

## Water mass distribution and geostrophic circulation off Namibia during April 1986

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**Abstract**—Water mass distribution and geostrophic circulation off Namibia are presented for April 1986, a month of relatively strong warm water intrusion from the north and west. The main result is that mesoscale processes develop in the area during the season when the coastal upwelling is relaxed, and these processes may be an alternative contribution to the fertilization of the region. The main features observed are the following.

Angolan waters entered the region through the surface layer, with a maximum flow at 50 m depth.

A frontal zone, centered between 20°S and 22°S separated Angolan and Benguela waters, at the surface layer.

Anticyclonic eddies with a radius of 15–30 miles occurred off central and southern Namibia.

Water upwelling off Walvis Bay appeared to derive from the core of the Angolan water, which laid at a depth of 50–100 m.

Anticyclonic gyres might contribute to the upwelling off Walvis Bay and to the occurrence of a local sinking in its centre, about 50 miles offshore, thus allowing long residence time and recirculation.

The occurrence of eddies may have been related to the general relaxation of the Benguela Upwelling System in the preceding 3 months and the penetration of the Angolan waters, in the region north of Walvis Bay, while in the south, the meanders of the oceanic front may remain most important.

### INTRODUCTION

It is well known that upwelling is an important oceanographic feature off the Namibian coast. The knowledge of upwelling causes, fluctuations and variability is essential to understand the distribution, migrations, spawning, etc. of the living resources.

Traditionally, the upwelling intensity and variability has been estimated by Sea Surface Temperature anomaly analysis and wind stress (LUTJERHARMS and MEUWIS, 1987). Other factors such as current pattern and water mass distribution can help to obtain a more precise picture of this phenomenon. This is particularly important at the season when the upwelling is relaxed. During this period, the area is dominated by mesoscale structures and frequent intrusions of warm northern water, but production levels still remain high in certain areas, such as near Walvis Bay (ESTRADA and MARRASÉ, 1987).

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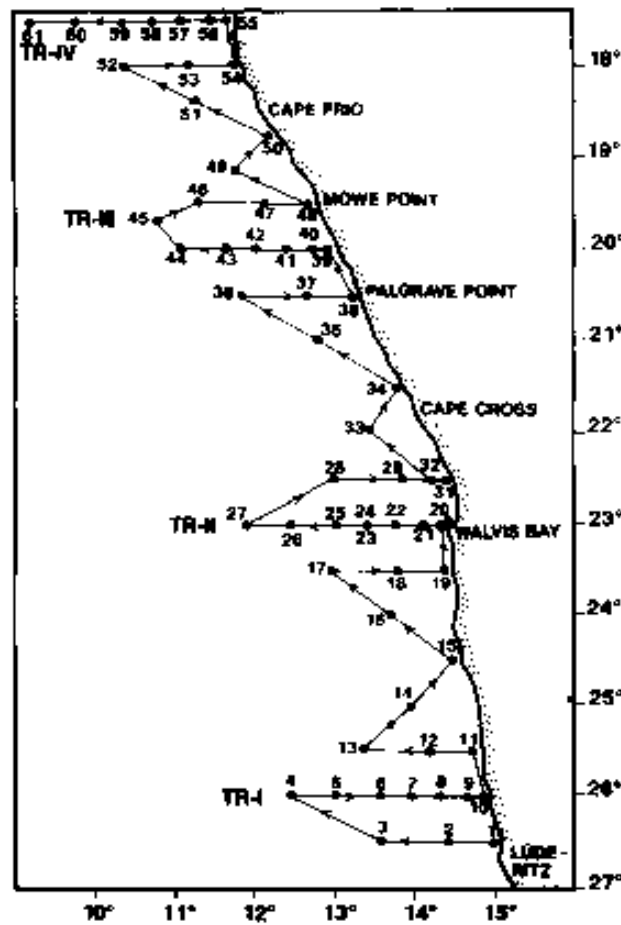


Fig. 1. Map of the stations visited in SNEC II.

The present paper is based on the information obtained from SNEC II (Spanish-Namibian Environmental Cruise) which surveyed the region from  $17^{\circ}30'S$  to  $26^{\circ}30'S$  during April 1986 (Fig. 1). A water mass analysis and the geostrophic circulation, estimated by the dynamic method, are presented and discussed. The main result is a confirmation of the role of mesoscale structures as alternative mechanisms to provide the nutrients found in the coastal surface waters (GUTIÉRREZ *et al.*, 1986).

