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SEPARATION OF A COASTAL UPWELLING JET AT CAPE BLANCO, OREGON, USA

*J. A. BARTH * and R. L. SMITH**

The coastal upwelling region near Cape Blanco (43°N), Oregon, off the west coast of the United States, was studied using a towed conductivity-temperature-depth instrument on SeaSoar, a shipborne Acoustic Doppler Current Profiler, satellite sea surface temperature maps and satellite-tracked surface drifters during three cruises: August 1994, May and August 1995. Results demonstrate that the baroclinic coastal upwelling jet (and associated front), which was over the shelf poleward of Cape Blanco in all three cruises, separates from the continental shelf, providing an important mechanism for transporting material across the continental margin to the deep ocean. This flow-topography interaction mechanism is a universal phenomenon, and is likely to be important in other eastern boundary current regions of the world. The observations from the two August cruises show two different phenomena. In 1994, cyclogenesis was observed, during which the coastal jet was connected with a cyclonic eddy offshore before the connection was severed and the jet again flowed continuously around Cape Blanco but shifted eastwards. In 1995, the coastal jet meandered in the vicinity of Cape Blanco and then continued equatorward as an oceanic jet in deep water, but it was stronger and displaced farther seawards than the previous year. Drifters released early in the upwelling season (May 1995), when the strengthening longshore upwelling jet was only minimally perturbed by the Cape, were transported rapidly equatorwards and were swept through a large portion of the eastern boundary current region. Drifters released later in the upwelling season (August) were initially swept offshore and equatorwards near the Cape, but after interaction with the spatially complex mesoscale circulation, eventually returned to the continental margin with the seasonal reversal in winds and near-surface currents. These differing flow trajectories are likely to have a significant impact on the biology of eastern boundary currents.

Ocean circulation off the north-west coast of the United States is driven by a variety of mechanisms, the most important of which is the seasonally varying wind stress. The response of the coastal ocean to strong equatorward (upwelling-favourable) winds during summer, described for example off the Oregon coast by Huyer (1983), consists of net offshore transport in the surface Ekman layer, upwelling of cold, saline water near the coast and the formation of a strong longshore coastal jet that is in geostrophic balance with the upwarped isopycnals. Winds become predominantly upwelling-favourable after the "spring transition" (Huyer *et al*. 1979), and the upwelling regime persists through the summer and early autumn before returning to winter conditions after the autumn transition. During the upwelling regime, the vertical structure of the longshore velocity field consists of a southward coastal jet in the upper water column, extending down to 50–75 m deep, and with maximum speeds near the surface of up to 0.5 $m \cdot s^{-1}$ and a more sluggish poleward undercurrent near the bottom over the outer continental shelf (Huyer *et al*. 1978).

The summer upwelling circulation is affected on short time-scales by changes in the wind stress on time-scales of 2–10 days (Huyer 1983). On longer time-scales, the timing and intensity of the upwelling circulation varies from year to year (Huyer *et al*. 1979, Strub and James 1988) under the influence of interannual variability in the atmospheric driving and in coupled ocean-atmosphere phenomena, for example, *El Niño* events (Huyer and Smith 1985). The discussion that follows will not focus on interannual variability of coastal ocean circulation, except to point out differences between two particular years along the Oregon coast (1994 and 1995), but rather it will concentrate on a description of spatial variation of the upwelling circulation associated with the interaction of a strong upwelling jet with a coastal promontory. Spatial variability in the coastal upwelling circulation is readily apparent in satellite sea surface temperature (SST) maps, an example of which is shown in Figure 1. Spatial and temporal variability are important factors to consider when assessing the influence of the coastal ocean on biological productivity and the transport of biogeochemical and anthropogenic material.

Historical observations (Huyer 1990, Smith 1992) and satellite imagery (Fig. 1) suggest that Cape Blanco (43°N), Oregon, is a dividing point between a region north of the Cape, where upwelling is fairly well confined inshore of the continental shelf-break (approximately the 200 m isobath), and a region south of the Cape, where a meandering equatorward

* College of Oceanic and Atmospheric Sciences, Oregon State University, 104 Ocean Administration Building, Corvallis OR 97331-5503, U.S.A. E-mail: barth@oce.orst.edu

