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A comparison of upwelling events in two locations: Oregon and Northwest Africa

by Adriana Huyer[1]

ABSTRACT

Intensive observations of the low frequency (less than one cycle per day) response of upwelling regimes to fluctuations in the wind have been made in two locations: the Oregon coast near 45°15′N, and the Northwest African coast at 21°40′N. Both regimes show an equatorward coastal jet at the surface, quasi-barotropic fluctuations in the alongshore flow, and a poleward undercurrent. Off Oregon, where the transition between the continental slope and shelf is gradual, the undercurrent appears over the shelf as well as the slope, but off Northwest Africa, where the slope is steep and the shelf is shallow, the undercurrent is limited to the continental slope region. Both systems show a single layer of offshore flow at the surface, a single compensation layer of onshore flow at intermediate depth, and weak onshore or offshore flow near the bottom. Off Oregon, where the density stratification is strong, maximum onshore flow is just below the maximum vertical density gradient, which occurs in the upper half of the water column; off Northwest Africa, the stratification is weak and maximum onshore flow is in the lower half of the water column. Off Oregon, changes in the density field due to wind fluctuations are greatest near the surface and very near shore; off Northwest Africa, they penetrate to the bottom over the shelf. Off Oregon, maximum vertical velocities are greatest very near shore, and well above the bottom, but off Northwest Africa maximum vertical velocities occur near the bottom in the vicinity of the shelf break. The coldest surface waters observed at the end of an upwelling event lie along the coast off Oregon and just inshore of the shelf break off Northwest Africa. In both locations, circulation and stratification begin to change within a day after the wind changes, and continue to build up until the wind weakens. Since favorable wind events are both more intense and longer off Northwest Africa than off Oregon, the onshore-offshore circulation and vertical velocities at the end of an upwelling event are stronger off Northwest Africa.

1. Introduction

In recent years, intense efforts have been made to better understand the process of coastal upwelling. Upwelling occurs when there is a divergence in the surface current at the coastal boundary, usually because of offshore Ekman transport induced by alongshore wind stress. Periods when the alongshore component of the wind stress is enhanced to cause more offshore transport are called "upwelling

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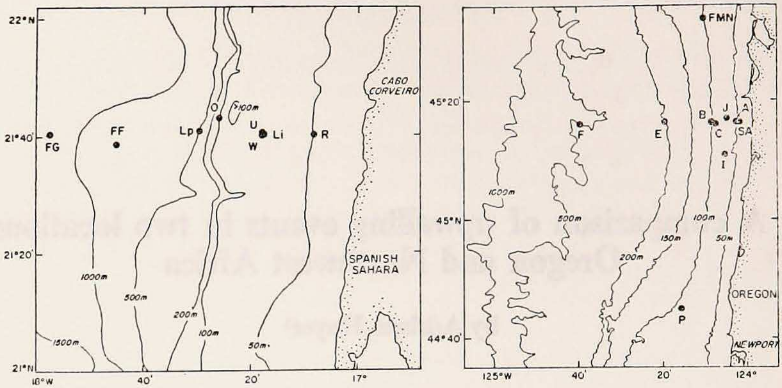

Figure 1. Location of the JOINT-I and CUE-II current meter arrays, off Northwest Africa and Oregon.

events" (e.g., Halpern, 1976). Recent intensive field studies now allow us to compare the effects of upwelling events in two locations: one off central Oregon, and the other off the Spanish Sahara near Cap Blanc. The purpose of this paper is to compare the response at low frequencies (less than one cycle per day) of the two systems to upwelling events, to find similarities and differences, and, if possible, to account for them.

Earlier studies (Jones, 1972; Halpern, 1974; Huyer, Smith and Pillsbury, 1974) had shown that significant temporal variations occurred in both locations. More complete descriptions of the low frequency changes resulted from CUE-II (Halpern, 1976; Wang, 1976; Holladay and O'Brien, 1975) and JOINT-I (Mittelstaedt, Pillsbury and Smith, 1975; Barton, Huyer and Smith, 1976). Both were experiments of the Coastal Upwelling Ecosystems Analysis program; CUE-II occurred during July and August 1973 at 45°15′N off Oregon, and JOINT-I occurred during March and April 1973 at 21°40′N off Northwest Africa (Fig. 1). The observations from both experiments have been published in data reports (Pillsbury *et al.*, 1974a; Huyer and Gilbert, 1974; Curtin, Johnson and Mooers, 1975; Curtin and Mooers, 1974, 1975; Johnson, 1976; Holbrook and Halpern, 1974; Halpern, Holbrook and Reynolds, 1974, 1976; Pillsbury *et al.*, 1974b; Barton, Stevenson and Gilbert, 1975). Details of the data collection and processing techniques are described in these reports; overall error estimates are about ± 2 cm $\sec^{-1}$ in currents (Halpern, Pillsbury and Smith, 1974), ± .02°C in temperature, ± .03‰ in salinity, and ± 1 m $\sec^{-1}$ in wind. In both experiments, winds were measured both ashore and from buoys, and the results of the two methods were very similar. All time series that are shown in this paper have been low pass filtered (with a half power point of 40 hours) to suppress diurnal and shorter period fluctuations.

