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TETHYS 6 (1-2) 1974 pp. 43-52

PHYSICAL INVESTIGATIONS IN THE UPWELLING REGION OF NORTH WEST AFRICA ON RRS DISCOVERY CRUISE 48

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Résumé : Les résultats préliminaires de la campagne 48 du "Discovery" dans la région située entre le Cap Bojador (26°10'N) et le Cap Blanc (20°50'N) montrent qu'en juillet et en aoùt 1972, l' upwelling est le plus intense dans la zone du Cap Bojador. De nombreuses stations de mesure áu moyen de la bathysonde (STD) et des mesures de. courant sur le plateau continental au large du Cap Bojador, confirment également l'existence d'un upwelling actif affectant les couches proches de la surface et les niveaux á proximité du fond entre 100 et 200 métres.

Une série de 98 stations de bathysonde répétées chaque demi-heure ainsi qu'une série de mesure du profil du courant par des enregistrements durant 9 heures au niveau d'une position par 105 m de fond ont permis d'établir la circulation dans un plan normal á la côte. Des ondes internes semi-diurnes, d'une amplitude considérable ant été mises en évidence á cette mìme station ; elles semblent jouer un rôle plus important qu'initialement prévu.

Rien ne semble indiqúer un transport vers le nord sur le plateau continental, mais des enregistrements courantométriques montrent l'existence d'un sous-courant allant vers le nord au niveau du talus continental. Une vitesse moyenne, en direction du nord, inférieure á 4 $cm.s^{-1}$ a été enregistrée sur une période de 7 jours, á une immersion de 450 m dans la couche d'eau, épaisse de 500 métres.

Summary : Preliminary results from Discovery cruise 48 in the region between Cape Bojador (26°10'N) and Cape Blanc (20°50'N) indicate that during July and August of 1972 upwelling was most intense off Cape Bojador. A concentrated series of STD and current measurements on the continental shelf off Cape Bojador provided further evidence of the presence of active upwelling, which was concentrated in the near surface layers and at depths near the bottom between 100 m and 200 m.

A series of 98 half hourly STD dips supplemented by 9 six hourly profiling current meter dips at a time series station situated in a depth of 105 m defined the circulation in the vertical plane normal to the coast. Semi-diurnal internal waves were found to have considerable amplitudes at the same station, and to contain contributions from modes higher than the first.

No evidence of northward flow on the continental shelf was found but moored recording current meter results indicated the presence of a poleward undercurrent over the continental slope. A mean northward velocity of less than 4 cm s^{-1} was recorded over a period of about seven days at a depth of 450 m in 500 m of water.

INTRODUCTION

A description of some preliminary results from Discovery Cruise 48 in July/August of 1972 will constitute the greater part of this paper, although reference will be made to certain measurements obtained during Discovery Cruise 26, which is more fully discussed elsewhere (Hughes and Barton, 1973a). Some results of Cruise 26 were also described at the recent CUEA workshop at Tallahassee, U.S.A. (Hughes and Barton, 1973 b).

Cruise 48 formed the second stage of a long term programme of study in the upwelling area off N.W. Africa, which started with Cruise 26 in April/May 1969. The primary aims of the two cruises were similar but the latter one benefitted from the previous experience off Spanish Sahara, and concentrated more on the problem of obtaining a well defined picture of the stratification and variability over the shelf area in conjunction with measurements of horizontal currents.

To these ends some 300 S.T.D. profiles were obtained, ranging in depth between 28m and 1000 m, 9 recording current meters were moored in depths between 100 m and 1000 m for a period of about seven days, and 22 dips were made over the continental shelf and slope with, a Profiling Current Meter (P.C.M.) as described by Düing and Johnson (1971).

The comparatively large amount of data obtained during Cruise 48 has not yet been fully analysed, and it will take some time for a final interpretation of- the data to be made. However, a description of some early results will now be made.

CRUISE TRACK

A general description of Discovery Cruise 48 with station positions is given in N.I.O. Cruise Report No. 53 (1973). During the first phase of the cruise, Discovery made five sections normal to the coast of Spanish Sahara between the Canary Isles and Cape Blanc, as shown in Figure 1. The survey area was chosen because of the supposed northward migration of the most intense upwelling during the summer months, as pointed out for example, by Wooster and Reid (1963), and also because the results of Cruise 26 indicated that the upwelling processes to the south of Cape Blanc were complicated by the particular distribution of water masses there. Thus it was felt that upwelling was likely to be present in. this area at the time of the survey, and would not be so difficult to interpret as further south.

Between the station lines Discovery followed the 500 m contour, monitoring continuously the surface temperature and salinity. Having completed the five sections of the initial survey, the ship put into Santa Cruz in the Canaries to exchange personnel.

The second phase was confined to the locality of Cape Bojador, as indicated by the position of the square on the chart (Fig. 1). Details of the station positions on this part of the cruise are shown in Figures 3a and b, which are discussed later.

