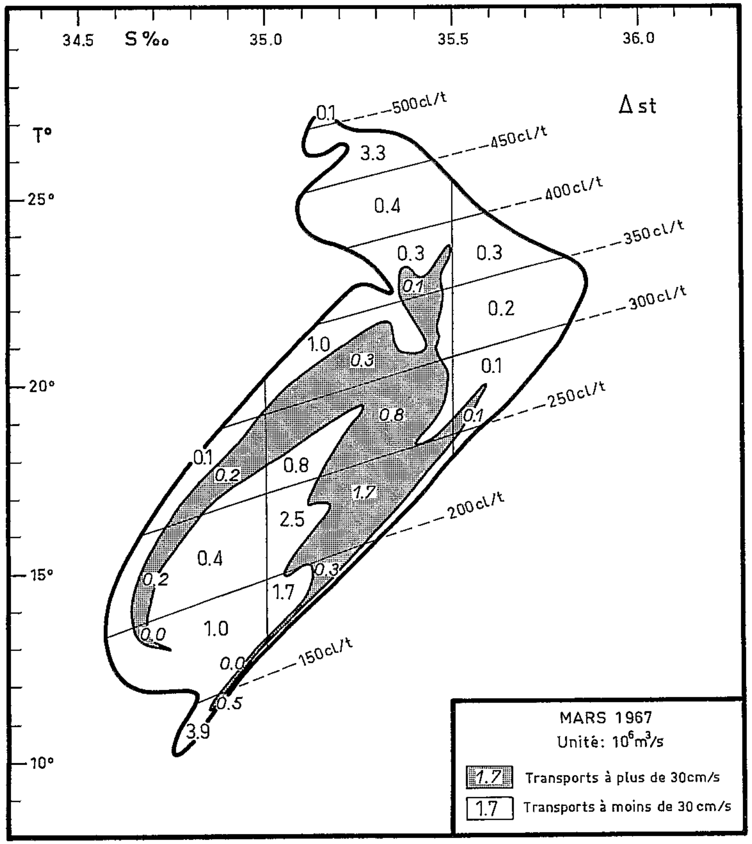

FIG. 18a. Cyclone 2.

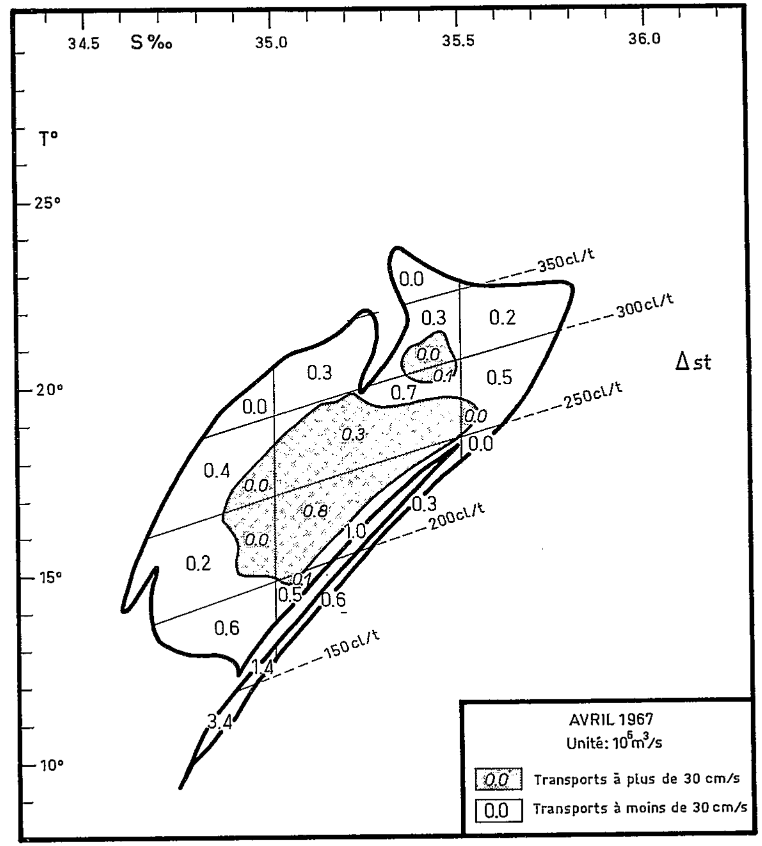

FIG. 18b. Cyclone 3.

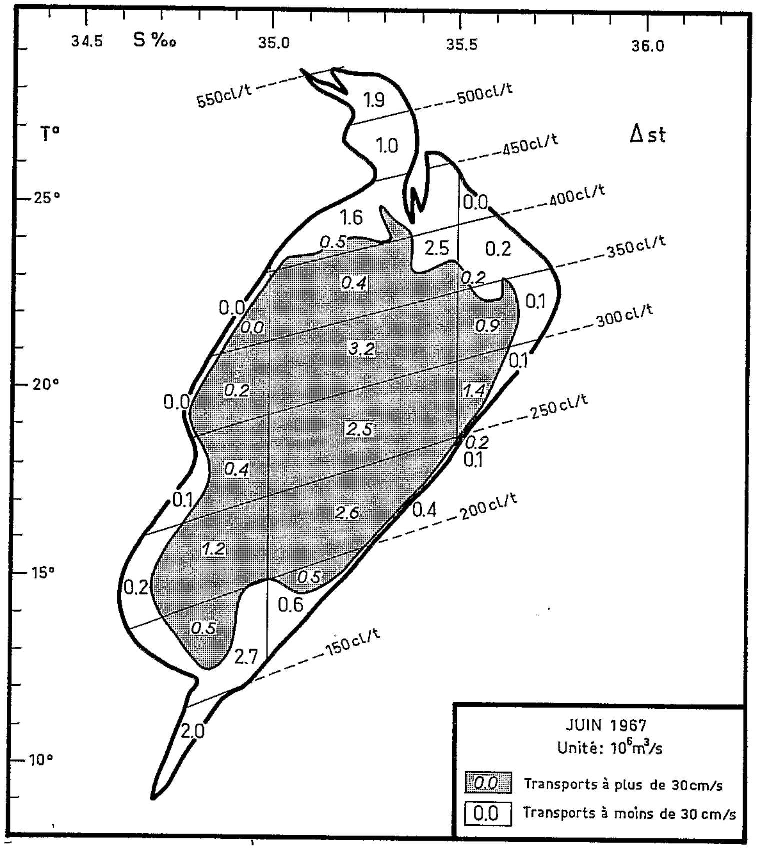

FIG. 18c. Cyclone 4.

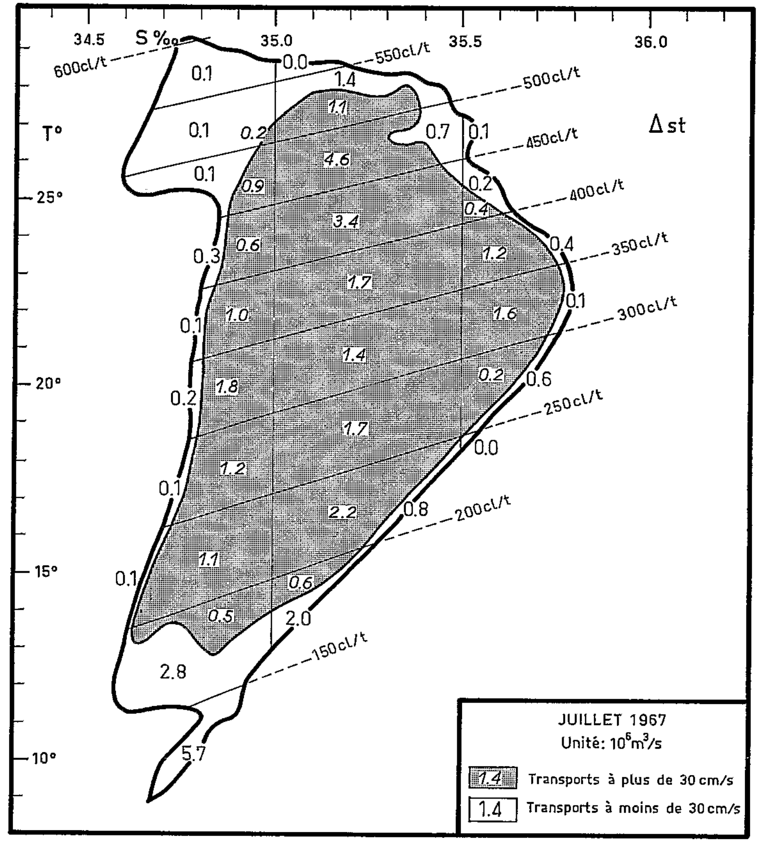

FIG. 18d. Cyclone 5.

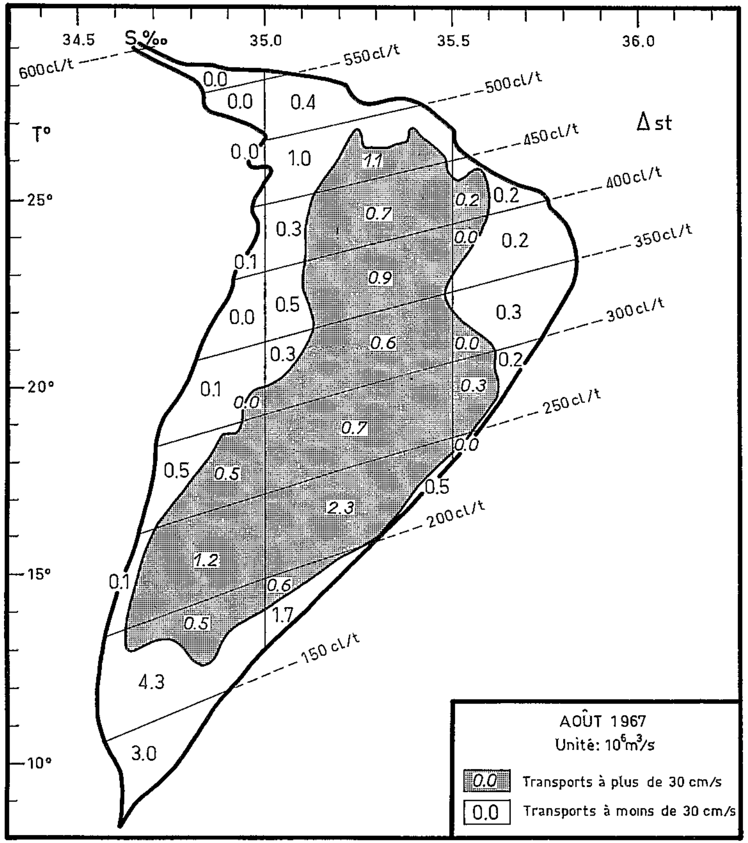

FIG. 18e. Cyclone 6.

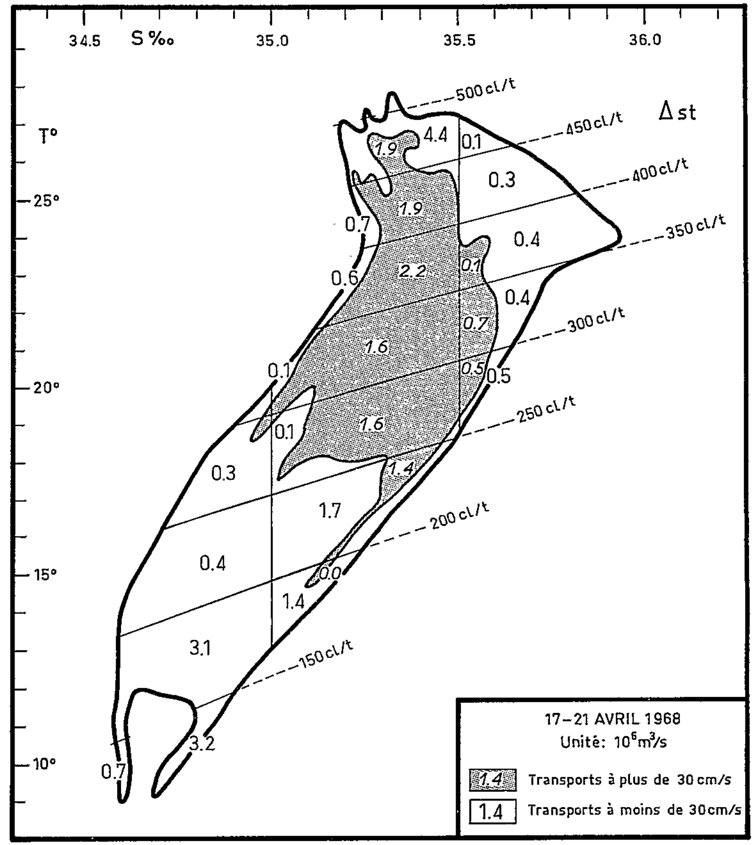

FIG. 18f. Cyclone 7_1.

