Cross-shelf circulation on the continental shelf off Northwest Africa during upwelling

by David Halpern,[1] Robert L. Smith[2] and Ekkehard Mittelstaedt[3]

ABSTRACT

During 10 March-6 April, 1974 simultaneous current records were obtained from 12 current meters, placed between 0.8 m and 67 m, in water approximately 75 m deep at 21°40′N, 17°18′W, about 32 km from the coast of Mauritania. Throughout the experiment the vertical stratification and horizontal density gradient were weak, and the winds were generally favorable for coastal upwelling. Vertical profiles of low-pass (cut-off frequency, f_c = 0.02cph) filtered currents were defined by a fifth-order least squares analysis. The thickness of the time-averaged near-surface flow was about 33 m. Throughout the experiment the onshore transport was always greater than the offshore transport, usually by a factor of 2 or 3. During a period of strong winds when the equatorward component of the near-surface wind stress was large, the onshore transport and the offshore transport tended toward balance but the onshore transport was still greater than the offshore transport by nearly 80%. When the winds were weak the flow was onshore throughout the water column with no significant vertical shear. None of the profiles of the low-frequency currents contained offshore flow at intermediate depths.

1. Introduction

Upwelling is a prominent process along the coast of northwest Africa, and is particularly strong near 20 N during winter and spring months when the prevailing surface winds blow from the north and northeast (Wooster *et al.*, 1976). Because the winds are not uniform in speed and direction, the process of upwelling is time-dependent. If for several days the winds are strong and more or less steady in a direction favorable for upwelling, near-surface drift currents may develop and be followed by considerable upwelling; this is sometimes referred to as a coastal upwelling event. One of the goals of the JOINT-1 Expedition to northwest Africa by the U.S. Coastal Upwelling Ecosystems Analysis (CUEA) program was the measurement of vertical profiles of horizontal currents in the upwelling region. One of the objectives was the determination of the relative importance of the two-dimensional (x-z plane) or three-dimensional nature of coastal upwelling dynamics for

1. Pacific Marine Environmental Laboratory, Environmental Research Laboratories, National Oceanic and Atmospheric Administration, Seattle, Washington, 98105, U.S.A.

2. School of Oceanography, Oregon State University, Corvallis, Oregon, 97331, U.S.A.

3. Deutsches Hydrographisches Institut, 2 Hamburg 4, West Germany.

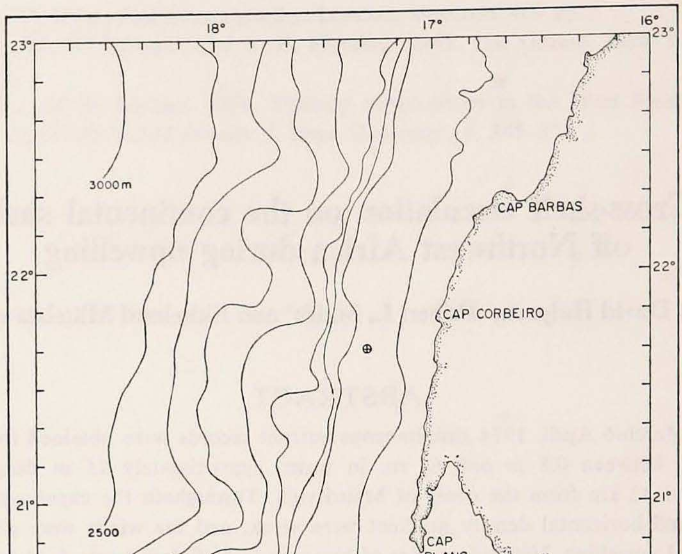

Figure 1. Location chart of the coastal and offshore region north of Cap Blanc and position (+) of moored array.

the event time scale and for the monthly time scale. The dynamics of coastal upwelling are considered to be two-dimensional (i.e., independent of alongshore variations) when the onshore transport is locally equal to the offshore transport. Another objective was to search for the existence of a "double-cell" circulation pattern for coastal upwelling, i.e., offshore flow near the surface and at intermediate depth. In this paper we describe the results of a small experiment designed to study the time variations of the vertical distribution of cross-shelf currents at a midshelf site. Relationships between the onshore and offshore transports are discussed *vis-à-vis* these experimental objectives. Papers by Mittelstaedt *et al.* (1975), Huyer (1976) and Halpern (1977) have discussed other results from the current measurement program during JOINT-1.

