YALE
PEABODY
MUSEUM

P.O. BOX 208118 | NEW HAVEN CT 06520-8118 USA | PEABODY.YALE. EDU

JOURNAL OF MARINE RESEARCH

The *Journal of Marine Research,* one of the oldest journals in American marine science, published important peer-reviewed original research on a broad array of topics in physical, biological, and chemical oceanography vital to the academic oceanographic community in the long and rich tradition of the Sears Foundation for Marine Research at Yale University.

An archive of all issues from 1937 to 2021 (Volume 1–79) are available through EliScholar, a digital platform for scholarly publishing provided by Yale University Library at https://elischolar.library.yale.edu/.

Requests for permission to clear rights for use of this content should be directed to the authors, their estates, or other representatives. The *Journal of Marine Research* has no contact information beyond the affiliations listed in the published articles. We ask that you provide attribution to the *Journal of Marine Research.*

Yale University provides access to these materials for educational and research purposes only. Copyright or other proprietary rights to content contained in this document may be held by individuals or entities other than, or in addition to, Yale University. You are solely responsible for determining the ownership of the copyright, and for obtaining permission for your intended use. Yale University makes no warranty that your distribution, reproduction, or other use of these materials will not infringe the rights of third parties.

This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License.
https://creativecommons.org/licenses/by-nc-sa/4.0/

Journal of
MARINE RESEARCH

Volume 38, Number 1

Upwelling in the Humboldt Coastal Current near Valparaiso, Chile

by Donald R. Johnson,[1] Thomas Fonseca,[2] and Helmuth Sievers[3]

ABSTRACT

In December, 1975, an upwelling study was conducted at Punta Curaumilla near Valparaiso, Chile. Previous work (Silva, 1973) had indicated a zone of relatively intense upwelling around this point of land. In the present study, a bathythermograph survey confirmed the presence of the intensification, identified as a tongue of cool water extending seaward and equatorward of the point. Following Arthur's (1965) scale analysis it is suggested that the acceleration of relative vorticity past the point of land is responsible for intensification.

From current measurements within the coolwater tongue, a double-cell cross shelf circulation was found similar to the model of Mooers, Collins and Smith (1976). In the alongshore flow, a thin ($\sim$ 30 m) equatorward flow was observed together with a relatively strong poleward flowing undercurrent ($\sim$ 25 cms^{-1}, core at 100 m).

During a later stage of the experiment, the upwelling-favorable wind stress decreased, accompanied by an increase in the nearshore poleward undercurrent and an increased seaward flow across the shelf. Such pulsations may lead to patchiness of upwelled water.

1. Background

The narrow coastal surface current flowing equatorward adjacent to the coast of Chile has its roots in the South Pacific West Wind Drift. Striking the coast and turning northward at about latitude 45S, this subantarctic water can be traced in a cold tongue which extends along the coast of Chile and reaches to about 20S. North of this latitude and adjacent to the coast of Peru, the sea surface temperature and

1. University of Miami, Miami, Florida, 33149, U.S.A.
2. Universidad Catolica de Valparaiso, Valparaiso, Chile.
3. Instituto Hidrografico de la Armada, Valparaiso, Chile.