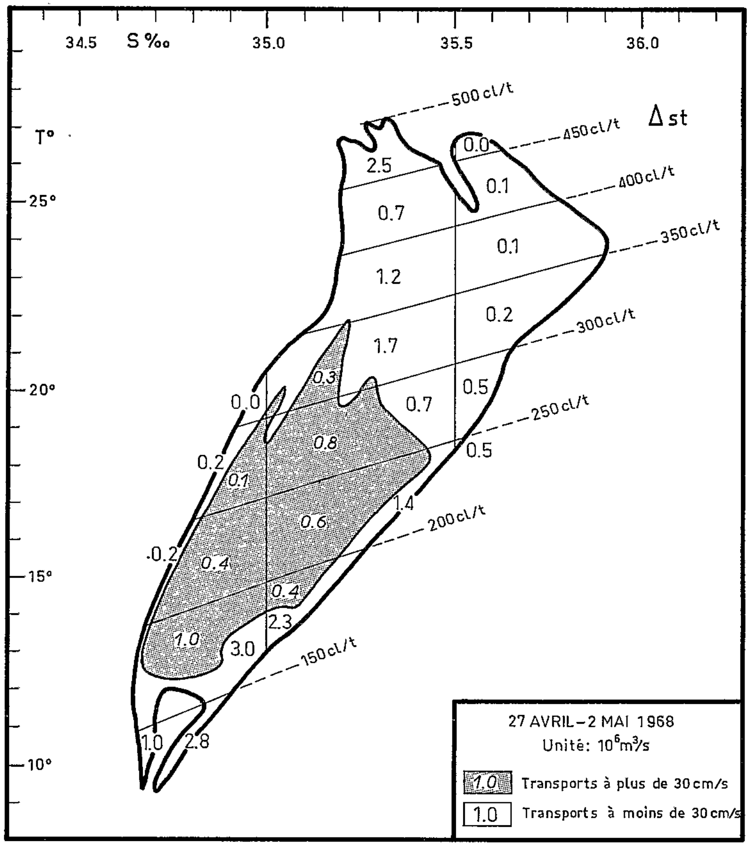

FIG. 18g. Cyclone 7_2.

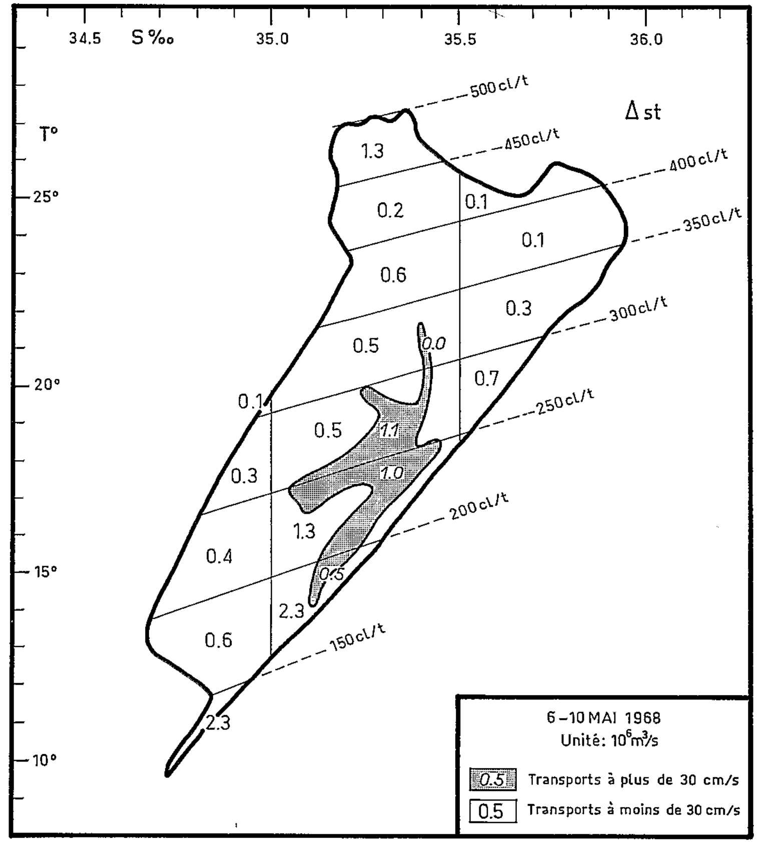

FIG. 18h. Cyclone 7_3.

FIG. 18a–h. "Cyclone" cruises, flow of the Equatorial Undercurrent. Division according to thermosteric anomaly and salinity: (a) Cyclone 2, (b) Cyclone 3, (c) Cyclone 4, (d) Cyclone 5, (e) Cyclone 6, (f) Cyclone 7_1, (g) Cyclone 7_2, (h) Cyclone 7_3.

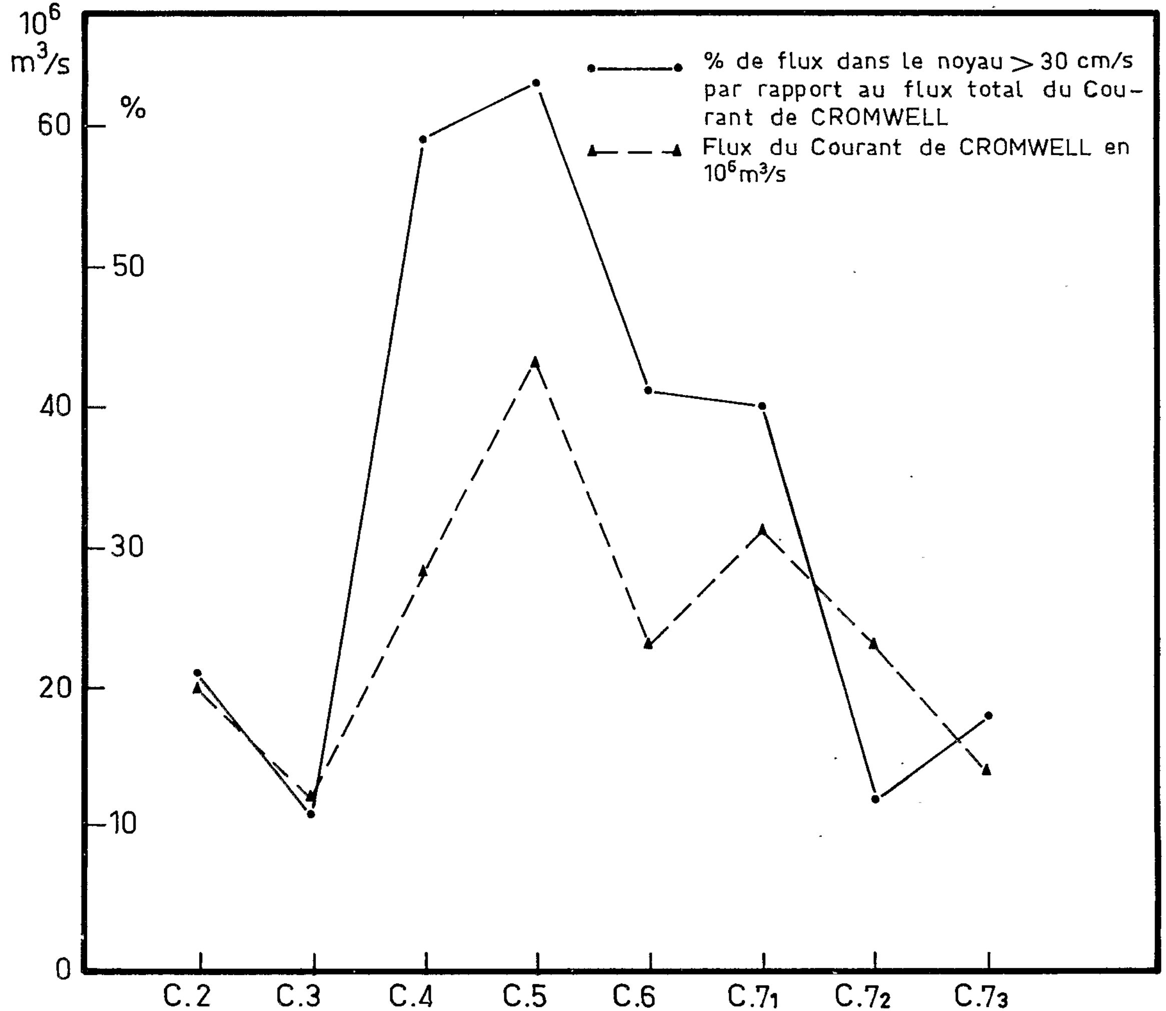

FIG. 19. Evolution during "Cyclone" cruises of the flow of the Equatorial Undercurrent, and of the percentage of this flow exceeding a speed of 30 cm/s.

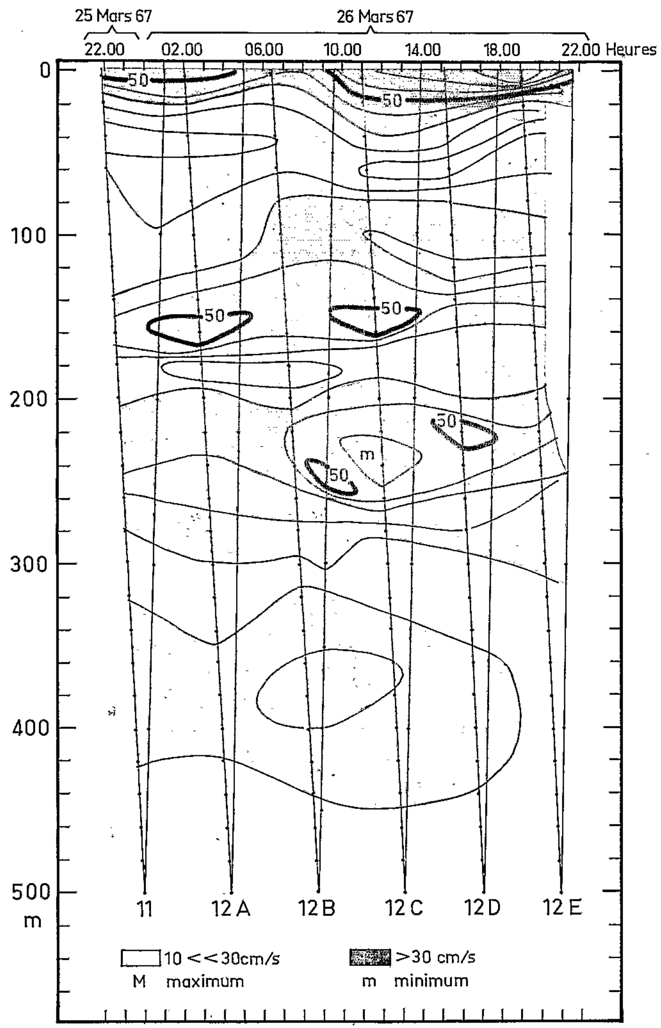

FIG. 20a. Intensity.

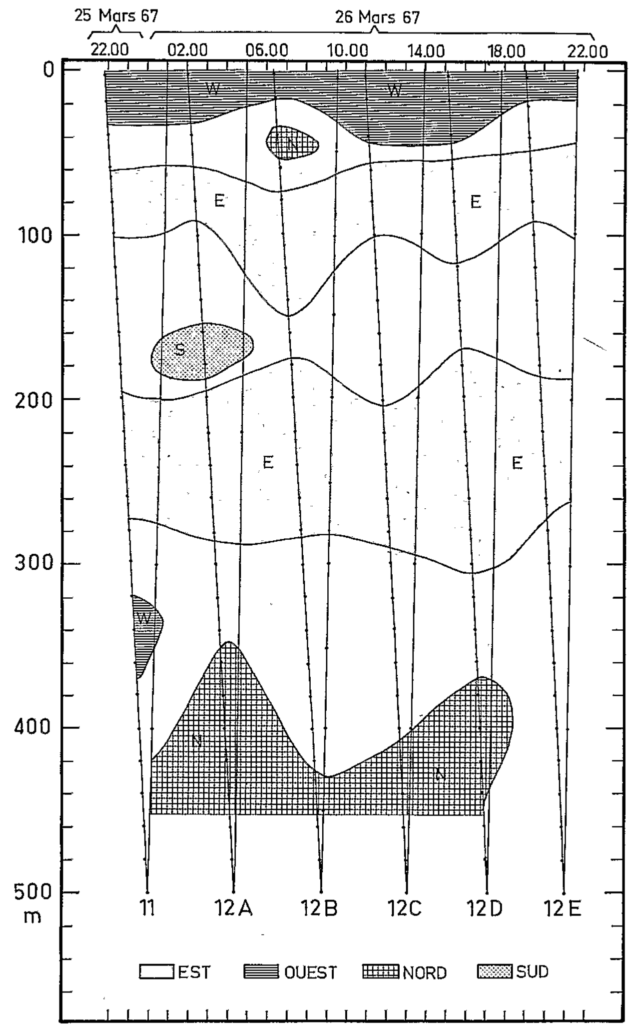

FIG. 20b. Direction.

