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ON THE PROCESS OF UPWELLING: NEW OBSERVATIONS AND UNDERSTANDING

by

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Abstract: Sverdrup (1938), in the first 'modern' paper on upwelling, stated the hope "that in the future it will be possible to undertake special series of observations during periods of upwelling in order to obtain better knowledge of the phenomenon and to answer many questions which now must be left open." During the past decade several major oceanographic experiments were conducted over the continental margins in coastal upwelling regions. The studies extended farther seaward than the continental shelf and often extended over the seasons. Our understanding of the processes associated with coastal upwelling, especially the Ekman transport in the surface layer and the processes affecting the ocean farther seaward, has increased. The wind-driven cross-shelf transport in the surface mixed layer agrees well in magnitude and variability with the Ekman transport estimated from the wind stress. The cool 'filaments' conspicuous in satellite images of SST during the coastal upwelling seasons off northern California, Portugal and Africa, have been studied; these cool filaments are usually the jets along the boundary (front) between recently upwelled water and the warmer adjacent ocean water. Sverdrup wrote: "One may ... raise the question whether a boundary region of the nature described can exist on a long horizontal distance ... it appears indeed likely that on a long distance it must be broken up owing to the intensive mixing processes, and that horizontal eddies of considerable dimensions may break away from the boundary region." Although the question remains, observations with new techniques suggest that the boundary is maintained over long horizontal distances as the jets meander equatorward, but that eddies do break away. The upwelled water (and the front associated with coastal upwelling) can extend farther offshore than previously realized. Cross-isobath flow, although generally small compared to the along-isobath flow over the continental margins, is of crucial importance to the physics and ecology of both the coastal ocean and the ocean boundary currents seaward of the shelf; this topic, especially over the inner shelf and in the bottom boundary layer, will be the focus of much future research, as will the problems of cross-frontal exchange and the adjustment of flow to spatial variations in wind and topography.

Introduction: A review of "the state of the art of upwelling understanding" was suggested as the topic for my paper, with a focus on upwelling as a coastal feature and as a physical process with consequences to the biogeochemical system. I thought a review of what we have learned about coastal upwelling in that other northern ocean along its eastern boundary might be of interest to the ICES oceanographers. Studies of the physical dynamics along the eastern boundary of the North Pacific in the 1980s have expanded the view of coastal oceanographers farther seaward, and have caused the physical oceanographers to think anew about coastal upwelling regions and, in particular, about interactions between the coastal ocean and the larger ocean seaward of the continental shelf. The observational and modelling results should be important for both contemporary fisheries problems and the interpretation of the sediment record - the focus of both are often seaward of the continental shelf but greatly influenced by processes over the shelf.

The Experiments: During the past decade (1981-93) several major physical oceanographical experiments were conducted over the continental margins along the ocean's eastern boundary. As a result, our understanding of the processes and phenomena associated with coastal upwelling has increased. The Coastal Ocean Dynamics Experiment (CODE), off northern California, investigated the dynamics of a small region of the continental shelf in a coastal upwelling region with more extensive instrumentation than ever before. Cross-shelf transport in the surface mixed layer agreed well with the Ekman transport inferred from the local wind stress. Indeed, comparisons of the Ekman transport computed for the surface layer agreed well with observations in all coastal upwelling regions studied (Lentz, 1992). Although the bottom Ekman layer is of equivalent importance in many models of coastal upwelling and cross-shelf transport, measurements in it have not been adequate to allow equivalent analyses (Lentz and Trowbridge, 1991). The CODE experiment also showed that flow patterns could be much more complex than inferred during earlier studies of coastal upwelling (e.g., Davis, 1985; Kosro, 1987; Send, 1989). A companion experiment, SuperCODE, looked at the large alongshore scale, from 35°N to 50°N, defined the seasonal cycle, and found that the tendency for subsurface poleward flow over the continental shelf was ubiquitous; the mean poleward flow actually increased at lower latitudes in spite of the increased equatorward mean wind (Strub et al., 1987).