There are important differences in the background in which upwelling events were observed in these locations: in latitude, shelf and slope topography, mean

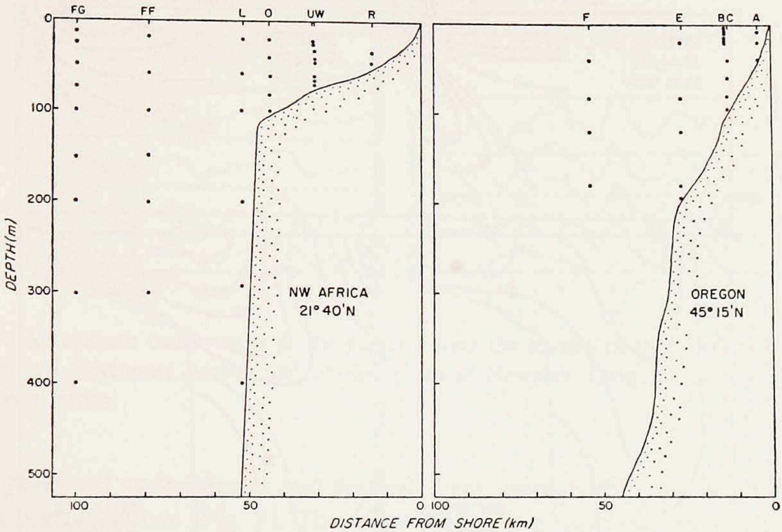

Figure 2. Bottom profiles along the main line of current meter moorings, CUE-II and JOINT-I.

stratification, seasonal wind patterns, and in the time scale and intensity of wind fluctuations. The difference in latitude, 45°N off Oregon and 22°N at Cap Blanc (Fig. 1) is reflected both in the strength of the Coriolis force, which increases with latitude, and in the seasonal wind patterns. Off Cap Blanc, the north-east trade winds predominate, and the monthly mean winds are favorable for upwelling all year (Wooster, Bakun and McLain, 1976); off Oregon the alongshore wind stress is predominantly southward (favorable for upwelling) from April through September, and northward (unfavorable for upwelling) from October through March (Bakun, 1973). During the upwelling season off Oregon, the wind fluctuates in both speed and direction, with periods of 3-7 days and speeds from about 0 to 8 m sec^{-1}. Off Northwest Africa, the wind direction remains nearly constant (favorable for upwelling), but its speed fluctuates from about 5 to 10 m sec^{-1} with periods of 7-10 days. The strong density stratification of the Northeast Pacific is enhanced off Oregon by the Columbia River plume, so that sigma-t increases from about 23.5 at the surface to 26.5 at 200 m (Huyer, 1976). Off Northwest Africa, the stratification is weaker: sigma-t increases from 26.2 at the surface to 26.7 at 200 m (Hughes and Barton, 1974).

In both locations, observations were made in regions of relatively simple bathymetry (Fig. 1), with local isobaths nearly parallel to the coastline. The bottom profiles in the vicinity of the observations (Fig. 2) show that the slope of the continental shelf is steeper off Oregon (a 1% slope) than off Northwest Africa (~ 0.3%), while the continental slope is less steep off Oregon (~ 3%) than off Africa (> 6%). Accordingly, there is a very well-defined shelf break off Africa but not off Oregon.

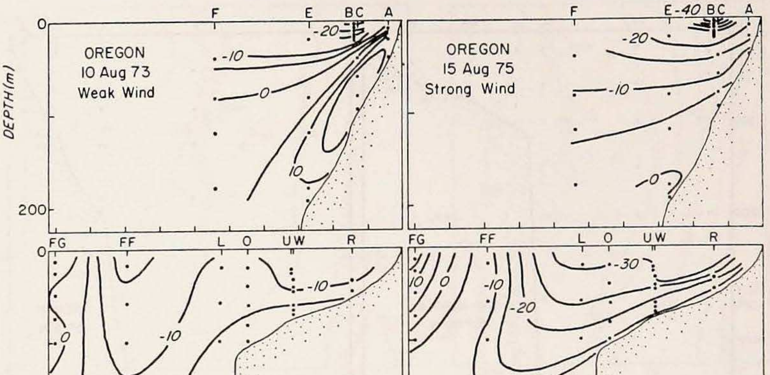

Figure 3. Distribution of the alongshore flow with weak wind and with strong favorable wind off Oregon and Northwest Africa. In both cases the contour interval is 5 cm sec^{-1}.

2. The alongshore flow

Off both Oregon and Northwest Africa the mean alongshore flow is southward at the surface, with a jet-like structure in the offshore direction, and decreasing with depth (Mooers, Collins and Smith, 1976; Smith, 1974; Huyer, Pillsbury and Smith, 1975b; Mittelstaedt *et al.*, 1975). A poleward undercurrent occurs over the continental slope off Northwest Africa (Mittelstaedt *et al.*, 1975) and over both shelf and slope off Oregon (Huyer *et al.*, 1975b; Huyer and Smith, 1976). Similar structure has also been observed at 26°N off Northwest Africa (Johnson *et al.*, 1975). The width of the southward "jet" can be only roughly estimated since the current meter moorings were about 10-20 km apart, but it appears to be about the same order as the Rossby radius of deformation, which is about 15 km off both Oregon and Northwest Africa (Mooers *et al.*, 1976; Mooers and Allen, 1973). Seaward of the upwelling regime, there may be eddies and other flow patterns which are not associated with coastal upwelling, as observed off Northwest Africa (Mittelstaedt *et al.*, 1975).