Four water types have been described at the surface layer within the shelf zone off central and northern Namibia, in the northern part of the upwelling area influenced by the Benguela current. All of these water types are derived from the South Atlantic Central Water (SACW, SVERDRUP *et al.*, 1942). O'TOOLE (1980) characterized three of them: (i) cool upwelled water ( $T = 12-18^{\circ}C$  and  $S = 34.9-35.2$ ), present all along the coast, (ii) Angolan water, warmer and more saline ( $T = 17-22^{\circ}C$  and  $S = 35.5-35.9$ ) always present in the northernmost area of the region but showing seasonal intrusions (BOYD *et al.*, 1987) towards the south, mainly during late summer and autumn, and (iii) oceanic water ( $T = 16-22^{\circ}C$  and  $S = 35.2-35.5$ ) coming from the west towards the coast in the region between  $19^{\circ}S$  and  $22^{\circ}S$ , mainly during summer and autumn. BOYD (1983a) defined another water type (iv), saline upwelled water ( $T < 15^{\circ}C$  and  $S = 35.3-35.5$ ), which is upwelled in the central region during autumn, but whose probable origin is from the north.

The periodic southwards intrusions of Angolan waters have been studied in several papers. A few intrusions had an extraordinary extent, and their effect on upwelling and the biota of the region is comparable to El Niño, off Peru (BOYD *et al.*, 1985; SHANNON *et al.*, 1986). The typical Angolan water intrusions also show much interannual variability. During the first quarter of 1986 one of the most important intrusions occurred even though it was not an El Niño type. In this case, the maximum southward penetration was observed in April (BOYD *et al.*, 1987).

Although the dynamic method reveals the pressure forces related to the density field, and is useful in the identification of eddies and other mesoscale structures, surface currents on the shallow Namibian shelf are mainly wind driven (BOYD, 1983b), so that the geostrophic approach would not be the most appropriate for that coastal region. Moreover, the selection of a reference level and the extrapolation to these shallower areas is always problematic. Furthermore having a wide spacing between offshore stations in the alongshore direction (Fig. 1), it is difficult to give a precise image of the general circulation in the region. However if geostrophic flow patterns are considered together with the distribution of water masses a better image can be presented, good enough to describe the observed features and to be related to other observations.

#### MATERIALS AND METHODS

The grid of hydrographic stations of SNEC II (Fig. 1) consisted of a series of transects, following parallels of latitude. Four of them, the "main" ones, extended between 5 and 135 miles offshore. Two smaller sections, up to 75 miles offshore, flanked the main sections 30 miles apart. Finally, the pattern was completed by some coastal stations. At every station, a CTD cast was obtained by means of a Neil Brown Mark III probe. The basic data, at the standard levels, and preliminary results can be found in GUTIÉRREZ *et al.* (1986) and MASÓ (1987), respectively.