2. Experiment

The location of the experimental array was chosen to be a midshelf site because of the large wind-generated response of the near-surface circulation observed midshelf in the upwelling region off Oregon (Halpern, 1976a). Three moorings (*Lisa, Urbinia,* and *Weed*), separated from one another by less than 1 km, were placed at a nominal location of 21°40′N, 17°18′W, approximately 32 km from the coast of

Mauritania and about 18 km from the continental shelf break (Fig. 1). The water depth was about 75 m. In the vicinity of the moorings the isobaths were approximately parallel to the coastline and the transisobath slope of the shelf was about 4×10^{-4}. Very detailed bathymetric charts (from the Ashland Oil Company, Houston and Deutsches Hydrographisches Institut, Hamburg) indicate the isobaths through the mooring location tend 006° - 186° True on scales of 2 and 200 km. On the intermediate upstream scale of 20 km the tendency of the isobaths is 357° - 177° True. We have chosen to define the transisobath, or onshore-offshore, direction as 090° - 270° True, i.e., east-west.

The moorings were deployed and recovered at various times with the R. V. *Oceanographer* and R. V. *Gilliss*. Of the eighteen current meters mounted on *Lisa, Urbinia,* and *Weed,* twelve current meters provided data of excellent quality during a common 27-day period from 10 March to 6 April. Currents were measured at 0.8 m, 9.8 m, 12.0 m with AMF model 610 vector-averaging current meters (VACM) and at 16.2 m with a Geodyne model 850 current meter suspended from a surface mooring (*Lisa*), and at 23 m, 25 m, 31 m, 41 m, 45 m, 61 m, 65 m, and 67 m with Aanderaa model RCM4 current meters suspended from subsurface (18 m at *Weed,* 20 m at *Urbinia*) flotation.

The angle of tilt from the vertical of *Lisa*'s mooring line was measured with Humphrey model CP17 precision pendulum sensors. Because the tilt angles (~11°) corresponded to a small (<10%) speed correction factor (Richardson *et al.*, 1963), no correction was applied to *Lisa*'s AMF and Geodyne current measurements. Additional errors might have been produced by the motion of the surface float (Pollard, 1973; Gould and Sambuco, 1975) and by the nonlinear response of the current sensors to high frequency surface waves (Karweit, 1974). Although the accuracy of near-surface current meters beneath surface buoys has been questioned, interpretations of such measurements by Pollard (1974), Halpern *et al.* (1974) and Saunders (1976) have encouraged further experiments using vector-averaging current meters beneath surface buoys, at least for instruments placed near the surface.

An intercomparison of measurement techniques virtually identical to those used in this experiment showed negligible differences between measurements by VACMs below a surface buoy and Aanderaa current meters suspended from a subsurface (15m) float (Halpern *et al.*, 1974). A comparison of similar depth Aanderaa current records from *Urbinia* and *Weed* showed negligible differences. This encourages us to assume the data obtained here from the different meters and moorings are directly comparable. However, measurements from Aanderaa current meters placed below the depth of influence of surface wave motions might contain larger speed values if the uppermost extension of the subsurface moorings was affected by high frequency surface wave motions (Halpern and Pillsbury, 1976). If the effect were severe, we would expect to see significant differences between the current meters for the semidiurnal tide, which is known to be barotropic over the continental shelf