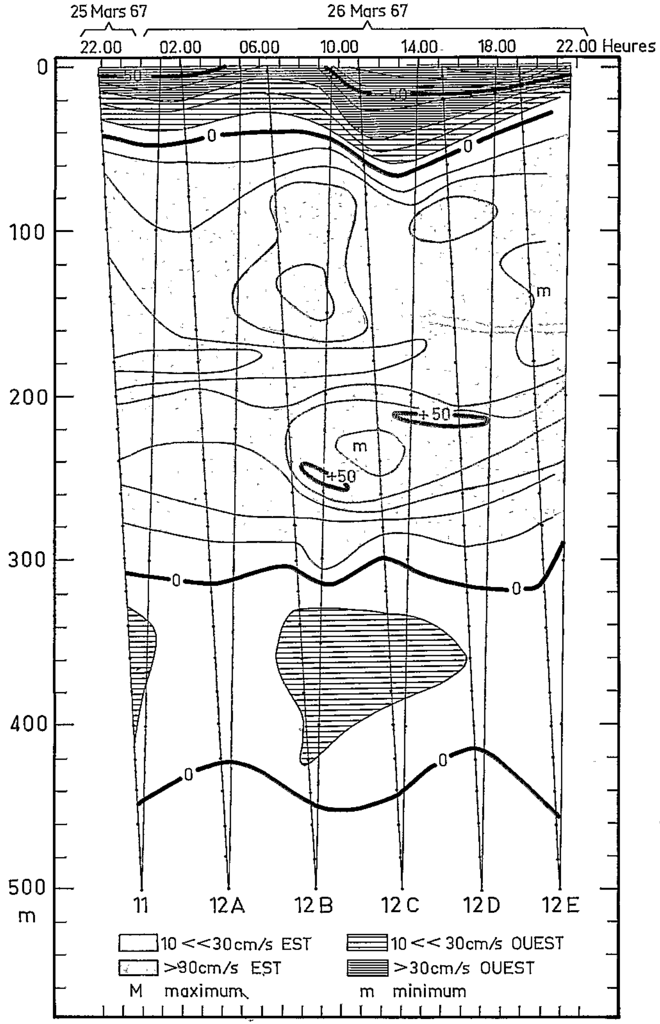

FIG. 20c. Zonal component.

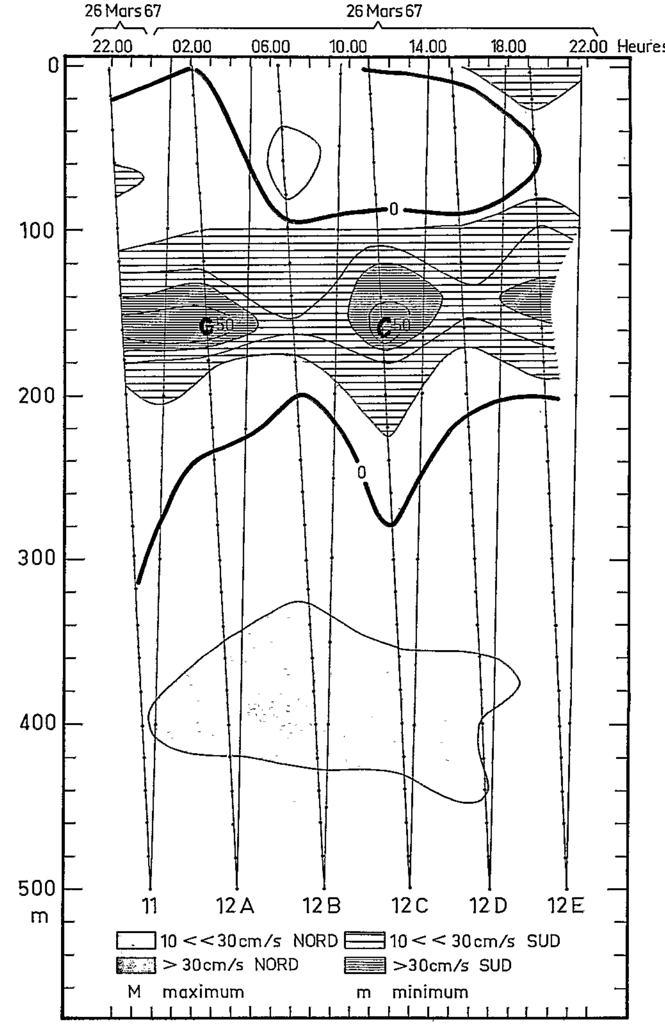

FIG. 20d. Meridional component.

FIG. 20a–d. "Cyclone" cruise 2, 0–170° E; variations with time of the current intensity and direction, and its zonal and meridional components. Reference 500 m. (a) Intensity, (b) Direction, (c) Zonal component, (d) Meridional component. Isotachs every 10 cm/s. Sector of $\pm 22.5°$ around cardinal points.

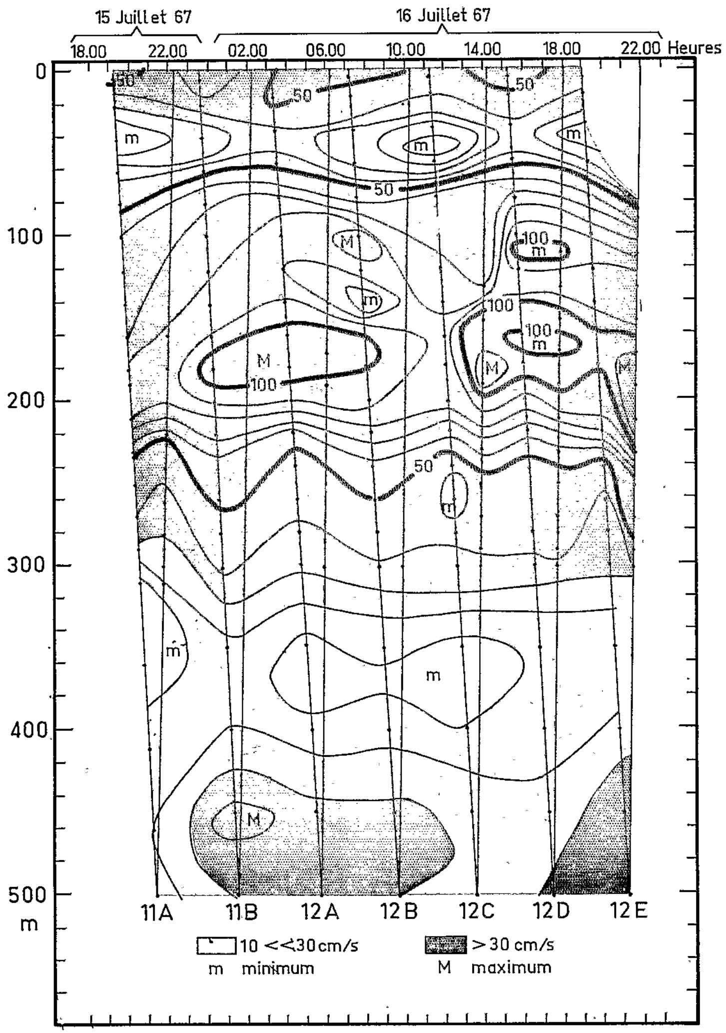

FIG. 21a. Intensity at 170° E.

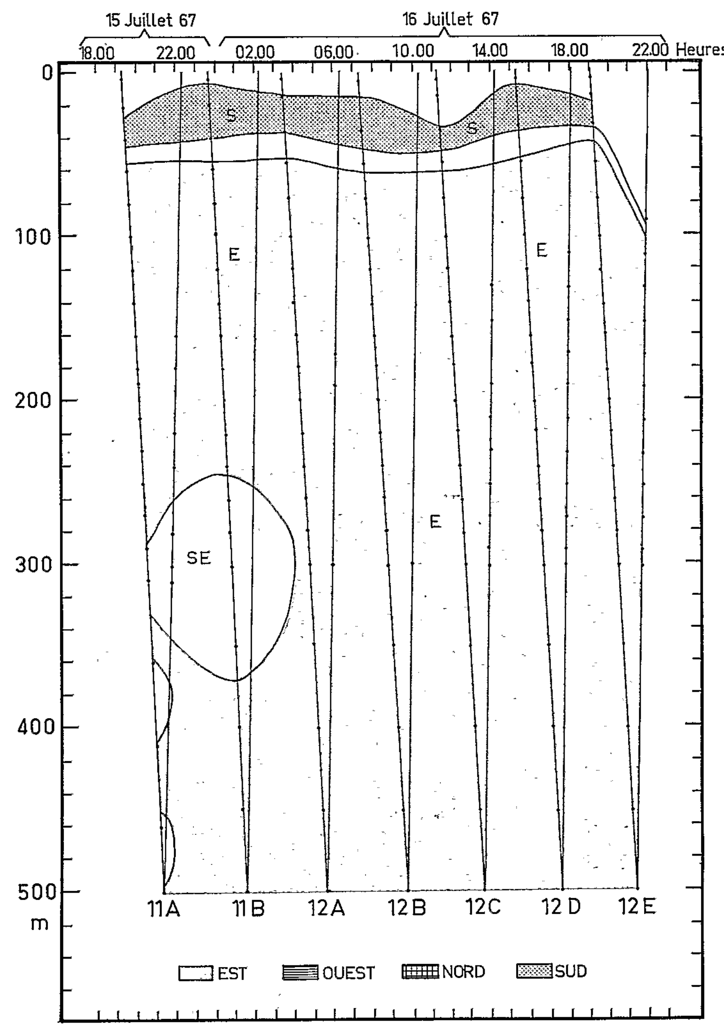

FIG. 21b. Direction at 170° E.

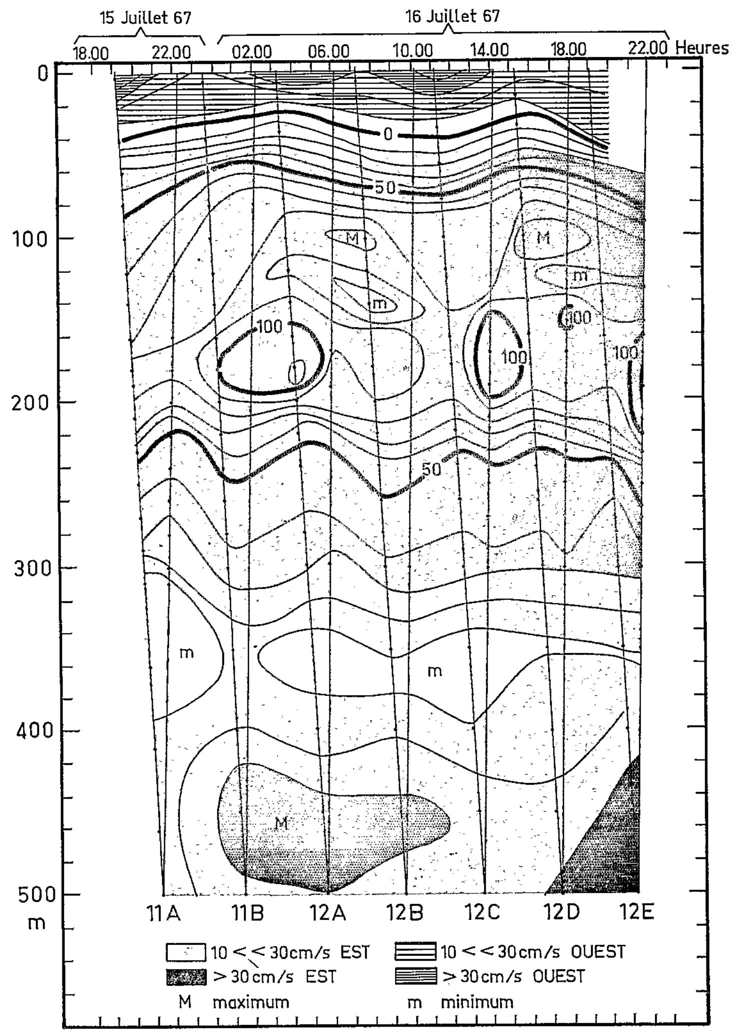

FIG. 21c. Zonal component at 170° E.

