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Flow along the continental slope off Washington,
Autumn 1971

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ABSTRACT

Observations of the hydrographic regime across the continental shelf and offshore to depths exceeding 2000 m were made in Autumn 1971 to investigate the possible extension of the California Undercurrent off the coast of Washington. Closely spaced stations, positioned by depth, were made to the bottom on each crossing of the continental slope. Geostrophic calculations relative to 1000 m and extending up the slope to shallower depths indicated a broad band of northward flow above the continental slope. Higher salinity and deepening of the density surfaces right at the continental slope indicated a possible intensifying of the currents at depths below the shelf break. No significant horizontal gradients of properties were observed at depths shallower than the shelf break. The flow was observed on a different density surface than off California.

1. Introduction

During 17–24 October and during 12–19 November 1971 seven sections of vertical profiles of temperature and salinity were made from the coast offshore to investigate the possible northward extension of the California Undercurrent along Washington and parts of Vancouver Island and Oregon. Wooster and Reid (1963) indicated that this kind of poleward undercurrent close to the boundary was a common feature of eastern boundary currents. Observations have shown the presence of the California Undercurrent from southern Baja California to about the northern border of California (Reid et al. 1958, Wooster and Jones 1970). North of California data are more limited. Off Washington and Vancouver Island some observations have indicated northward flow at 200 m near the continental slope (Ingraham 1967), and others have indicated evidence of the California Undercurrent below 200 m (Dodimead et al. 1963). Additionally, in the historic hydrographic data of the University of Washington (numerous unpublished data reports), we found a few sections with stations which indicated northward geostrophic flow, relative to 1000 db, only above the continental slope and below the depth of the continental shelf break (about 200 m). Thus, it was decided to make sections of closely spaced stations to the bottom across

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the continental slope to attempt to estimate the flow above the slope from the distribution of properties and from calculations of geopotential anomaly relative to 1000 db using a technique outlined by Sturges (1967). This note summarizes those observations.

2. Observations

Salinity-temperature-depth (STD) measurements were made with a Plessey model 9006 system from the National Oceanic and Atmospheric Administration (NOAA) ship Oceanographer. The stations were made within 2–4 m of the bottom by attaching a pinger to the STD system and using the ship's fathometer to monitor the depth of the system. On each section the positions of the stations over the slope were determined by depth such that there would be an even distribution of bottom observations between depths of 200 and 2000 m. Data were recorded by electric typewriter printout at about 3-m depth intervals and as analog traces while lowering the STD. Calibration of the STD system was made by Nansen bottle samples collected just above the STD during ascent. No corrections were necessary for the October data, and the precision of the measurements was less than ±0.01 per mil or C. A depth-dependent salinity correction was necessary for the November data. Details of the calibration, description of the cruise, and the temperature and salinity sections are in Ryan et al. (1973). The November cruise repeated the October cruise with a few exceptions. The observations from each are similar, except where noted below, thus the November data are not presented.

Wooster and Jones (1970) found the California Undercurrent represented on the surface of constant thermosteric anomaly (isanoMesic surface) of 150 cl/ton (sigma-t of 26.54 g/l) which characterized a bulge in the temperature-salinity (t-s) curves. This surface off southern California occurred at depths of 250–300 m. They also found the Undercurrent represented in the geopotential topography of the 200-db surface relative to 1000 db along all of California. Off southern California their data indicated the shelf-slope break occurred nearer to 150 m, thus the 200-db surface was deeper than the break.
Figure 2. Salinity (per mil) on the isanosteric surface 125 cl/ton, 17–24 October 1971. Values are the decimal part only of salinities slightly greater than and slightly less than 34.00 per mil. Corresponding temperature for 34.00 ± .01 per mil at 125 cl/ton is 5.82 ± .06 C. The number assigned to each section, given by a Roman numeral, is shown in the figure. The approximate offshore limit of the shelf is shown by the 100-fathom (183-m) isobath.

