Longshore advection during an upwelling event in the Canary Current area as detected by airborne radiometer

Upwelling
Sea surface temperature
Remote sensing
NW Africa
Upwelling
Température de surface
Télédétection
Afrique nord-ouest

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ABSTRACT

Airborne temperature measurements made during February and March, 1975, are reported and analysed with reference to hydrographic and current meter observations made simultaneously by RRS "Discovery" and FS "Meteor". Maps of the sea surface temperature for an area north of Cap Blanc of approximately 200 km longshore extent show a band of cold upwelled water at mid-shelf and a high degree of longshore alignment of the main temperature features during an upwelling event. It is argued that longshore advection of warm coastal water and of cold upwelled water is as important as active local upwelling and that mid-shelf or shelf-break upwelling are very unlikely north of Cap Blanc. The distribution of sea surface temperature is less patchy than could be expected from the highly variable distribution of water masses at the source level of the upwelling, and it is suggested that this is the consequence of increased mixing in the surface layer.

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RÉSUMÉ

Advection le long de la côte, déterminée par télédétection radiométrique, au cours de l'upwelling dans la région du courant des Canaries

Des observations télémétriques de température effectuées en février et mars 1975 sont présentées et analysées par rapport à des observations hydrologiques et des mesures de courant réalisées simultanément par le RRS « Discovery » et le FS « Meteor ». Les distributions de la température superficielle dans une région de 200 km environ au nord du Cap Blanc mettent en évidence une bande d'eau froide d'upwelling au milieu de la bande côtière et un haut degré d'alignement, le long de la côte, des structures thermiques pendant un évènement d'upwelling. On en déduit que l'advection d'eau chaude d'origine côtière et d'eau froide en provenance de l'upwelling, le long de la côte, est aussi importante que l'upwelling local, et qu'il n'y a guère la possibilité d'upwelling au milieu de la zone côtière ou sur le rebord du plateau continental, au nord du Cap Blanc. La distribution de la température superficielle est moins structurée que ce que l'on pouvait prévoir d'après la distribution des masses d'eau à l'origine de l'upwelling, où existe une variété considérable. Cette observation suggère un taux élevé du mélange dans la couche superficielle, qui efface les traces de la variabilité observée au niveau de la source.

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INTRODUCTION

Early in 1975 RRS "Discovery" and FS "Meteor" co-operated in a joint study, "Upwelling 75-Auftrieb 75", to investigate the current system and water mass distribution of the northwest African upwelling area. A data report on wind observations, currents and hydrography was prepared by Brockmann *et al.* (1977), and results were published by Tomczak and Hughes (1980). Kullenberg (1978) published results from optical measurements made during the same cruise.

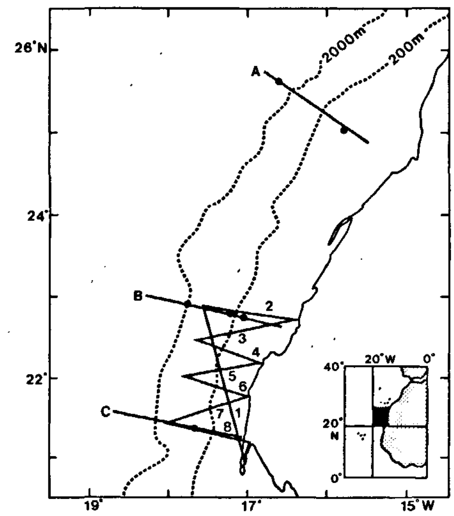

Figure 1
The expedition area. A, B, C: repeated hydrographic sections. Full circles: positions of current meter moorings (these moorings are referred to as ACM 1, ACM 3, BCM 1, BCM 2, etc. in the text; the first letter refers to the section and the number to the position on the section: 1 = shelf, ca. 75 m; 2 = slope, ca. 500 m; 3 = deep, ca. 2000-3000 m water depth). The standard flight path for airborne temperature measurements is indicated by the saw-tooth-shaped track between sections B and C, and individual transects are labelled 1-8 for later reference.

As in earlier programmes the mapping of sea surface temperature with the aid of remote sensing devices installed in an airplane formed part of the study. Results of the airborne measurements are reported here and compared with data taken by the participating research vessels.

Figure 1 shows the area covered by the remote sensing programme and the working area of RRS "Discovery" and FS "Meteor". Most of the work of the research vessels was done on the standard profiles A, B or C, but some data are available for comparison within the area covered by the airplane.

INSTRUMENTATION AND METHODS

Details of the instrumentation were reported in an earlier study (Tomczak, Miosga, 1976). Changes in instrumentation since the previous work are: The aircraft used was a D0 28 D1, and the line scanner was a modified Reconofax XIII A instrument. All flights were made at an altitude of 1200 m at a speed of 200-250 km/h. In total, 10 surveys of the area were made over a period of 31 days, at intervals of between 2 and 6 (usually 3) days, following the standard pattern of Figure 1 whenever possible.

As in the earlier study, only the radiometer records are included fully in this analysis but occasional reference will be made to colour photographs. For the charts of sea surface temperature, the radiometer data were read to half (and occasionally to quarter) degrees Celsius and isotherms drawn manually. For the calculation of correlation coefficients between profiles the data were digitized and interpolated to constant space increments along the flight path, and series obtained along a westbound course were inverted for compatibility with eastbound courses.