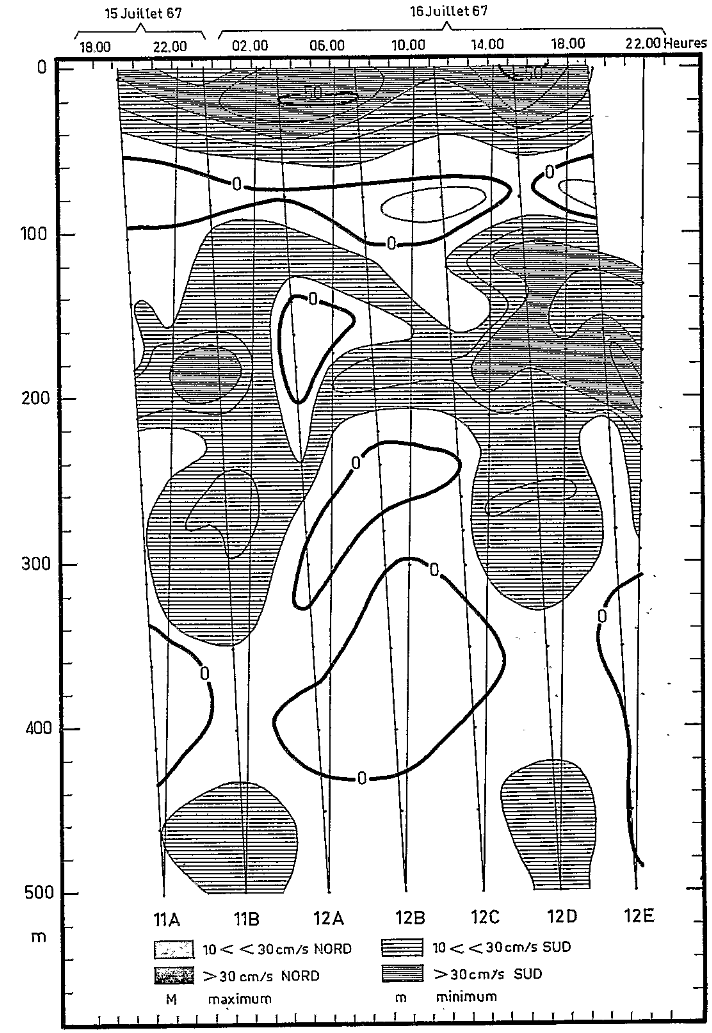

FIG. 21d. Meridional component at 170° E.

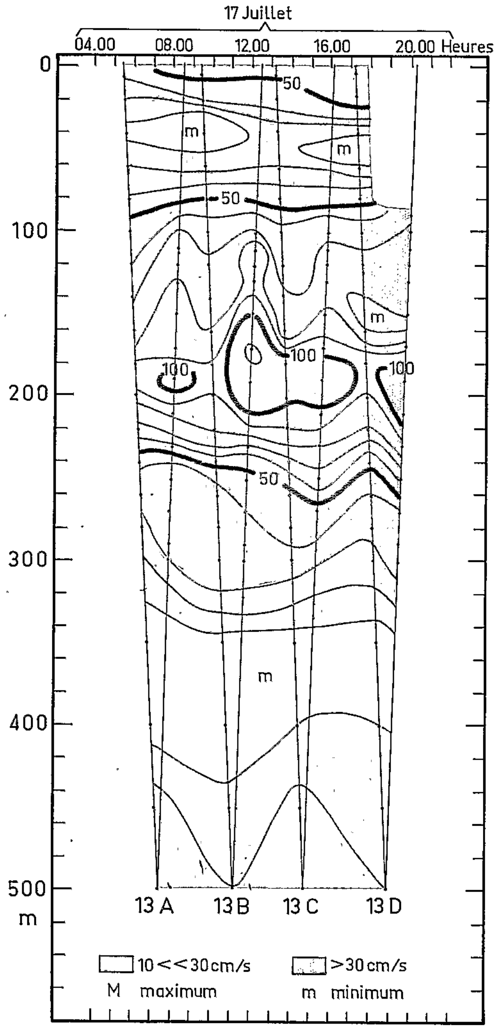

Fig. 21e. Intensity at 169° E.

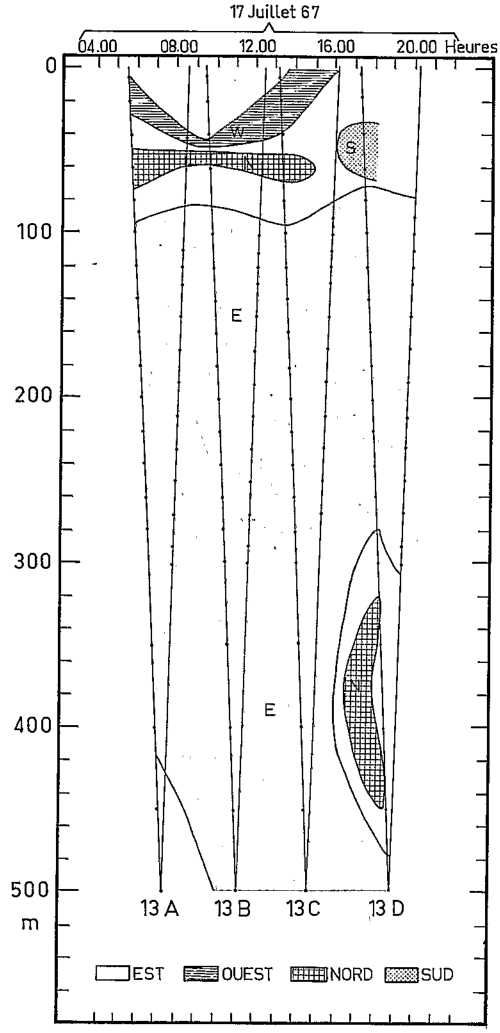

Fig. 21f. Direction at 169° E.

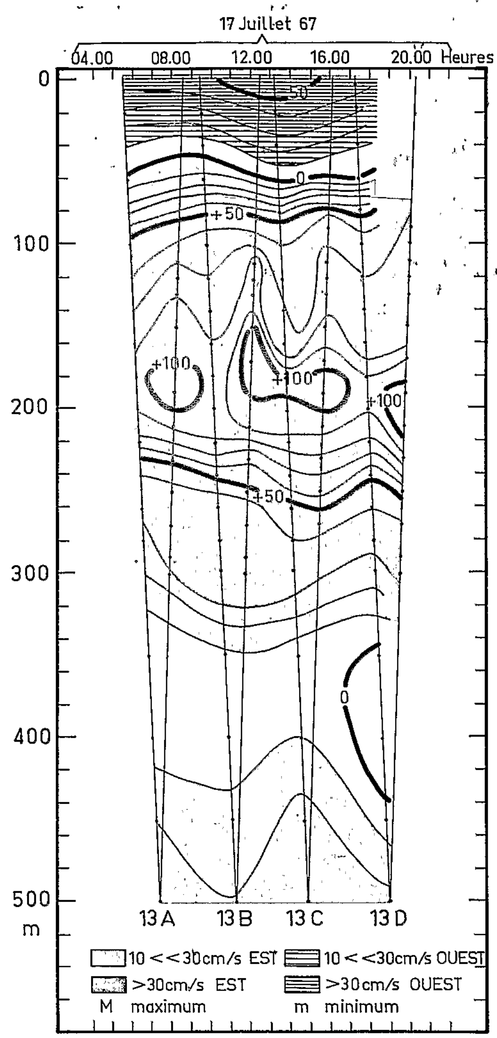

FIG. 21g. Zonal component at 169° E.

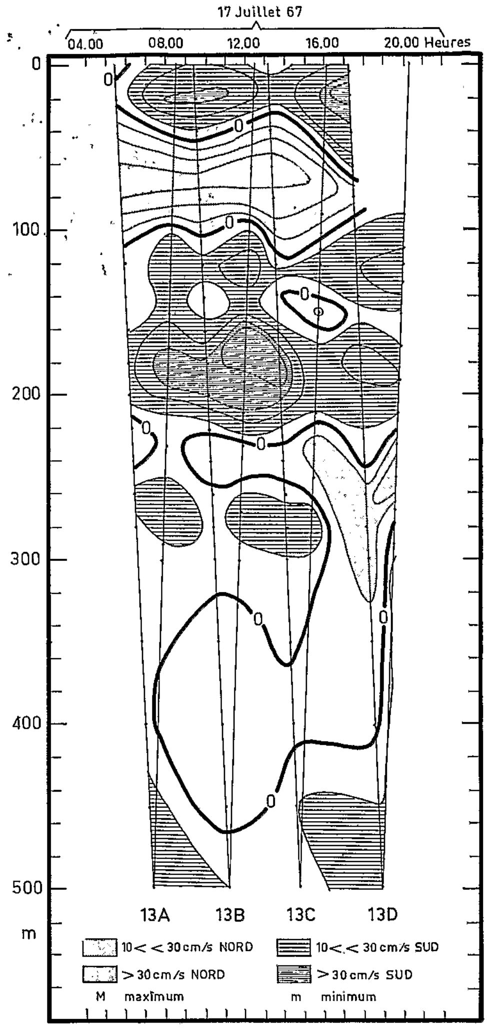

FIG. 21h. Meridional component at 169° E.

FIG. 21a–h. "Cyclone" cruise 5, Equator. Variations in time of the current strength and direction, and its zonal and meridional components. Reference 1000 m. (a) Intensity at 170° E, (b) Direction at 170° E, (c) Zonal component at 170° E, (d) Meridional component at 170° E, (e) Intensity at 169° E, (f) Direction at 160° E, (g) Zonal component at 169° E, (h) Meridional component at 169° E. Isotachs every 10 cm/s. Sector of ±22.5° around cardinal points.

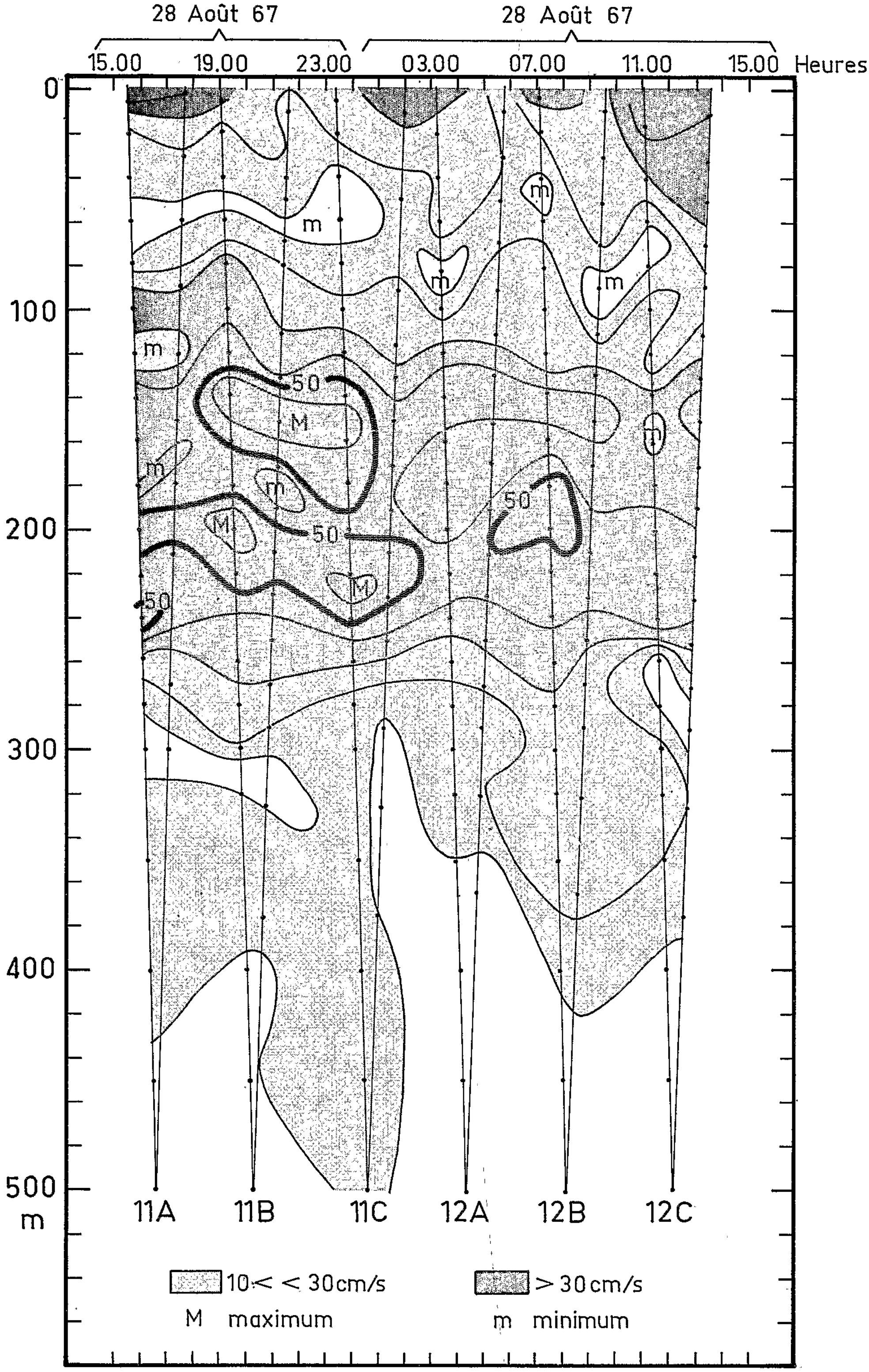

FIG. 22a. Intensity.