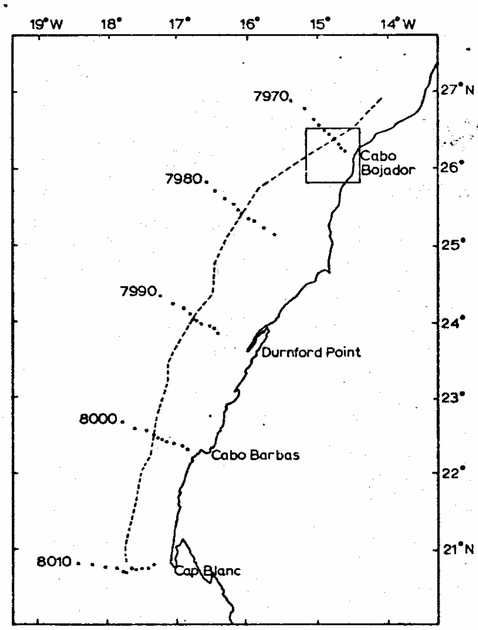

Figure 1 – Station chart for part 1 of *Discovery* Cruise 48, *Discovery* stations 7970 to 8020, 23/27 July 1972.

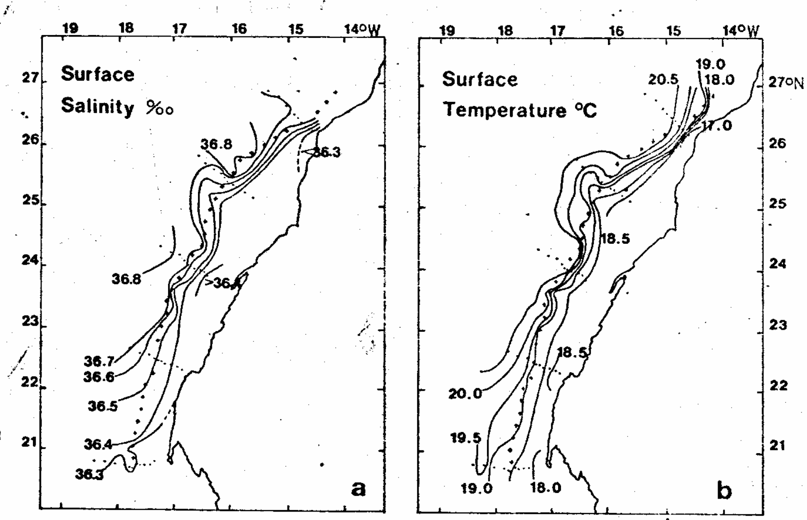

Figure 2 – The surface distribution of (a) salinity (‰) and (b) temperature (°C).

SURFACE SALINITY AND TEMPERATURE

Figure 2a and b is drawn up from a combination of temperature and salinity values obtained from the S.T.D. probe on stations and from the continuous measurements made with the surface T, S recorder whilst underway, Hourly positions of the ship between sections are denoted by crosses. At these points, values of temperature and salinity were read from the continuous record, averaged over the preceding and following half hour intervals.

Throughout the survey area there is an overall decrease of temperature and salinity towards the coast and although the isolines appear in general to follow the line of the edge of the continental shelf, there is nevertheless much irregularity in the recorded profiles because of the complicated nature of the surface distributions. The surface profiles show a number of localised regions of warmer or cooler water of scales less than 10 nm, similar to those investigated by Tomczak (1973).

In the part of the area from Cape Barbas southwards, the isohalines appear to turn out to sea. This is a similar situation to that in 1969 during Cruise 26, when it was found that Cape Blanc marked a region of transition, the less saline surface water being situated to the south (Hughes and Barton, 1973a). The dominant central water mass in the region of the present survey is the North Atlantic Central Water, but along the Cape Blanc sections there is evidence of intrusions of a lower salinity water mass in the layers above 300 m, as was also found in 1969.

From offshore the temperature decrease towards Cape Blanc is the smallest encountered in the region, the temperature contrast between nearshore and offshore station being 1.5°C. Comparing this with the situation off Cape Bojador, it may be seen that the temperature near the coast there is lower, being 3.5°C colder than offshore. Also the horizontal temperature and salinity gradients normal to the coast are much stronger off Cape Bojador.

Inspection of the vertical sections and T-S curves (not shown here) confirms that the most intense upwelling was present off Cape Bojador, where water situated on the continental shelf had very similar characteristics to that offshore at 200 m depth. Accordingly, the site of the more detailed investigations of the second phase of the cruise was selected to be Cape Bojador. This choice of site was also fortunate in that it minimised the steaming distance from Tenerife, thus enabling a longer period to be spent in the working area.