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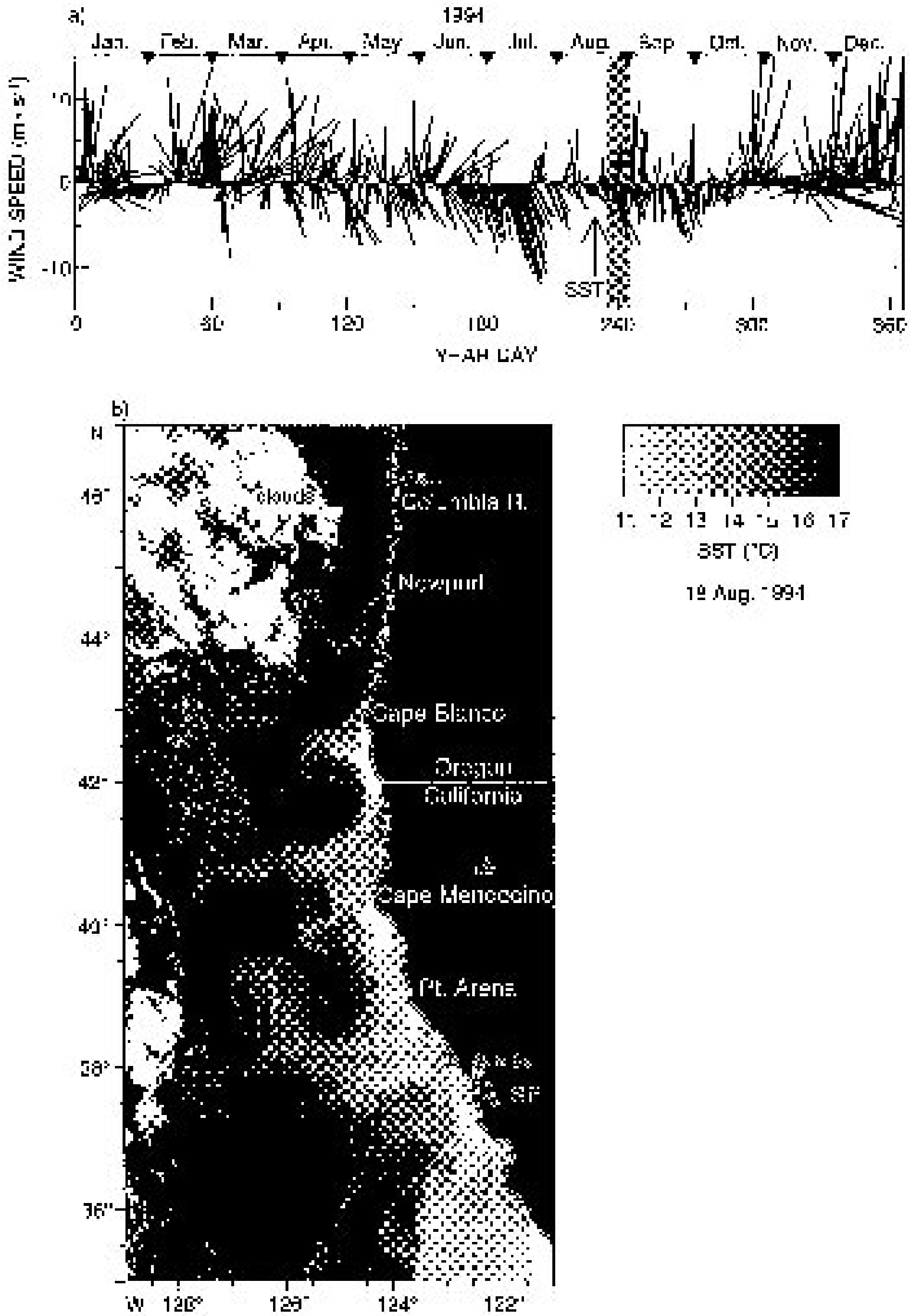

Fig. 1: (a) Vector winds (m·s^{-1}) for 1994 measured at Newport, Oregon. The date of the sea surface temperature (SST) image is indicated by an arrow and the time of the 10-day R.V. *Wecoma* cruise is denoted by a grey bar; (b) satellite infra-red sea surface temperature (°C) for 18 August 1994, showing cold, upwelled water near the coast separated from warmer water offshore by a meandering front