This basic structure of the alongshore flow field, including the southward surface

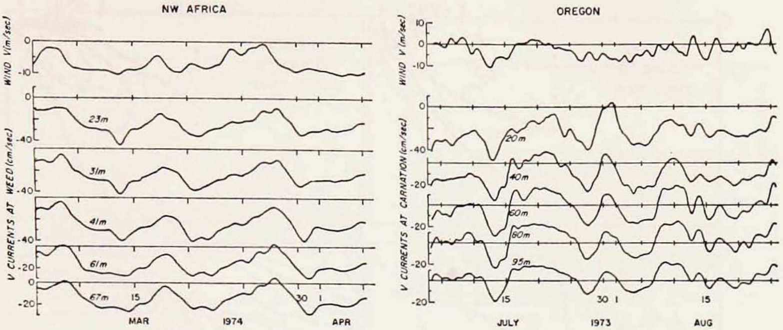

Figure 4. Alongshore components of the currents over the middle of the continental shelf off Oregon and Northwest Africa, and of the winds at Newport, Oregon and from buoys off Northwest Africa.

jet, the poleward undercurrent and vertical shear, persists throughout an upwelling event in both locations (Fig. 3). The main change is a quasi-barotropic strengthening of the southward flow (Huyer *et al.*, 1974; Smith, 1974; Kundu, Allen and Smith, 1975; Wang, 1976; Mittelstaedt *et al.*, 1975) which usually results in the strengthening of the coastal jet and the weakening or disappearance of the poleward undercurrent. Figure 4 demonstrates this relationship between the currents over the midshelf and the local wind. Off Northwest Africa, all changes in the currents appear to be associated with changes in the wind. Off Oregon, the current fluctuations are usually but not always (e.g., from 29 July to 2 August, 1973) related to changes in the wind. Such anomalies may reflect the presence of free continental shelf waves or similar phenomena which are believed to occur off Oregon (Cutchin and Smith, 1973; Huyer *et al.*, 1975a; Kundu *et al.*, 1975; Kundu and Allen, 1975).

3. Onshore-offshore flow

The JOINT-I observations off Northwest Africa encompassed three upwelling events. In each case a similar circulation pattern developed: offshore flow at the surface and down to about half the water depth over the shelf; onshore flow in the lower half of the water column over the shelf and in a layer sloping down to about 200 m over the slope; and offshore flow at the bottom over the slope (Mittelstaedt *et al.*, 1975). Figure 5 shows examples of the weak circulation over the shelf that occurs when the wind is weak, and the strong circulation that occurs near the end of an upwelling event.

Off Oregon, the onshore-offshore circulation (Fig. 5) is also weak when the local wind is not favorable for upwelling. After several days of favorable winds, the circulation is much stronger, with onshore velocities exceeding 10 cm/sec at midshelf. The offshore flow occurs in a shallow surface layer, less than 20 m thick. The on-

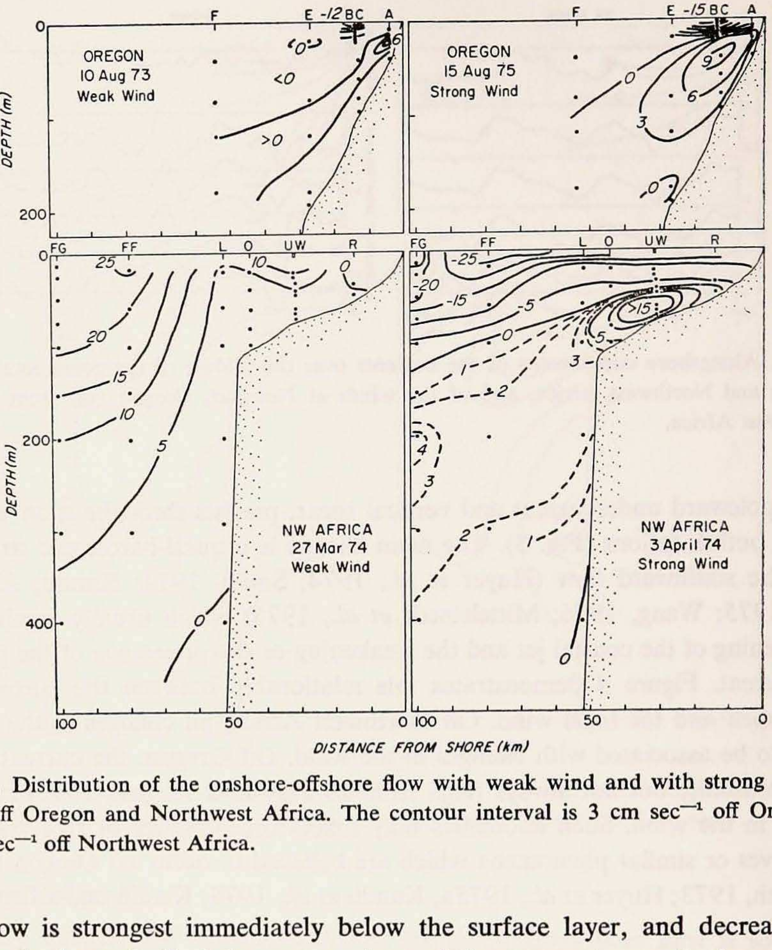

Figure 5. Distribution of the onshore-offshore flow with weak wind and with strong favorable wind off Oregon and Northwest Africa. The contour interval is 3 cm sec^{-1} off Oregon and 5 cm sec^{-1} off Northwest Africa.

shore flow is strongest immediately below the surface layer, and decreases with depth in the lower half of the water column; it is strongest over the inner part of the shelf.

In both experiments, there were adjacent moorings at the midshelf so that current meters spanned the entire water column there. The current meters below 20 m were moored from subsurface flotation as usual (Pillsbury *et al.*, 1974a, b). Shallower current meters were moored from a surface buoy (Halpern *et al.*, 1974, 1976); those closest to the surface were AMF vector averaging current meters. The time variation of the onshore flow (Fig. 6) indicates the depth of maximum onshore flow is fairly stable in both regions: off Oregon, it remains just below the offshore layer, and off Northwest Africa it is in the lower part of the water column. Off Northwest Africa, the onshore flow increases and decreases in obvious response to the wind: the strength of the circulation continues to increase until the alongshore wind stress achieves its maximum, and decreases when the wind stress decreases, even though its direction remains favorable. Off Oregon, the onshore flows seems