INTENSIVE MEASUREMENTS OFF CAPE BOJADOR

During the second phase of the cruise, two hydrographic surveys separated by an interval of about ten days, were carried out over the continental shelf and slope off Cabo Bojador. In the period between the surveys, 9 recording current meters were moored in depths of 105 m, 504 m and 1000 m at stations 8047, 8048 and 8049, as shown in Figures 3a and b. At the same time, station 8050 was maintained for four days near the 504 m mooring, and then station 8051, close to the shallowest mooring, was occupied during the following two days. At each of the two time series stations 98 S.T.D. profiles were obtained : at station 8050 lowerings were made hourly, and at station 8051 at half-hourly intervals. In addition, six-hourly P.C.M. lowerings were made at both stations by Dr. D. Johnson of the University of Miami.

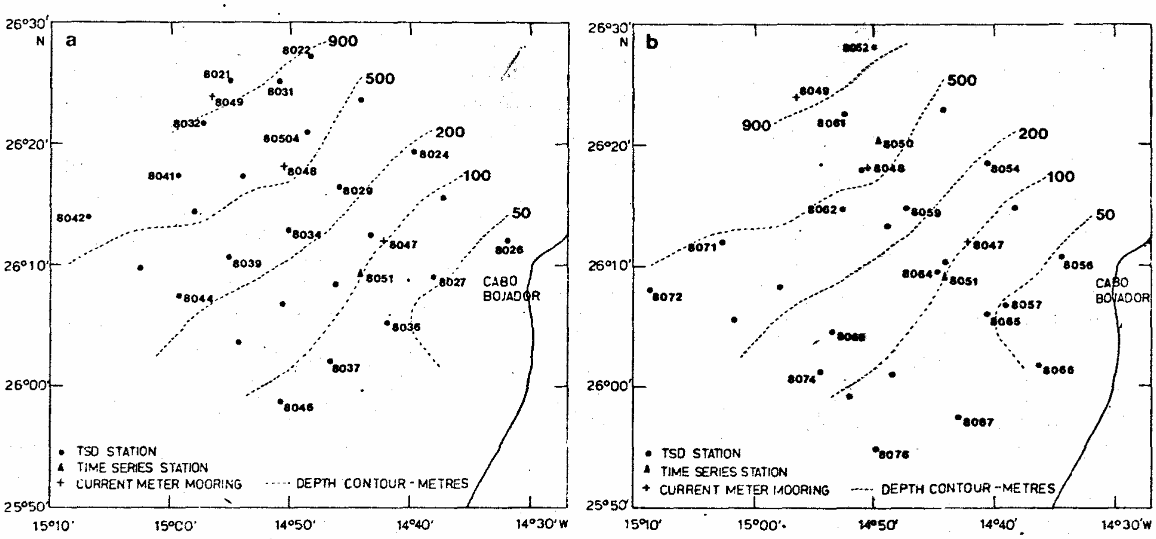

Figure 3 – Station charts for part 2 of *Discovery* Cruise 48, (a) Grid 1 stations 8021 to 8046, (b) Grid 2, stations 8052 to 8076. Time series stations and current meter moorings are indicated on both charts.

The two hydrographic surveys were based on a grid, approximately 20 nm square, consisting of five lines of five uniformly spaced stations. At each station the S.T.D. probe was lowered to 500 m or to as near the bottom as possible where the depth was shallower. Navigational difficulties resulted in the second survey (Fig. 3h) being not so evenly spaced as the first (Fig. 3a).

SEA SURFACE WINDS

During the two surveys the winds were very constant in direction from about 030°, as shown in Figure 4. The winds were stronger during Grid 2 with an average speed of 22 knots, as compared to an average of 14 knots during the first survey, Grid 1. Wind speeds of about 20 knots were recorded at station 8050, and during the two days at station 8051 the wind appeared to increase from about 15 knots initially to greater than 20 knots. At the same time the variability in the direction decreased. For the whole of this period therefore, the winds were favourable to upwelling.

INDICATIONS OF UPWELLING

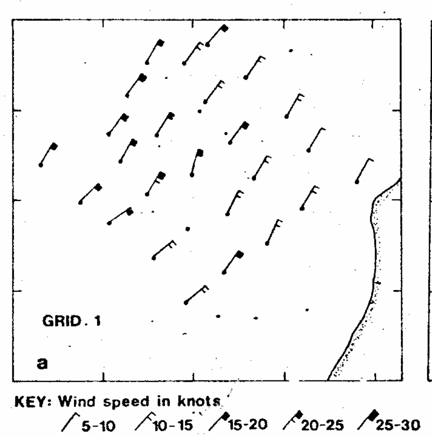

Figure 4 – Sea surface wind during part 2 of *Discovery* Cruise 48 (a) Grid 1, 2-3 August 1972 (b) Grid 2, 12-14 August 1972.

The horizontal distributions of T, S, σ_t off Cape Bojador

The charts shown in Figure 5 represent the salinity, temperature and density at 5 m during the two surveys. Although they are not truly: synoptic because of the strong southward surface currents (over 1 knot) and the time lapse (over 24 hrs) involved in making the survey, the contours of the various properties may be interpreted as an indication of the surface distributions.

