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The presence of a southward-moving undercurrent along the west coast of South America, underlying the Peru Current at depths of several hundred meters, has been established by direct measurements with parachute drogues, by calculations of geostrophic motion, and by analysis of the distributions of salinity and dissolved oxygen. The undercurrent extends from northern Peru to at least 41°S. Speeds of 4–10 cm/sec were measured off Peru and northern Chile; the geostrophic transport appears to decrease downstream, from $2.1 \times 10^6$ m$^3$/sec at 5°S to about $3 \times 10^6$ m$^3$/sec at 15°S. At its coastal edge the flow parallels the edge of the continental shelf. South of 15°S, waters of the undercurrent are characterized by relatively high salinity and temperature as well as low oxygen content.

The surface currents which flow equatorward along the eastern margins of the major ocean basins are relatively well known. They include the California and Peru currents in the Pacific Ocean and the Canary and Benguela currents in the Atlantic Ocean. But little, if anything, is known about the
subsurface circulation in these regions, although there are some indications of poleward coastal currents several hundred meters beneath the equatorward surface flow.

For example, a common feature of the density distribution on cross-stream profiles off such coasts is a deepening of the isopycnals shoreward below the ascending isopycnals characteristic of coastal upwelling (Wooster and Reid, in press). A similar deepening (or trough) is also found along the equator in association with the Equatorial Undercurrent or Cromwell Current (Knauss, 1960). In the coastal region geostrophic computations based on this density distribution indicate the presence of a subsurface countercurrent, or undercurrent.

The similarity in distributions of mass and circulation in the equatorial and eastern boundary coast regions has been noted by Yoshida and collaborators (Yoshida, 1955; Yoshida and Tsuchiya, 1957; Yoshida 1958, 1959), who have made a theoretical investigation of the boundary phenomena. But until now no one has actually measured a coastal undercurrent and attempted to relate such measurements to other physical and chemical observations made in the vicinity at the same time.

In a recent paper Wooster and Reid (in press) discussed the evidence for coastal undercurrents on the eastern boundary coasts of California, Peru and Chile, northwest and southwest Africa. The scarcity of data suggested the desirability of including direct current measurements in the scientific program of the STEP-I Expedition of the University of California’s Scripps Institution of Oceanography. The present paper is based primarily on observations of this expedition aboard R/V Horizon off the west coast of South America during October 1960.

Observations and Methods. The track and station arrangement of the STEP-I Expedition are shown in Figs. 1 and 2. Observations along the profiles consisted of oceanographic stations at 40–100 mile intervals with numerous BT and surface salinity observations between stations. On most stations measurements were made between the surface and at least 1000 m, and in some cases to depths of several kilometers. Station measurements included temperature, salinity, dissolved oxygen, phosphate, silicate and nitrite, made by conventional methods (salinities were determined with a conductivity-type salinometer: Paquette, 1959).

South of Talara at six locations, measurements of surface and subsurface currents were made with parachute drogues close to shore (Fig. 2) but beyond the edge of the continental shelf because the undercurrent was believed to be a boundary phenomenon and because it was desired to use offshore islands as reference points for navigational control. The drogues, similar to those described by Jennings and Schwartzlose, 1960 (see Volkmann, et al., 1956, for discussion of the method), consisted of seven-meter diameter aviator’s
Figure 1. Track chart of STEP-I Expedition, 15 September to 14 December, 1960.
Figure 2. Station plan of STEP-I Expedition.
parachutes connected by wire to seven-meter bamboo poles suitably equipped to serve as surface indicators of the drogue positions.

At each location two drogues were customarily placed at each of the following approximate depths as indicated by the length of wire used: 10 m, 100 or 150 m, 250 or 300 m. The true depth differs only slightly from the wire length (Volkmann, et al., 1956). The parachutes at 10 m were connected to the surface floats with 7 x 7 aircraft cable, 2.4 mm diameter; for deeper parachutes, including those of the two reference drogues, 2.1 mm diameter music wire was used; connections were made with "Nicopress" sleeves. On the southernmost station, combinations of aircraft cable and music wire were used due to shortage of the latter. Parachutes were sent unopened to the desired depth, weights at the parachute apex then being dropped by a time release device.

Along the Peruvian coast, numerous small steep islands are perched near the edge of a narrow continental shelf, and on four of the six stations, these were used as reference points for position control. On the other two stations, where such islands were not available, parachutes at 1000 m were used as reference points. After a suitable interval following launching, the positions of drogues relative to the reference point were determined with a U.S. Navy SPS-5 radar and by occasional visual inspection. Ranges and bearings were determined at approximately half-hour intervals, the total tracking time varying from 18-43 hours. It was usually possible to track all drogues on a station simultaneously, from ranges of several thousand meters (the radius of sea return) to more than 14,000 m (under ideal wind and sea conditions). After 12-24 hours, surface drogues had usually moved out of range and were abandoned so that subsurface drogues would not be lost.