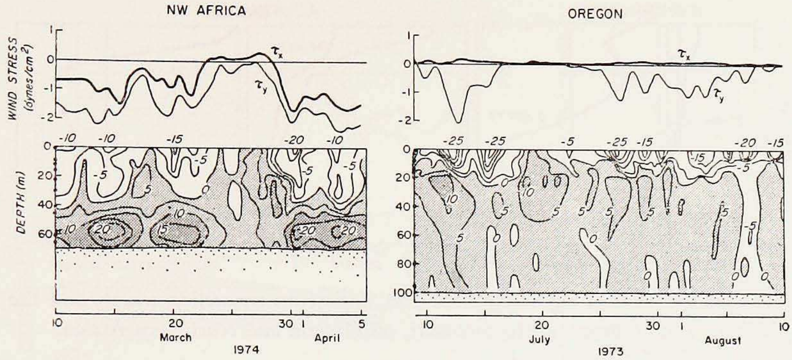

Figure 6. Components of the wind stress, and contours of the onshore flow from current meters at the midshelf on a time-depth plane, for Oregon and Northwest Africa. Wind observations are from Newport, Oregon and from buoys off Northwest Africa. Current observations are from Carnation and Buoy B (CUE-II) and Weed, Urbinia and Lisa (JOINT-I). The contour interval is 5 cm sec^{-1} in both cases.

much more erratic. During major upwelling events (e.g., 11-12 July, 26 July, and 15 August), both onshore and offshore flow increase when the wind increases, and decrease when the wind decreases. However, there are other periods when the onshore flow increases during weak unfavorable winds (e.g., 18-20 July) and when the onshore flow appears to be weak during fairly strong favorable winds (2-3 August). This may in part be due to sampling problems: the layer of strong onshore flow is thin, and the maximum onshore velocity could easily be underestimated with the 20 m vertical spacing of the current meters. There are a number of occasions when the flow at all depths is either onshore or offshore; these might be associated with continental shelf waves since the barotropic mode of the onshore flow lags the alongshore flow by 90° (Kundu *et al.*, 1975). Near the bottom, the direction of the onshore-offshore component is consistent with Ekman veering off both Oregon (Kundu, 1976) and Northwest Africa (Mittelstaedt *et al.*, 1975): it tends to be onshore when the alongshore flow is southward and offshore when the undercurrent is present.

Wind fluctuations have shorter periods off Oregon than off Africa, and maximum winds are weaker. As a result, the onshore-offshore circulation at the end of an upwelling event is much stronger off Africa than off Oregon.

4. Stratification

Isopycnals which slope upward toward the coast have long been used as indicators of coastal upwelling. Off Africa such an upward slope is observed down to 200 m, and offshore beyond the shelf to as much as 80 km from the coast (Barton, Pillsbury and Smith, 1975). Off Oregon, isopycnals slope down to about 150 m, about 60 km offshore (Barstow, Gilbert and Wyatt, 1969). The stratification over

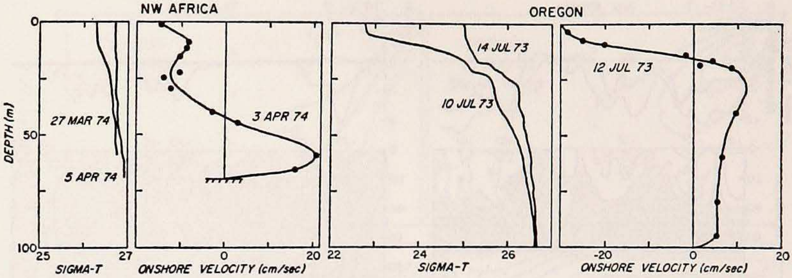

Figure 7. Vertical profiles of sigma-t before and during an upwelling event, and the onshore flow at the height of an event, at the midshelf, off Oregon and Northwest Africa.

the shelf (Fig. 7) is weak off Northwest Africa (sigma-t increases from 26.3 at the surface to 26.7 at the bottom) but stronger off Oregon (sigma-t increases from 23.0 to 26.6); the depth of maximum vertical density gradient is much shallower off Oregon than off Northwest Africa. The depth of maximum density gradient seems to coincide with the bottom of the layer of offshore flow (Fig. 7).

Off Northwest Africa, the distribution of sigma-t (Fig. 8) changes significantly down to the bottom over the shelf and upper slope during a wind event (Barton *et al.*, 1976). In contrast, the density distribution off Oregon changes a great deal in the upper 30 m and very near shore but much less at greater depths (Huyer *et al.*, 1974; Halpern, 1976). Off Oregon, the greatest changes occur very near shore, essentially along the coast. Off Northwest Africa, the greatest changes occur just inshore of the shelf break. The sea surface temperature has similar patterns: off Oregon, the coldest water is almost always adjacent to the coast (Holladay and O'Brien, 1975) but off Northwest Africa, the coldest water lies just inshore of the shelf break at the end of an upwelling event (Barton *et al.*, 1976).

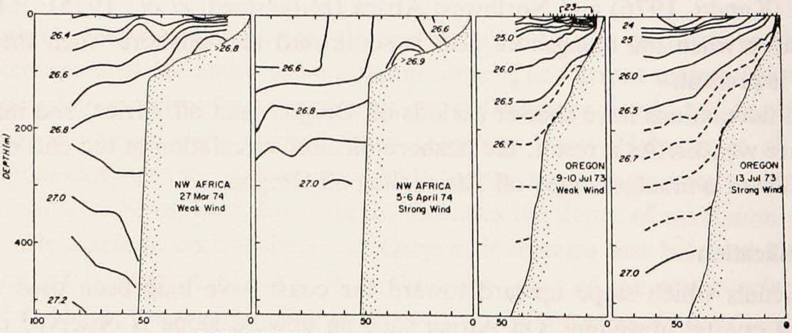

Figure 8. Distributions of sigma-t with weak wind and with strong favorable wind, off Northwest Africa and Oregon. The contour interval is 0.1 off Northwest Africa and 0.5 off Oregon, with additional (dashed) contours at 26.6, 26.7, 26.8 and 26.9.