Grid 1 is characterised by almost uniform temperature, salinity, and density at distances greater than 15 miles offshore. Shoreward of this region there is decrease of temperature and salinity towards the coast, accompanied by a related increase in density. The contours are aligned approximately along the isobaths, except in the uniform region offshore. A minimum temperature of 18°C is found at the station nearest to the coast, about 3° C cooler than the offshore water. Minimum salinity and maximum density are found at the same station, which is situated in a depth of less than 50 metres and within about three miles of Cape Bojador.

At the time of the second survey (Grid 2) it was apparent that an intensification of the horizontal gradients towards the coast had taken place. This was very pronounced in the isotherms and isopycnals. Note that in the distribution of σ_t alternate isopycnals have been removed for the sake of clarity. The increase in the horizontal gradients has been caused by the appearance of colder, denser water near the coast, and also by warmer, more saline water appearing at the offshore side of the grid. It can be seen that there has been an offshore movement of 5 miles in the position of the 18° C isotherm between the two surveys. A similar magnitude of offshore displacement is apparent in the density distribution, but the

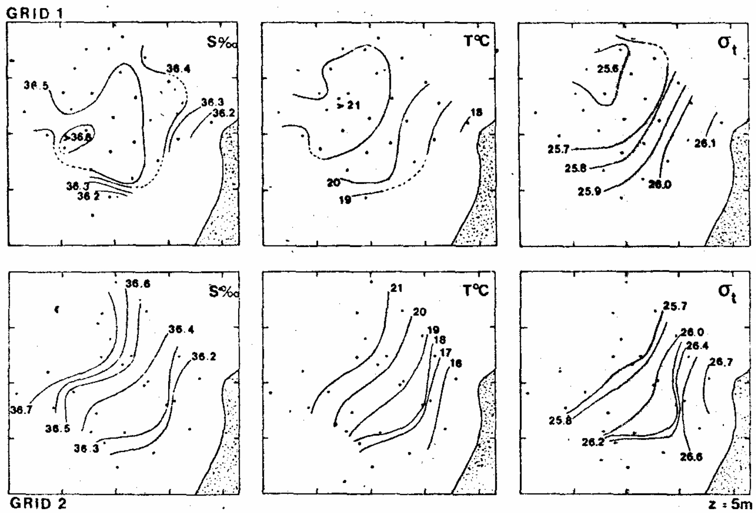

Figure 5 – The horizontal distributions of S, T and σ_t at 5 m depth on 2-3 August 1972 (Grid 1) and on 12-14 August 1972 (Grid 2).

effect is not so noticeable in salinity. While the coldest water found in Grid 2 is cooler by 2°C than in Grid l, and the maximum density has increased by 0.6 σ_t units near the coast, the minimum salinity value is found to be very nearly the same in the two surveys. This discrepancy is explained by the fact that the vertical salinity gradient found near the surface at these stations is small whereas the vertical temperature gradient is large, as may be seen in the vertical sections.

Vertical distributions

Section 7 and section 12 from Grids 1 and 2 respectively are situated along the same line between the current meter mooring sites and the time series stations. Some isopycnals near the surface have been omitted for the sake of clarity *e.g.* 26.1. - 26:4 in the pycnocline.

Section 7 displays several features worthy of note (see Fig. 6a). Firstly, in the layers above 100 m the salinity is relatively uniform and several inversions are present in the offshore region but not over the nearshore shelf where salinity is weakly stratified. Secondly, a degree of upwelling is evident in the shallower layers above 100 m *e.g.* the 18°C isotherm at about 90 m offshore rises almost to the surface at the innermost station 8027. Thirdly, a body of cooler, less saline denser water, which is situated on the shelf above 100 m is separated from water with the same characteristics found below 200 m further out on the slope. This is a feature of all the Grid 1 sections and it is concluded that this effect is due to the cessation of a previous upwelling of water onto the shelf.

The very pronounced down warping of the isolines between 200 and 400 m may be partly indicative of a northward flow at this depth, as is described later, but is certainly also due to the effect of internal waves, as sections to the north and south of section 7 indicated a slight upward displacement of the isolines at these levels.

Section 12 was surveyed some eleven days after Section 7 and indicates some interesting developments over that period. Again, in the shallower layers the presence of a salinity maximum is evident, but the upwelling in these layers has intensified. For instance the 36.2 ‰ isohaline and the 18°C isotherm which previously did not quite break the surface now do so. Furthermore, the water previously isolated on the shelf is now connected to the deeper layers. These changes are evident in all five sections of Grid 2.