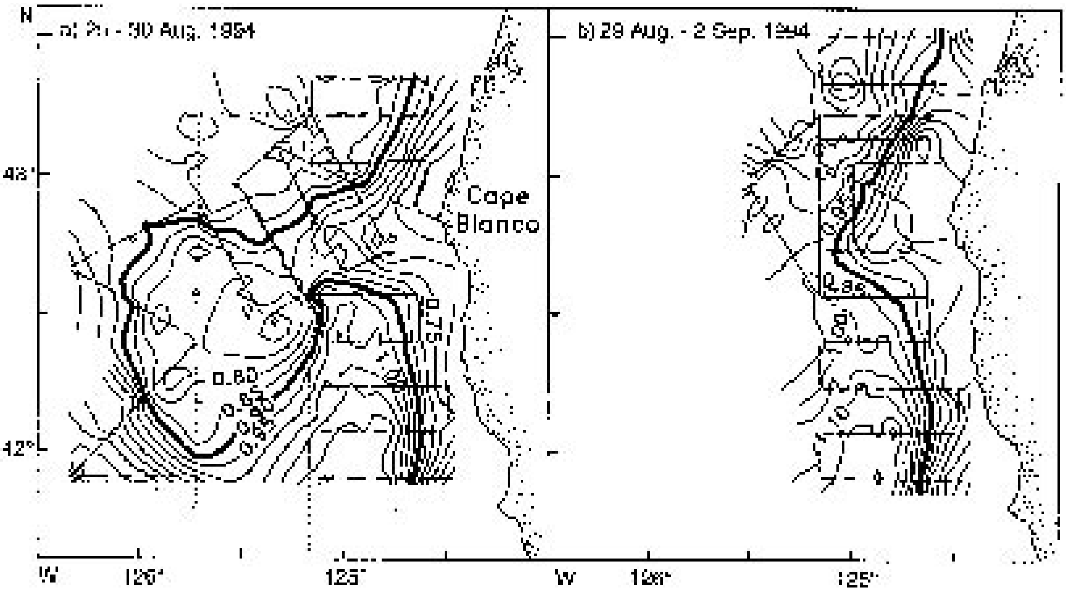

Fig. 2: Contour maps of geopotential anomaly (dynamic height in meters multiplied by the acceleration of gravity) at 23 m relative to 55 m from SeaSoar surveys during (a) 25–30 August 1994 and (b) 29 August –2 September 1994. Individual CTD depth profiles are denoted by dots along the ship's track and the 0.9 m^2s^{-2} geopotential anomaly contour is highlighted to emphasize the pinching-off of a counter-clockwise (cyclonic) eddy off Cape Blanco, Oregon

jet and upwelled water extend well seawards of the continental margin (Kosro and Huyer 1986). In the present study, results are described from an observational programme conducted near Cape Blanco, which was designed to understand how and why the strong longshore coastal upwelling jet turns offshore, crosses the steep topography of the continental margin and becomes an oceanic jet (Barth *et al.* 1994, Barth and Smith 1996, Smith *et al.* 1996).

DATA

The observational component of the Coastal Jet Separation Experiment consisted of three hydrographic and velocity surveys conducted during 1994 and 1995 onboard the R.V. *Wecoma* (Barth *et al.* 1996, Pierce *et al.* 1996), tracking of surface drifters, and analysis of satellite SST imagery and winds measured at the coast. Hydrographic data were collected by means of a towed, undulating vehicle, SeaSoar (Pollard 1986), which cycles rapidly from the surface to depth while being towed at 4 $m{\cdot}s^{-1}$ (8 knots) behind the ship. The majority of the conductivity-temperature-depth (CTD) data were collected by towing the SeaSoar from 0 to 120 m and back to the surface every four minutes. This gave hydrographic data of very high spatial resolution (1 km between alongtrack surface points) that were obtained rapidly (cross-shelf sections in 2–3 h and large-area maps in 1–2 days), so that a detailed "snapshot" of the system could be studied. Over the shallow continental shelf, the SeaSoar was flown from 0–55–0 m, cycling every 1.5 minutes, which resulted in alongtrack profile spacing as small as $\frac{1}{3}$ km. The SeaSoar was also towed offshore in deep water using a cable equipped with aerodynamic fairing to reduce drag, which allows the vehicle to cycle from 0 m to in excess of 300 m and back to the surface every eight minutes. CTD data, obtained in a sawtooth pattern as SeaSoar cycles from the surface to depth, were averaged into 2-db vertical bins and 5- or 12-minute intervals alongtrack for shallow (120 m) and deep (>300 m) traces respectively. This results in vertical profiles spaced every 1.2 km or 2.9 km alongtrack for shallow and deep traces respectively. The averaged temperature, salinity and pressure data were used to compute geopotential anomalies (the vertical integral of the specific volume anomaly) at a depth of 23 m relative to 55 m ($\Delta\phi_{23/55}$). Geostrophic currents flow along contours of geopotential anomaly and their speed is inversely proportional to the distance between the contours. Upwarping of the strong, seasonal pycnocline, driven by coastal upwelling, and the accompanying strong longshore coastal jet are discernible in fields of $\Delta\phi_{23/55}$.

Winds were measured hourly at a National Oceanic and Atmospheric Administration (NOAA) station on the coast at Newport (45°N), Oregon. Wind time-series were low-pass filtered, using a filter with a 40-h width at half amplitude to remove short-period (e.g. diurnal) fluctuations. Satellite SST data were obtained usually four times per day from NOAA polar-orbiting satellites, registered to a geographical grid and then displayed using a histogram-based greyscale shading to enhance strong frontal signatures.

Surface-drifter trajectories were obtained by deploying World Ocean Circulation Experiment standard, holey-sock drifters drogued at 15 m (Niiler *et al*. 1995) and tracked via the Argos satellite system. Typically, seven fixes were obtained per day. Drifter trajectories were calculated by fitting a cubic spline to the raw fixes and, in addition, smoothing the fitted trajectories by minimizing the overall curvature while not allowing the root-mean-square deviation between the fitted locations and the actual fixes to exceed 1 km.