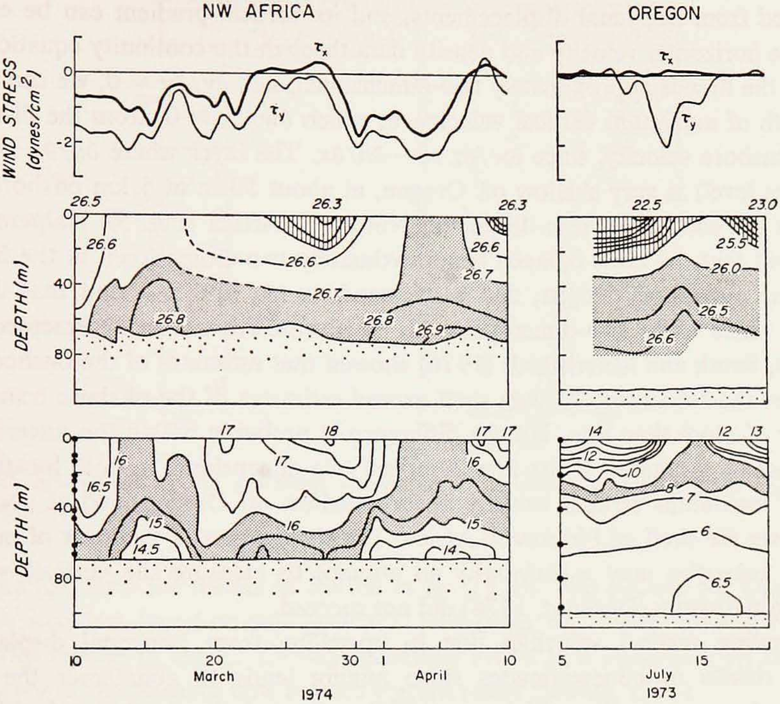

Figure 9. Wind stress components and contours of sigma-t (from CTD data) and of the temperature (from moored current meters) at midshelf, for Northwest Africa and Oregon. The contour interval for sigma-t is 0.1 off Northwest Africa and 0.5 off Oregon; the temperature contours are at intervals of 0.5 C off Northwest Africa and 1.0 C off Oregon.

The temporal variation of the sigma-t profiles at midshelf was inferred from frequent hydrographic casts (Fig. 9). Off Northwest Africa, isopycnals at all depths descend with weakening winds and rise with increasingly favorable upwelling wind; one of the isopycnals (26.7) migrates over the entire water column. The short-interval time series off Oregon in 1973 spans only one upwelling event, but the observations are typical of other events observed in 1972: with upwelling favorable winds, isopycnals in the upper 20-30 m rise rapidly and soon intersect the surface; with weakening winds, near surface isopycnals fall and less dense water reappears at the surface; isopycnals at mid-depth rise and fall but never intersect either the surface or the bottom. Temperature observations from the moored current meters (Fig. 9) show very similar patterns; some isotherms off Northwest Africa migrate over most of the water column, but most isotherms at the midshelf off Oregon migrate less than 20 m during an upwelling event.

5. Vertical velocities

The vertical velocity was not measured directly in either experiment. It may be estimated from isopycnal displacements, and its vertical gradient can be estimated from the horizontal velocity and density data through the continuity equation. If we assume the flow is approximately two-dimensional, i.e., $\partial v/\partial y = 0$, we can estimate the depth of maximum vertical velocity, at which $\partial w/\partial z = 0$, from the distribution of the onshore velocity, since $\partial w/\partial z \cong -\partial u/\partial x$. The layer where $\partial u/\partial x \cong 0$ (isotachs are level) is very shallow off Oregon, at about 10 m at 5 km offshore and at 20 m at the shelf edge; it is deeper off Northwest Africa (Fig. 5). Halpern (1976) has found that the mass balance is approximately two-dimensional at the height of upwelling events off Oregon, and Mittelstaedt *et al.*, (1975) found that the mass balance tends to be two-dimensional off Northwest Africa. In a presented paper, Halpern, Smith and Mittelstaedt (1976) showed that estimates of the onshore transport over the Northwest African shelf exceed estimates of the offshore transport by a factor of more than two, but the difference is probably within the uncertainty of the transport estimates. If the flow is indeed two-dimensional in both locations, the layer of maximum vertical velocity is very shallow off Oregon, and at about mid-depth over the shelf off Northwest Africa. The shallowness of the layer of maximum upward velocities may explain why an attempt to measure the vertical velocities off Oregon directly (Deckard, 1974) did not succeed.

Estimating vertical velocities due to upwelling from isopycnal displacements usually results in underestimates since mixing tends to counteract the density changes due to upwelling. Halpern (1976) estimated the vertical velocities from isopycnal displacements during the 12-15 July, 1973 upwelling event off Oregon: he showed that the vertical displacement of the 26.0 sigma-t surface decreased with distance from shore, with corresponding vertical velocities of 2×10^{-2} cm sec^{-1} at 3 km from shore and 0.5×10^{-2} cm sec^{-1} at 30 km from shore. This surface is below the level of maximum vertical velocity as determined above, but shallower isopycnals which intersect the surface during the event indicate a similar decrease of the vertical velocity with distance from shore. The maximum upward velocity during an upwelling event seems to be about 5×10^{-2} cm sec^{-1}. Off Northwest Africa, the most intense ascending motions seem to occur right at the shelf break, at about 150 m depth (Mittelstaedt *et al.*, 1975). From isopycnal displacements, Barton *et al.* (1976) estimated the vertical velocity there to be about 10^{-1} cm sec^{-1} at the height of an upwelling event.