The Coastal Transition Zone (CTZ) experiment, motivated in part by the results from CODE, investigated the cool 'filaments' or 'jets' that are so conspicuous in satellite images of SST within a couple of hundred kilometers of the coast off northern California. Similar features are seen in the satellite images of other coastal upwelling regions, especially in the Benguela Current region off South Africa. The CTZ experiments were centered off northern California at about 39°N, and took place during the summers of 1987 and 1988 (Strub et al., 1991), the season when the alongshore wind-stress exceeds 1 dyne cm^{-2} and the resulting seaward Ekman transport exceeds 1 Sv (i.e., 10^6 m^3s^{-1}) per 1000 km. The 1987 experiment looked at the larger scale (42 to 37°N) and provided evidence that the structures seen in the satellite images were not simply upwelling 'squirts' or a field of oceanic mesoscale eddies interacting with the coastal ocean, but the result of a strong alongshore jet meandering equatorward, perhaps starting as a coastal jet and eventually meandering as far as 300 km seaward. The jet flowed along the front separating the cool, productive, recently upwelled water from the warmer, relatively barren waters offshore (Kosro et al., 1991; Hood et al., 1990). These jets are of sufficient depth (and transport) to be a major influence on the surrounding ocean; the upwelling front and its associated jet meander quasi-continously equatorward and offshore, allowing the upwelled water to extend much farther seaward (by almost an order of magnitude) than the shelf width. Figure 1 is a satellite image of SST upon which near-surface (25 m depth) currents, measured with ship-borne ADCP, have been overlaid (Smith, 1992). Figure 2 shows the temperature and alongshore velocity in sections normal to the coast at 43°, 41.5°, and 40°N about the time of the image. The section at 43°N shows a 'classic' coastal jet and upwelling front. This jet, and the front, meandered farther seaward as the two southern sections show. The two southern sections had additional measurements that support the interpretation that the jet and front are the boundary between water upwelled at the coast and oceanic water (Figure 3, based on Hood et al., 1991). The jet and front continued equatorward to at least 37°N; maps of various properties, including satellite and ship SST, dynamic topography, and chlorophyll concentration, are given in CTZ Group (1988) and Hood et al. (1990, 1991).

The 1988 experiment, looking in detail at a smaller region (37.5 to 39.5°N), confirmed that the jet flows along the front, then 100-200 km seaward of the shelf break, separating upwelled water from the nutrient poor water seaward (Chavez et al., 1991). The jet is narrow, 30-75 km, rapid (at times > 1 m s^{-1}) at the surface, and extends to >200 m, although with diminished velocity (10 cm s^{-1}). Since the jet flows rapidly equatorward, it efficiently advects water with upstream properties. Off northern California the jet carries water of lower salinity than that present either offshore or onshore at that latitude (Huyer et al., 1991). Indeed, the large volume of water transported within the jet (3-5 Sv) suggests that it may be a major constituent of the California Current. Satellite SST images are not useful in determining whether the current velocity structure is seasonal, since the cold upwelled water which serves as a "dye" or tracer is present only during seasons of coastal upwelling. On the basis of limited winter cruises, these strong narrow currents seem to occur only during the seasons of persistent coastal upwelling, i.e., strong equatorward winds (Kosro et al, 1991).

The results of the CTZ program show that the upwelling front may advance seaward a couple of hundred km beyond the continental shelf as the jet continues to flow equatorward for several hundred km without breaking up. The jet itself is not a region of abundant nutrients and phytoplankton (Chavez et al., 1991). The jet and front remain a boundary, albeit an active one with some exchange across the front, perhaps by upwelling and downwelling along the jet's edges. As the upwelling front meanders much farther seaward, the upwelling 'signal' extends much farther seaward than earlier thought likely; this must have a significant effect on fisheries recruitment and the sediment record.

Present: A major study is now (1992-4) taking place off northern California. The goal of this study, sponsored by the Office of Naval Research, is to understand the physical and biological dynamics of the mesoscale interactions in what is assumed to be the weakly nonlinear flow regime of eastern boundary current regimes. Although the California Current is the most studied of the eastern boundary currents, its large variability and the difficulty of quasi-synoptic sampling leave many questions about the mesoscale flow field unanswered. The CTZ experiment showed that 'spectacular' features are superimposed on the long term average circulation of the California Current, which is characterized by a southward drift near the surface of the order of 10 cm/s. Superimposed on the broad flow are mesoscale eddies and jetlike flows of 25 to 100 cm/s, that deform the main thermocline by 100 to 200 m vertically and have horizontal scales of 10 to 1000 km. Among the hypothese are that these features have their origin on the continental shelf or inner slope (eddies are perhaps 'spun off' the meandering jet as it transits the slope) and that the circulation accompanining the meanders has a significant vertical component. No direct measurements of these features have been made over their 'lifetimes'(the duration of the CTZ experiments was on the order of one month) so we have little knowledge of their dynamical and energetic interactions. Moored arrays of current meters have been deployed for two years, extending from just seaward of the continental shelf break to about 300 km offshore over the abyssal plain. Lagrangian drifters, towed CTD systems, and satellite derived SST and sea surface altimetry will be employed. Some measurements are being made over the shelf and inner slope by the U. S. National Fisheries Service because the habitat of the U. S. west coast groundfish is between the 50 and 1500 m isobath in a narrow band along nearly the entire U.S. west coast. The adults spawn in this region but the young must return to the shelf to begin demersal life.