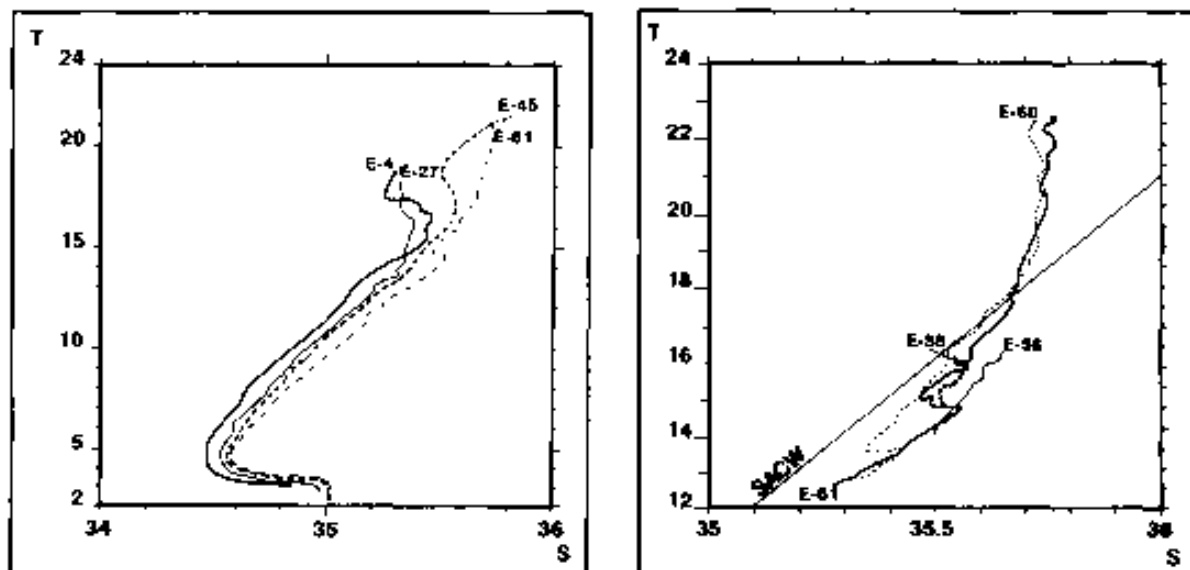
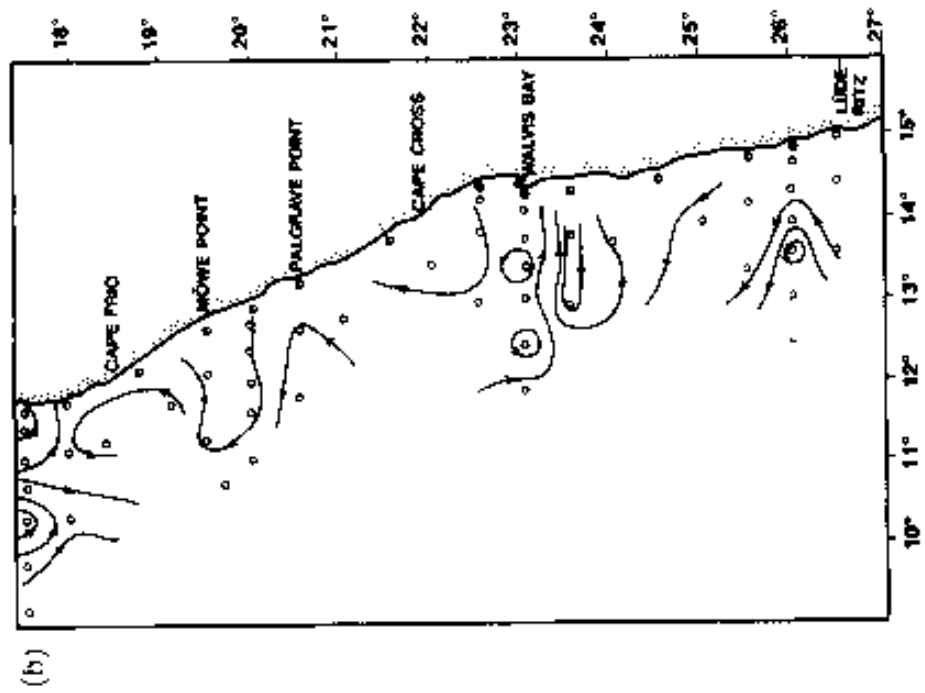
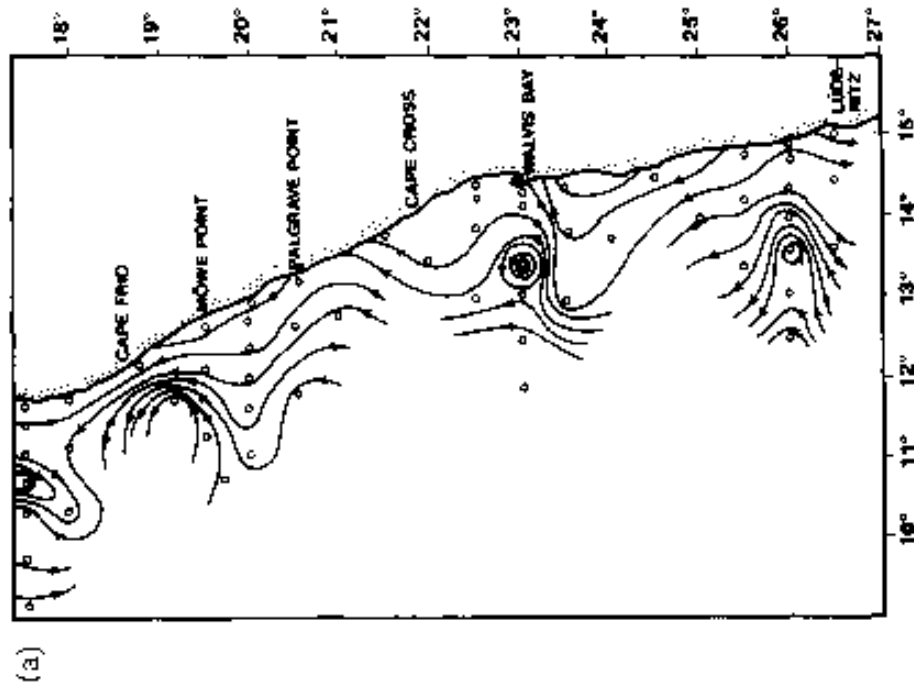


Fig. 2. TS diagram of stations: (a) at 135 miles offshore and (b) upper part TS diagram of the stations at the extremes of the northernmost line.