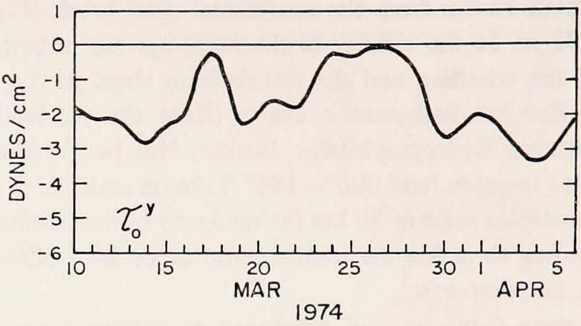

Figure 2. Low-pass (f_c = 0.02cph) filtered north-south component of near-surface wind stress.

in this region (Horn and Meincke, 1976). In the frequency band containing the semidiurnal tide there was little difference in the spectral estimates determined from the VACM and Aanderaa current records. This supports the assumption that the low frequency data is directly comparable among all current meters in this experiment.

3. Results

The wind record used in this study was a composite record which Mittelstaedt *et al.* (1975) made by combining measurements obtained at *Lisa* and *Urbinia* with data obtained at a meteorological mooring located 17 m eastward from *Lisa*. During 10 March to 6 April the vector-mean wind speed and direction was 8.1 m sec^{-1} toward 205°T, which is representative of the northeast trade wind regime. Wind-stress components were computed by the method described by Halpern (1976b), in which the 2 m level wind measurements from the meteorological buoys were referenced to 10 m height and a drag coefficient of 1×10^{-3} was used. The low-pass filtered (f_c = 0.02cph) north-south component of the wind stress (τ_0^y), which was usually much larger than the east-west component, is shown in Figure 2. The average value of τ_0^y was -1.8 dynes cm^{-2}. According to simple Ekman theory, a mean Ekman transport, directed offshore, of about 3.3×10^4 gm cm^{-1} sec^{-1} would result from the mean alongshore wind stress.

The mean current was predominantly southward in direction with a depth-averaged mean shear of about 0.002 sec^{-1}. The vector-averaged mean currents near the surface (~1 m) and close to the bottom were 32.1 cm sec^{-1} toward 192°T, and 19.3 cm sec^{-1} toward 146°T, respectively. The vertical profile of the vector-mean north-south (v; positive northward) component (Fig. 3) did not contain evidence of a subsurface northward flowing undercurrent, which is a characteristic feature of the circulation on the continental shelf off Oregon (Smith, 1974). The vertical distribution of the vector-mean east-west (u; positive eastward) current

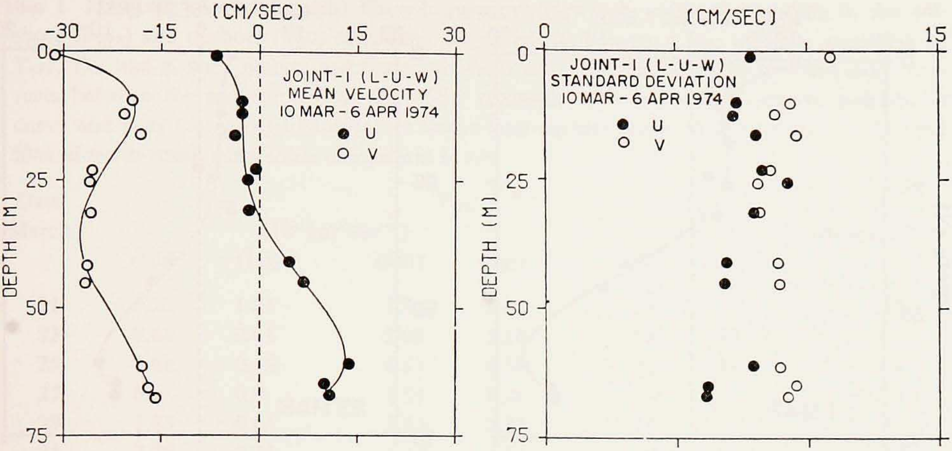

Figure 3. Vertical profiles of mean and standard deviation values of the east-west and north-south current components. A fifth-order curve has been fitted to the mean value.