Examination of our data showed the 150-cl/ton isanosteric surface occurred everywhere at depths of 150–200 m, thus it was shallower than off California and shallower than the shelf break in this region. Salinity on this surface was very uniform, apparently because it was able to mix freely with waters on the shelf. However, the characteristic bulge in the $t-s$ curves that indicates the undercurrent also was present at 150 cl/ton in our data (Figure 1). Below the shelf break our data generally showed warmer and saltier water nearest the coast, the same distinguishing characteristics observed by Wooster and Jones. These features are exhibited well on the 125-cl/t surface (Figures 2 and 3). This surface also is one that was used to characterize large-scale features of the Intermediate waters throughout the Pacific (Reid 1965).
Two significant features are shown best in the data without using contours. The first is the slight increase in salinity of about 0.02–0.03 per mil, but as high as 0.07 per mil between two stations on section 6, as the continental slope is approached on all but two sections (Figure 2). The change in salinity from less than to greater than 34.00 per mil helps emphasize the feature, but it should not be interpreted as a boundary. On sections 1 and 6 the increase only occurred at one station. On sections 4, 5, and up the submarine canyon there were higher salinities across the entire slope with a more pronounced increase at the innermost one or two stations as on sections 1 and 6. Reid's (1965) study showed along this coast the highest salinity water was in the lowest latitudes. Thus, this relatively higher salinity water is interpreted to flow north from a more southern source.

Two sections had exceptions to the above. Section 7, the southern most, had highest salinities further offshore and beyond the continental slope. Possibly, higher salinities were missed, but the trend was the same on the November cruise. Section 2
Figure 4. Distribution in section 4 of temperature (top), C, and salinity (bottom), per mil, 21 October 1971. Bottom temperatures and the decimal part of bottom salinities are given. In the mid continental slope is an isolated shoal.

had one relatively low value (33.93 per mil) over the slope which was combined with a significant deepening of the isanosteric surface (Figure 3). This feature appeared to be an eddy, and by the November cruise it had moved along the coast to section 1. The $t-s$ characteristics for the stations with the relatively low salinities were similar on both cruises, but they differed from the other stations indicating a different source of water (Figure 1).

The second feature of significance is the coincident deepening of the isanosteric surface at the inshore stations with relatively high salinities (Figure 3). On section 6 there was considerable change from about 320 m to more than 380 m in a relatively short distance of about 4 km. Four stations showed deepening on the section up the submarine canyon. On section 2 the isanosteric surface at the station with the lowest salinity was deeper than 400 m and was characteristic of a single station on section 1 in November. Section 1 in October had a more gradual deepening of the surface across the entire slope.

Section 7 appears anomalous with continuous shoaling toward the coast. The
November cruise, however, showed shoaling only at the offshore stations with deepening across the slope and a change in depth of 40 m between the two inshore stations. Although the salinity is more uniform, section 7 may have had the same characteristics. Alternately, about 180 km south the 200-m isobath lays east-west at Heceta Bank and extends offshore about 70 km to about 125°W longitude. North and south of the bank, this distance narrows to 20–30 km and is about 50 km at section 7. Heceta Bank is a major protrusion along the slope, and it possibly causes the northward current to flow offshore. Thus, the high salinities offshore at section 7 possibly are the source of those right at the slope on sections 6, 5 and 4.

The vertical temperature and salinity distributions on section 4 (Figure 4) are representative of all the sections indicating northward flow above the continental slope. The deeper isotherms generally dip more steeply as the continental slope is approached, and they are relatively horizontal further offshore. None of the sections showed the more abrupt change in dip of the isotherms near the coast observed by Wooster and Jones (1970). The near-surface isotherms and isohalines gradually shoal toward the coast. However, only some of the deeper isohalines dip near the continental slope.