Attempts to correct the data for atmospheric effects were unsuccessful. Originally it was hoped that ground truth data from "Discovery" and "Meteor" could be used for calibration, but both ships operated rather independently of the airplane's programme, and ground truth data were very scarce. Constant background sea surface temperatures over the period of the experiment as observed in most surveys suggest that atmospheric conditions were similar for most flights. Elevated background temperatures occurred during flight 4, and during flights 2, 5 and 6 background temperatures were unusually low. Since no data exist to assess the reasons, readings from these flights were adjusted to produce background temperatures comparable to other flights. Maps of sea surface temperature consequently display isotherms referred to an arbitrary reference temperature, but original readings (not corrected for atmospheric effects) are used in plots of temperature profiles along flight tracks. The corrections used for sea surface temperature maps are listed in Table 1.

Table 1
Wind observations of RV "Meteor" during "Auftrieb 75", 3-day means, and corrections ΔT applied in the drawing of isotherms.

Date	Speed ($m.s^{-1}$)	Direction (degrees)	Survey No.	Date	ΔT (°C)
26-28/1	11.2	59			
29-31/1	6.8	20	1	30/1	0.0
1-3/2	8.4	46			
4-6/2	6.9	40	2	5/2	+1.0
7-9/2	7.5	20	3	8/2	0.0
10-12/2	9.2	28	4	11/2	−0.5
13-15/2	14.3	44	5	14/2	+0.5
16-18/2	8.0	43	6	16/2	+0.5
19-21/2	7.5	22	7	20/2	0.0
22-24/2	9.0	51	8	23/2	0.0
25-27/2	7.5	16	9	27/2	0.0
28/2-2/3	10.9	17	10	1/3	0.0

Navigation was another major problem and relied mainly on landmarks. A further check on the aircraft's positions could be made after completion of the survey by comparison of detected temperatures at cross-points of profiles. In all cases but one, minor adjustments of the profiles resulted in reasonable to excellent fits at cross-points, differences being less than 0.2°C. Flight path adjustments necessary to achieve good fits were up to 5 nautical miles (1 nautical mile = 1.8532 km) and are without doubt partly due to advective changes in the temperature distribution during each survey which typically took four hours to complete. In the temperature maps such adjustments can be estimated from the deviation of individual paths from a straight line. The only case where it proved impossible to reconcile measurements from two crossing profiles was at the southern end of survey 3 (8 February) where only data obtained during the eastbound course were used for analysis.

RESULTS: LOCAL UPWELLING VERSUS ADVECTION

The distribution of sea surface temperature as inferred from the radiometer measurements is shown in Figure 2. Table 1 lists mean wind speed and direction, for periods of 3 days which correspond to the repetition cycle of the aircraft observations, from the observations of RV "Meteor" at varying positions on or between standard profiles B and C (Fig. 1). The same wind is indicated by arrows in Figure 2 where it is seen that winds were most favourable for upwelling at the end of the observation period and in mid-February. It was pointed out already that insufficient ground truth data do not allow the establishment of a relationship between winds and large-scale temperature and that arbitrary reference temperatures are used for the labelling of the isotherms. However, a strengthening of temperature gradients at scales smaller than the offshore extent of the survey area can clearly be seen during mid-February and seems to be related to changes in the wind. This feature will be addressed later in detail.

A contouring interval of 0.5°C was chosen for Figure 2. Wave numbers not adequately resolved by the flight pattern still contribute significantly to variations of above 0.5°C peak-to-peak amplitude. This leaves many alternatives for the drawing of isotherms, and as a consequence the representation of the actual sea surface temperature in Figure 2 is highly subjective (as an example, the banded structure during 23 February can equally well be contoured as an ensemble of isolated patches). The principle adopted for contouring was to prefer bands to patches, i.e. to enhance possible one-dimensionality of the field. The reason for this is two-fold: First, some arguments will be put forward in this paper to support the importance of longshore advection in coastal upwelling against the classical picture of a basically two-dimensional process, and retaining as much one-dimensionality in the surface temperature field as possible rules out the possibility that longshore variability is only the result of subjective contouring. Second, closer inspection of the data supports the idea that some degree of one-dimensionality is imminent even in features with amplitudes less than 1°C. Figure 3 shows a plot of temperature against normalised distance for the 10 surveys. The similarity of successive transects and even ones separated by larger distances is evident, particularly during periods of strong upwelling such as surveys 4 to 6. These similarities exist not only in the general trend of the temperature but also in minor features such as secondary maxima in the band of cold water (transects 2 to 4 of survey 5, transects 5 to 7 of survey 6). Although it is impossible to include such details in the horizontal mapping they support the approach of retaining maximum one-dimensionality.