(b)



(a)

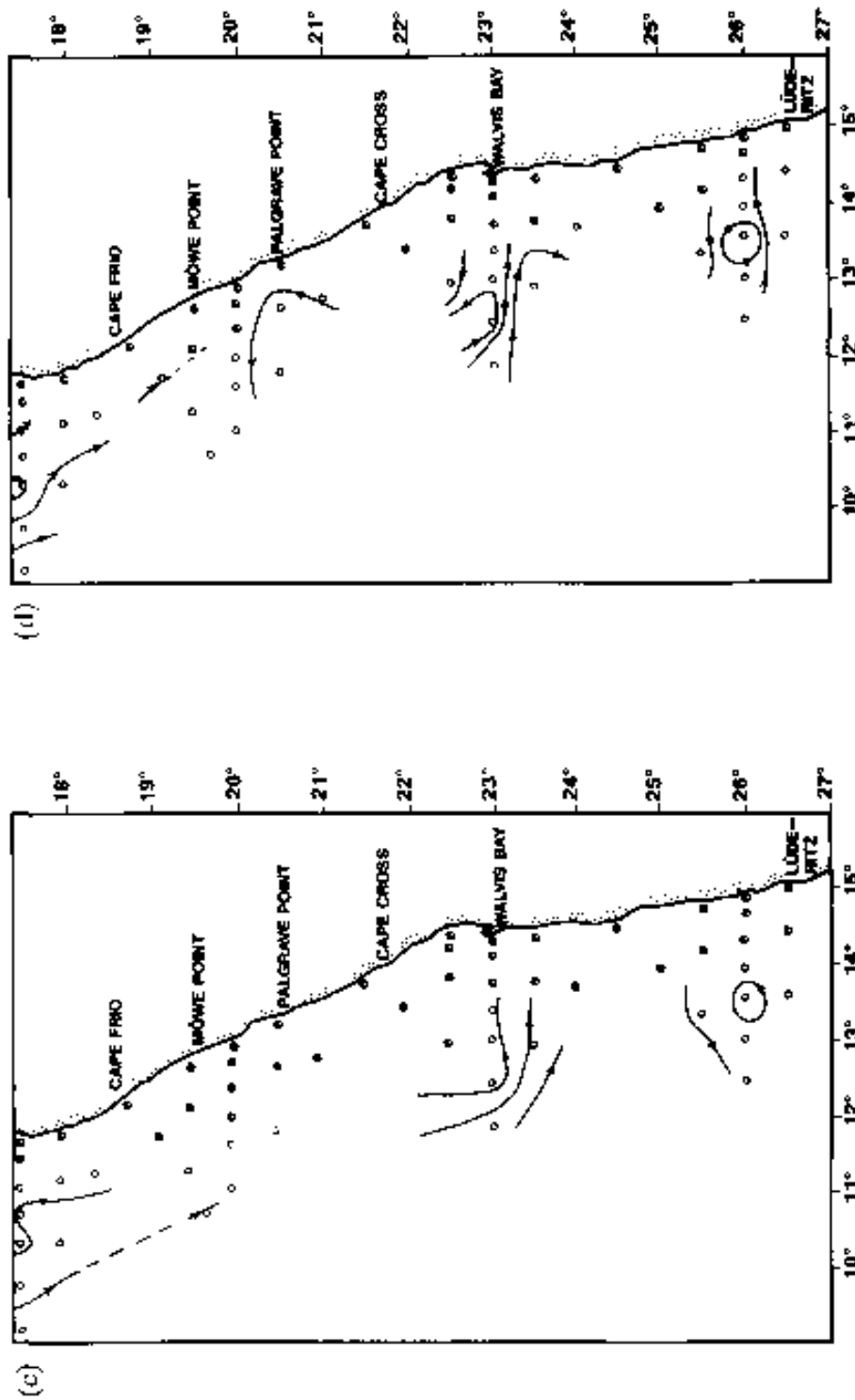


Fig. 3. Dynamic topographies at: (a) surface; (b) 100 m and (d) 700 m. (Half filled stations are not deep enough.)