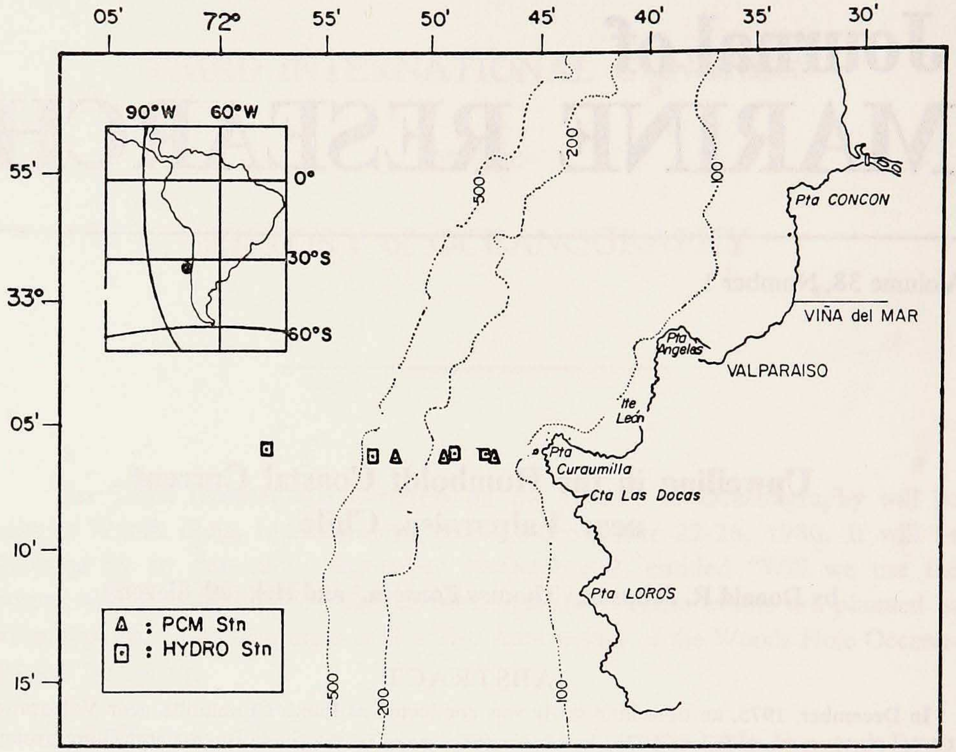

Figure 1. Location of PCM and hydrographic stations.

salinity appear to change in character (Wyrtki, 1964), giving rise to the speculation (Wooster, 1970) that most of the Chile coastal current passes offshore at about 20S and that the Peru coastal current arises along the southern coast of Peru. It is also noted (Gunther, 1936; Wyrtki, 1963) that the coastal currents in these regions are hydrologically different than the offshore currents which form part of the South Pacific Gyre and which share the general equatorward movement. The distinctive nature of the coastal current (higher salinity, lower temperature) may be generated, in part, by baroclinic adjustments to upwelling.

Below the surface layer, the current system exhibits a complex structure. In a classic work, Gunther (1936) was able to discern a poleward undercurrent with a core at around 150-300 m, characterized as a tongue of high salinity, low oxygen water of subequatorial origin. This undercurrent was later confirmed by parachute drogue observations and geostrophic calculations (Wooster and Gilmartin, 1961). It has been known as the Peru-Chile Undercurrent or, more commonly, as the Gunther Undercurrent. Just below the undercurrent lies Antarctic Intermediate Water, presumably as a weak equatorward flow.

Within this system of currents lies one of the world's most productive fisheries, due to the upwelling favorable winds which blow persistently alongshore and equatorward for most of the year. The coast of Peru has the strongest seasonal (winter) potential upwelling, as defined by calculation of offshore Ekman transport (Wooster and Reid, 1963). The coast of Chile experiences relatively lighter, but persistently favorable, upwelling winds during spring, summer and autumn, with a maximum potential near Valparaiso (30-35S).

In this paper we describe an upwelling study made in early December (spring), 1975, within a small region in the coastal current system near Valparaiso, Chile (33S). The surface current will be referred to as the Humboldt Current and the poleward undercurrent as the Gunther Undercurrent. The purposes of the study are:

(1) to examine the coastal upwelling characteristics in the southern part of the South American upwelling system and,

(2) to examine the hypothesis that intensified upwelling occurs around a seaward projecting point of land.