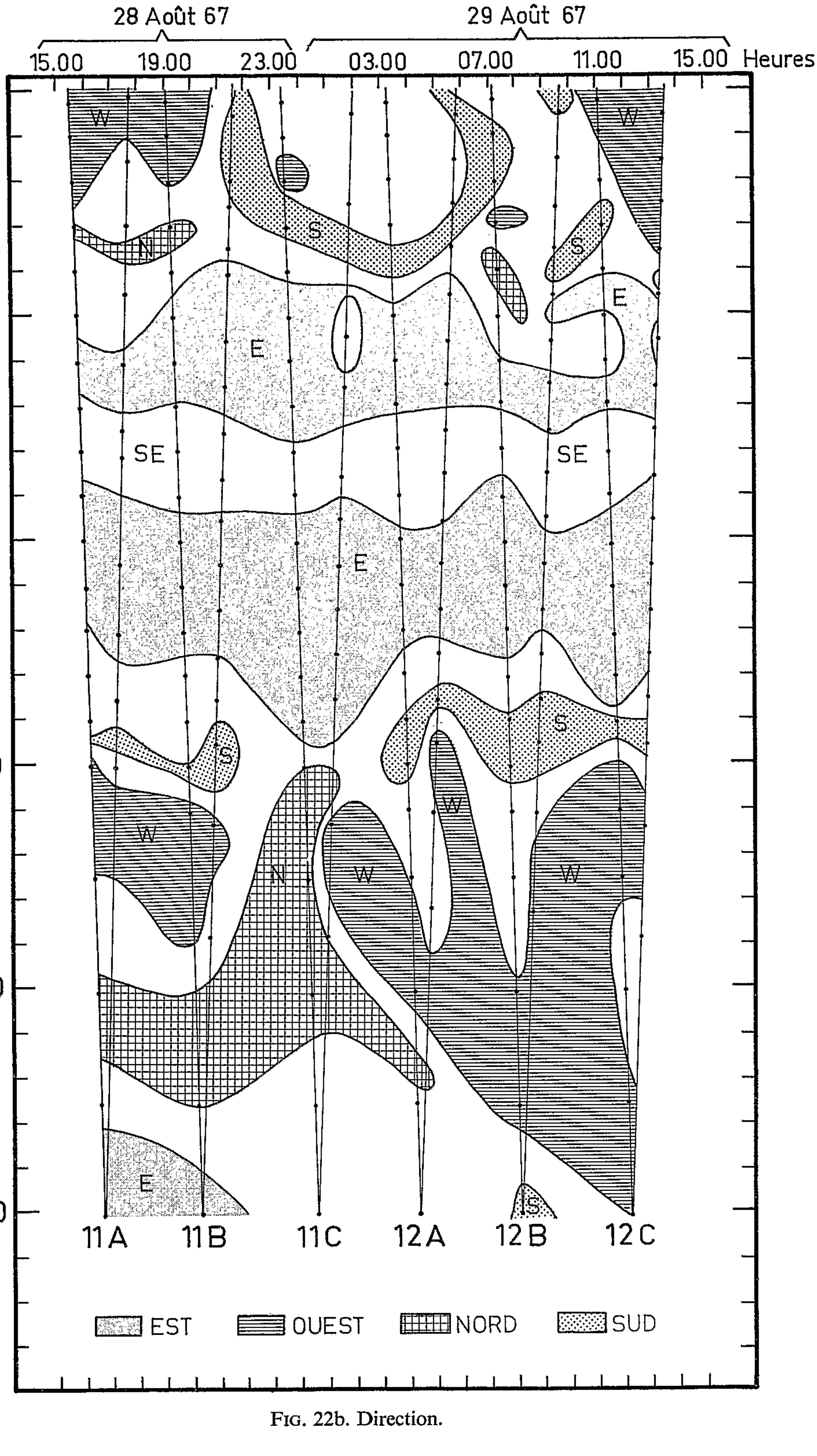

FIG. 22b. Direction.

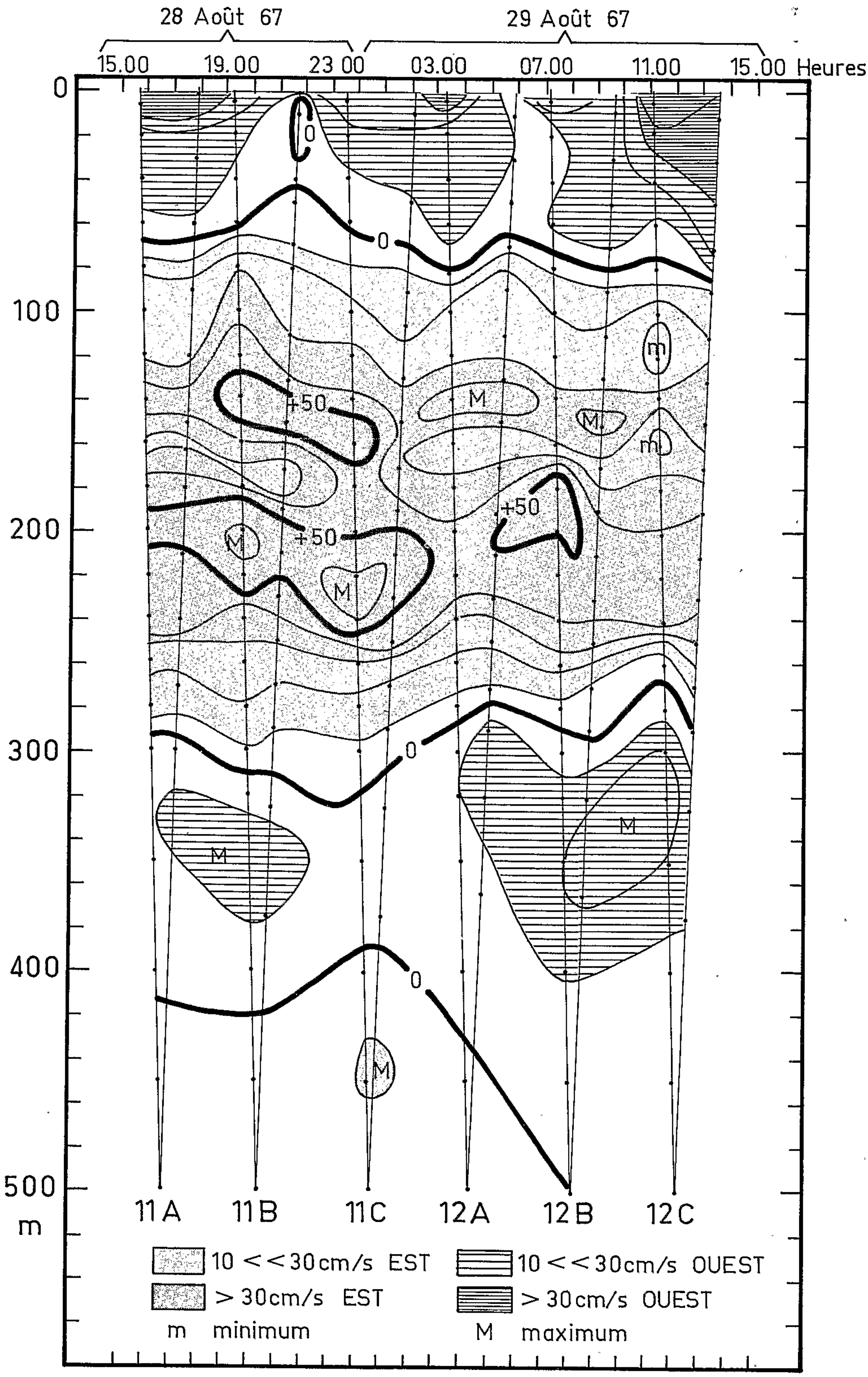

FIG. 22c. Zonal component.

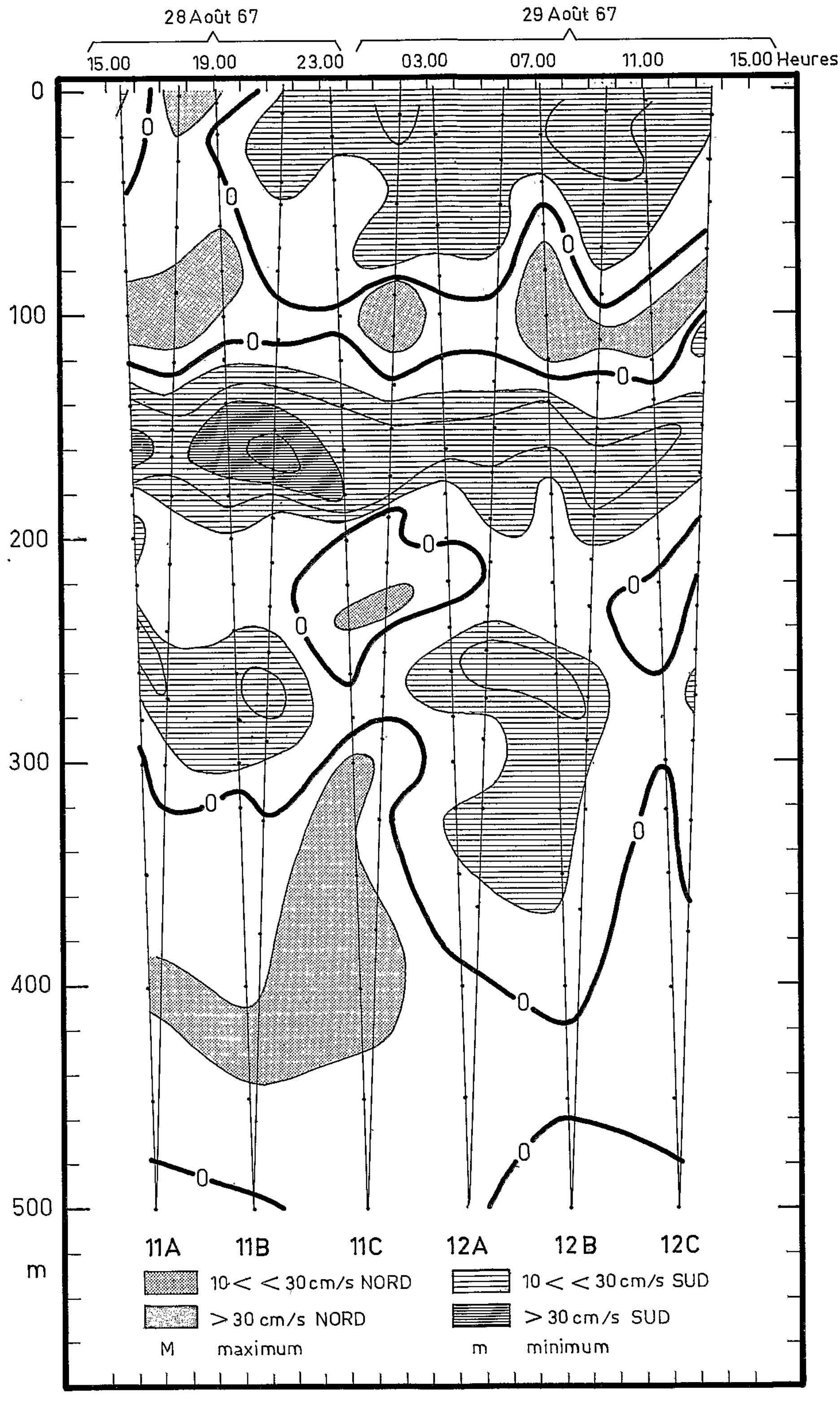

FIG. 22d. Meridional component.