In an attempt to quantify the one-dimensionality of the field, correlation coefficients were computed between successive transects using variable horizontal lag. Figure 3 indicates the lags which result in maximum positive correlation and the corresponding value of the correlation coefficient (maximum correlation is obtained when the curves are shifted until the connected vertical bars coincide or form a straight line). Occasionally, negative correlations were larger in absolute value but were disregarded because they link the negative gradient on the offshore side of the low-temperature belt in one transect with the positive gradient on the inshore side in

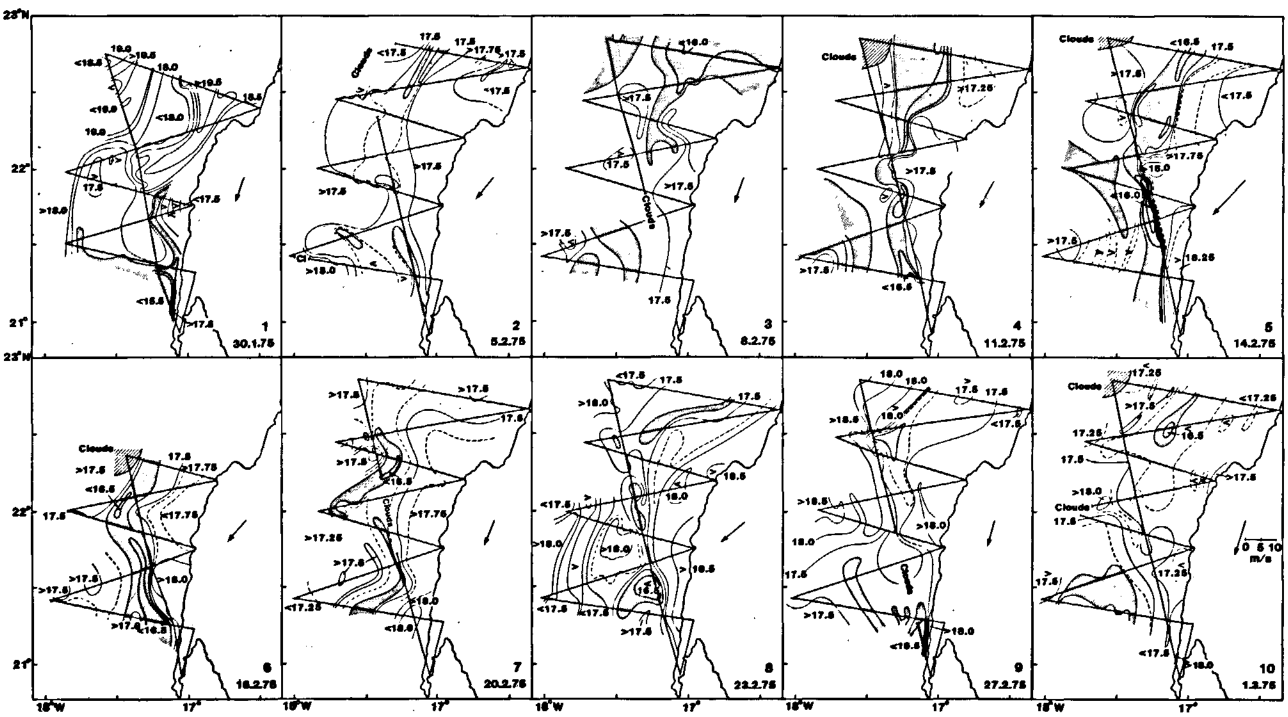

Figure 2

Sea surface temperature as measured with an airborne radiometer, 30 January to 1 March, 1975. The path of the airplane is indicated. Areas without data coverage because of clouds are hatched; reduced data coverage because of clouds is indicated by gaps in the airplane path (for gap in path of survey 3 see text). Temperature is in degrees Celsius relative to an arbitrary reference level (see Table 1 for corrections applied). Arrows show winds as defined in the text and listed in Table 1.

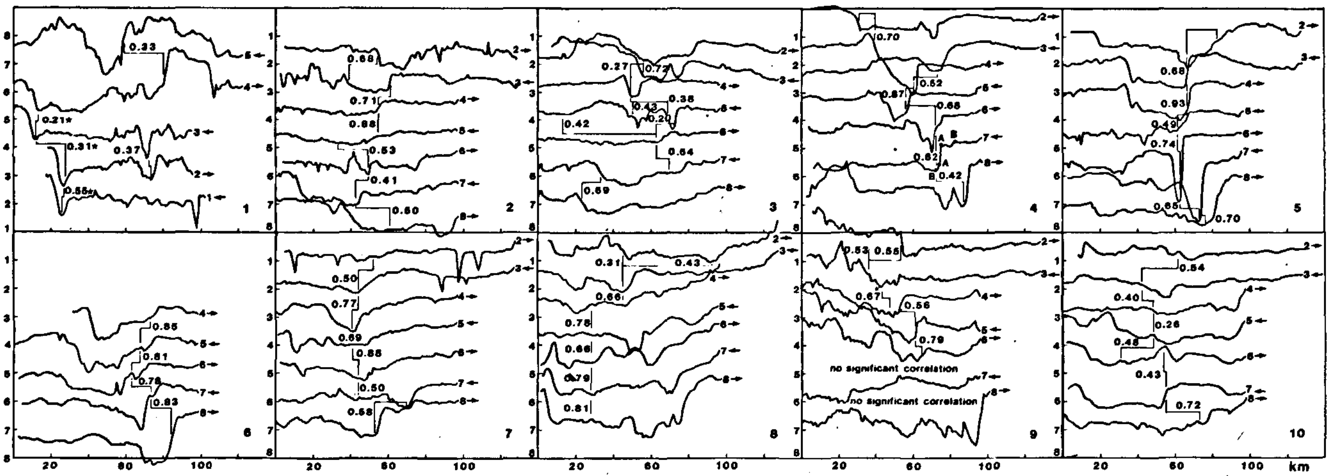

Figure 3

Temperature as a function of normalised distance for transects 2-8 of all surveys. Normalised distance is defined as the shortest distance from a line, roughly parallel to the coast, between 21°26' N, 18°00' W and 22°51'N, 17°36' W which is the seaward limit of the survey area. Arrows indicate the direction of flight for each transect. Tick marks on the temperature scale give the 16° reference and are labelled with the number of the curve to which they refer; distance between tick marks corresponds to 1°C. All temperatures are uncorrected observed temperatures. The marks on transect 7 of survey 4 serve for an illustration of the calculation of gradients: maximum gradients are derived from points A, overall gradients from points B. For correlation coefficients between transects see text.