2. Observations

Punta Curaumilla (Fig. 1), a few miles south of Valparaiso Harbor, was selected for the study since a previous hydrographic survey indicated relatively intense local upwelling here (Silva, 1973). This is in conformity to the hypothesis advanced in several theoretical studies (e.g., Arthur, 1965; Yoshida, 1967; Peffley and O'Brien, 1976) that intensification should be expected around such a projection of land. From Figure 1, the radius of curvature of the point is approximately 20 ± 10 Km. The isobaths at the shelf break tend to curve more gently, with a radius of curvature of roughly 60 Km. The 200 m isobath, which approximately marks the shelf break, changes from a near North/South direction south of the point to about 25E north of the point. Repeated sections of current/hydrographic measurements were made on a seaward extending line cutting through the area in which the curvature is strongest (Fig. 1). The continental shelf width along this line is only about 8.5 Km.

The experiment covered approximately three days during early December, 1975, and consisted of two repeated PCM (Profiling Current Meter) sections, two repeated hydrographic sections and one area BT survey. Figure 2 shows the time sequence of the observations superimposed on the shipboard measured wind components. The winds were generally light, but favorable for upwelling with an average equatorward vector component of approximately 6 ms^{-1} over the duration of the experiment and a superimposed seabreeze component reaching nearly 3 ms^{-1} in amplitude. The wind speed tended to decrease during the progress of the experiment, a feature which will be important in later discussion.

The PCM (Düing and Johnson, 1972) is lowered over the side of the drifting ship, measuring relative current speed and direction with a 3-5 m vertical resolution. Relative measurements are converted to absolute measurements by including

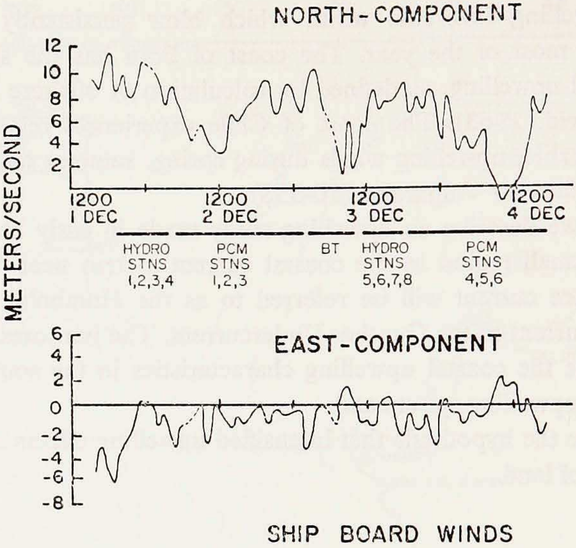

Figure 2. Wind component with the experiment time history.

the ships drift from radar tracking of a shore target. A straight line fit of the ships position at 10 min. intervals gave the drift vector. From the dispersion of points about this fit, the accuracy of the method is judged to be within ± 2 cms^{-1}. PCM casts were made in rotational sequence about the three stations in the section line (Fig. 1), sampling at 2 hr intervals and returning to each station with a 6 hr interval. Hence, four casts are made at each of the three stations over a 24 hr sampling period. These casts are vertically filtered by "Hanning" (cosine taper over three points), interpolated to 5 m depth intervals, and averaged over the 24 hrs at each station (to reduce the influence of tidal and inertial frequency oscillations).

The hydrographic casts were made using Nansen bottles with reversing thermometers. Salinity was determined with an Auto-Lab salinometer; dissolved oxygen was determined by the Winkler titration method. After each hydrographic cast, a bathythermograph cast was made to aid in interpreting the hydrographic structure and to calibrate the BT for a rapid area survey. From a comparison with the reversing thermometers, a constant 0.4°C had to be subtracted from the BT readings.