It would appear that over the time between the two surveys Grids 1 and 2, upwelling occurred both in the near surface as was illustrated by the surface distributions and in layers as deep as 200 m *e.g.* 26.9 isopycnal in section 12. It is concluded that the time series and current meter measurements were made during a period of active upwelling. Some of these measurements may now be examined

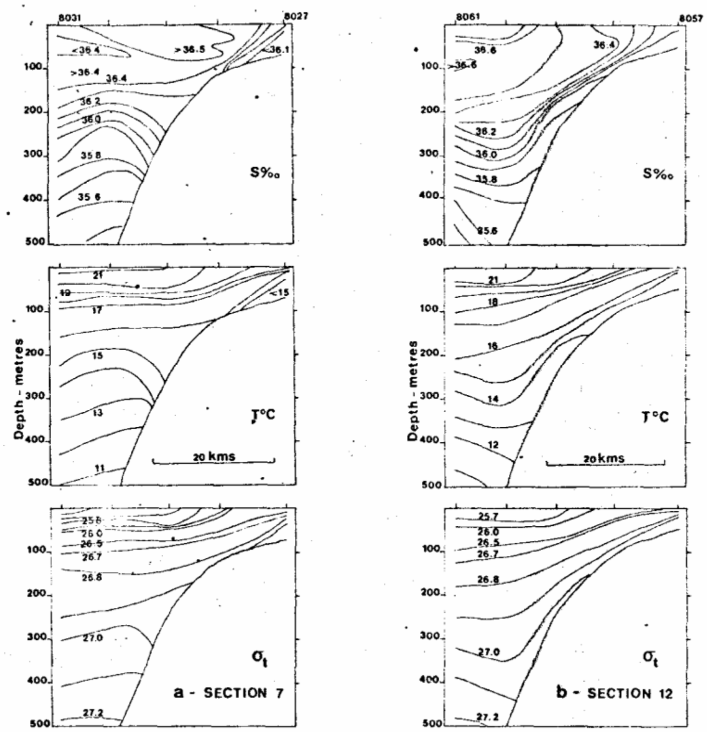

Figure 6 – The vertical distributions of S, T and σ_t along the line of the current meter moorings on (a) section 7 on 2 August 1972 (stations 8027 to 8031) and (b) section 12 on 13 August 1972 (stations 8057 to 8061).

MEAN STRATIFICATION AND CURRENTS AT THE SERIES STATION (8051) ON THE CONTINENTAL SHELF

Figure 8 illustrates (a) the overall means of T, S, σ_t , static stability E, alongshore velocity v and onshore velocity u for the two days and (b) and (c) the means for individual days, all of which portray similar characteristics. Velocity data for u and v have been provided by courtesy of Dr. D. Johnson, University of Miami, who carried out the PCM measurements on the cruise..

A summary of the main features of the profiles is as follows. Temperature and density profiles exhibit a sharp thermocline and pycnocline extending from the surface to a depth of about 30 m. Between 30 m and 80 m more gradual gradients are present and below 80 m the vertical gradients increase again to the limit of the observations which was about 5 m above the bottom. The maximum static stability E is situated at 20 m and a small secondary maximum due to the increased gradients is present near the bottom.

A salinity minimum is evident in the centre of the pycnocline in the mean distribution, but whether this is a genuine feature or a consequence of salinity spiking in the thermocline is debatable. Inspection of the individual master traces does not completely resolve the problem. Below the minimum, a salinity maximum is centred at about 45 m, beneath which level salinity falls off rapidly to the bottom of the profile.

The velocity co-ordinate system is rotated 33° east of north to imitate the natural co-ordinates of the region. Longshore flow is strongly southwards at all depths with a maximum value at the surface of over 80 cm s^{-1}. At 90 m the flow is still 50 cm s^{-1} towards the south. In the region of the pycnocline a high shear (1-2 cm s^{-1} m^{-1}) is present. Between 30 m and 80 m there is a layer of lower shear beneath which a second region of high shear is evident although this is not measured below 90 m.

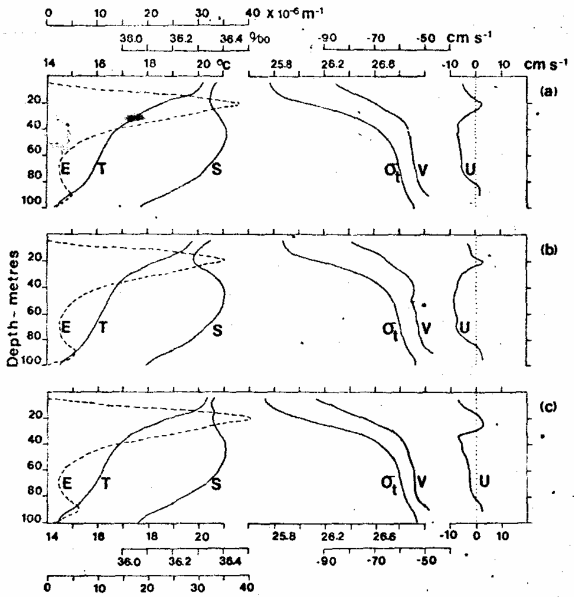

Figure 7 – Mean profiles at time series station 8051 (26°09'N, 14°44'W), for details see text.