the adjacent transect. Usually, pairs of curves were right-adjusted for computation, but where this resulted in the loss of significant parts of a curve at its left end, coefficients were determined from left-adjusted curves; these coefficients are marked by an asterisk. Occasionally, the correlation function shows two maxima where the larger one seems oceanographically less meaningful than the other; both shifts and corresponding coefficients are given in these cases. All correlations are raw correlations in the terminology of Sciremammano (1979), computed from between 80 and 120 observations per transect after removal of the trend. Normalised correlation coefficients were not determined but it is estimated that the length scale for the series to gain a new degree of freedom is set by the width of the range of low temperatures which is about 10-30 km, reducing the degrees of freedom from above 80 to about 5 and resulting in 90 and 99% confidence levels of 0.67 and 0.87, respectively.

The correlations suggest that there is significant one-dimensional structure in the observations at least during strong upwelling events. Average maximum correlation increases from values in the range 0.3-0.6 during periods of weak winds to values in the range 0.6-0.85 during the mid-February upwelling event. It appears that nearly half of the observed variability in the temperature distribution can be described in terms of a two-dimensional model at all times. The remainder is due partly to small-scale structure superimposed on the one-dimensional field, partly to lack of one-dimensionality (an example for the first situation are transects 5 and 6 of survey 2, an example for the second case transects 4 and 5 of survey 1 in their western part). Highest correlations resulted from observations made during the upwelling event of surveys 4-6 which therefore needs special attention.

A conspicuous feature of the event is the occurrence of a narrow band of cold water, somewhere between mid-shelf and the shelf edge, with the upwelling-favourable winds during surveys 4-6. The existence of a temperature minimum during periods of strong upwelling has often been recognised in the vicinity of Cape Blanc and has given the Canary Current Upwelling Region a reputation of being typical for "shelf-break upwelling" (Huyer, 1976). Most of the evidence is based on a two-dimensional representation of upwelling. Barton *et al.* (1977) reiterated the argument in another analysis of two-dimensional data although they included a set of 6 aerial surface temperature surveys. These surveys covered about one third of the area of the present study and were performed 11 months before in its southern inshore part (21°00'-21°50'N, coast-17°40'W). They also showed a band of cold water which shifted its position from mid-shelf to the shelf-break over a period of a week in a fashion consistent enough to be accepted as real (the authors did not include aircraft tracklines in the surface temperature maps which makes interpretation of details difficult). A survey north of the area of Figure 1 but of similar size was made during August, 1973 (La Violette, 1974) which did not reveal, however, any evidence for "shelf-break upwelling". Tomczak (1978) estimated upwelling intensity from the surface distribution of temperature and salinity for the coastal area south of Cap Vert to the northern end of the present investigation area at all seasons and again did not find "shelf-break upwelling". Data presented by Domain (1979) taken from records of the Meteosat satellite and covering the period February-September, 1978, show a narrow strip of slightly warmer water close to the shore during May and June.

Theoretically it is difficult to perceive why upwelling should not show maximum intensity inshore when conditions are favourable but be strongest in the vicinity of the shelf-break instead. Hsueh and Ou (1975) who studied possibilities for shelf-break and mid-shelf upwelling in a stratified linear model with β-plane dynamics came to the conclusion that shelf-break upwelling can occur as a result of Ekman layer veering near the bottom in the region of an equatorward offshore current and mid-shelf upwelling could result in situations of extreme baroclinicity on the shelf. They noted, however, that under conditions favourable for coastal upwelling the upwelling in the inshore boundary layer which is directly wind-driven is much stronger than the other two types of upwelling. This does not necessarily hold true in a situation where the surface Ekman layer "feels" the bottom, i.e. on a very shallow shelf where Ekman layer transport is directed downwind rather than at right angle. However, in coastal upwelling situations Ekman layers tend to be shallow, and Hughes and Tomczak (1979) presented evidence that during the 1975 experiment the surface and bottom boundary layers were well separate on the shelf, with an intermediate layer of purely barotropic longshore flow inbetween. It should also be noted that, as Barton *et al.* describe for the 1974 data, the coldest water is often observed, at the onset of an upwelling event, close to the shore and gradually moves across the shelf during the following days, giving rise to the temperature minimum at mid-shelf or close to the shelf-break. The fact that the minimum temperature can still decrease during this process is again taken as an indication for "shelf-break upwelling", but little attention is paid to the problem how the warmer inshore waters get there. In a two-dimensional scheme local heating is the only possibility. In a three-dimensional system longshore advection could be much more efficient, both in increasing inshore temperatures and in decreasing temperatures in the band of so-called "shelf-break upwelling". It will now be shown that the present data supply evidence for advection to play an important role in the area north of Cap Blanc and to make upwelling a highly three-dimensional process.