3. Results

a. BT survey. Although taken out of sequence, the results of the area BT survey are presented first in order to illustrate the obvious three-dimensionality of upwelling at this location, a feature that will influence interpretation of results from the cross shelf sections. BT casts were made over an 8 hr period at 16 stations surrounding Punta Curaumilla (Fig. 3). Although some aliasing may have taken place by

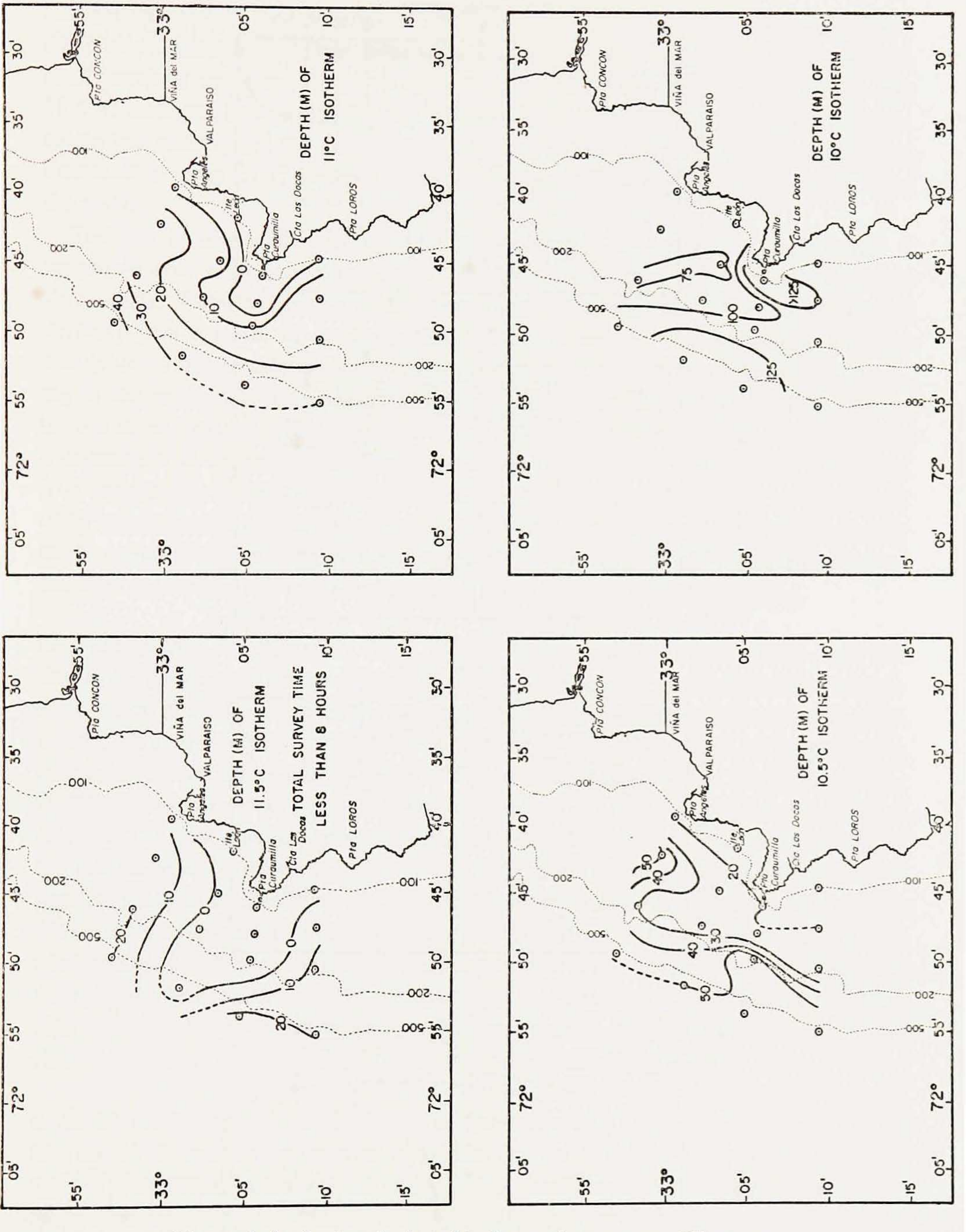

Figure 3. Isodepths of selected isotherms from an area BT survey.