FIG. 22a–d. "Cyclone" cruise 6, 0–170° E. Variations with time of current intensity and direction, and its zonal and meridional components. Reference 500 m. (a) Intensity, (b) Direction, (c) Zonal component, (d) Meridional component. Isotachs every 10 cm/s. Sector of ±22.5° around the cardinal points.

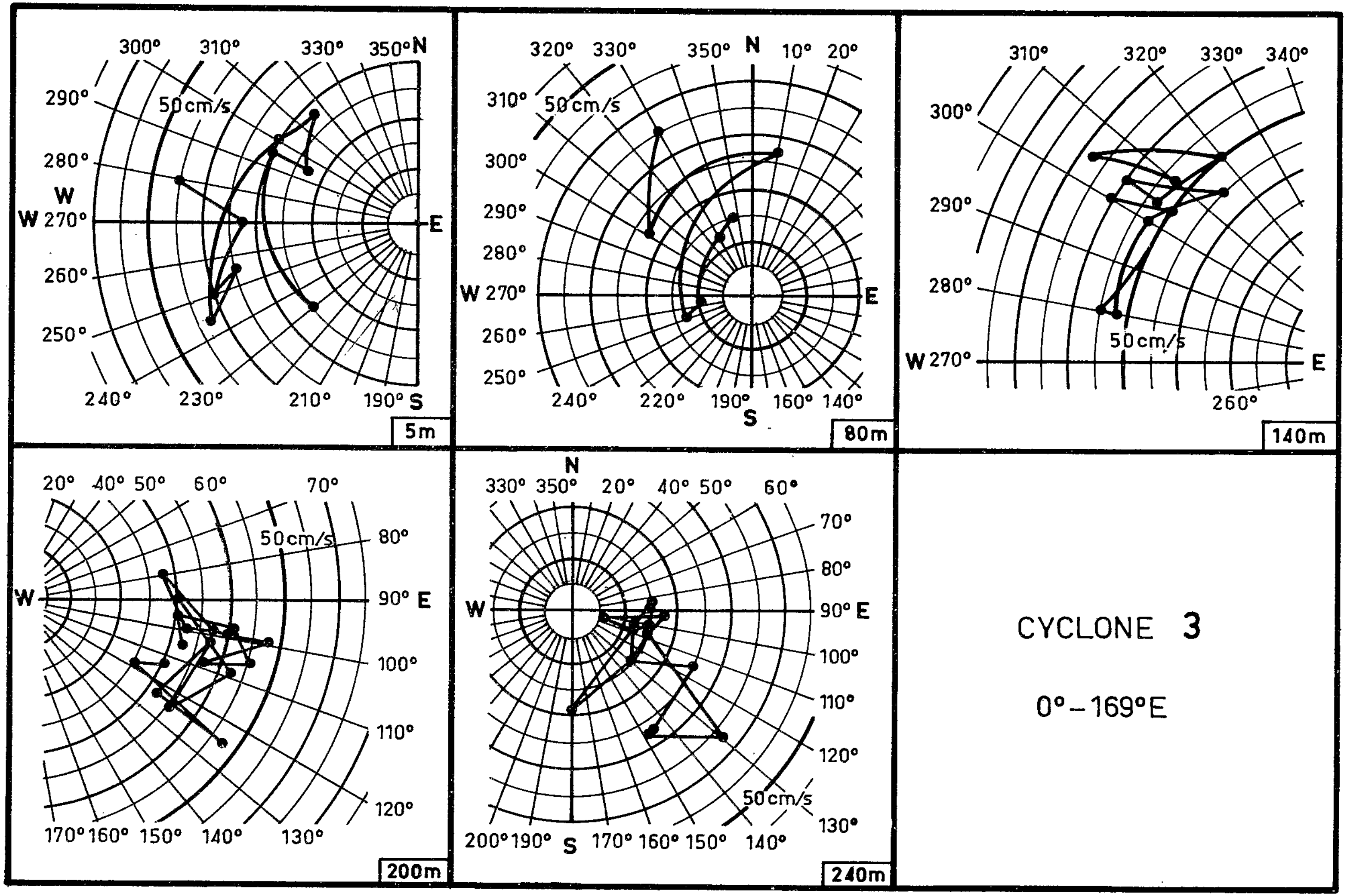

Fig. 23. "Cyclone" cruise 3, 0–169° E hodograph of the current at five different depths during a period of 15 hr. One division equals 5 cm/s.

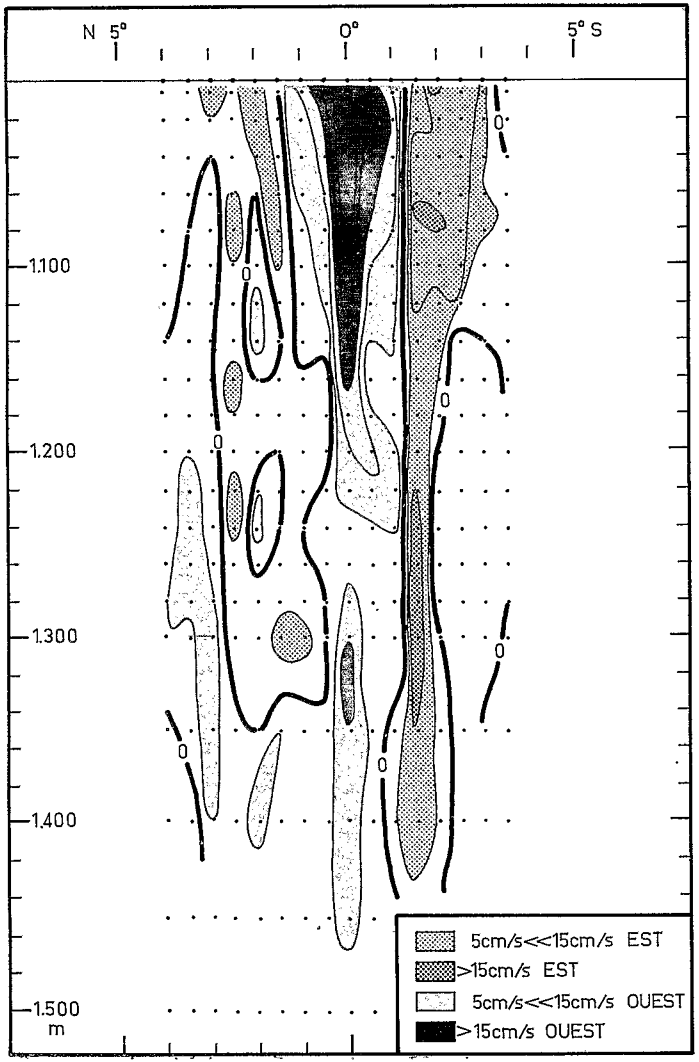

FIG. 24a. E–W component.

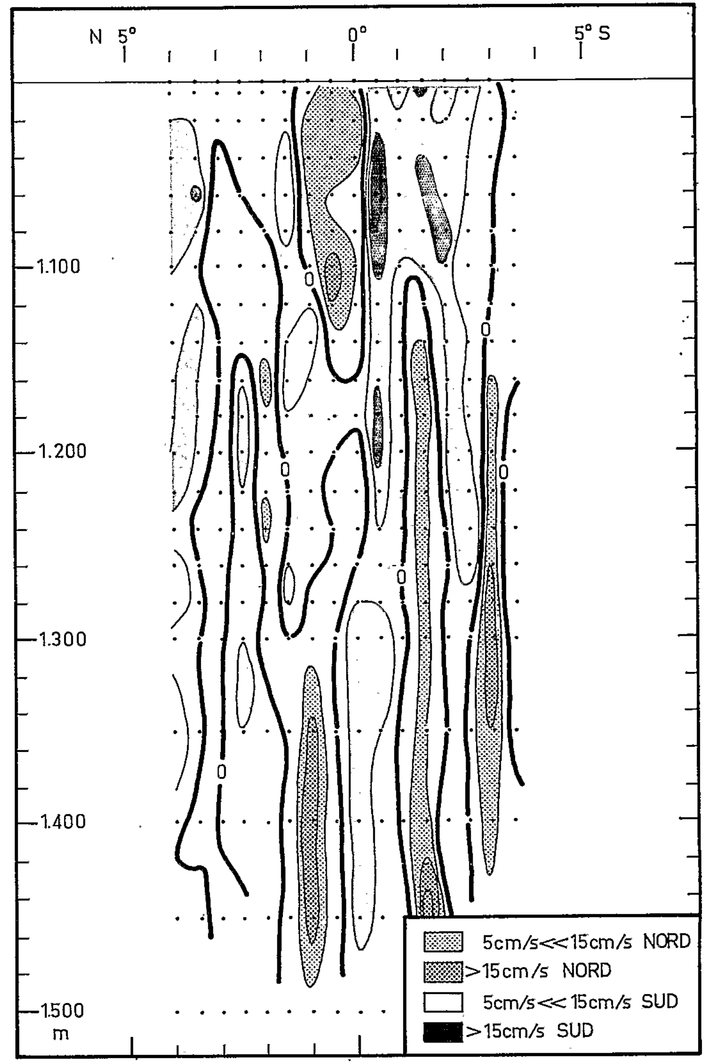

FIG. 24b. N–S component.

FIG. 24a–b. "Cyclone" cruise 6, distribution from 4° S to 4° N of the current components between 1000 m and 1500 m relative to 1500 m. (a) E–W component, (b) N–S component. Isotachs every 5 cm/s.

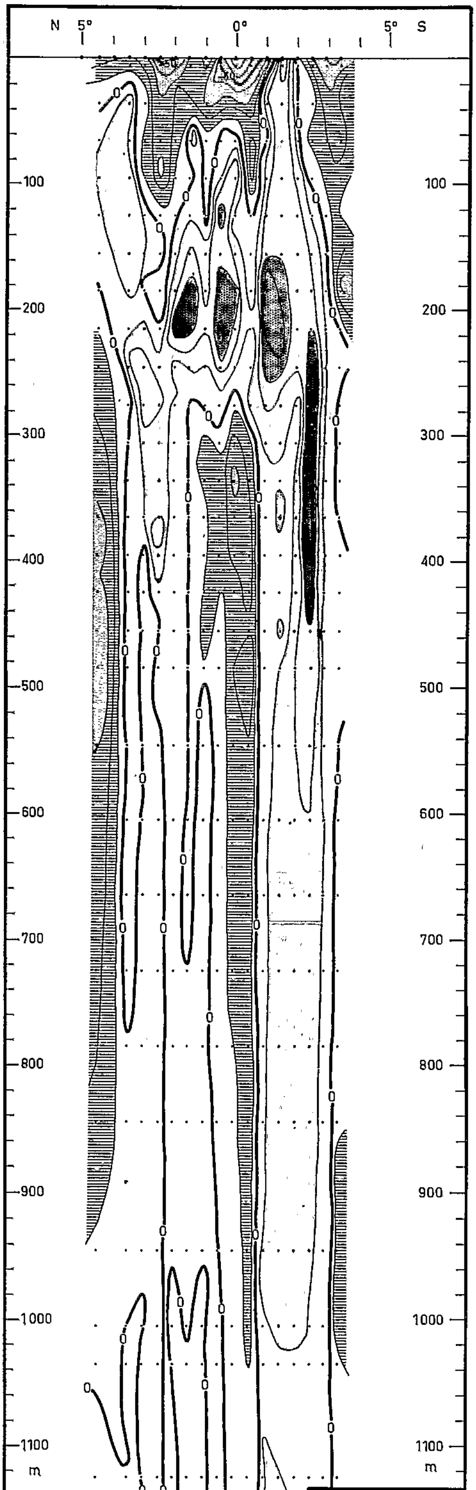

FIG. 25a. Cyclone 7_1.