The various water masses have been identified from *TS* diagrams and horizontal distributions of salinity and temperature, according to the traditional methods. Complete hydrographic profiles were used, based on data density of one CTD reading per meter.

Dynamic topographies were obtained by calculating the dynamic anomaly profile for every station according to the International Sea Water State Equation (UNESCO, 1981). The reference level was taken at 700 m. This level was chosen because the difference between dynamic anomalies every 100 m presented a minimum between 700 and 800 m. The Helland–Hansen method was used to extrapolate dynamic heights at shallower stations (STANDER, 1964). This method consisted of substituting the bottom by a quiescent water body. Other authors like STANDER (1964) and MOROSHKIN *et al.* (1970) chose a reference level of 1000 m, but in both cases, more stations were done offshore and the density of stations was lower. In our case, the choice of a 1000 m reference level would have given a bigger anomaly gradient at the reference level, and a greater number of stations would have required extrapolation.

## RESULTS

*TS* diagrams based on the four stations furthest offshore on each main line are given in Fig. 2a. These diagrams show the presence of the core of the South Atlantic Central Water between 100 and 800 m depth in all the stations. Near the surface, the water can be seen to have been locally modified by contact with the atmosphere and the surrounding waters, generally in the sense of increasing temperature. The characteristics of the SACW showed a zonal distribution in the sense of higher salinity at lower latitude, for the same temperature (Fig. 2a).

The upper 100 m of *TS* profiles for the stations at the extremes on the northern line are shown in Fig. 2b. Near the shore, the surface water had the same properties of the SACW found at 70–100 m at the offshore stations, which is an indication of active upwelling in this area, from depths of up to 100 m.

Dynamic topographies of different depth surfaces all relative to the 700 m reference level are presented in Fig. 3. It can be observed that the geostrophic circulation at the surface shows a net flow directed northwards over all the region except in the northern zone (18°S). Other features such as anticyclonic eddies, can also be observed. Their dynamic signatures penetrate deeper than 100 m, but less than 200 m. Both the major northern (19°S) and southern (26°S) anticyclonic eddies fall partially beyond the edge of the continental shelf, but the Walvis Bay eddy falls instead wholly on the shelf, with northward flow within 35 miles of the coast and further offshore than 75 miles.

The estimated speed of surface current ranges from values of the order of  $15 \text{ cm s}^{-1}$  to  $35 \text{ cm s}^{-1}$  where the current was dominated by the eddies. The mean flow of the Benguela countercurrent towards the south, suggested by the dynamic topography at 200 and 300 m depth (Fig. 3c and d), is supported by the advection of the dissolved oxygen. The intrusion of equatorial low oxygen water is clearly shown in the section parallel to the coast at 135 miles offshore in Fig. 4.

Coastal upwelling was most intense at both extremities of the sampled region, as can be inferred from distributions of temperature, salinity, dissolved oxygen and nutrients (MASÓ, 1987). The horizontal salinity distributions at the surface and 100 m depth (Fig. 5) show the signature of a front with important gradients in a transition zone between 23°S and 19°S. The horizontal temperature distribution at the surface (Fig. 6) show that coastal

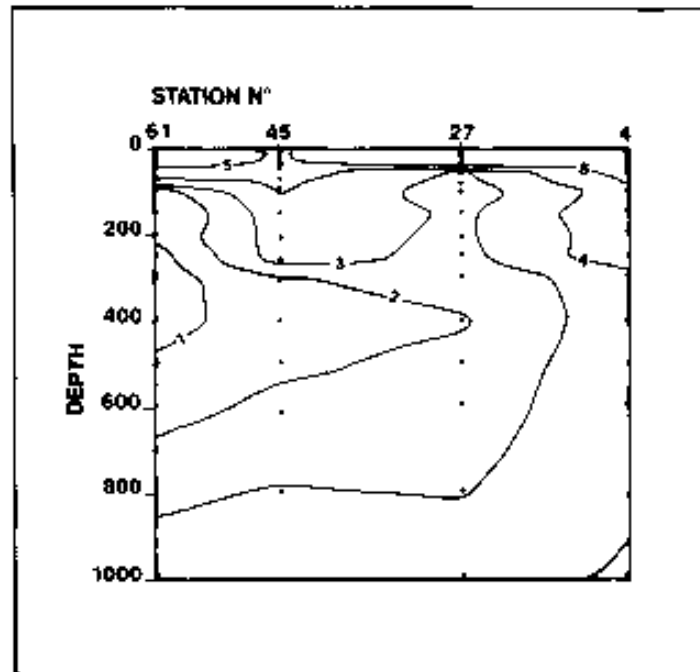


Fig. 4. Vertical distribution of dissolved oxygen ( $\text{ml l}^{-1}$ ) in a section at 135 miles offshore.

upwelling was weak at  $20^{\circ}\text{S}$ , at the northern zone of the transition zone, but active at  $23^{\circ}\text{S}$  at its southern boundary. The upwelling of this relatively high salinity water at the surface off Walvis Bay will be discussed.