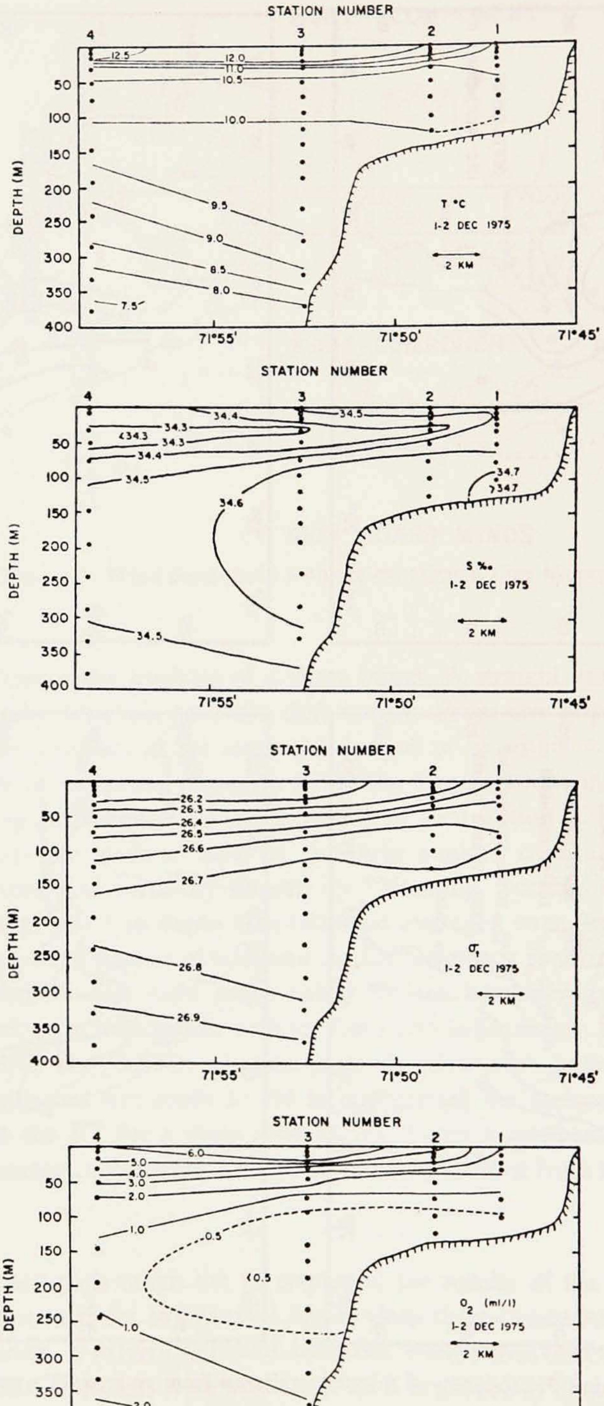

Figure 4. Temperature, salinity, oxygen and σ_t from the first hydrographic section.

undetermined tidal and inertial oscillations, the general structure seems reliable since it is a strong signal, and since work by Silva (1973) had indicated its presence on a previous occasion. Figure 3 shows the depth of four selected isotherms: the 11.5°C isotherm lies toward the top of the near-surface thermocline, the 11°C isotherm lies within, and the 10.5°C isotherm lies near the bottom of the nearsurface thermocline. The 10°C isotherm lies toward the bottom of the water column over the shelf.