Weakening of the favorable winds results in weaker onshore and vertical velocities. At some point, the weaker upward velocities are not sufficient to overcome the effects of mixing and lateral advection, and isopycnals descend. Net downward velocities probably occur only when the wind direction is unfavorable for upwelling.

Schematics of the upwelling circulation at the height of an upwelling event are presented in Fig. 10. These show the qualitative relationship between the vertical velocities and the onshore flow, and the regions where vertical velocities are strongest. The pattern for Northwest Africa is from Mittelstaedt *et al.* (1975), and

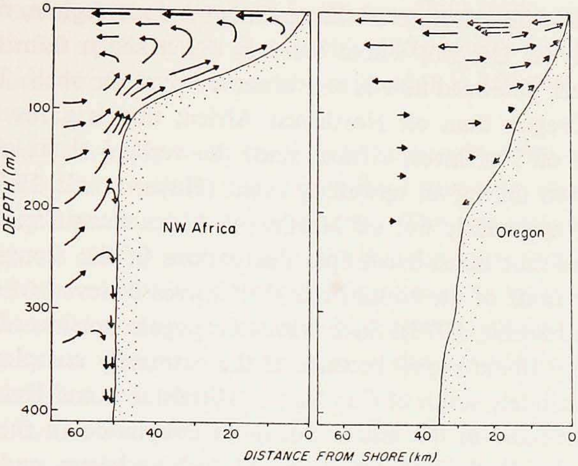

Figure 10. Schematics of the upwelling circulation for Northwest Africa (from Mittelstaedt *et al.*, 1975) and Oregon.

it is consistent with the results of Barton *et al.* (1976). The pattern for Oregon is a new interpretation, based on data presented here (Figs. 6, 7 and 8) and on Halpern's (1976) description of the 12-15 July upwelling event; it is supported by the three-week means of the onshore flow at each current meter (Myers, 1975).

6. Discussion

Similarities in the way the two systems respond are apparent in the general structure of the alongshore and onshore flow, and in the rapidity with which both circulation and stratification reflect changes in the wind. In both cases, the structure of the alongshore flow persists through fluctuations in the wind; both show an equatorward coastal jet whose width is the order of the width of the continental shelf, a poleward undercurrent, and relatively stable vertical shear. The alongshore flow of both regimes exhibits quasi-barotropic fluctuations which are similar to fluctuations in the wind. The onshore-offshore circulation patterns in both regimes have offshore flow in a single layer at the surface, a single compensation layer with maximum onshore flow at some intermediate depth, and weak, frictionally governed flow along the bottom. In both locations, the circulation and stratification changes lag the wind by less than a day. In both cases, the upwelling circulation seems to be more-or-less balanced in a two-dimensional (vertical, offshore) plane. These features, which are common to the two systems, may be representative of all coastal upwelling regimes with fairly uniform shelf topography.

Significant differences in the alongshore flow regimes of the two regions include differences in the position of the undercurrent, the strength of the vertical shear, and the occurrence of fluctuations not attributable to changes in the wind. The undercurrent seems to be a feature of the continental slope regime, rather than of the continental shelf; off Oregon, where there is not a sharp transition between the slope and the shelf, poleward flow is also observed over the shelf. The vertical shear is stronger off Oregon than off Northwest Africa; this is a result of the weaker density gradients off Northwest Africa, since the vertical shear obeys the thermal wind equation even during an upwelling event (Huyer *et al.*, 1974; Smith, 1974). Off Oregon (but apparently not off Northwest Africa near Cap Blanc), there are occasionally significant quasi-barotropic fluctuations in the alongshore flow which may be manifestations of the continental shelf waves believed to occur off Oregon (e.g., Cutchin and Smith, 1973). Such waves propagate northward and may not be present in the Cap Blanc region because of the extremely complex shelf and slope topography immediately south of Cap Blanc (Mittelstaedt and Koltermann, 1973).

The main differences in the onshore-offshore circulation in the two regions are the difference in the depth of the offshore and onshore layers, and the difference in intensity of the convergence of the onshore flow at depth. The depth of the offshore Ekman flow layer off Oregon seems to be limited by the strong shallow pycnocline; off Northwest Africa the circulation over the shelf is more nearly as expected in a homogeneous fluid. Probably also because of the stratification, the depth of the compensation layer and the maximum onshore flow is shallower off Oregon than off Northwest Africa. Off Africa, much of the compensation layer offshore is deeper than the shelf break. As a result, there is strong convergence of the onshore flow with resulting large vertical velocities just seaward of the shelf break. Off Oregon, the compensation layer is not as deep as the shelf break, and the strongest convergence zone occurs where the shelf is steepest, within 10 km of shore. The difference in the intensity of the onshore flow (stronger off Northwest Africa) at the end of an upwelling event is due to the greater strength and duration of the wind event.

Off Oregon, there is often a surface convergence zone over the continental shelf, not far seaward of the surface divergence. Its presence has been inferred from hydrographic and optical observations (Pak, Beardsley and Smith, 1970; Mooers *et al.*, 1976; Huyer and Smith, 1974), and it has been observed directly by means of surface drogues (Stevenson, Garvine and Wyatt, 1974). The low frequency current data from the current meters do not provide additional evidence, perhaps because they are too deep, or too widely separated, or because the convergence occurs only over periods shorter than a day. No surface convergence was observed over the continental shelf off Northwest Africa. The occurrence of a surface convergence zone may depend on the presence of a strong horizontal density gradient at the surface; these are weak off Northwest Africa and strong off Oregon.

Perhaps the greatest difference in the response of the two regions occurs in the density and other hydrographic fields. Off Northwest Africa, temporal variations of the density due to wind events penetrate to 150 m, well beyond the shelf edge.