#### DISCUSSION AND CONCLUSIONS

SNEC II was carried out at the beginning of the autumn, which is an especially interesting season in the Namibia region because of the relaxation of the coastal upwelling in the preceding 3 months and the development of Angolan water intrusions. According to BOYD *et al.* (1987), during 1986 a typical but important intrusion was present, under which the coastal upwelling was not extinguished and good nutrient supply to the surface layer was continued. In other papers dealing with geostrophic calculations, the grid of stations covered a larger area and extended further offshore (STANDER, 1964) or northwards (MOROSILKIN, 1970; DIAS, 1983). Some of the features discussed in these papers, such as the existence of a large subtropical cyclonic eddy, fall outside of the coverage of the SNEC II cruise. Conversely, the higher resolution in the nearshore area of SNEC-II produced evidence of mesoscale features that did not appear in previously mentioned papers. Another important aspect to be considered is that the importance of the Angolan intrusion in April 1986 was apparently much stronger than that corresponding to the same month in 1959/1960 or in March 1968.

The most important results obtained in the present study can be summarized as follows:

Strong anticyclonic eddies were made evident by geostrophic calculations where the sampling density was high. This also suggests that more eddies might have existed in areas of lower sampling density. The importance of eddies was pointed out as early as in the work of HART and CURRIE (1960), who reported that "The Benguela current consists of a series of anticyclonic eddies, of interlocking tongues of cool and warmer water, of