The line of intersection of the 11.5°C isotherm with the sea surface bounds a tongue of cool upwelled water which extends seaward and equatorward of Punta Curaumilla. This conforms to theoretical models involving the advective change of vorticity past a point of land (Arthur, 1965). However, it is surprising that the alongshore scale is only about ¾ of the offshore scale. Also in evidence is a bending of the isodepths of this isotherm toward the south over the shelf. This feature is even more evident in the depths of the 11°C and 10.5°C isotherms, and indicates a depression of warmer water near the surface lying just equatorward of the point. The topography of the deeper 10°C isotherm shows a mound (tongue) of cool water lying below the warm water depression. Since the PCM/hydrographic sections were made at the southern edge of these distinctive features, it is clear that an interpretation of the section data must take note of the strong alongshore gradients.

b. Hydrography. In Figure 4, the T(°C), S ‰, σ_t and O_2 (ml/l) results from the first hydrographic section are presented. The T-section shows a shallow, thin thermocline which is upwarped over the continental shelf in a characteristic upwelling signature. The pycnocline is somewhat thicker than the thermocline with upwarping commencing further seaward. Deeper in the water column over the slope, downwarping of the isopycnals gives an indication of the presence of the Gunther Undercurrent. The S‰ section shows a tongue of low salinity water around the depth of the nearsurface thermocline. This tongue, which extends shoreward over the continental shelf, is formed from water of subantarctic origin modified by heavy rainfall and river run-off in the south of Chile (Gunther, 1936). Below the shallow minimum is a salinity maximum of subequatorial origin. The O_2 section shows a very pronounced minimum (0.5 ml/l) associated with the salinity maximum. This high salinity, low oxygen water is characteristic of the Gunther Undercurrent, (Gunther, 1936). It appears to be confined to the shelf-slope region.

c. PCM. In Figure 5, vertical profiles of the averaged u (positive east) and v (positive north) components of current are given for the first PCM section (station 1, 2 and 3). Two remarkable features of the v-component are the thinness (~ 30 m) of the surface equatorward flowing Humboldt Current, and the strength of the poleward flowing Gunther Undercurrent. The undercurrent has its core at around 100 m where it reaches a speed of -25 cms^{-1}. From Figure 6, it is evident that the

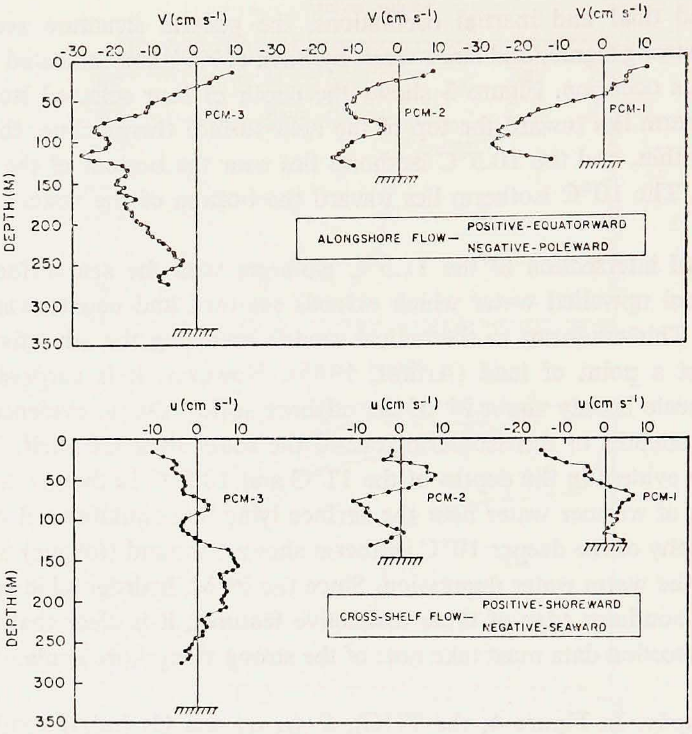

Figure 5. Profiles of current velocity components from the first PCM section.

undercurrent coincides with and fills the region of the high salinity water. Although no alongshore jet (Allen, 1973) is observed in the *v*-component, measurements may not have extended far enough seaward to detect it.