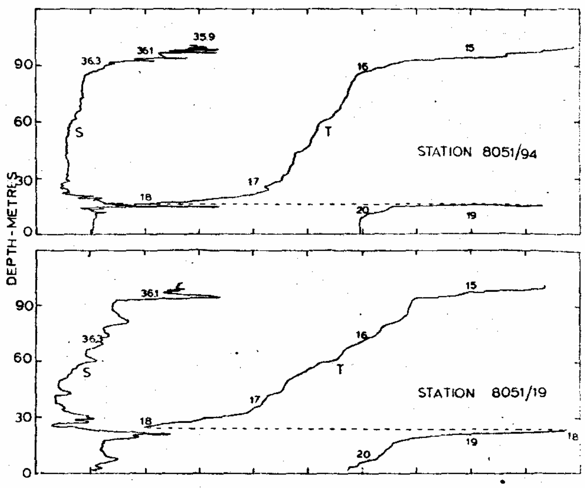

Figure 8 – Two typical S.T.D. traces from the time series observations on the continental shelf at station 8051. Note the large temperature gradients near the surface and bottom. Dotted line indicates a change of scale.

The cross stream flow in the upper region is offshore above 15 m and onshore in the region of maximum static stability 15-25 m. Below 30 m a well defined offshore flow is present to a depth of 80 m. From there to the bottom of the mean profile an onshore flow is indicated. The maximum average offshore velocity is over 7 cm s^{-1} in mid depths and maximum onshore velocity is less than 3 cm s^{-1} at 20 m.

There is a very good correspondence between the mean velocity and hydrographic profiles. Longshore flow corresponds closely to temperature and density profiles and onshore/offshore flow corresponds with salinity and static stability. Onshore flow occurs at the level of maximum stability 20 m, and below 80 m where the secondary maximum is present. Offshore flow at mid depths coincides with the maximum of salinity and the regions of low temperature, density and longshore velocity gradients.

Dynamic stability as expressed by the Richardson number, Ri, has been investigated. For the mean profiles Ri was calculated at 5 m incremets from the mean of the nine PCM profiles and the mean of the 98 S.T.D. based Brunt Väisälä frequency profiles. The result is very similar to that calculated by Johnson and Moers (1973); with Ri < S above 30 m, higher values down to 80 m and then low values again beneath this level. Individual Richardson Number profiles calculated from each PCM profile and the mean of S.T.D. profiles before and after show high variability, with low values of Ri < 0,25 occurring at all depths at some time i.e. dynamic instability occurred at all levels in the course of time.

The mean cross-stream velocity profile suggests that a two-celled circulation was present over the continental shelf at Station 8051. This type of circulation has been proposed by Mooers, Collins and Smith (1973) in connection with upwelling off the Oregon coast. However, it is difficult to see how the offshore flow at mid-depths is compatible with the existence of a salinity maximum at that level. The source of the offshore flow is in a region of lower salinity and hence a salinity minimum might be expected. One possibility is that the offshore current in the surface layers has been underestimated by the profiling current meter as the ships hull may have affected the compass reading near the surface. If the surface offshore flow is actually greater than is recorded then the relative maximum in mid-depths may be explained by the greater advection of lower salinity water in the surface layers.

Reference to two typical profiles shown in Figure 8 will indicate the sharpness of the temperature gradients in the upper and lower layers, and also the problem presented by salinity spiking.

The question arises, how are the very strong gradients of temperature and salinity illustrated in Figure 8 maintained in the bottom region of apparent high shear where u and v fall off to zero ? Many of the individual T and S profiles at this station indicate the presence of a thin mixed layer above the bottom, below depths of 95-100 m. It is possible that the greater part of the velocity shear is concentrated in this region of presumably onshore flow thus producing the mixing mechanism for the mixed layer. The strong gradients immediately above the mixed layer are maintained by difference of properties between the mid-depth water travelling offshore and the colder, less saline water being upwelled along the bottom in a manner similar to that indicated by the distribution of T and S in Figures 6a and b.

VARIABILITY AT THE TIME SERIES STATION ON THE CONTINENTAL SHELF

Johnson and Mooers (1973) mentioned the existence of a large amplitude semidiurnal tide at Station, 8051 as deduced from the variation in currents. The internal tide is also very evident in the temporal variation in the depths of the isolines of temperature, salinity and density, illustrated in Figure 9. It is particularly clear in temperature and density but somewhat obscured by the salinity maximum which itself oscillated in value semidiurnally.