In analyzing these drogue measurements, the apparent relative motion of the drogues was corrected for the effect of wind and surface current on the surface float and for drag of the connecting wire. A discussion of drag forces acting on the various components of the drogue system has been presented by Volkmann et al. (1956). The convenient graphical method of Brown (in press) was used for computing the necessary corrections. As a rule, corrections for forces acting on the surface float were significant whereas those for wire drag were negligible. A discussion of the errors involved in these current measurements is given in the Appendix.

Evidence from drogue measurements. Pertinent information concerning the drogue stations and a summary of measurements are presented in Table I. The observed drogue trajectories, uncorrected for drag of the wire and surface apparatus, are shown in Figs. 3-8.

Corrected mean current vectors, estimated by comparing the first and last reliable drogue positions, are shown superposed on charts of bottom topography in Fig. 9.
TABLE I. SUMMARY OF DROGUE MEASUREMENTS.

<table>
<thead>
<tr>
<th>Drogue Station</th>
<th>Station Depth (m)</th>
<th>Width of Cont. Shelf (km)</th>
<th>Distance Offshore (km)</th>
<th>Mean Wind (cm/sec) dir °T</th>
<th>Depth of drogue (m)</th>
<th>No. of drogues</th>
<th>Max. Time Observed (hours)</th>
<th>Observed speed cm/sec</th>
<th>Drift direction °T</th>
<th>Corrected Drift speed cm/sec</th>
<th>Corrected Drift direction °T</th>
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</thead>
<tbody>
<tr>
<td>A ...............</td>
<td>320</td>
<td>7</td>
<td>26</td>
<td></td>
<td>10</td>
<td>3</td>
<td>12.5</td>
<td>11.9 ± 3.5</td>
<td>292 ± 3</td>
<td>11</td>
<td>287</td>
</tr>
<tr>
<td>B ...............</td>
<td>300</td>
<td>35</td>
<td>49</td>
<td>30/162</td>
<td>10</td>
<td>2</td>
<td>20.4</td>
<td>25.8 ± 0.9</td>
<td>272 ± 2</td>
<td>26</td>
<td>270</td>
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<tr>
<td>C ...............</td>
<td>290</td>
<td>65</td>
<td>73</td>
<td>76/152</td>
<td>10</td>
<td>2</td>
<td>5.2</td>
<td>29.3 ± 2.3</td>
<td>306 ± 5</td>
<td>28</td>
<td>314</td>
</tr>
<tr>
<td>D ...............</td>
<td>465</td>
<td>11</td>
<td>34</td>
<td>53/156</td>
<td>10</td>
<td>2</td>
<td>19.6</td>
<td>18.1 ± 0.4</td>
<td>352 ± 3</td>
<td>17</td>
<td>353</td>
</tr>
<tr>
<td>E ...............</td>
<td>650</td>
<td>4</td>
<td>10</td>
<td>2/123</td>
<td>10</td>
<td>4</td>
<td>15.5</td>
<td>28.7 ± 3.2</td>
<td>308 ± 7</td>
<td>29</td>
<td>308</td>
</tr>
<tr>
<td>F ...............</td>
<td>3135</td>
<td>3</td>
<td>27</td>
<td>37/168</td>
<td>10</td>
<td>2</td>
<td>22.7</td>
<td>19.3 ± 0.5</td>
<td>065 ± 2</td>
<td>19</td>
<td>067</td>
</tr>
</tbody>
</table>

Figure 3. Uncorrected drogue trajectories, St. A (5°57'S, 81°26'W). Surface drogues indicated by dash-dot lines, intermediate drogues by dashed lines, and deep drogues by solid lines. Ticks along trajectory indicate 2-hour time intervals.

Figure 4. Uncorrected drogue trajectories, St. B (11°26'S, 78°05'W); symbols as in Fig. 3.
Within the time periods during which drogues were tracked, fluctuations in speed and direction are evident and are undoubtedly related to the forces causing and modifying the flow (such as wind stress and tides); these will not be examined in detail here. However, the good coherence between drogues at the same depths (Figs. 3–8) suggests that the observed motion is a reliable indication of water movement.