component (Fig. 3) showed offshore motion above 33 m and onshore flow beneath this level. From the mean profiles the offshore transport is about 1.0×10^4 gm cm^{-1} sec^{-1}, while the onshore transport is about 3.2×10^4 gm cm^{-1} sec^{-1}, assuming the onshore velocity decreased linearly to zero from the deepest current observation at 67 m to the bottom at 75 m. Because the temporal variability (represented by the standard deviations) of the u-component was equal to or greater than the mean values (Fig. 3), the mean vertical profile of u cannot be taken as representative. Large temporal variations of the u-profile and in the onshore-offshore transport would be expected during the 27-day experiment. However, the standard deviation of the v-component was a factor 2 to 3 less than the mean values and the mean v-component profile adequately represents the alongshore flow throughout the period.

Each current record was divided into two frequency bands on the basis of the features of the kinetic energy density spectrum. Fluctuations with frequencies between 0.003cph and 0.02cph (333 hrs. to 50 hrs.) were called low-frequency variations. The high frequency interval contained the statistically significant inertial (32.5 hrs.), diurnal and semidiurnal period oscillations. The high frequency (frequencies > 0.02cph) fluctuations, which contained approximately 40% of the total variance, were removed from the records and the residuals then analyzed. For each u and v series, the Fourier coefficients were computed by means of the fast Fourier transform algorithm, the harmonics with frequencies > 0.02cph were subtracted, and the residual coefficients were retransformed to produce time-series of low-pass filtered current vectors.