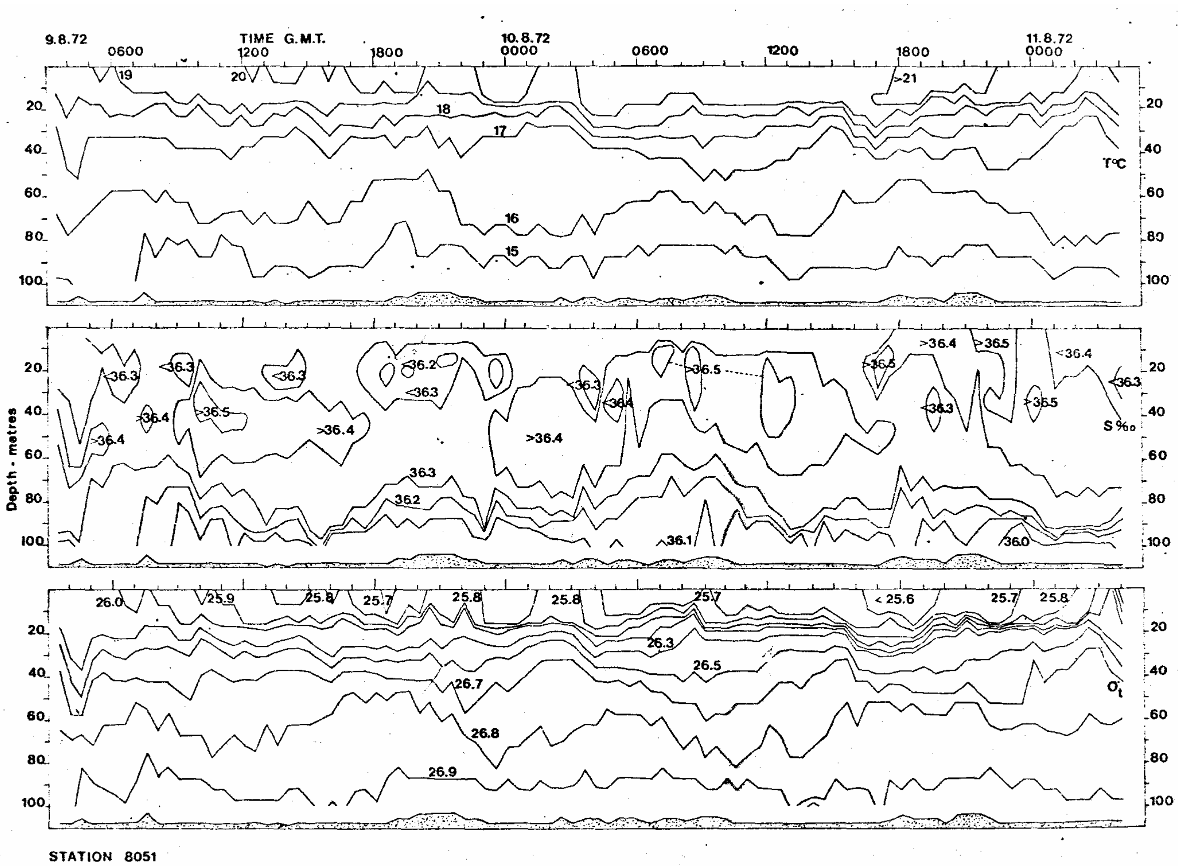

Figure 9 – Temporal variations of T, S and σ_t on the continental shelf off Cape Bojador (*Discovery* station 8051 : 0330 GMT 9 th August 1972 to 0400 GMT 11 August 1972, 26o 09'N, 14o 44'W).

The semidiurnal oscillation appears to contain contributions from the second or possibly higher modes e.g. 2000 hrs. 9.8.72 and later. A full modal analysis of the oscillations is underway at the moment and, it is hoped, will be completed in the near future.

A very large amplitude semidiurnal tide was found to be present in May 1969 in a location on the shelf off Cape Bojador very close to Station 8051. 4n that occasion the oscillation appeared to be almost entirely of the first mode (see Fig. 10). The data for this station 6985 is presently being analysed by Dr. C.N.K. Mooers at the University of Miami.