**Surface Motion.** Fifteen drogues were placed at a depth of 10 m on the six stations. In all cases they moved rapidly out of the operational area and thus were followed for relatively short periods (5–23 hours). On all but the southernmost station, surface drift was toward the northwest (270°–353°), with mean speeds of 11–29 cm/sec. This motion is consistent with the generally accepted picture of surface flow in the Peru Current.

On the southernmost station, average surface drift was toward 067° at a speed of 19 cm/sec; during the first eight hours motion was toward the east, but as the drogues approached the coast they swung toward the northeast and speeded up. Offshore the eastward motion (090° ± 4°) was at a speed of 16–17 cm/sec. Five days later, at a position 35 km west of the drogue station,
a surface current measurement by geomagnetic electrokinetograph\(^3\) gave a velocity of 13 cm/sec toward 097°, consistent with the observed motion of the surface drogues.

**Subsurface Motion.** In most cases subsurface movement was significantly different from that at the surface. At four stations, the deepest drogues moved

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\(^3\) On the other stations such measurements were not possible because of the proximity of the magnetic equator.
Figure 7. Uncorrected drogue trajectories, St. E (17°00'S, 72°15'W); symbols as in Fig. 3.

southward (133°–211°) at speeds of 5–9 cm/sec; on a fifth station (13°51'S), corrected motion was also southward but at almost negligible speed (1 cm/sec); and on the sixth (11°58'S), motion was toward the northwest. On three stations, the drogues moved southward (160°–225°) at 4–8 cm/sec at intermediate depths and faster at greater depths, suggesting that the principal motion lies somewhat deeper than 100–150 m.

Thus on all but one station there was some indication of a subsurface current flowing southward along the coast in a direction more or less opposite to that of the surface flow. The anomalous station (11°58'S), with motion
at all levels toward the northwest, was the shallowest one occupied, and was located off a wider continental shelf than were the other stations.

The direction of subsurface motion is closely related to the direction of the 100 fm contour (Fig. 9). This relationship is particularly striking on the stations at 17° and 23°30'S, between which there occurs a major change in orientation of the edge of the continental shelf.

**Evidence from Distribution of Properties.** A southward current below the surface along the west coast of South America has been discussed by Gunther (1936), whose principal evidence for this circulation is a meridional profile of salinity about 100 miles offshore, extending from 2°–35°S (his fig. 42). The high salinity tongue reaching southward from about 15°S is considered indicative of a coastal return current which deepens as it flows southward – from about 100 m at 15° to 300 m at 35°S. Other characteristics of this water are said to be relatively high temperature and low oxygen content.

A profile analogous to that of Gunther has been constructed (Fig. 10), as far south as 24° from STEP-I data, and to 41°S from CHIPE and OB Cruise 3 data (manuscript data from U.S. Hydrographic Office and World Data Center A, respectively). Evident here also are the high salinity tongue reaching south from 15° to at least 41°S between low salinity waters of southern origin and a downstream decrease from greater than 34.8°/oo at 15°S to less than about 34.5°/oo at 41°S. At the same time thermosteric anomaly at the core of the tongue decreases, from 160 to less than 140 cl/T (centiliters per
Figure 9. Corrected mean current vectors and bottom topography. Surface drogue vectors (not to scale) indicated by dash-dot lines, intermediate vectors by dashed lines, and deep vectors by solid lines.
Figure 10. Distribution of salinity (‰) on a profile parallel to the west coast of South America about 100 miles offshore. Stations from STEP-I, CHIPER, and OB' Cruises (see text). Isanosteres of 140 and 160 cl/T shown by dashed lines.
ton), suggesting that attenuation of the tongue is due to mixing with water of lower temperature.

A profile of dissolved oxygen from the same data sources (Fig. 11) shows clearly the low oxygen content of the southward-moving water in contrast to the much higher values in the underlying water. Off the Peruvian coast subsurface water contains about 0.1 ml/L of dissolved oxygen; as the water moves southward, mixing with deeper water causes the oxygen content in the minimum layer to increase to about 1.7 ml/L at 41°S. Highest values of salinity and lowest values of dissolved oxygen are observed next to the coast (Figs. 12 and 13) with attenuation of the maximum and minimum offshore. Width of the high-salinity, low-oxygen tongue decreases downstream. At the southern end of the profile the undercurrent is also evidenced by phosphate and silicate maxima (see Ob' St. 447 data).

Evidence of an undercurrent can also be seen in the profiles of geostrophic velocity based on STEP-I data. In making the computations, thermosteric anomaly was used rather than specific volume anomaly, this approximation being considered adequate for the purposes of this paper (Montgomery and Wooster, 1954). A reference level of 1000 db was used; although motion on this surface is not known, it is probably small relative to that of the underlying water. The use of a conductivity bridge to determine salinity reduces the effect of measurement errors on geopotential anomaly to less than 0.01 dyn m (Wooster and Taft, 1958), and reporting relative geostrophic speeds to the nearest few cm/sec may be justified.