3. Geostrophic flow

In order to estimate the geostrophic flow in this region, the calculation of geopotential anomaly must be extended into relatively shallow water. Sturges (1967) in his study of sea level along the Pacific coast presented a technique which appeared generally applicable and is briefly summarized here. The geopotential anomaly, \( \varphi_a \), is calculated from the equation

\[
\varphi_a = - \int_{p_1}^{p_2} \delta dp
\]

where \( \delta \) is the anomaly of specific volume and \( p \) is pressure. The integration is usually performed along a vertical from a reference pressure, \( p_1 \), to the pressure of interest, \( p_2 \). However, Sturges showed the integration could be performed along the bottom up the slope in the absence of strong currents, and eastern boundary currents are generally broad and slow. His technique was to estimate the distribution of \( \delta \) along the bottom and to plot it as a smooth curve. This curve then was used to integrate the above equation between the bottom depths of neighboring stations. Additionally, Sturges discussed the appropriateness of using 1000 db as a reference level near the coast. Data in the present study, as indicated above, were sampled such that \( \delta \) along the bottom on the slope could be plotted versus pressure as a smooth curve.

Because most previous studies close to this coast have used dynamic heights and because the 300-db surface was near but everywhere shallower than the 125-cl/ton isanosteric surface (Figure 3), its geopotential topography relative to 1000 db was used to estimate the geostrophic flow (Figure 5). The differences from station-to-station were small (given to .001 dynamic meters; 1 dyn m = 10 J/kg), but the trend
across several of the sections was in the same direction and added up to a few dynamic centimeters. For example, on section 4 the .027-dyn m difference between the inshore five stations over a horizontal distance of about 41 km equaled a geostrophic current of 6.3 cm/sec, and on section 1 .033 dyn m between the inshore five stations over 31 km equaled 10.0 cm/sec. A one nautical-mile (1.85 km) error in the horizontal separation would change these speeds by 0.3 and 0.6 cm/sec on sections 4 and 1, respectively. A larger difference occurred at the inshore two stations on section 5 corresponding with the larger changes in salinity and depth (Figures 2 and 3). The .72-dyn m contour could be extended through section 7 offshore of the two highest values, a possible source of the high salinities farther north. Additional contours did not add clarity, and examination of individual sections appeared to be the best alternative.

The 500-db surface was deeper than the 125-cl/ton isanosteric surface, and its
Table 1. Relative topography in dynamic meters between successive stations on section 5 starting offshore with station a. Plus indicates northward flow. A station between e and f was omitted. The bottom depths of stations c to h were 1650, 1420, 1000, 740, 560, and 170 m, respectively. Stations a and b exceeded 2000 m.

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topography relative to 1000 db showed the same patterns and about the same magnitudes as the 300-db surface. The same five stations on section 4 showed a geostrophic current of about 5 cm/sec.

Table 1 shows the geostrophic flow through section 4. One station (.714 dynamic meters on Figure 5) was omitted because of the closeness (2.6 km) of the pair. Speeds are not given between pairs of stations because their closeness makes them questionable, and the detailed structure in the flow regime probably is not significant. The important feature is that over most of the slope where the bottom is shoaler than 1000 m, there was flow to the north. This section was representative of the sections indicating northward flow above the slope. In this case, but not on all sections, the flow extended offshore beyond bottom depths of 1000 m. The speeds of 6.3 and 4.7 cm/sec at 300 and 500 m, respectively, were between the four inshore stations in the table. Speeds between pairs of stations separated by about 10 km were up to 10–15 cm/sec, but these values are subject to larger uncertainties because of station = position uncertainties.

The surface geostrophic flow on most sections was southerly above the base of the slope and offshore, and it was northerly over much of the slope during both October and November. There were several storms of one-two day duration during
these cruises, but they were not of the intensity or duration of winter storms. In October one storm prior to occupying the first section (7) was followed by variable and northerly (southward flowing) winds during the 14th through 16th. A second storm offshore caused southerly winds from the 17th for the duration of the cruise. Thus, the storms and the surface flow were characteristic of the autumn transition (Ryan et al. 1973).