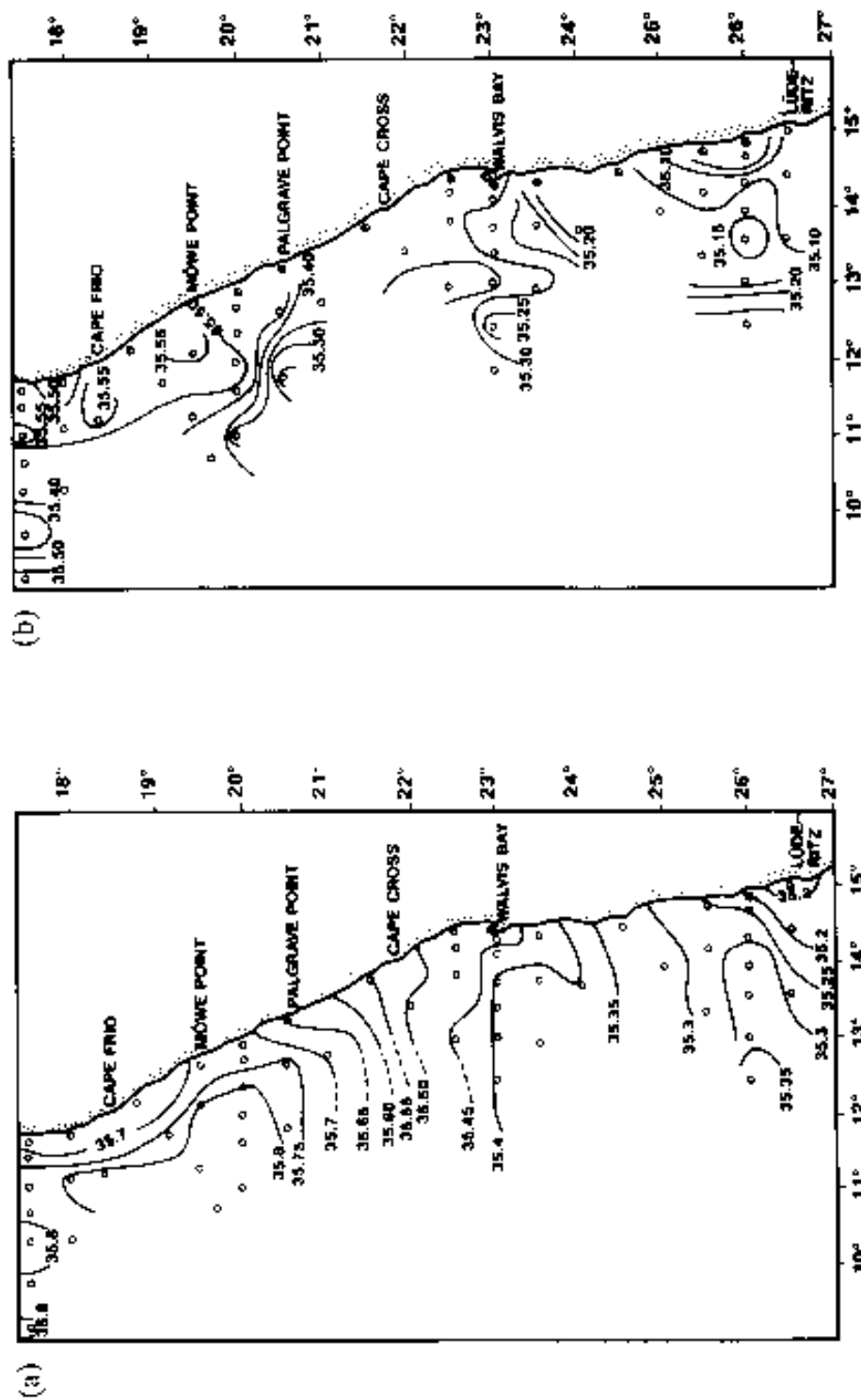


Fig. 5. Horizontal distribution of salinity at: (a) surface and (b) 100 m. (Half filled stations are not deep enough.)

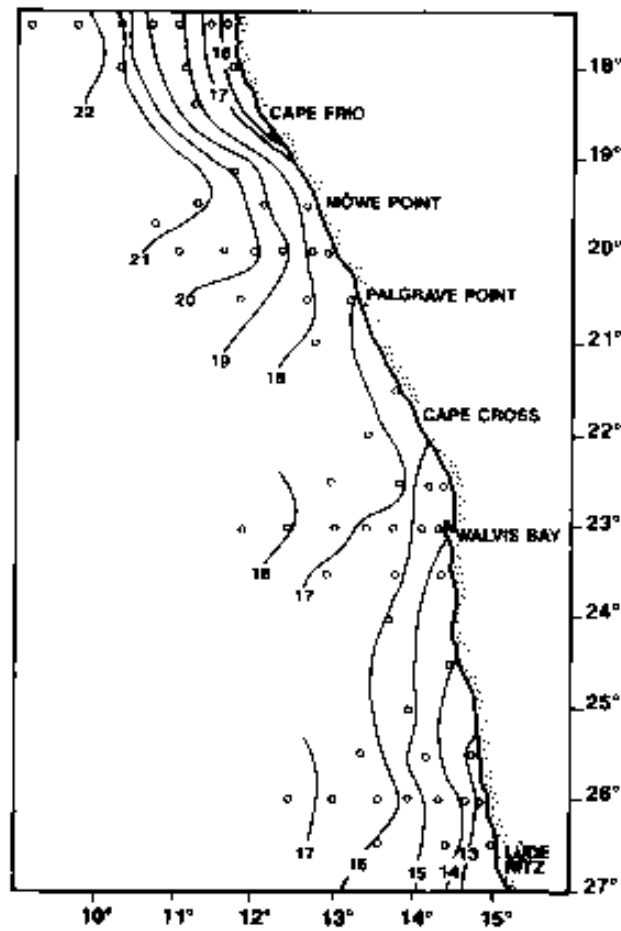


Fig. 6. Horizontal distribution of temperature at surface.

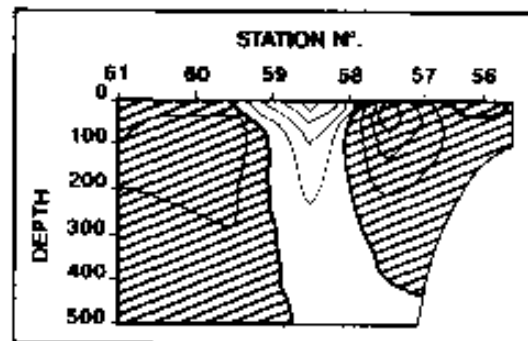


Fig. 7. Vertical distribution of the transversal component of geostrophic velocity through the northernmost section ( $17^{\circ}30'S$ ). The isotachs are drawn every  $8 \text{ cm s}^{-1}$ . The region where the current is directed towards the south is shaded.