Off Oregon, the density changes associated with upwelling events are usually limited to about the upper 30 m. Although part of this difference is due to the difference in intensity and duration of the wind events, most of it is believed to be due to the difference in the stability.

Results presented here apply to a very limited time scale—that of days to weeks. Shorter period fluctuations, such as tidal and inertial processes and their interaction with upwelling, may also be of great importance. The two-celled circulation proposed by Mooers *et al.* (1976) may be valid for these shorter scale processes (Johnson, Van Leer and Mooers, 1976) although it does not seem valid for the time scale examined here. Seasonal time scales are also important, particularly for the coastal jet and the undercurrent. Neither of these time scales has yet been sufficiently examined to warrant a similar comparison.

In this paper I have attempted only to describe the qualitative similarities and differences in the two regions. There has been no effort to relate the differences in dynamics to any of the numerous theoretical and numerical models of coastal upwelling and its variability (e.g., Peffley and O'Brien, 1976; Thompson and O'Brien, 1973; Gill and Clarke, 1974; Allen, 1976; Pedlosky, 1974). Such a study could shed a great deal more light on the dynamics of coastal upwelling, and I hope (and expect) that it will be undertaken in the near future by someone more qualified. Meanwhile, this paper may be useful, both to upwelling ecosystems analysts, and to guide continuing observations of other coastal upwelling regions.

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REFERENCES

Allen, J. S. 1976. Some aspects of the forced wave response of stratified coastal regions. J. Phys. Oceanogr., *6*, 113–119.

Bakun, A. 1973. Coastal upwelling indices, west coast of North America, 1946-71. NOAA Tech. Rept. NMFS SSRF-671, 103 pp.

Barstow, D., W. Gilbert and B. Wyatt. 1969. Hydrographic data from Oregon waters, 1968. Department of Oceanography, Oregon State University, Ref. 69-6, 84 pp.

Barton, E. D., A. Huyer and R. L. Smith. 1976. Temporal variations observed in the hydrographic regime near Cabo Corveiro in the NW African upwelling region, February-April 1974. Deep-Sea Res., in press.

Barton, E. D., R. D. Pillsbury and R. L. Smith. 1975. A compendium of physical observations from JOINT-I. Vertical sections of temperature, salinity and sigma-t from R. V. *Gilliss* data and low-pass filtered measurements of wind and currents. School of Oceanography, Oregon State University, Ref. 75-17, 60 pp.

Barton, E. D., M. R. Stevenson and W. E. Gilbert. 1975. CTD/STD measurements off the NW

African coast near Cabo Corveiro during JOINT-I. R. V. *Gilliss* cruise GS7401, Feb. 9-Apr. 23, 1974. School of Oceanography, Oregon State University, Ref. 75-3, 102 pp.

Curtin, T. B., W. R. Johnson and C. N. K. Mooers. 1975. Coastal Upwelling Experiment—II, hydrographic data report. R. V. *Yaquina* cruises R7307-B and C7308-A (15-18 July and 16-20 August 1973); R. V. *Cayuse* cruise C7308-E (18-31 August 1973). Rosenstiel School of Marine and Atmospheric Science, University of Miami, UM-RSMAS 75003, 100 pp.

Curtin, T. B. and C. N. K. Mooers. 1974. Coastal Upwelling Experiment—I and II. Surface hydrographic fields data report. Rosenstiel School of Marine and Atmospheric Science, University of Miami, UM-RSMAS 74026, 94 pp.

—— 1975. Coastal Upwelling Experiment—II. Profiling current meter data report: R. V. *Yaquina* cruises Y7307-B, Y7307-D and Y7308-A (15-18 July, 29 July-6 August, and 16-20 August 1973). Rosenstiel School of Marine and Atmospheric Science, University of Miami, UM-RSMAS 75002, 179 pp.

Cutchin, D. L. and R. L. Smith. 1973. Continental shelf waves: Low-frequency variations in sea level and currents over the Oregon continental shelf. J. Phys. Oceanogr., *3*, 73–82.

Deckard, D. E. 1974. Vertical current measurement in the Oregon coastal upwelling region. M.S. thesis, School of Oceanography, Oregon State University, 57 pp.

Gill, A. E. and A. J. Clarke. 1974. Wind-induced upwelling, coastal currents and sea level changes. Deep-Sea Res., *21*, 325–345.

Halpern, D. 1974. Variations in the density field during coastal upwelling. Téthys, *6*, 363–374.

—— 1976. Structure of a coastal upwelling event observed off Oregon during July 1973. Submitted to Deep-Sea Res.

Halpern, D., J. R. Holbrook and R. M. Reynolds. 1974. A compilation of wind, current, and temperature measurements: Oregon, July and August 1973. Pacific Marine Environmental Laboratory/NOAA, University of Washington, Tech. Rept. 6, 190 pp.

—— 1976. A compilation of wind, current and temperature measurements near Spanish Sahara during March and April, 1974. Pacific Marine Environmental Laboratory/NOAA, University of Washington, Tech. Rept. 10, 100 pp.

Halpern, D., R. D. Pillsbury and R. L. Smith. 1974. An intercomparison of three current meters operated in shallow water. Deep-Sea Res., *21*, 489–497.

Halpern, D., R. L. Smith and E. Mittelstaedt. 1976. Vertical profiles of low-frequency currents in the Northwest African upwelling region. E⊕S, 57, pp. 263. Abstract only.

Holbrook, J. R. and D. Halpern. 1974. STD measurements off the Oregon coast (July/August 1973). Pacific Marine Environmental Laboratory/NOAA, University of Washington, Data Rept. 12, 397 pp.

Holladay, C. G. and J. J. O'Brien. 1975. Mesoscale variability of sea surface temperatures. J. Phys. Oceanogr., *5*, 761–772.