RESULTS

A seasonal cycle in the wind stress is apparent in the 1994 wind measured at Newport (Fig. 1a). In July, winds were typically strong and upwelling-favourable. However, in August equatorward winds were anomalously weak. An SST image from 18 August 1994 (Fig. 1b) reveals a band of cold, upwelled water near the coast, confined to inshore of the continental shelf-break north of Cape Blanco (the wide cold feature near 44°N is the influence of Heceta Bank – see the bottom topography in Fig. 3) and extending much farther seawards south of the Cape. The equatorward upwelling jet, associated with the temperature front between cold upwelled water inshore and warmer water offshore, meanders westwards at Cape Blanco, but returns toward the coast downstream in a counter-clockwise bend before meandering over 300 km offshore near 41°N. A ship survey of the region from 25 to 30 August 1994 (Fig. 2) confirmed the existence of the strong longshore coastal jet north of the Cape, as exemplified by the strong gradient in geopotential anomaly found there. The geopotential anomaly map shows continuity of the southward jet, with a counter-clockwise (cyclonic) eddy roughly 80 km in diameter offshore of the Cape. A second geopotential anomaly map reveals the pinching off of the eddy and a reconnection of the equatorward jet on the inshore side, as illustrated by the 0.9 m^2s^{-2} geopotential anomaly contour. This creation of a large counter-clockwise eddy is termed "cyclogenesis" and is a result of a flow-topography interaction between the coastal upwelling jet and the Cape. The eddy contains water of coastal origin, and this process is an important mechanism for injecting biologically important material into the deep ocean.

Three satellite-tracked surface drifters were released across the coastal jet to the north of Cape Blanco (Fig. 3) at the beginning of the survey. All three drifters were initially swept offshore by the separating jet (Fig. 3a), but the most inshore drifter (long dashed line) split from the other two to follow an inshore pathway to the south (cf. the 0.8 m^2s^{-2} geopotential anomaly contour in Fig. 2). Unfortunately, the inshore drifter failed on 5 September 1994. The other two drifters moved together around the northern edge of the cyclonic eddy at speeds of up to 0.6 $m\cdot s^{-1}$, before one drifter (dashed line, Fig. 3a) moved off in a north-west direction while the other made one complete revolution of the eddy before exiting to the north. Both drifters then made counter-clockwise revolutions around a cold eddy (near 43°N, 126.5°W, see Fig. 1b) formed earlier (mid-July) in the upwelling season at the offshore edge of the cold, upwelling zone off Cape Blanco, as discerned from time-series of satellite SST maps. One drifter (dashed line, Fig. 3a) again left the cyclonic feature to the north and spent the next five weeks in the low-velocity region well offshore of central Oregon, while the other drifter remained trapped in the counter-clockwise eddy.

In mid-October, the winds became south-southwesterly through the autumn transition (Fig. 1a) and the circulation responded, as shown by drifter tracks in Figure 3b. The drifter in the stagnant offshore area (dashed line, Fig. 3b) was transported shorewards, passing through 126°W on 29 October 1994. This drifter was then swept back onto the continental shelf, and returned very close to its deployment point after spending 2.5 months offshore. This demonstrates a Lagrangian pathway for passive particles to leave the coastal ocean, but to then return through the influence of seasonally and spatially varying circulation. The other drifter (solid line, Fig. 3b) executed additional revolutions around the eddy before transiting northwards, passing through 42.5°N on 5 January 1995, and then was also swept onto the central Oregon shelf. Because the cold offshore eddy was formed in July, this indicates a minimum eddy lifetime of 4–5 months. Finally, both drifters were transported rapidly polewards (speeds up to 1 $m\cdot s^{-1}$) by the Davidson Current (Jones 1918) transiting north of Vancouver Island. In summary, the ultimate destination of two of the three drifters released over the shelf in the coastal upwelling jet north of Cape Blanco late in the upwelling season (August 1994) was north of their release latitude.