During the period of the experiment the wind stress was generally greater than

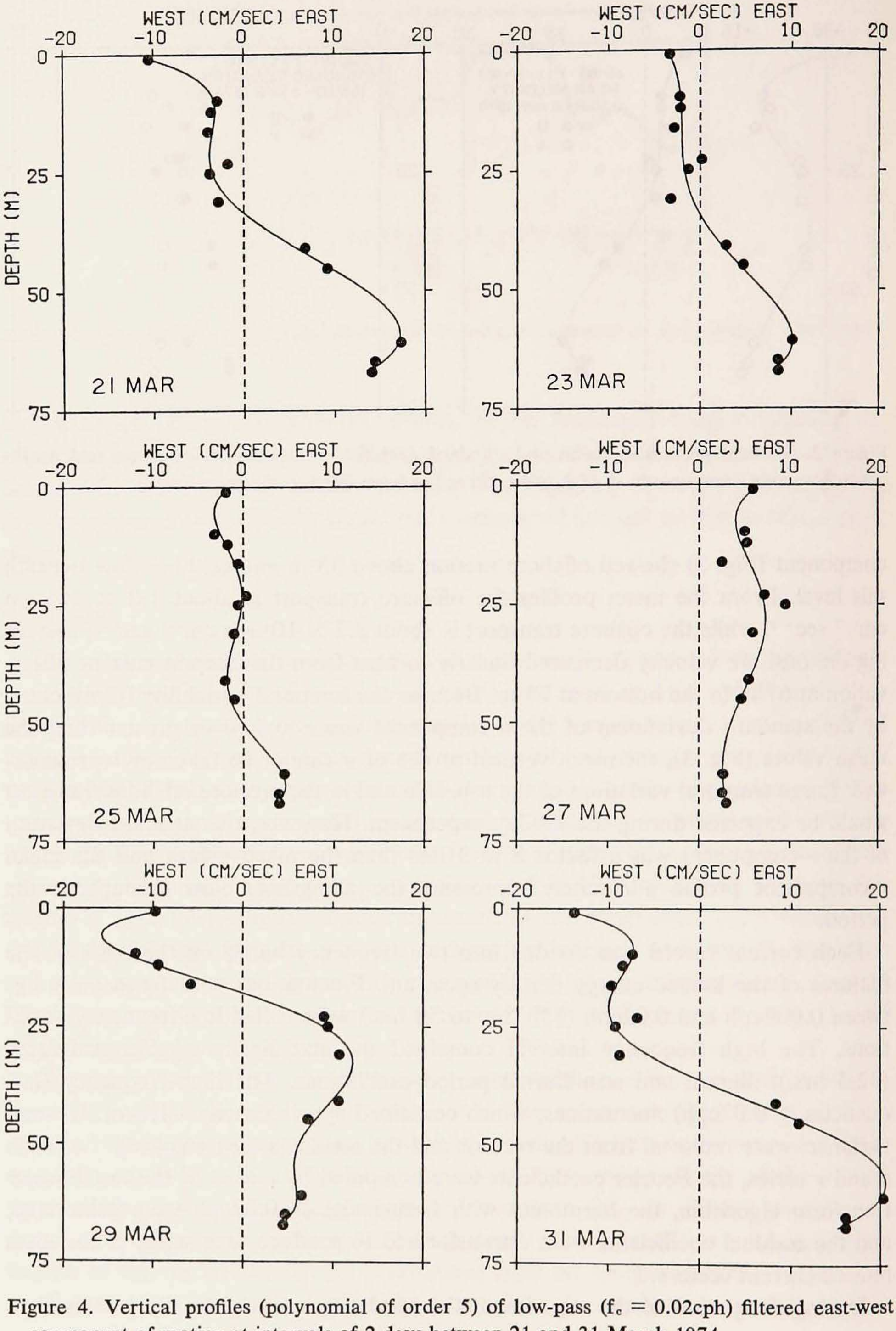

Figure 4. Vertical profiles (polynomial of order 5) of low-pass (f_c = 0.02cph) filtered east-west component of motion at intervals of 2 days between 21 and 31 March 1974.

Table 1. Low-pass (f_c = 0.02 cph) filtered transports per unit width of coastline in the offshore (T_{OFF}) and onshore (T_{ON}) directions. Depth of the bottom of the offshore motion is z_0. T_{OFF}, T_{ON} and z_0 were determined from two vertical profile curves of the low-frequency currents between the surface and 67 m: (5th) represents fifth-order least-squares polynomial curve and (1st) represents first-order or linear least-squares curve. Low-pass (f_c = 0.02 cph) filtered north-south wind stress component is τ_0^y.

Date March	T_{OFF} (5th)	T_{OFF} (1st)	T_{ON} (5th)	T_{ON} (1st)	z_0 (m) (5th)	z_0 (m) (1st)	τ_0^y (dynes cm^{-2})
	(10^4 cm^2 sec^{-1})						
21	1.20	1.24	3.82	3.26	34	27	−1.72
23	0.64	0.63	2.03	1.84	34	27	−0.95
25	0.68	0.48	0.51	0.57	51	34	−0.34
27	0.0	0.0	3.25	3.28	—		−0.10
29	1.83	0.65	3.83	2.22	19	23	−1.53
31	2.79	2.51	4.47	3.21	37	34	−2.30

1.8 dynes cm^{-2} except for brief intervals of light winds—which were followed by periods of equatorward winds of moderate intensity. This pattern is called an upwelling event. We have already noted the appreciable variability in the u-component. To examine the fluctuations in response to variations in the wind, we show vertical profiles of the low-pass filtered u-component for the period 21-31 March (Fig. 4). This period depicts an event cycle from moderate winds (21-23 March) to very light winds (24-27 March) increasing rapidly to strong upwelling favorable winds (28 March-1 April). The magnitude of the variations are striking, demonstrating the unrepresentativeness of a single profile or of even the mean profile. The onshore and offshore transports per unit width of coastline, and the depth (z_0) of zero u-component are given in Table 1. The low-pass values at 0000 GMT are given; these closely approximate what would be obtained with a 2 day running mean. Any contribution to the transport by flow beneath the deepest current meter was neglected. In the early stages of the analysis, the vertical profile was determined with a least-squares linear curve. However, because the linear curve did not adequately fit the data for 29 and 31 March (and for other times), higher order polynomial curves were used. A fifth-order curve appeared to fit the data best under all conditions. The transports were generally about equivalent whether calculated with first-order or fifth-order curve (Table 1), except on 29 March because of the large shear between 10 m and 25 m.