Hughes, P. and E. D. Barton. 1974. Stratification and water mass structure in the upwelling area off N.W. Africa in April/May 1969. Deep-Sea Res., *21*, 611–628.

Huyer, A. 1976. Seasonal variation in temperature, salinity and density over the continental shelf off Oregon. Submitted to Limnol. Oceanogr.

Huyer, A. and W. E. Gilbert. 1974. Coastal Upwelling Experiment hydrographic report, June-August 1973. School of Oceanography, Oregon State University, Ref. 74-8, 102 pp.

Huyer, A., B. M. Hickey, J. D. Smith, R. L. Smith and R. D. Pillsbury. 1975a. Alongshore coherence at low frequencies in currents observed over the continental shelf off Oregon and Washington. J. Phys. Oceanogr., *80*, 3495–3505.

Huyer, A., R. D. Pillsbury and R. L. Smith. 1975b. Seasonal variation of the alongshore velocity field over the continental shelf off Oregon. Limnol. Oceanogr., *20*, 90–95.

Huyer, A. and R. L. Smith. 1974. A subsurface ribbon of cool water over the continental shelf off Oregon. J. Phys. Oceanogr., *4*, 381–391.

—— 1976. Observations of a poleward undercurrent over the continental slope off Oregon, May-June 1975. E⊕S, 57, p. 263. Abstract only.

Huyer, A., R. L. Smith and R. D. Pillsbury. 1974. Observations in a coastal upwelling region during a period of variable winds (Oregon coast, July 1972). Téthys, *6*, 391–404.

Johnson, D. R., E. D. Barton, P. Hughes and C. N. K. Mooers. 1975. Circulation in the Canary Current upwelling region off Cabo Bojador in August 1972. Deep-Sea Res., *22*, 547–558.

Johnson, W. R. 1976. Cyclesonde measurements in the upwelling region off Oregon. Rosenstiel School of Marine and Atmospheric Science, University of Miami, TR76-1, 124 pp.

Johnson, W. R., J. C. Van Leer and C. N. K. Mooers. 1976. A cyclesonde view of coastal upwelling. Submitted to J. Phys. Oceanogr.

Jones, P. G. W. 1972. The variability of oceanographic observations off the coast of Northwest Africa. Deep-Sea Res., *19*, 405–432.

Kundu, P. K. 1976. A note on the Ekman veering observed on the Oregon continental shelf. Submitted to J. Phys. Oceanogr.

Kundu, P. K. and J. S. Allen. 1975. Three-dimensional structure of low frequency current fluctuations near the Oregon coast. Submitted to J. Phys. Oceanogr.

Kundu, P. K., J. S. Allen and R. L. Smith. 1975. Modal decomposition of the velocity field near the Oregon coast. J. Phys. Oceanogr., *5*, 683–704.

Mittelstaedt, E. and K. P. Koltermann. 1973. On the currents over the shelf off Cap Blanc in the Northwest African upwelling area. Dt. Hydrogr. Z., *26*, 193–215.

Mittelstaedt, E., D. Pillsbury and R. L. Smith. 1975. Flow patterns in the Northwest African upwelling area. Results of measurements along 21°40′N during February-April 1974. JOINT-I. Dt. Hydrogr. Z., *28*, 145–167.

Mooers, C. N. K. and J. S. Allen. 1973. Final report of the Coastal Upwelling Ecosystems Analysis Summer 1973 Theoretical Workshop. School of Oceanography, Oregon State University.

Mooers, C. N. K., C. A. Collins and R. L. Smith. 1976. The dynamic structure of the frontal zone in the coastal upwelling region off Oregon. J. Phys. Oceanogr., *6*, 3–21.

Myers, A. H. 1975. Vertical distribution of zooplankton in the Oregon coastal zone during an upwelling event. M.S. thesis, Oregon State University.

Pak, H., G. F. Beardsley, Jr., and R. L. Smith. 1970. An optical and hydrographic study of a temperature inversion off Oregon during upwelling. J. Geophys. Res., *75*, 629–636.

Pedlosky, J. 1974. Longshore currents and the onset of upwelling over bottom slope. J. Phys. Oceanogr., *4*, 310–320.

Peffley, M. B. and J. J. O'Brien. 1976. A three-dimensional simulation of coastal upwelling off Oregon. J. Phys. Oceanogr., *6*, 164–180.

Pillsbury, R. D., J. S. Bottero, R. E. Still and W. E. Gilbert. 1974a. A compilation of observations from moored current meters, Vol. VII, Oregon continental shelf, July-August 1973. School of Oceanography, Oregon State University, Ref. 74-7, 87 pp.

Pillsbury, R. D., J. S. Bottero, R. E. Still and E. Mittelstaedt. 1974b. A compilation of observations from moored current meters, Vol. VIII, Wind, currents, and temperature off Northwest Africa, along 21°40′N during JOINT-I, February-April 1974. School of Oceanography, Oregon State University, Ref. 74-20, 143 pp.

Smith, R. L. 1974. A description of current, wind and sea level variations during coastal upwelling off the Oregon coast, July-August 1972. J. Geophys. Res., *79*, 435–443.

Stevenson, M. R., R. W. Garvine and B. Wyatt. 1974. Lagrangian measurements in a coastal upwelling zone off Oregon. J. Phys. Oceanogr., *4*, 321–336.

Thompson, J. D. and J. J. O'Brien. 1973. Time-dependent coastal upwelling. J. Phys. Oceanogr., *3*, 33–46.

Wang, D. P. 1976. Coastal water response to the variable wind theory and Coastal Upwelling Experiment. Rosenstiel School of Marine and Atmospheric Science, University of Miami, TR76-2, 174 pp.

Wooster, W. S., A. Bakun and D. R. McLain. 1976. The seasonal upwelling cycle along the eastern boundary of the North Atlantic. J. Mar. Res., *34*, 131–141.

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