4. Discussion

In Reid's (1965) study of Intermediate waters, the map of acceleration potential of the 125-cl/t surface showed that the features presented here probably extend northward until they become part of the subarctic gyre. His map of the depth of the surface showed depths exceeding 300 m as far north as Vancouver Island. Onshore deepening indicated by his 350-m contour appeared to stop south of 40°N. The data here including the November cruise indicated that the deepening occurred at least as far north as the mouth of the Strait of Juan de Fuca. Reid's map of oxygen concentration showed extending northward along the coast and out the Aleutians a narrow band of less than 2.0 ml/l which could only come from the low latitude minimum by a northward flowing current close inshore.

The existence of the California Undercurrent and similar features elsewhere have been known for a long time (Wooster and Reid, 1963). The fact that the Undercurrent occurred very close inshore was pointed out off California by Wooster and Jones (1970) and off Washington by Ingraham (1967). Our data indicated that northward flow occurs reasonably regularly over the continental slope below the depth of the shelf break. This flow did not show up in much of the historical data off Washington and Oregon, apparently because of a sampling technique. Cruises designed for other purposes took stations near the shelf break and then offshore in water deeper than 1000 m. Also, most of the recent studies of coastal upwelling off Oregon did not extend down the continental slope. Mapping of the current on the 200-db surface appeared most successful off California where the shelf break apparently was shallower. Off Washington there appeared to be easier mixing of water on and off the shelf at 200 m. Further north this flow is part of the subarctic gyre. However, the continuity of these current systems is beyond the scope of the present study.

Unfortunately, no direct observations of the flow were made. The only possible auxiliary indication is the apparent eddy on section 2 shown by 33.93 per mil salinity at 424 m (Figures 2 and 3). This feature was evident on section 1 during the November cruise by the same salinity at 399 m. If it is an observation on the same feature as indicated by t-s characteristics (Figure 1), then it drifted at a speed of about 3.4 cm/sec during the approximate month interval and is at least comparable with the geostrophic speeds indicated above. The two low-salinity stations on section 4 may have drifted to section 2 by November, also indicating a comparable speed.

 Eleven stations exceeded 2000 m. The geopotential anomaly of 1000 db relative to 2000 db was .60 ± .01 dyn m. Reid and Arthur's study (this volume) of this
surface over the entire Pacific shows the same value in this region. The lack of gradients on the 1000-db surface in this region indicates its appropriateness for the present study.

Reed and Halpern (1973) made two sections further offshore from Washington and Vancouver Island during the fall following our study. Their results indicated a broader northward flow at 300 db, but only one station extended over the slope inshore of 1000 m. Their error analysis of 12-hr time series stations showed that at 300 db a difference in dynamic topography of about .009 dyn m was sufficient to indicate direction of flow between pairs of stations. Many pairs of our stations, not necessarily adjacent, exceeded this difference. However, our stations were occupied at one-two hour intervals, thus this difference probably was a maximum. Also, as previously indicated, the trend across most sections was larger and in the same direction.

Theoretical discussions related to upwelling have indicated poleward undercurrents (Yoshida 1967, Pedlosky 1974). These studies have been directed at the continental shelf region, and it is not clear that they apply to the deeper flow along and offshore of the slope. Although most observations have been from other than winter, it is uncertain whether the present theoretical work accounts for the northward flow during winter when the predominant winds are southerly. However, Pedlosky indicated the curl of the wind stress to be a major factor for determining flow over a sloping bottom, with a positive curl supporting poleward flow along the bottom. Winter observations on the slope and offshore would be most useful in clarifying the year-round existence of the poleward flow. Other studies have indicated that sloping bottoms tend to trap and intensify motions on many scales (Wunsch and Hendry 1972). None seemed applicable here to a broad current flowing along a sloping bottom with a possible intensification where the current impinges on the bottom.

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This paper is dedicated to Professor Raymond B. Montgomery on his retirement from The Johns Hopkins University. His dedication to high scientific principles and his personal interest in his colleagues, students, and their families have provided a lasting inspiration.

REFERENCES


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