First of all, whenever an upwelling event occurs, the isotherms are not aligned along the isobaths but come closer inshore in the south than in the north (the same phenomenon can clearly be seen in the maps of Barton *et al.*). At the time of the upwelling event of 10-18 February strong southward currents were observed at current meter mooring BCM 1, the easternmost of the three northern moorings, which was located at 74 m water depth. These currents were of the order of 20-25 $cm.s^{-1}$ and in the direction of the band of cold water in which the mooring was located. Although current observations were restricted to depths of 39 m or more, it is reasonable to assume that an appreciable transport of water occurred along the axis of the band of cold water. This idea is supported by the southward progression of the mid-shelf temperature minimum during the event: During survey 3 it did not reach further south than 22°N, during surveys 4 and 5 it advanced to the southern end of the survey area and in survey 6 minimum temperatures were limited to the area south of 22°N; thereafter, the cold band broke up into patches. Further support comes from the observation that the northward undercurrent at CCM 2, the southern mooring, was dramatically interrupted at 59 m depth (which was the uppermost observation level) by southward flow of about 25 $cm.s^{-1}$ during 18-22 February when the remainder of the cold band swung westward at its southern end and came close to the position of CCM 2 (survey 7 of 20 February). This sudden change of current direction at CCM 2 was interpreted in Tomczak and Hughes (1980) as a burst of outflow from the shelf as a consequence of the large inflow at BCM 1. The surface temperature maps now suggest that southward flow was established earlier, inshore of CCM 2 along the position of the cold band, but swung seaward at the relaxation of upwelling.

Secondly, the southward advance of the cold band observed in surveys 3-6 is accompanied by northward motion of warm water, and immediately following the event a small parcel of water enters the area in the south and can be traced up the coast during surveys 7-9. What its origin and characteristics are is difficult to decide. T/S diagrams of inshore stations from the sections taken by "Discovery" and "Meteor" indicate that coastal water can have higher salinities than could be explained from upwelling, but a consistent pattern of a distinct coastal water mass is not evident from the data. The observed range of temperatures and salinities at inshore stations is shown in Figure 4. Distance from the coast ranges from 12 to 40 nautical miles on section B and from 3 to 20 nautical miles on section C. Highest salinities were observed on section B, some of which clearly fall out of the range of what is usually accepted as upwelled water. This range can be defined with the aid of T/S characteristics of the water masses at source level for the upwelling process which in the Canary Current upwelling system are North and South Atlantic Central Water, NACW and SACW, respectively. A detailed analysis of the "Auftrieb'75" data showed that the T/S-curves of these water masses in the upwelling region are defined by the straight lines labelled $NACW_{25}$ and $SACW_{21}$ (Tomczak, Hughes, 1980), and T/S ranges of upwelled surface water should fall between these two lines, apart from some surface heating which would shift the ranges upward in the figure. It seems thus likely that at least the water encountered at stations 3 654, 3 653 and 3 652 was not upwelled but of coastal origin.

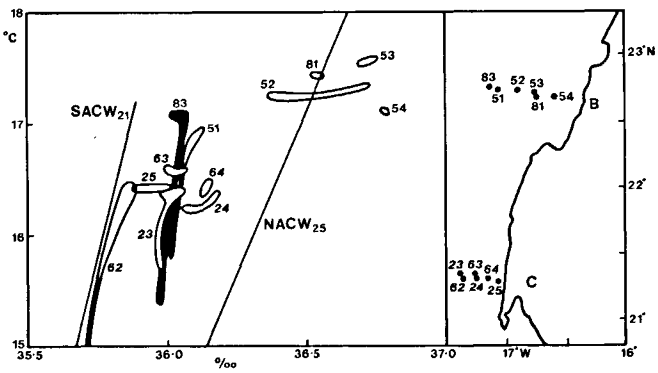

Figure 4

Envelopes of TS-values observed at inshore "Meteor" stations. Station numbers in italics refer to standard section C, upright station numbers refer to standard section B (add 3 600 to all station numbers to obtain true "Meteor" station numbers). $NACW_{25}$ and $SACW_{21}$ indicate water masses defined in Tomczak and Hughes (1980).

Unfortunately, all observations on section C were made before 9 February, i.e. before the onset of the apparent northward advance of warm coastal water. On section B, observations exist throughout the period covered by the remote sensing programme and stations closest inshore show salinities of $36.5^0/_{00}$ or above, but the lack of data on section C for the period of surveys 7-9 inhibits conclusions on the movement of the coastal water from shipborne data.

An attempt was made to extract information on the movement of upwelled and coastal waters from nutrient data. While it proved possible to trace water masses at the source level of upwelling (below 150-200 m depth) with a high degree of accuracy when nutrients are included in the analysis (Tomczak, in press), changes in nutrient concentrations due to biological activity prevented a simple interpretation in the surface layer. It was felt that researchers with expertise in marine biology could contribute to the understanding of the surface circulation, and this representation of temperature observations, wind and inferred circulation may be seen as an invitation to biologists to develop an interpretation of nutrient distributions which incorporates biological activity, recycling and advection.