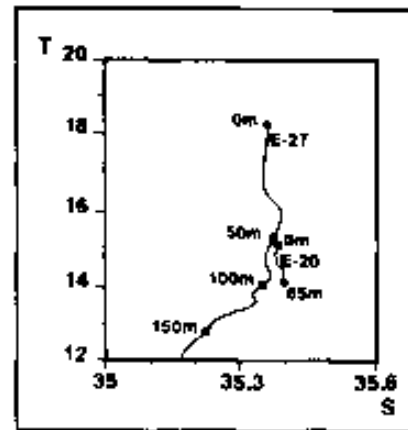


Fig. 8. *T-S* diagram of stations: 20 and upper part of 27 (at the extremes of the 23°S line)

areas of rich and relatively poor phytoplankton, all of which merge into a complex pattern which is in a constant state of change or flux. This quality of irregularity and instability is in fact one of the features which emphasize the discrete character of this upwelling region." Most of the subsequent authors reported the occurrence of eddies in the southern Benguela region (SHANNON *et al.*, 1985). The development of these eddies suggest that the main Benguela current was still unstable, after the relaxation of coastal upwelling in the preceding 3 months, and a transfer of energy to the eddies was occurring at that time.

The presence of a frontal strip, north of 22°S, separating the southern water mass from the Angolan waters. In this zone, up to 19°30'S, the main northwards current was decaying, the coastal upwelling was weak, and from 20°S to 22°S geostrophic flow appears to be weak and more uniformly longshore (although this could partially be due to the low sampling density). This is the signature of the boundary between the Angola and Benguela waters (SHANNON and AGENBAG, 1987) which extended as far as the southern limit of the normal seasonal excursion, as pointed out by BOYD *et al.* (1987).

According to the dynamic topographies, the Angolan waters had penetrated the region from the north, following the continental shelf edge, with a maximum southerly component at 50 m depth at 17°30' (Fig. 7). Further south these waters were conducted towards the coastal region (Fig. 3) thus becoming available for coastal upwelling off Walvis Bay. This last aspect is well evidenced by the salinity distributions (Fig. 5). The high salinity values near the shore could be interpreted as an indication of no upwelling but, if these values are compared to those of the water column offshore, it can be seen that the upwelled water had a salinity slightly higher than the corresponding value according to temperature for this latitude in the SACW (Fig. 8), which is an indication of its more northerly origin. This is an important confirmation regarding the origin and the path for the saline upwelled water described by BOYD (1983a) off Walvis Bay in late summer and early autumn, referred to in the Introduction as the fourth water type.

Some differences in mechanisms, among the three main observed upwelling centres, are found.

(i) In Lüderitz region the classical picture of coastal upwelling was observed. There was a large coastal band where the upwelled water, originated from more than 150 m

depth, was transported offshore and northwards at the surface by the combined effect of Ekman transport and the main current.

(ii) The upwelling process off Walvis Bay, near the frontal region and with more saline upwelled waters, as pointed out previously (Fig. 8), seems to be very complex. It cannot be described easily by a two-dimensional scheme. Moreover, the data coverage of the cruise was not complete enough to be conclusive. However, the available information confirms that the eddies could have a significant role contributing to conduct northern offshore waters towards the coast at 100 m depth (Fig. 3). This figure also shows that the water upwelled to the surface near the shore appears to be trapped by the eddies 50 miles offshore.

(iii) Close to the mouth of the Cunene River, at the northern boundary of the sampling area, the upwelled water came from shallow depths of not more than 100 m, according to transport from offshore. The water mass present in this region is clearly Angolan water. The northward extent of this upwelling centre cannot be described as no measurements were made north of this line.

The instabilities in the Benguela Current have been generally related to fluctuations of the oceanic front between coastal and open sea waters (NELSON and HUTCHINGS, 1983; SHANNON, 1985). In this case, the occurrence of these eddies within the coastal region, north of Walvis Bay, appear to be related with the previous relaxation of the upwelling, the subsequent penetration of the Angolan waters in the region (BOYD *et al.*, 1987), and the re-establishment of the Benguela current in course. South of Walvis Bay, the meanders of the oceanic front, offshore, may remain most important. If all these phenomena are indeed related, they would combine at the Walvis Bay region between 24°S and 22°S. Here, the coexistence of waters of different origin that were mixing, upwelling and recirculating appears to have led to enrichment reflected in the results of phytoplankton and primary production obtained by ESTRADA and MARRASÉ (1987), using data from the same cruise, which show that the area off Walvis Bay was the most productive within the whole region studied.

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