Future: Future studies, I expect, will again focus on the shelf: the inner shelf where the cross-shelf divergence of the Ekman transport is maximum, the flow in the bottom boundary layer (where because of the few measurements in the bottom boundary layer in coastal upwelling regions even the Ekman transport is untested), and the behavior of coastal upwelling fronts and their possible transition from the shelf to the open ocean (how does the front over the continental margin respond to wind variability, and how does it 'regulate' the distribution and transport of planktonic forms?). Another topic deserving of study are the ubiquitous poleward currents, usually subsurface over the inner slope and outer shelf, that have been observed in all coastal upwelling regions in spite of equatorward winds (Neshyba et al., eds., 1989). There is not yet a satisfactory model for poleward undercurrents. They may be a source of upwelling water, and they may provide a 'recycling conveyor belt' for nutrients and biota. Unlike the jets of the coastal transition zone, the poleward undercurrents seem trapped to the continental margin. The time scale of the undercurrents variability over the slope is greater than that of typical shelf currents responding to the local wind. Although there is evidence for the existence of poleward undercurrents along the eastern boundaries of the Atlantic and Pacific Ocean in both hemispheres, there is no definitive study of their continuity over even a few hundred kilometers.

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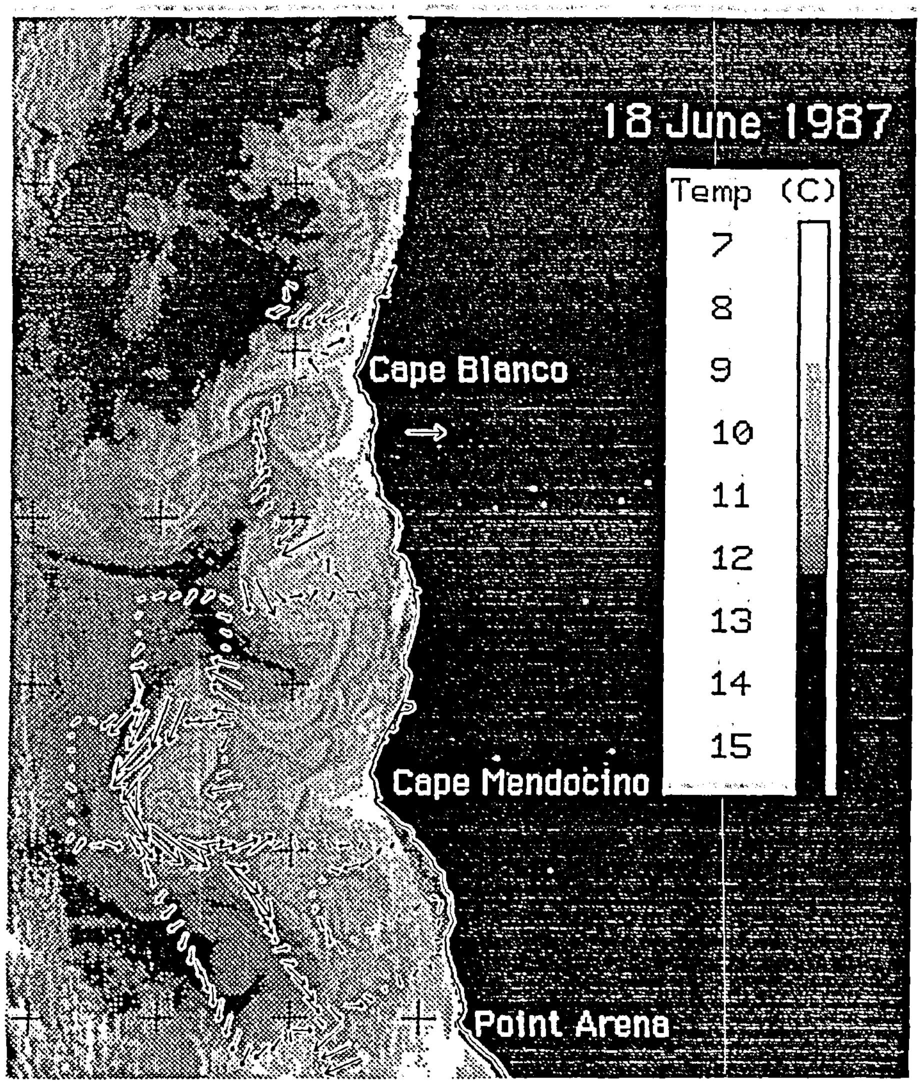
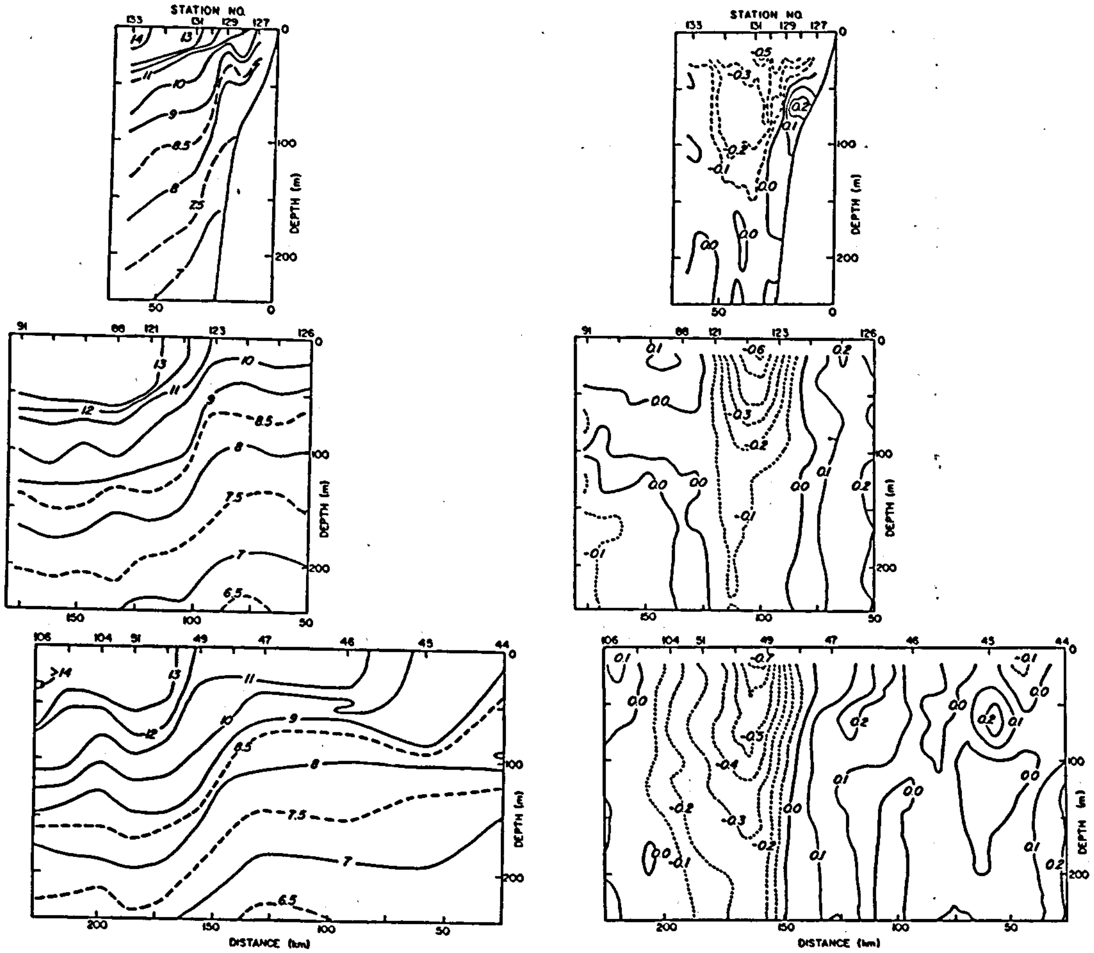
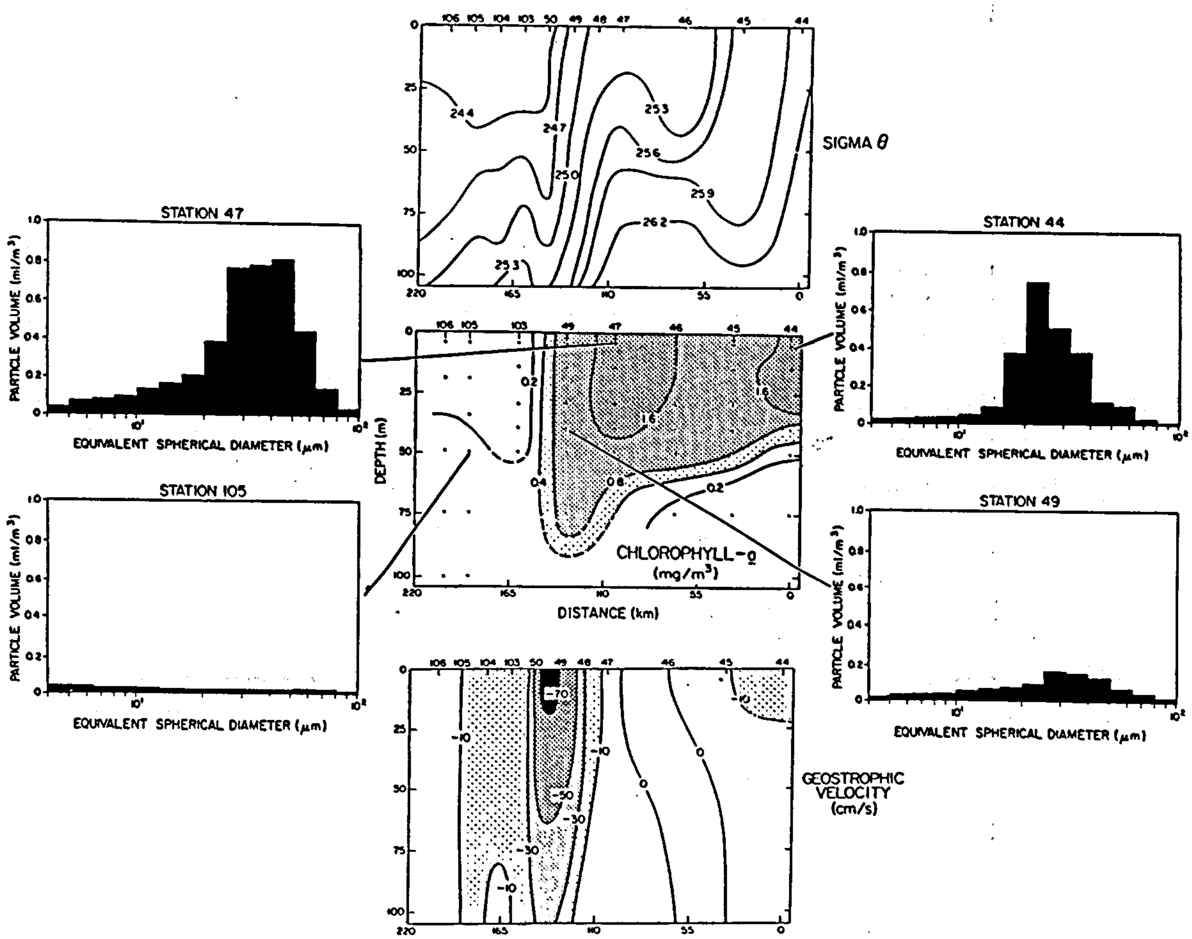