Geostrophic speeds perpendicular to the five profiles extending offshore are shown in Figs. 14–18. Speeds less than 2 cm/sec have been considered negligible. Some southward motion is apparent in each of the profiles; it predominates in the northernmost profile and becomes progressively less intense to the south. Highest southward speeds, shown in the coastal portions of the profiles, usually appear at depths of 100–200 m. In Profiles II and III, the principal southward flow seems to separate from the coast, although some southward motion is still apparent between coastal station pairs as far south as Profile IV. On Profiles IV and V, southward geostrophic flow is very much reduced. Speeds decrease from 20 cm/sec in the northernmost profile to about 2 cm/sec on Profile IV. Southward transport decreases from about $21 \times 10^6$ on Profile I to about $3 \times 10^6$ m$^3$/sec on Profile III.

**Discussion.** Results from the parachute drogue measurements and from analyses of the distribution of properties and the geostrophic computations demonstrate clearly the presence of a southward undercurrent along the coast of Peru and Chile. Characteristics of the undercurrent can be summarized as follows:

4 In one instance (see Appendix) the motion of a 1000 m reference drogue was estimated to be 1 cm/sec or less.
Figure 11. Distribution of dissolved oxygen (ml/L) on same profile as Fig. 10.
Figure 12. Distribution of salinity (‰) on Profile IV; see Fig. 2 for location.
Figure 13. Distribution of dissolved oxygen (ml/L) on Profile IV; see Fig. 2 for location.
Figure 14. Geostrophic speed (cm/sec) perpendicular to Profile I; see Fig. 2 for location. Darker shading represents southward motion.
Figure 15. Geostrophic speed (cm/sec) perpendicular to Profile II; see Fig. 2 for location. Darker shading represents southward motion.
Figure 16. Geostrophic speed (cm/sec) perpendicular to Profile III; see Fig. 2 for location. Darker shading represents southward motion.
Figure 17. Geostrophic speed (cm/sec) perpendicular to Profile IV; see Fig. 2 for location. Darker shading represents southward motion.
Figure 18. Geostrophic speed (cm/sec) perpendicular to Profile V; see Fig. 2 for location. Darker shading represents southward motion.
1. Flow originates off northern Peru, in the region of the boundary of the Peru Current or farther north, and extends at least as far south as 41°S at depths of several hundred meters.

2. Speed and transport of the geostrophic flow decrease from north to south. The geostrophic and measured speeds (4–10 cm/sec) are, in general, compatible except on the northernmost profile where the geostrophic speed (20 cm/sec) is significantly higher.

3. At its coastal edge, the flow closely parallels the edge of the continental shelf. On the northern profiles, principal appears to separate from the coast.

4. South of about 15°S, waters of the undercurrent are characterized by relatively high salinity and temperature and low oxygen content. Off southern Chile the undercurrent is also evidenced by phosphate and silicate maxima.

The strong southward flow observed on the northernmost geostrophic profile suggests that there is a supply of warm, high-saline water from the equatorial region north of the Peru Current regime. Between there and 15°S, the undercurrent is presumably associated with the boundary processes of upwelling and related enhanced vertical mixing. The significant decrease in transport of the geostrophic current from Profiles I to III suggests that much of the water may be brought to the surface in the upwelling process in addition to that lost by zonal transport.

The surface geostrophic flow to the south on the inshore end of Profile I does not appear to be compatible with the motion of the surface drogue (Fig. 9) or with the presence of upwelling. The high surface phosphate content (2.05 µg at/L) as well as the vertical distribution of density and other properties there suggest that vigorous upwelling may have occurred just prior to our observations. There is little evidence of upwelling on Profile II, but the inshore end of Profile III shows clearly all the usually accepted indications of the process.

It should also be noted that the flow measured with the parachute drogues and the flow estimated from the distribution of mass, although related, are not the same. In general, the drogue measurements were close to shore in relatively shallow water and pertained to rather specific time intervals and layers of water. The geostrophic currents, computed from the station pairs lying farther offshore in deeper water, involve a certain averaging of conditions over distances of 40 miles or more. In the immediate vicinity of the boundary, the geostrophic approximation may not be applicable because of its neglect of frictional forces, accelerations and vertical velocity.