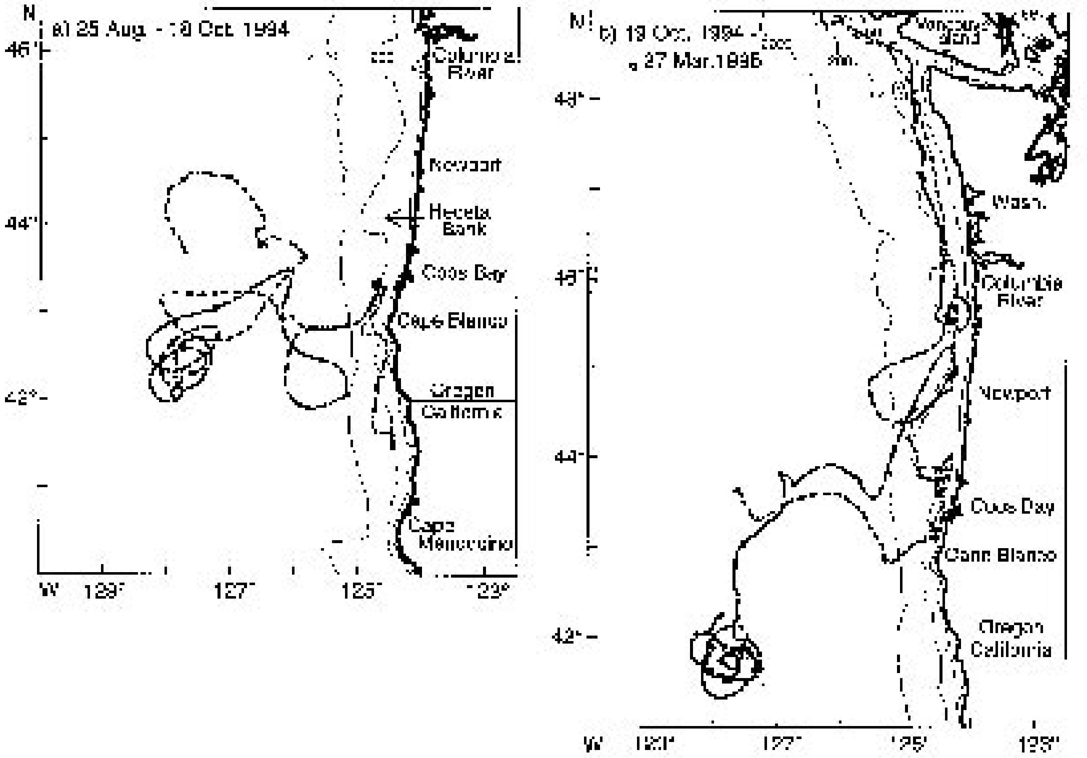

Fig. 3: Trajectories of three satellite-tracked drifters released on 25 August 1994 at the beginning of the SeaSoar surveys shown in Figure 2. Release points off Coos Bay are denoted by asterisks and marks along the drifter tracks are at weekly intervals. Trajectories are (a) from the release until 18 October 1994 and (b) 19 October 1994 through 27 March 1995, where the drifter denoted by the dashed line reached 49°N on 26 December 1994

In 1995, winds became upwelling-favourable for an extended period, beginning in mid-May (Fig. 4a). A satellite SST image from 18 May 1995 (Fig. 4b) shows a relatively narrow band of cold upwelled water near the coast during this early part of the upwelling season. The southward upwelling jet and front meander only slightly near Cape Blanco (cf. the SST image in Fig. 1b). A ship survey of the Cape Blanco region (not shown) confirmed the existence of the nearly straight southward jet along the continental shelf-break. Five satellite-tracked surface drifters were released across the continental margin north of Cape Blanco on 21 May 1995 (Fig. 5a). The four inshore drifters transited rapidly to the south at speeds of up to 0.6 $m \cdot s^{-1}$, again demonstrating the relatively straight longshore flow (cf. Fig. 3a). The drifter released farthest west was placed in the surface salinity minimum associated with the Columbia River influence offshore of the coastal upwelling jet and front (Huyer 1983) and transited slowly (0.05–0.25 $m \cdot s^{-1}$) to the south-west. Throughout the remainder of the upwelling season, the drifters were swept equatorwards in the eastern boundary current region by a meandering jet (Fig. 5b).

Evidence for eddies, meanders, swift jets and more sluggish flow far offshore (e.g. near 37–40°N, 129–132°W) exists in the drifter tracks. These Lagrangian trajectories confirm the hypothesis that the separating coastal upwelling jet off Oregon contributes significantly to the meandering jet, now accepted as making up a large fraction of the equatorward flow in the California Current system (Huyer *et al.* 1991). None of the drifters released in May returned to the coast, nor did they remain or return to their release latitude. This demonstrates that material carried by the coastal upwelling jet off Oregon early in the upwelling season can be carried far from its point of origin by the swift, relatively straight southward flow.