ABOVE: Figure 1. Satellite sea surface temperature (SST) and shipborne acoustic doppler current measurements at 25 m during CTZ experiment 12-18 June 1987. Arrow below Cape Blanco represents 0.5 m/s; crosses indicate 1 degree latitude/longitude grid (cross just offshore of Cape Blanco is at 43°N, 125°W; cross just offshore of Point Arena is at 39°N, 124°W). Data and figure provided by P. M. Kosro and P. T. Strub.

NEXT PAGE: Figure 2. Sections normal to the coast at about 43°, 41.5°, and 40°N (see Figure 1) showing temperature from CTD stations and alongshore velocity (northward is positive, units are m/s) from acoustic doppler current profiler (ADCP). Distances are from the coast; the innermost stations of the southern two sections are seaward of the shelf break. Note the similarity of the equatorward velocity structure (jet) in the vicintiy of the front (13°C).

Figure 3. Potential density (sigma-theta), chlorophyll-a, alongshore geostrophic velocity, and particle volume along the cross-margin section at 40°N (just south of Cape Mendocino) shown in Figures 1 and 2; station numbers as in Figure 2 but distance scale in Figure 3 is relative to most inshore station, which is 25 km offshore. Figure is adapted from Hood et al., (1991).


STATION NO.
DEPTH (m)
DISTANCE (km)


SIGMA θ
STATION 47
STATION 44
STATION 105
STATION 49
PARTICLE VOLUME (ml/m³)
EQUIVALENT SPHERICAL DIAMETER (μm)
DEPTH (m)
CHLOROPHYLL-a (mg/m³)
DISTANCE (km)
GEOSTROPHIC VELOCITY (cm/s)