South of 15°S, on Profiles IV and V, there are no indications of upwelling. This is in agreement with the findings of Wooster and Reid (in press) who showed that except in winter, there is little or no Ekman transport offshore between 15° and 30°S. In this region an overflow of low-salinity water from the coastal current off Chile and the presence at depth of cold, low-salinity water make the undercurrent apparent as a layer of high salinity.
Despite the relatively small volume of southward flow, particularly south of 15°S, waters with the characteristics of the undercurrent are widespread. Nothing is known concerning seasonal variations in the strength of southward flow, and it is conceivable that this may be stronger at some other time of year than October. A few of the drogue measurements suggest that stronger flow is present than is indicated by the geostrophic data. It is also possible that even a slow, and possibly intermittent, subsurface flow may be capable of developing the observed distributions of properties. Certainly the decrease in volume of southward flowing water mentioned above suggests a continual loss through vertical and horizontal transport.

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WOOSTER, W. S. and J. L. REID
APPENDIX

ACCURACY OF PARACHUTE DROGUE MEASUREMENTS

In estimating the absolute motion of water at a certain depth by means of parachute drogues, one is faced with (1) errors in determining the uncorrected motion of a drogue relative to the reference point, and (2) errors in positioning of the reference point itself. In addition there may be systematic errors in the correction of the apparent relative motion for the drag forces acting on the drogue system. We have considered as unimportant for the present problem the uncertainty of the magnitude of these drag forces and have accepted the empirical values of Brown (in press) without modification.

In determining the motion of a drogue relative to the reference point, the primary errors are in range and bearing as measured by radar. The inherent accuracy of the equipment itself is high, but random errors arise from operator interpretation of the radar targets. Such errors depend on operator experience, sea state, condition of the drogue's radar reflector, tuning of the radar set, etc. A measure of these errors can be obtained from analysis of the duplicate readings of range and bearing of the reference point, customarily taken every half hour or so while on a drogue station.

The within-replicate variance, $\sigma^2$, for a large number of replicates is estimated by the equation

$$\sigma^2 = \frac{\sum (x - y)^2}{2n},$$

where $x$ and $y$ represent the replicate values and $n$ the number of replicate sets used in the analysis. The results of such analyses for each drogue station are included within the total error presented in Table I.

These errors can be assumed to be independent of range. The total error in positioning the drogue relative to the reference is the sum of the errors in positioning the ship (S) relative to the reference (R), and the drogue (D) relative to the ship. The S–R relation is determined from the mean of duplicate measurements of range and bearing, the S–D relation by a single measurement; the total error in the drogue position, $E$, is given by

$$E = 2\sqrt{\frac{\sigma^2}{2} + \sigma^2} = \sigma\sqrt{6}.$$  

Estimates of total error are presented in Table I.

Errors in positioning the reference point depend on whether an island or a deep parachute drogue was employed. In the former case, the island is not a point target and may appear to shift in position when viewed from different bearings. The islands selected in this study were small and precipitous and at a sufficient distance so that we feel such errors can safely be neglected.
When it was necessary to use deep (1000 m) parachute drogues as references, the radar reflector was essentially a point target, but the assumption of negligible motion at such depths may not be valid. On one station (6°S) a rough estimate of reference drogue motion was made by bringing the ship alongside the reference drogue on three occasions and by determining the ranges and bearings of four points on the shore. Although these shore points were not ideal for this purpose, the successive measurements showed an average southward movement of 1-2 cm/sec. No correction has been made for this apparent change in reference position, but such a correction would serve to increase slightly the estimated speed of the undercurrent.

In treating all of the drogue data it was assumed that all ranges and bearings of a given set were measured simultaneously. In practice, 5-6 minutes were required for the measurements, during which the ship may have drifted approximately 70 m (20 cm/sec for 6 min). Since the ships position relative to the reference was determined by averaging measurements at the beginning and end of the set, the drift error was of the order of 35 m, a small value relative to other errors.

The final positioning of the drogue depends on the coupling of the reference point-ship vector to the ship-drogue vector. Because of errors in range and bearing, the probable position of the ship or of the drogue will lie somewhere within an annular area, with the difference between the concentric circles representing the error in range, and the enclosed angle between the radii representing the error in bearing. The total error in the final drogue position will result from the coupling of these areas. The result is a function, not only of the size of errors in ranges and bearings, but of the size of the angle enclosed by the two bearings. The solving of such vector coupling is a complex operation, and for simplification it was assumed that the position of the ship lay somewhere within a circular area representing both error in range and error in bearing. The coupling of two such circular areas is independent of the angle enclosed by the bearing. The larger of the two errors resulting from range and bearing determinations was taken as the radius of the circular area. Provided that the two errors differ by at least 15%, the situation at all stations, such an assumption will result in an overestimation of the error in final drogue position and is therefore considered justified.