Finally, advection of coastal water is strongly indicated by the observed development of temperature fronts. Fronts are observed quite frequently in coastal upwelling regions and are commonly thought to be the result of the thermocline outcropping at the surface as a consequence of intense upwelling (Mooers *et al.*, 1976 and 1978). Thus, such coastal upwelling fronts separate the upwelled water which is found on the inshore side of the front from the oceanic regime. Examples of this type of front can be seen in the present data during the upwelling event. Transect 4 of survey 6 possibly comes closest to the theoretical picture: It shows a temperature front between the band of cold upwelled water and the offshore regime and a gradual increase of temperature towards the coast. Most if not all transects which show a band of cold water, however, show fronts on either side of this band, with the front on the inshore side of it generally being much more strongly developed than the coastal upwelling front. The same phenomenon was reported for the observations of 1972 for which maximum gradients of 0.46-2.00°C.km^{-1} and overall gradients of 0.13-0.29°C.km^{-1} were derived (Tomczak, Miosga, 1976; the maximum gradient is calculated over the region of most rapid temperature change and the overall gradient from the minimum and maximum temperatures encountered in the band of cold water and the coastal water, respectively; see Figure 3 for an example). Table 2 lists gradients derived from the present data. Although overall gradients are smaller by a factor of 3, maximum gradients are comparable in size to those measured in 1972 (when the observations were made south of the survey area of 1975, off the Banc d'Arguin) and definitely larger than gradients encountered seaward of the band of cold water.

More evidence for the strength of the inner front in relation to the proper upwelling – or outer – front comes from colour photographs. A total of 520 pictures were taken during 8 surveys (no pictures during surveys 1 and 3), of which 114 were used for this study. Of these, 8 clearly showed the front between the cold band and the coastal water, 3 showed visible streak-like features within the cold band and 5 showed visible features close inshore (presumably suspended matter and/or depth variations). No visual indication of the outer (upwelling) front was observed. The observations of the inner front were made during surveys 4, 5 and 7 and showed structures similar to those published earlier for the area south of Cap Blanc (Tomczak, Miosga, 1976). The difference in water colour again suggests that the waters on both side of the front are of different origin.

Table 2
Observed frontal gradients in the coastal zone:

Survey No.	Transect No.	Observed steepest temperature step (°C/km)	Observed total temperature step (°C/km)	Normalised maximum gradient (°C/km^{-1})	Normalised overall gradient (°C/km^{-1})
4	4	1.00/2.5	1.10/ 5.0	0.40	0.22
	5	0.44/1.2	1.13/17.9	0.37	0.06
	6	0.46/1.1	1.40/16.2	0.42	0.09
	7	0.81/2.6	1.11/19.9	0.31	0.06
	8	1.27/4.6	1.54/12.3	0.28	0.13
5	3	0.75/2.2	1.25/20.9	0.34	0.06
	4	0.65/3.4	1.43/25.8	0.19	0.06
	6	1.44/0.8	2.39/13.0	1.80	0.18
	7	1.51/1.5	2.09/15.3	1.00	0.13
	8	0.71/5.0	1.78/40.7	0.14	0.04
6	7	0.80/2.1	1.64/14.4	0.38	0.11
	8	0.89/1.9	1.87/29.8	0.47	0.06

How the observed intense front inshore of the band of cold water could be formed in a two-dimensional upwelling scheme is difficult to imagine, even when "shelf-break" or "mid-shelf upwelling" is allowed for. It seems quite certain that a fairly strong surface convergence is needed to create and maintain the front in an area which, in the concept of two-dimensional upwelling, is governed by divergent surface flow. This is independent of any assumption on the development of upwelling in time and also holds true if slow southward propagation of the upwelling is allowed for. A convergence could be produced by longshore northward advection of coastal warm water against mid-shelf southward advection of upwelled cold water. The observed maximum gradients just north of Cap Blanc in the area where the largest horizontal current shear is then likely to occur and the northward decrease of the gradient support this interpretation.

The proposed mechanism does not imply that the observed surface temperature distribution does not reflect active upwelling. The observed advective movements of water masses are most likely caused by, or linked with, an upwelling event, and the band of cold water certainly is upwelled water. However, longshore variations of the topography and the driving forces give rise to a circulation which does not result in a local balance of cross-shelf mass transport [Halpern *et al.* (1977) calculated a net onshore transport as large as 2-3 times the offshore Ekman transport for the area under study during early 1974], and as a consequence, longshore advection is a necessary ingredient of coastal upwelling in this area. The increase of maximum correlation between successive profiles observed during the upwelling event, which is clearly linked with the development and sharpening of the fronts, could indeed be interpreted as an indication of increased advection. The results of the present data indicate that the idea of "mid-shelf" or "shelf-break upwelling" should be carefully reassessed for the northwest African shelf where the observations can be equally well, and perhaps more plausibly, interpreted in terms of longshore advection.

RESULTS: SURFACE WATERS VERSUS SOURCE WATER MASSES

Tomczak (1978) showed that it is possible to trace the surface waters of the Canary Current upwelling region back to the water masses encountered at the source level of the upwelling, North Atlantic Central Water (NACW) and South Atlantic Central Water (SACW), on the basis of their respective temperature/salinity characteristics. Tomczak and Hughes (1980) studied the distribution of NACW and SACW in the depth range 100-800 m (or more precisely the density range 26.40-27.37 σ_t) in detail and showed that both water masses undergo intensive mixing, particularly in the vicinity of line B, and that their distribution at those depths is extremely patchy. In the following section an attempt is made to link the distribution of water masses at the surface as it is reflected in the present observations to the subsurface water mass distribution.