A ship survey and drifter release were conducted

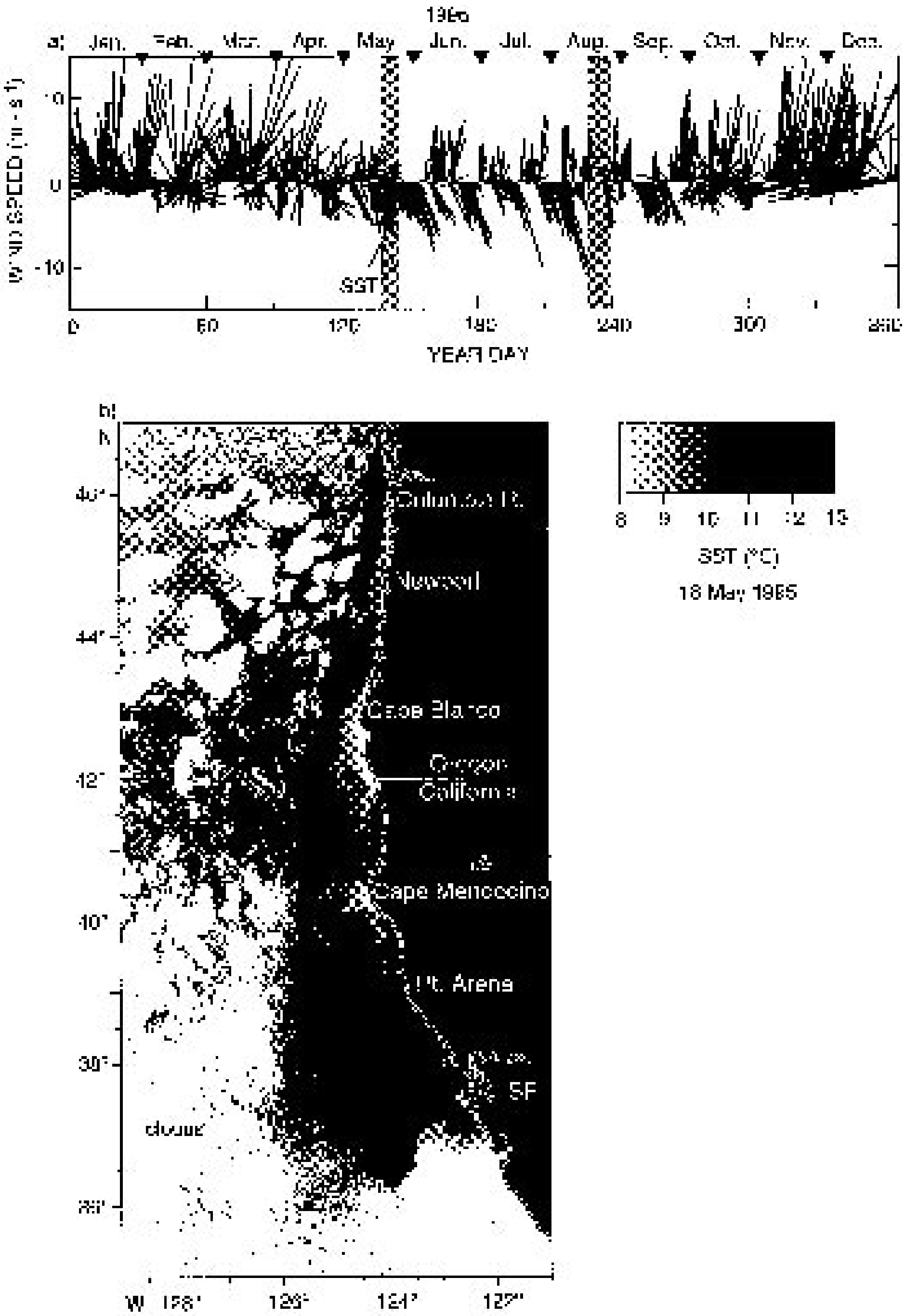

Fig. 4: (a) Vector winds ($m \cdot s^{-1}$) for 1995 measured at Newport, Oregon. The date of the SST image is indicated by an arrow and the times of two R.V. *Wecoma* cruises are denoted by grey bars; (b) satellite infra-red sea surface temperature (°C) from 18 May 1995, showing a relatively narrow band of cold, upwelled water near the coast at the beginning of the upwelling season