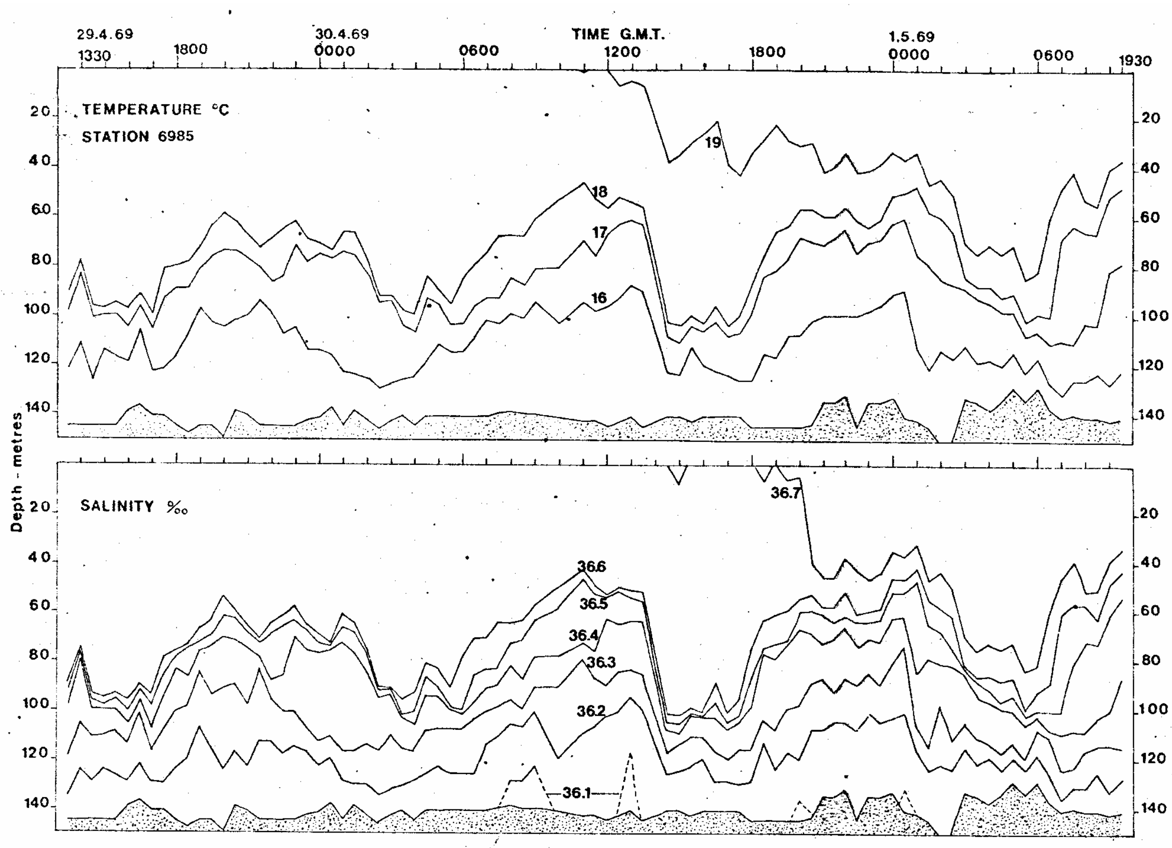

Figure 10 – Temporal variations of T and S on the continental shelf off Cape Bojador 29 April to 1 May 1969 (*Discovery* station 6985 : 26°15'N, 14°43'W).

MEASUREMENTS OF THE SUBSURFACE POLEWARD FLOW

Of the nine current meters moored off Cape Bojador only four functioned successfully. None functioned on the shallow mooring and only one at the outer mooring. However, good measurements of velocity were obtained at 50 m, 200 m and 450 m at the slope mooring. Means of the velocities obtained from PCM profiles made to 230 m at the slope station were in good agreement with means from the moored meters at levels of 50 m and 200 m. The current meter at 450 m indicated a net northward flow of 4 cm s^{-1} over a period of about seven days with a net onshore velocity of less than 2 cm s^{-1}. Thus although there was no evidence of northward flow on the shelf a poleward undercurrent was found over the continental slope 50 m above the bottom in a depth of 500 m. Note that at times the direction of flow was reversed.

Figure 11 shows the time variation of the northward and eastward components of flow measured at 50 and 450 m. The shallowest meter recorded a strong flow towards 210° with an average speed of 42 cm s^{-1}. Semidiurnal and longer period oscillations which have not yet been fully investigated are apparent in both current meter records.

CONCLUSIONS

1. During the period of July/August of 1972 upwelling was most intense off Cape Bojador.

2. The circulation in the vertical plane normal to the coast supports the ideas of Mooers, Collins and Smith (1973) although it was felt that measurements of the current in the near surface layers were not completely reliable, possibly underestimating the Ekman transport.

3,. Semi-diurnal internal waves have considerable amplitude over the shelf-slope break off Cape Bojador and possibly play a significant role in coastal upwelling.

4. No evidence of a northward subsurface flow was found on the continental shelf but a

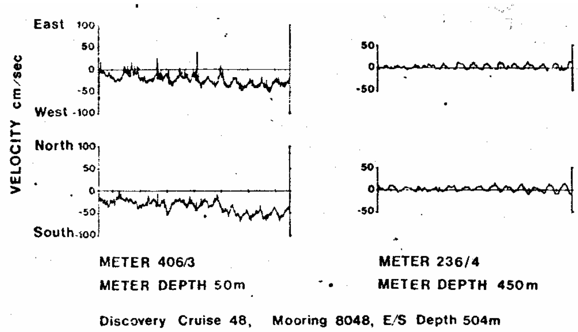

Figure 11 – Current measurements over the continental slope off Cape Bojador, showing southwesterly flow at 50 m and the poleward undercurrent at 450 m.

poleward undercurrent was measured over the continental slope, its average northwards velocity being 4 cm s^{-1} at 450 m.

The measurements described above will be subject to more detailed analysis and further conclusions will undoubtedly be derived later within the framework of a more complete description of *Discovery* Cruise 48.

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ACKNOWLEDGEMENTS

We thank our colleagues from the Department of Oceanography, University of Liverpool and the National Institute of Oceanography who took part in *Discovery* cruise 48. We would also like to thank Sue Barton for preparing the diagrams. This research was partially supported by N.E.R.C. grant GR3/1818, E.D. Barton is supported by N.E.R.C. studentship GT4/70/OF/13.