The result of the analysis at subsurface levels can briefly be summarised as follows: NACW is found on line A and at distances of 60 or more nautical miles offshore on line C. SACW is found in the undercurrent on line A and inshore of the NACW area on line C. Both NACW and SACW are found, mixed to various degrees, on line B where the distribution of the water masses displays strong interleaving, patchiness and variability. A certain degree of patchiness is present on line C, too, but most of the mixing seems to occur between lines C and B. Patches of water which differ in NACW (or SACW) content by 30% or more from their surroundings can be as small as a few kilometres in horizontal and 50 m in vertical extent and were observed frequently. Sheets of water with similar water mass contrast may extend several tens of kilometres horizontally and up to 50 m vertically.

Because temperature alone is not a unique indicator of the water masses in the region, only limited conclusion can be drawn from the surface temperature maps. NACW is about 3.5°C warmer than SACW at the 26.4 σ_t level, and this difference decreases to about 2.5°C at 27.0 σ_t; but the same temperature variation is of course observed for NACW at different densities, for SACW at different densities or for intrusions of coastal water. It is therefore impossible to quantitatively determine the contributions of NACW and SACW from surface temperature maps. The maps should, however, reflect the water mass structure seen at source level unless the patches and sheets of water undergo significant changes while rising towards the surface.

Another look at Figure 2 with the above remarks in mind shows that at the surface, there is not much evidence for features of a few kilometres up to some tens of kilometres in extent and temperature changes of 1°C or more across. Evidently, such features are small compared to the distance between transects and, if present, could not be contoured properly with the present data. Some degree of smoothing was of course applied in the preparation of the maps, but comparison with Figure 3 proves that features suppressed by this procedure showed variations well below 0.5°C. Typical temperature changes at depths between 100 and 250 m along line B, on the other hand, over distances of typically 20 km, were well in excess of 1°C and should clearly show up in the maps if upwelled undistorted. As discussed earlier, it is unlikely that the banded structure of the temperature field is an artefact introduced by the subjective mapping of an ensemble of small-scale features. A tentative conclusion is that the distribution of water masses is different at source level and at the surface, and the question to be answered is what creates the difference.

As discussed in detail in Tomczak (1978), upwelled surface water in the area between Cap Blanc and 23°N is a mixture of NACW and SACW, in contrast to the area south of Cap Blanc where it is of SACW origin and north of 23°N where NACW can be traced as its origin. Thus, the entire area surveyed in 1975 is an area of intense mixing, and a difference in water mass structure at different depths could reflect differences in the conditions of mixing. At depths of 100-250 m patches of water are frequently advected into the area on isopycnal surfaces, surrounded by a very pronounced temperature/salinity front, and mixing seems to be weak (Tomczak, Hughes, 1980). The indications from the surface temperature maps are that in the upwelled water strong gradients are restricted to the offshore front, and to the front which separates it from the advected coastal water and do not seem to be linked with a patchy distribution of upwelled water.

Further support for differences in variability and mixing at different depths comes from temperature and salinity records obtained from a number of instruments on the moorings along lines B and C. Long-term salinity measurements on unattended moorings pose some specific problems which are discussed in the appendix. Figure 5 shows temperature and salinity at BCM 1, BCM 2, BCM 3 and CCM 2 after application of a low-

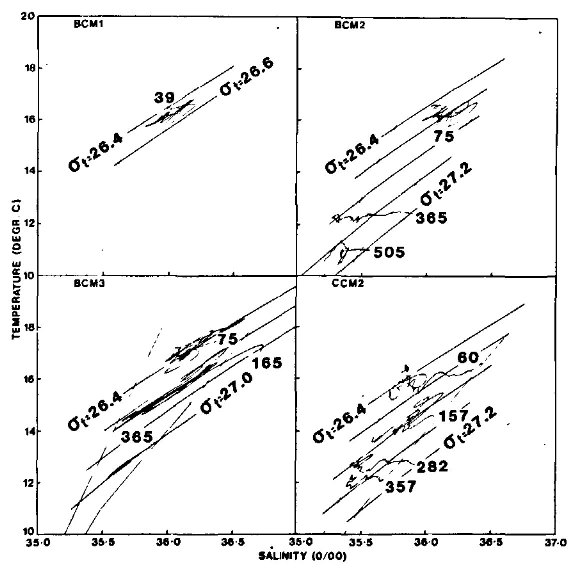

Figure 5

T-S-time diagrams from time series of temperature, conductivity and pressure at four moorings. The figure on each curve gives the depth of observation in metres and indicates the beginning of the diagram. The observations span approximately 30 days. Filter used: Cut-off frequency 0.03 cycles per hour, taper width 0.01 cycles per hour, number of weights 200, cosine taper. The thin lines are the T/S characteristics of NACW (lower) and SACW (upper) for the area.

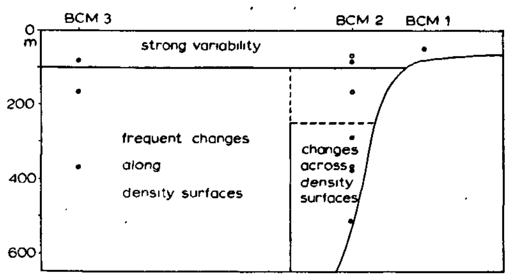

Figure 6
Variability characteristics in the Canary Current upwelling north of Cap Blanc. Dots and circles show the instrument depths, circles refer to CCM 2.

pass filter which cuts out tidal and inertial variations. The observations can be grouped into three distinct categories: In the surface layer, variations of temperature and salinity are quite irregular and cause variations in density of up to 0.4 units of σ_t. Below this layer, large variations of temperature and salinity which closely follow the lines of constant density are observed in the offshore area, whereas in the vicinity of the shelf-break the T-S-time diagrams display changes in temperature and salinity which very often produce significant changes in density.