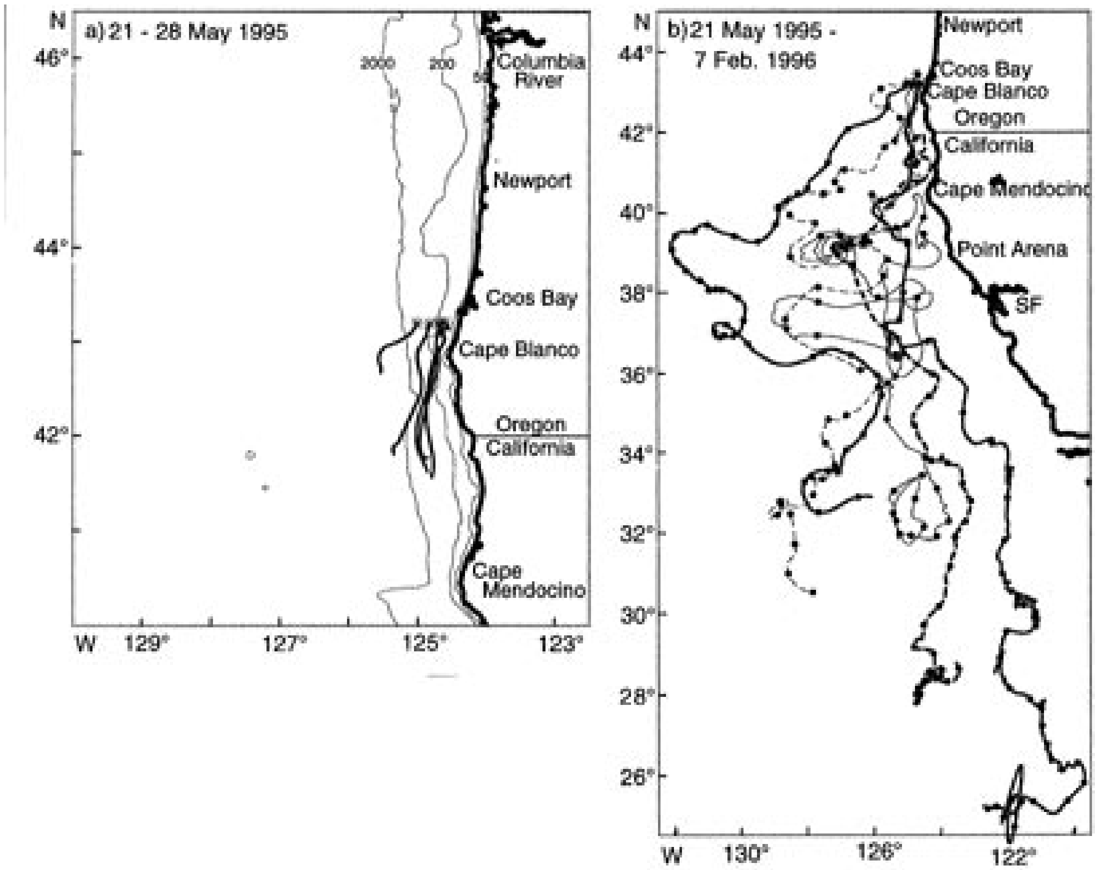

Fig. 5: Trajectories of five satellite-tracked drifters released on 21 May 1995 off Coos Bay, Oregon. Drifter tracks are (a) for one week and (b) for $8\frac{1}{2}$ months after the release. For the early trajectories, drifter tracks are all drawn as solid lines, whereas in (b) the tracks are differentiated by line type and marks along the tracks are at weekly intervals. The drifter released second farthest west failed on 30 May 1995. An additional drifter (thin dashed line) is included in (b), beginning on 31 May 1995 just to the north of the earlier five-drifter release latitude

near the end of August 1995, after a period of typical, strong, upwelling-favourable wind stress (Fig. 4a). A map of geopotential anomaly (Fig. 6a) shows a strong, southward jet centred on the continental shelf-break north of Cape Blanco, which then meanders offshore near the Cape and separates from the coast to become an oceanic jet. The jet gains in strength downstream of the Cape, in part from a flow contribution that joins the separating jet from the north-west (43.25°N, 125.5°W) and is associated with flow around Heceta Bank (44°N) upstream. The flow contribution from around Heceta Bank is evident in maps of near-surface velocity measured with a shipboard Acoustic Doppler Current Profiler (not shown), and is consistent with a temperature front extending south-westwards and then shorewards south of the Bank, as measured by satellite SST (not shown).

Five satellite-tracked drifters were released on the continental shelf north of Cape Blanco (Fig. 6b) and initially all were carried to the south in the upwelling jet. Whereas the most inshore drifter grounded south of Cape Blanco, the other four drifters were swept swiftly (speeds in excess of 1 $m{\cdot}s^{-1}$) offshore in the separating jet. The drifters executed both clockwise (anticyclonic) and cyclonic loops, associated with the strong, unstable meandering jet. Drifters released on the shelf moved more than 400 km from the coast before turning southwards and delineating the equatorward eastern boundary current jet, with its core located between 127 and 128°W near 40°N. As the winds became south-south-westerly in autumn along the coast from 37°N and to the north (Strub *et al.*