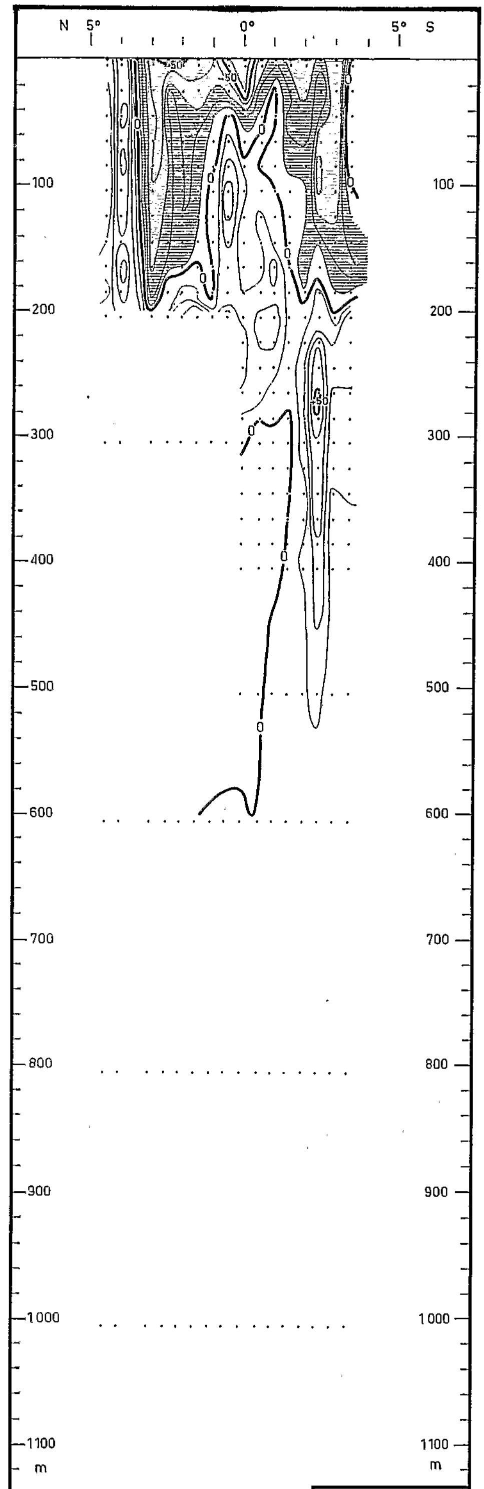

FIG. 25b. Cyclone 7_2.

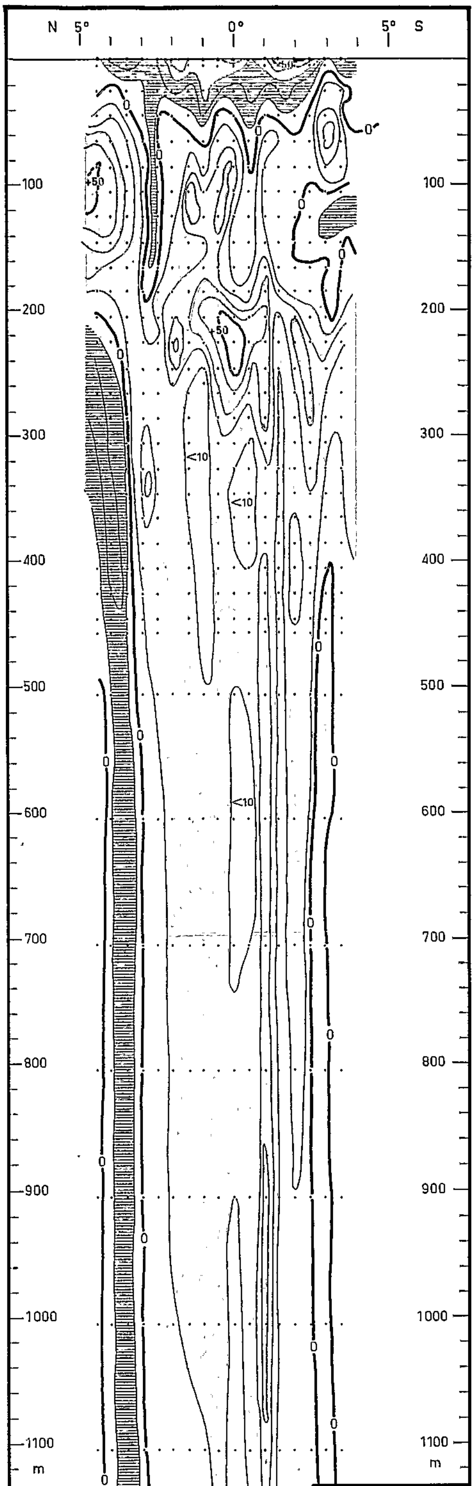

FIG. 25c. Cyclone 7_3.

FIG. 25a–c. "Cyclone" cruise 7, zonal component of the current relative to 1400 m: (a) Cyclone 7_1, (b) Cyclone 7_2, (c) Cyclone 7_3. Isotachs every 10 cm/s.

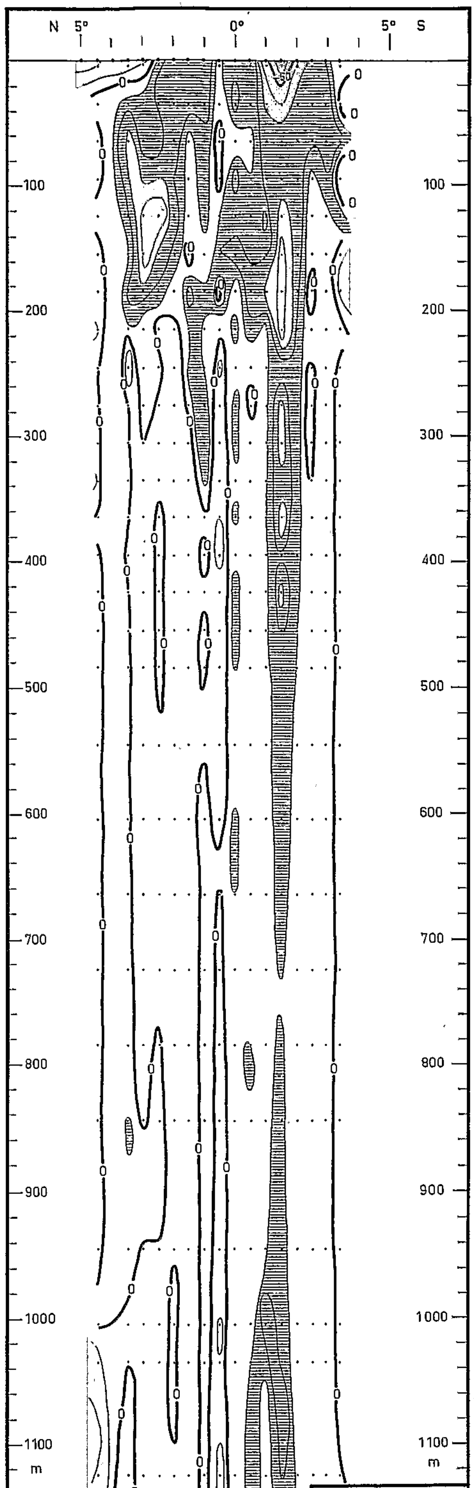

FIG. 26a. Cyclone 7_1.

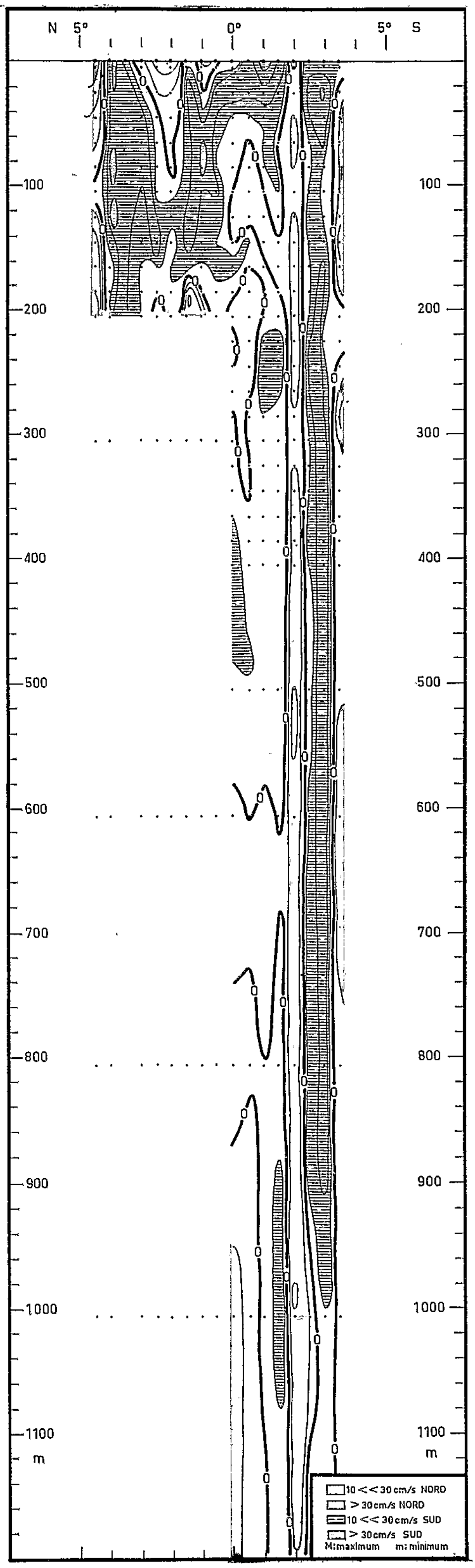

FIG. 26b. Cyclone 7_2.

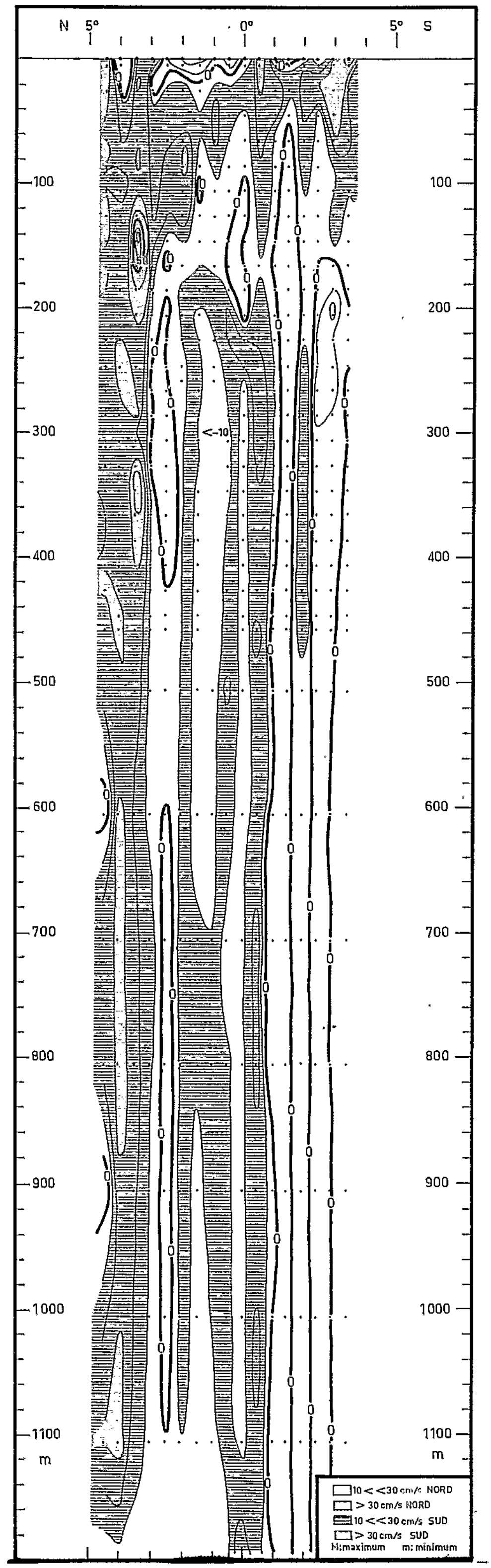

FIG. 26c. Cyclone 7_3.

FIG. 26a–c. "Cyclone" cruise 7, meridional component of the current relative to 1400 m: (a) Cyclone 7_1, (b) Cyclone 7_2, (c) Cyclone 7_3. Isotachs every 10 cm/s.

TABLE 8. COMPARISON BETWEEN THE PERCENTAGES OF THE FLOWS OF EACH DENSITY LAYER RELATIVE TO THE TOTAL FLOW OF THE EQUATORIAL UNDERCURRENT AT 150°W AND 170°E

Thermosteric anomaly in cl/t	150–200	200–250	250–300	300–350	350–400	400–450	450–500	500–550
150°W	28	23	14	15	8	6	0	0
170°E	20	15	12	10	8	7	12	3
Difference	+8	+8	+2	+5	0	−1	−12	−3

KNAUSS (1966) puts forward as a partial explanation of the variations in strength of the Equatorial Undercurrent, the fact that it is "embedded" in the west-flowing Equatorial Current and is to some extent carried along by it; thus it is masked when the Equatorial Current grows stronger. Knauss therefore suggests that the flow of the Equatorial Current be algebraically subtracted from the measured flow of the Equatorial Undercurrent to obtain a relative flow whose variations should be greatly reduced. This can be seen in Table 9, where these relative flows are between 42 and 49 million m^3/s for six sections out of eight.