On 27 March the wind blew onshore with only a weak component. The water flow had an onshore component at all depths; the onshore component of the low-pass (f_c = 0.02cph) filtered transport per unit width of coastline was about 3.3 × 10^4 cm^2 sec^{-1}. With the onset of large equatorward wind stress on 28 March, the offshore transport increased from zero to 1.8 × 10^4 cm^2 sec^{-1} on 29 March and −2.8 × 10^4 cm^2 sec^{-1} on 31 March. The onshore transport now at depth did not increase equivalently. The depth of the bottom of the offshore motion increased from 0 m on 27 March, to 19 m on 29 March and 33 m on 31 March. On 31 March the onshore transport per unit width of coastline was nearly 60% larger than the offshore transport. Had we assumed either a logarithmetic layer or an Ekman layer velocity profile between the deepest current meter and the bottom, the onshore transport would have been 80%, or more, greater than the measured offshore transport. Even this slight tendency toward a two-dimensional balance was not typical since throughout the experiment the onshore transport was usually greater than the offshore transport by a factor of 2 or 3.

4. Discussion

Johnson *et al.* (1975) reported a "double-cell" cross-shelf circulation pattern and a thin surface layer of offshore flow from 2 days of profiling current meter observations made in August, 1972, at a midshelf site approximately 450 km north of our moored array (i.e., near Cabo Bojador). During their investigation the wind-stress was similar to the values we recorded during the 28 March event. The vertical stratification at midshelf was similar in the two regions; but at Cabo Bojador a weak frontal zone occurred over the continental shelf. At no time during our 27-day experiment on the continental shelf near Cap Corviero was a "double-cell" circulation pattern observed, not was it observed there in the profiling current meter observations made by Johnson (1976). Probably the closest approach to an intermediate-depth onshore flow occurred on 25 March, which coincided with a period of virtually calm winds. During summer off Oregon where the vertical stratification is large and a strong frontal zone exists over the shelf, Halpern (1976a) did not find evidence of a "double-cell" cross-shelf circulation, but Mooers *et al.* (1976) and Johnson *et al.* (1976) have reported the existence of a "two cell" pattern. Because these analyses were made on data recorded at different times, further studies seem warranted to explore the environmental conditions required for the cross-shelf circulation to change from a "one-cell" to a "two-cell" pattern.

The low frequency onshore transport per unit width of coastline was always larger than the offshore transport, usually by a factor of 2 or 3. The closest approach to a balance of the measured onshore and offshore transports occurred after the 28 March onset of strong equatorward winds, when the onshore transport was only 60% larger than the offshore transport. The distinction between cross-shelf flow and alongshore flow is not always clear because the definition of onshore-offshore direction depends on the coordinate system used. Earlier we noted that the bathymetric charts would allow choices of the onshore direction between 087° to 096° True, depending on the alongshore smoothing scale. A clockwise rotation from 090° to 095°, roughly that suggested by Figure 1, would increase the net onshore transport by about 50%, further aggravating the imbalance. To balance the mean measured onshore and offshore transport would require choosing an onshore direction of 082°, which is a greater counterclockwise rotation than can be justified through the uncertainty in either the current meter direction measurements or the bathymetry. Thus in any reasonably chosen coordinate system, there is a significantly large measured net onshore transport.

Without a 3-dimensional array of current meters it is difficult to speculate about the reason for the absence of a 2-dimensional mass balance. The magnitude of the imbalance between the local measured offshore and onshore transport is clearly time dependent, which suggests the possibility of coastal trapped waves playing a role, as has been suggested by Gill and Clarke (1974). Although the estimates of Ekman transport computed from the buoy wind measurements have a greater inherent uncertainty than any other numbers cited in this paper, the good agreement between the mean measured onshore transport in the lower layer and the estimated offshore Ekman transport in the upper layer suggests the lack of balance between the measured onshore and offshore transport is not simply the result of local bathymetry. Although the bathymetry off Peru is less regular than off northwest Africa, the 3-dimensionality of the current meter array in a recent experiment (JOINT-2 off Peru in 1976-1977) may allow us to better understand the 3-dimensional aspects of coastal upwelling.

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