Figure 6 gives a sketch of the situation. It will be noticed that the data points to support the scheme are scarce. Only two observation levels at BCM 3 can be presented as evidence for the large offshore area where changes of properties occur along density surfaces. On the other hand, the striking similarity of the T-S-time diagrams at the lower observation levels of BCM 2 and CCM 3 suggests that the proposed scheme might extend over considerable distances along the coast. The difference in variability below 100 m offshore and along the slope is probably smaller than apparent from Figure 6. Close to the shelf-edge the surfaces of constant density depart strongly from level surfaces, and a change of density in the diagrams might reflect the presence of a vertical or a cross-stream density gradient, i. e. vertical motion or a contraction or expansion of the undercurrent. All these processes were observed during the expedition (Tomczak, Hughes, 1980). When the effect of the sloping of the density surfaces is disregarded, the degree of variability is similar offshore and in the undercurrent. The difference between the surface layer and the deeper layer, on the other hand, is more fundamental and cannot be explained by a similarly simple argument.

It is of course impossible to determine the nature of the different mixing processes on the basis of the present data, but the data do suggest a basic difference between the distributions of water mass properties in the upwelling region at the surface and at source level which can only be maintained if the waters undergo important mixing on their way to the surface.

CONCLUSIONS

The Canary Current upwelling region has probably been one of the most intensely studied areas of the World Oceans for about a decade, and apart from new insight into the dynamics of coastal upwelling the regional peculiarities of the region emerged slowly during these years. No two coastal upwelling regions are completely alike, and to separate features which define the individual character of one region from properties common to all of them is a task which still requires extensive effort, both observational and theoretical. To achieve it on the basis of a comparison of a two-dimensional observation network is certainly impossible. With limited data temptation is always great to generalise and describe an observed feature as a basic ingredient of upwelling rather than a regional feature.

The present study tried to combine airborne observations with subsurface information in order to arrive at a three-dimensional picture. It supplied evidence that longshore advection of coastal water as well as of cold upwelled water is quite common during upwelling events along some 200 km of coast north of Cap Blanc, and that as a consequence of this type of circulation there is no need for any mechanism such as "mid-shelf" or "shelf-break upwelling" to explain the observations. Whether or not "shelf-break upwelling" is a phenomenon of importance in coastal upwelling in general is left undecided, but it is noted that more observational evidence from areas other than the vicinity of Cap Blanc is needed to make its importance likely. The study also supplied some evidence that the nutrient-rich waters undergo increased mixing during their rise to the surface. Again, it is left undecided whether this is a process of general significance to upwelling or a regional phenomenon linked with the particular distribution of water masses at source level.

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Processing and evaluation of conductivity records from the "Auftrieb 75" moorings as described in the appendix was done in cooperation with P. Hughes at the University of Liverpool.

APPENDIX

Treatment of conductivity records from current meter moorings

The instruments used on BCM 1, BCM 2, BCM 3 and CCM 2 were Aanderaa type current meters, fitted with conductivity cells and pressure sensors. The measurement of conductivity over periods of weeks on unattended moorings is liable to pose a number of problems, particularly for the calibration of the conductivity cells which can be altered by fouling in a non-reproducible manner. Some difficulties associated with the use of these sensors have been discussed by Huyer (1975). We devoted some effort to determine calibration curves as functions of time for the conductivity cells from comparison with CTD and STD casts obtained in the vicinity of the moorings. While this resulted in reasonable estimates for constant corrections for every instrument, it did not allow us to determine any calibration changes with time. Table A gives the amounts which were added to the calculated salinities in order to make them coincide roughly with the ship observations or, in the event of too few observations for comparison, to fit them into the range of $SACW_{21}$ and $NACW_{25}$ T-S values. We suspect that some of the salinity time series still contain a trend which can be due to a drift in the calibration.

A low-pass filter was applied to the corrected series, with cut-off at a period of 33 hrs. 20 min. and full response for periods above 50 hours. It should be pointed out that this procedure produces a slowly varying temperature and salinity series which describes the actual slowly varying mean temperature and salinity conditions only when the spatial gradients are uniform. In the vicinity of fronts, differences between actual mean properties and calculated filtered series might be significant. In the time series discussed here, such differences cannot be excluded. For example, the low-passed temperature at BCM 2 at 505 m i. e. 10 m above the bottom varies less than 1°C while the variation over a tidal period can be as much as 3.6°C. Similarly, variations in salinity at the 75 m level over the observational period were in excess of $0.8^0/_{00}$ compared to $0.42^0/_{00}$ which is the total variation in the filtered series. Thus, a high amount of energy is contained in high frequency oscillations and other processes suppressed by the applied filter, and a certain amount of distortion due to non-uniform spatial gradients must be expected.

Table A
Corrections applied to salinities from moored instruments.

Mooring No. (water depth)	Depth of instrument (m)	Correction applied ($^0/_{00}$)
BCM 1 (74 m)	39	None
BCM 2 (515 m)	75	None
	365	−0.10
	505	+0.07
BCM 3 (2015 m)	75	−0.15
	165	−0.45
	365 (*)	−0.78
CCM 2 (507 m)	60	−0.50
	157	−0.20
	282	−0.94
	357 (*)	−2.04

(*) No pressure record, salinity calculated with assumed constant pressure.

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