TABLE 9. FLOW OF THE ZONAL COMPONENT (10^6 m^3/s)

Cruises	Equatorial Undercurrent (east)	Equatorial Current (west)	Algebraic difference
C_2	20	−22	42
C_3	12	−34	46
C_4	28	−14	42
C_5	43	−20	63
C_6	23	−26	49
C_{7_1}	31	−15	46
C_{7_2}	23	−25	48
C_{7_3}	14	−16	30

Fixed point stations on the equator

After each section 4°S–4°N, the ship made longer stations on the equator, during which three types of current measurement were undertaken:

recording of current profiles every four hours, taking measurements on the way down and up;

measurements at some fixed depths every half hour;

continuous measurements at constant depth.

(*a*) Average statistics and variations in time over a period of about 24 hours of the current on the equator, either at 170°E or 169°E, are summarized in Table 10. These characteristics are confirmed by data collected at isolated stations.

As they are intended as a study of short-term fluctuations, rather than for a comparison between cruises, comparison should not be made between the sections showing variations in time of the currents in the first 500 m below the surface, as they have different reference depths. These measurements, besides confirming the equatorial structure encountered during the sections 4°S–4°N, reveal the extreme variability of the phenomena taking place at the level of the cores, and the stability of the zones of strong gradient.

During "Cyclone" 2 (March 1967) (Fig. 20a–d) an apparently periodic rotation of speed in the upper core of the Equatorial Undercurrent from east to south-east took place between 100 m and 200 m; the maximum values for the south component are inserted between the maxima of the easterly component, while the total speed section shows no notably extreme values. This confirms previous observations (NOEL and MERLE, 1969) on the possible effect of tides on the equatorial currents.

In March (Fig. 20a–d) and August (Fig. 22a–d) the deep northwestward current is again identified in all the sections 4°S–4°N. The unusual aspects of the July section (Fig. 21a–h)—

Table 10. Fixed Stations on the Equator

			Cyclone 2 24 hr at 170°E relative to 500 m	Cyclone 5 27 hr at 170°E relative to 1000 m	Cyclone 5 15 hr at 169°E relative to 1000 m	Cyclone 6 22 hr at 170°E relative to 1500 m	Remarks
Equatorial Current		Average characteristics: Core Position Speed	0 m 60 cm/s	0 m 40 cm/s	0 m 50 cm/s	0 m 25 cm/s	
		Vertical extent	0–50 m	0–40 m	0–40 m	0–70 m	
		Direction	W	SW from 0 to 10 m S from 10 to 40 m	SW to W according to time of day	W to S according to time of day	
		Variations in intensity of core and thickness of current	30 to 80 cm/s 40 to 60 m	30 to 50 cm/s 30 to 40 m	40 to 50 cm/s 40 to 50 m	10 to 50 cm/s 40 to 90 m	
Equatorial Undercurrent	Secondary Core	Average characteristics: Core Position Speed	150 m 45 cm/s	100 m 80 cm/s	120 m 75 cm/s	140 m 50 cm/s	Secondary core not always very apparent
		Vertical extent	50–170 m	40–120 m	40–140 m	70–170 m	
		Direction	E from 50 to 110 m SE from 110 to 170 m	E	N from 40 to 60 m NE from 60 to 80 m E from 80 to 140 m	N or S from 70 to 80 m E from 80 to 150 m SE from 150 to 170m	
		Variations in intensity of core and thickness of current	40 to 60 cm/s 100 to 120 m	60 to 100 cm/s 80 to 100 m	60 to 90 cm/s 70 to 110 m	35 to 65 cm/s 70 to 140 m	
	Intermediary Minimum	Average characteristics: Core Position Speed	180 m 20 cm/s	130 m 70 cm/s	140 m 75 cm/s	170 m 35 cm/s	The minimum appears only proportionately with the appearance of the secondary core itself. Its direction is more southward than the two cores
		Vertical extent	170–190 m	120–140 m	130–150 m	160–190 m	
		Direction	SE	E	E	SE	
		Variations in intensity of core and thickness of current	10 to 30 cm/s 20 to 40 m	60 to 80 cm/s 0 to 30 m	70 to 80 cm/s 10 to 20 m	25 to 50 cm/s 10 to 60 m	
	Main Core	Average characteristics: Core Position Speed	220 m 40 cm/s	170 m 100 cm/s	190 m 100 cm/s	210 m 50 cm/s	
		Vertical extent	200–310 m	140–330 m	160–340 m	190–280 m	
		Direction	E from 200 to 290 m variable from 290 to 310 m	E	E	E	
		Variations in intensity of core and thickness of current	35 to 50 cm/s 90 to 140 m	85 to 120 cm/s 130 to 200 m	90 to 110 cm/s 150 to 190 m	45 to 60 cm/s 60 to 110 m	
Deep West Current (relative to 500 m or 1500 m)		Average characteristics: Core Position Speed	380 m 15 cm/s			340 m 10 cm/s	Current only exists in the case of currents relative to 500 and 1500 m
		Vertical Speed	330–440 m			290–400 m	
		Direction	N to W according to time of day			W to N according to time of day	
		Variations in thickness of core and thickness of current	70 to 140 m 5 to 25 cm/s			60 to 110 m 0 to 25 cm/s	
Minimum of East Current (relative to 1000 m)		Average characteristics: Core Position Speed		350 m 10 cm/s	360 m 5 cm/s		Minimum only exists in the core of currents relative to 1000 m
		Vertical extent		330–420 m	340–410 m		
		Direction		SE in first hours E afterwards	E N in closing hours		
		Variations in intensity of core and thickness of current		5 to 15 cm/s 60 to 120 m	0 to 10 cm/s 50 to 90 m		
Deep East Current		Average characteristics: Core Position Speed		450 m 30 cm/s	500 m 25 cm/s	450 m 10 cm/s	Current really only apparent in the case of sections relative to 1000 m
		Vertical extent		420–500 m	410–500 m	400–500 m	
		Direction		E	E	E to NE	
		Variations in intensity of core and thickness of current		15 to 40 cm/s	20 to 30 cm/s	5 to 10 cm/s	
Remarks				Secondary core not very definite and not always present	Secondary core almost undetectable		

replacement of the deep north-west current by a minimal eastward current, appearance of an eastward current at 500 m—appear to be due to the reference layer selected (1000 m) where, as will be seen below, a considerable westward current probably prevails. Relative sections at a depth of 500 m or 1500 m would restore a deep north-westward current of about 20–30 cm/s, and a minimal current at 500 m.

The variations observed suggest an approximately semi-diurnal periodicity in the equatorial surface current as well as the Equatorial Undercurrent. These variations may be as much as ±20 cm/s in the surface current and the upper core of the Equatorial Undercurrent, but do not appear to exceed ±15 cm/s in the main core. The zones of easterly current are very stable in direction, while the zone of deep westward current is very stable in speed but very variable in direction (Fig. 6 and Table 2).

TABLE 11. MEAN CURRENT VECTOR AND ITS VARIATIONS
CYCLONE 3, 0°–169°E

Depth in metres	Mean V/500 m		$\Delta D°$	ΔV cm/s
	V cm/s	$D°$		
5	30	275	±45	±10
80	20	325	+45 −70	±10
140	50	305	+15 −25	±10
200	35	105	+20 −25	±10
240	15	110	+70 −20	+20 −10

(*b*) Measurements repeated at five depths in April 1967 on the equator at 169°E were also intended to evaluate the variability of currents at different levels (Fig. 23). Ten to fifteen measurements at each level, over a period of about 15 hours, made it possible to define a mean vector and its variations (Table 11), but did not give evidence of any periodicity.

(*c*) Continuous recordings of about 15 hours were carried out at constant depth in the main core of the Equatorial Undercurrent on the equator at 169°E during "Cyclone" 2 and 6 (March and August 1967). The two recordings gave similar results (Figs. 11 and 12). The maximum variations recorded were ±20 cm/s and ±25°. These are the sum of variations with a period of the order of 6 to 12 hours, and short-term variations between 10 minutes and 1 hour. For the long periods the variations were ±15 cm/s and ±15°, while for the short periods they were ±10 cm/s and ±10°.

This group of fixed point measurements reveals the great speed and extent of variation of equatorial phenomena, tending to distort the profiles and sections, and greatly complicating the work of description and analysis.

Deep currents

Measurements were taken down to a depth of 1400 m, in an attempt to find very thick layers with a constant measured current between 4°S and 4°N. However, the measurements showed the existence of strong meridional gradients throughout the explored zone.

A special study was made of the deep currents in August 1967 and in April-May 1968, after their existence had been suspected in previous cruises. RUAL (1969) has described the currents relative to 1500 m encountered in August 1967 between 1000 m and the reference depth (Fig. 24a–b).

Between 3°S and 1°S, an eastward current flowed, with a core at about 250–300 m which sometimes reached a speed of 20–30 cm/s. This current had already been detected by geostrophic calculations relative to 2000 db (BURKOV and OVCHINNIKOV, 1960); it was confirmed by the measurements of April-May 1968 relative to 1400 m (Figs. 25a–c and 26a–c). At the end of April 1968, it even reached a speed at the core of 50 cm/s.

A westward current, centred on the equator and with the same latitudinal extent as the Equatorial Undercurrent, was measured in August 1967; its upper limit was unknown as no measurements had been taken between 500 and 1000 m. But in April-May 1968, observations seemed to indicate that it was connected with the westward current measured on all the cruises at a depth of 300–400 m (Fig. 25a–c); this group might be named the deep equatorial current. In July-August 1967, it had a strength of 30 cm/s at 1000 m; in April-May 1968, with a core at 400–500 m, it dropped from 30 cm/s to zero in less than 20 days; in the third section relative to 1400 m it was replaced by a minimal current travelling east. At the time of the first cruises, some profiles at the equator had suggested the existence of a variable north-westward current at a depth of about 1000 m; thus it would appear that it exists for the greater part of the year.

In the north zone, between 2°N and 4°N, the currents in August 1967 were very weak with a slight eastward tendency; in April-May 1968 the same was true, but it was possible to establish the continuity between the deep part of the North Equatorial Countercurrent, whose core is at about 3°N–300 m, and this slight eastward current which is in fact merely its extension (Fig. 25a–c).

The measurements carried out at 4°30′N reveal a westward current, reaching a speed of 20–30 cm/s at the core, on all three sections of "Cyclone" 7 (April-May 1968). This current lies beneath the North Equatorial Countercurrent, and only its southern border appears.

All these deep currents seem to have been little studied, and their lack of intensity makes them extremely sensitive to the choice of reference layer. However, meridional gradients indubitably exist, and it would therefore be extremely interesting to take absolute measurements and obtain mean values for the currents at these depths, as their great thickness implies extremely substantial flows.

CONCLUSION

Although it has not provided any absolute measurements, the "Cyclone" programme at 170°E will have established the extreme variability of the equatorial phenomena, in the very short term of periods less than an hour, as well as in the longer-term evolutions of the order of a month. There seems also to be approximately semi-diurnal perturbation which might be due to tides.

In spite of this, the permanence of the general characteristics is fairly noticeable, especially in the following respects:

The existence of an Equatorial Undercurrent with two cores, of which only one, at 100 m, is present in the central Pacific, either because the cores have joined by isentropic ascent of the main core, or because only the latter core exists there.

The stability of the deep southern branch (2°30S–250 m) of the group of eastward currents—a branch which may represent a trace at 170°E of the geostrophic current described by REID (1965) between 3°S and 7°S on the 125 cl/t isanostere.

The permanent divergence encountered at the level of the bridge connecting the Equatorial Undercurrent with the North Equatorial Countercurrent, which seems to confirm the hypothesis (BURKOV and OVCHINNIKOV, 1960) of their common origin north of New Guinea, and that of their separation east of 170°E (HISARD *et al.*, 1969).

Lastly, the almost certain existence of a deep equatorial current, running westward, lying beneath the Equatorial Undercurrent.

Hydrological and physico-chemical analysis of this zone has amply confirmed the specificity of the various currents as well as the validity of their limits as defined in this study (HISARD *et al.*, 1969; HISARD and RUAL, 1970; HISARD *et al.*, 1970; ROTSCHI and WAUTHY, 1969). A complete description is given elsewhere of the oceanographic characteristics encountered at 170°E; it clearly indicates the relationship between circulation in this zone and the distribution of the hydrological and chemical variables, the principal flows being generally identifiable by an extreme value in the horizontal or vertical distribution of the chemical properties, or for waters lying beneath the homogeneous surface layer, by a significant slope of the isotherms and isopycnals (ROTSCHI *et al.*, 1972).

It would now be of interest to study the development of these structures across the Pacific Ocean, and to evolve a circulation model capable of accounting for the particular structure of the equatorial circulation in the western Pacific, as well as for variations in flow of the order of those observed.

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