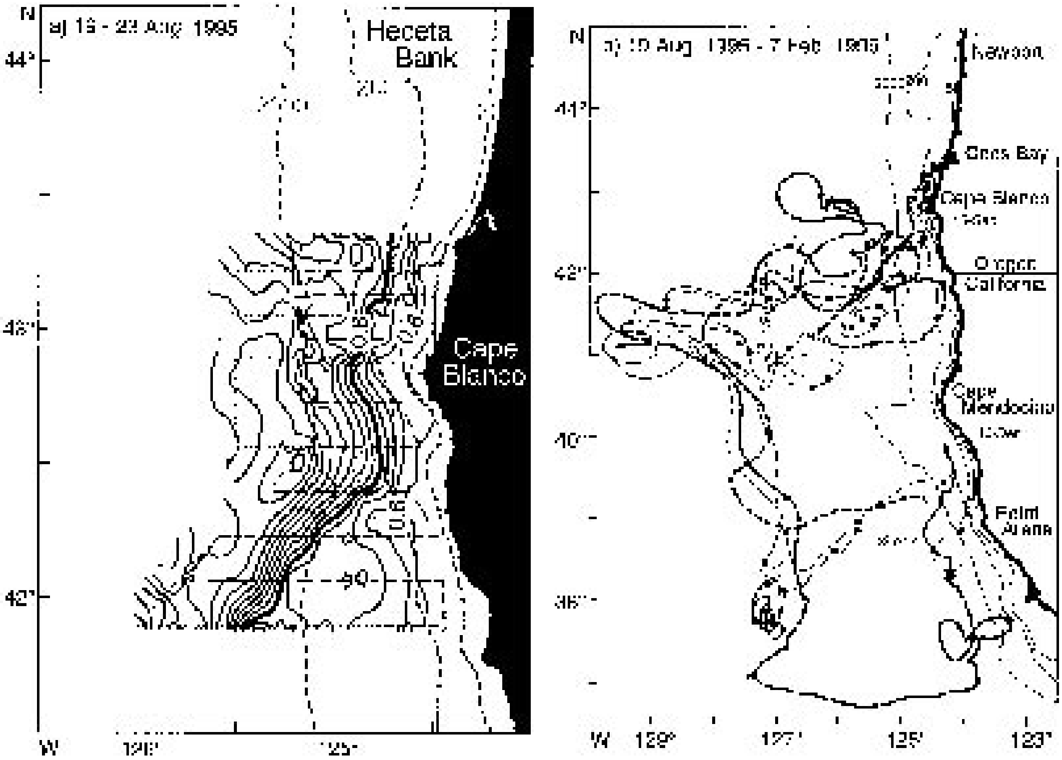

Fig. 6: (a) Contour map of geopotential anomaly (dynamic height in meters multiplied by the acceleration of gravity) at 23 m relative to 55 m from a SeaSoar survey during the period 19–23 August 1995. Individual CTD depth profiles are denoted by dots along the ship track and the 50-, 200- and 2 000-m isobaths are shown in grey. The 0.8 m^2s^{-2} geopotential anomaly contour is highlighted to show the separation of the coastal jet from the continental shelf; (b) trajectories of five satellite-tracked drifters released on 19 August 1995 off Coos Bay, Oregon. Drifter tracks are marked at weekly intervals. The drifter released farthest north and most landward (thick solid line) ran aground just south of Cape Blanco on 15 September 1995, one drifter (thick dashed line) failed on 28 November 1995 just offshore of the 2 000 m isobath north of Point Arena and one drifter (thin dashed line) came ashore south of Cape Mendocino on 16 December 1995

1987), the circulation responded and all four drifters were swept shorewards between 37 and 39°N. On 16 December 1995, one drifter (thin dashed line) came ashore south of Cape Mendocino (40.5°N), California, whereas by 7 February 1996 one drifter (thick solid line, Fig 6b) was transiting polewards over the continental slope and another drifter (thin solid line, Fig 6b) had exited from a cyclonic eddy near 38°N, 127°W and was transiting shorewards to the north-west. The fourth drifter (thick dashed line, Fig. 6b) was moving onshore along roughly 39°N before it stopped transmitting on 28 November 1995 while over the continental slope just north of Point Arena (39°N), California.

In summary, as a result of the jet-topography interaction, which leads to a meandering jet with a substantial East-West component, passive material released on the shelf in the coastal upwelling jet north of Cape Blanco late in the upwelling season (August) can return to the coast within approximately five degrees of latitude to the south under the influence of the seasonal change in wind stress and the resulting ocean circulation.

DISCUSSION

The results presented demonstrate the existence of strong spatial variability in the upwelling circulation off the Oregon and northern California coasts. Understanding the processes that lead to and control this spatial variability is critical to assessing the influence of ocean circulation on biological productivity and the transport of biogeochemical and anthropo-genic material on to and off the continental shelf. The existence of separated coastal upwelling jets, recirculating eddies, meandering equatorward jets and return flows to the coast has been documented. There is a distinct difference in the behaviour of the system between early (May) and later (August) in the upwelling season. In May, the coastal jet remains relatively straight as it transits around Cape Blanco, and drifters released on the shelf are flushed far to the south in the eastern boundary current region. This differs from the behaviour in August, when the upwelling circulation is more fully developed and the jet-topography interaction creates a spatially complex flow pattern that can retain drifters released on the shelf near their release latitude, enabling their return to the continental margin after the seasonal winds change direction.

These different early- and late-upwelling season flow trajectories and the contrasting ultimate destinations for passive material originally found over the continental shelf may have important consequences for the biology of eastern boundary current systems. For example, organisms found over the continental shelf early in the upwelling season, in that part of the water column influenced by wind-driven circulation, are likely to be swept rapidly equatorwards and offshore in the developing coastal upwelling jet and the relatively straight equatorward eastern boundary current farther south. For passive or weakly swimming organisms, this suggests diminished opportunities for these organisms of returning to the continental margin and being successfully recruited into adult populations found over the continental shelf and slope. In contrast, passive or weakly swimming organisms found in the mid- to upper-water column over the continental shelf late in the upwelling season can be transported far out into the eastern boundary current before being returned to the continental margin through advective effects alone. This suggests an increased opportunity for those organisms to successfully join populations found over the continental shelf and slope.

Lastly, interannual changes in the strength and timing of upwelling occur and are important to levels of biological productivity. Whereas this paper has not concentrated on interannual variability, marked differences exist between the two August realizations presented here. In August 1994, upwelling-favourable winds were anomalously weak and the jet-Cape interaction resulted in the generation of cyclonic eddies, whereas in August 1995, after a month of typical, strong, upwelling-favourable winds, the coastal jet was fully separated from the coast near Cape Blanco. In both August realizations, however, the jet-topography interaction was sufficiently developed to generate mesoscale variability (eddies, separated jet) that, in turn, provided Lagrangian pathways for material to be retained near the latitude of its departure from the continental shelf.

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