The *u*-component profiles (Fig. 5) show evidence of a cross shelf circulation system similar to the double-cell model of Mooers, Collins and Smith (1976), and similar to that observed both off Cabo Bojador, NW Africa (Johnson, Barton, Hughes and Mooers, 1975) and off Oregon (Johnson, Van Leer and Mooers, 1976). The nearsurface flow is seaward. Below the nearsurface thermocline a relatively strong (~ 10 cms^{-1}) onshore/offshore flow occurs at the midshelf station (stn. 2). At the slope station (stn. 3), the onshore/offshore flow is deeper and weaker, and at the nearshore station (stn. 1) it does not exist. The highly local nature of this double-cell type of flow as seen here (strong in mid-shelf, weak at the shelf-break) is in conformity with previous work in other upwelling regions. (Johnson, Barton, Hughes and Mooers, 1975; Johnson, Van Leer and Mooers, 1976; Johnson, 1977; Johnson and Johnson, 1979).

In Figure 6, the *u*-component profiles are superimposed on isohalines from the previous hydrographic section. The onshore flow at 50 m at the midshelf station coincides with the lower half of the low salinity tongue. Although the *u*-component

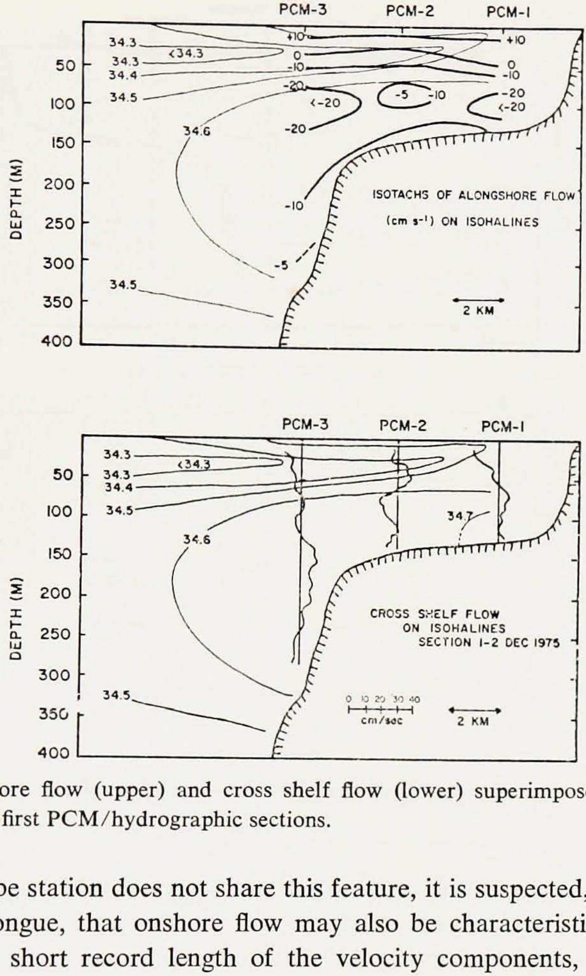

Figure 6. Alongshore flow (upper) and cross shelf flow (lower) superimposed on the salinity section from the first PCM/hydrographic sections.

profile at the slope station does not share this feature, it is suspected, from the shape of the salinity tongue, that onshore flow may also be characteristic here. In view of the relatively short record length of the velocity components, this is not unreasonable. Below 125 m at the slope station, the flow is shoreward and, presumably, up the slope. This flow extends to a depth of 250 m, and gives an indication of the limiting depth of water which is participating in upwelling. The crossover point between nearsurface offshore flow and the underneath return flow at PCM-1 and PCM-2 coincides very well with the zero isotach of the alongshore flow. This means that the upwelled water over the shelf is principally from the Gunther Undercurrent. On reaching the surface layer, the poleward flowing Gunther water would tend to decelerate the equatorward flow. This may be partially responsible for the thinness of the equatorward flowing surface layer.

In the double-cell model, part of the nearshore water in the seaward flowing Ekman layer sinks down inclined isopycnals near a frontal region (where the near-surface pycnocline intersects the sea surface), and continues to flow seaward at a deeper level. Examining the nearshore *u*-component profile (Fig. 6), some evidence

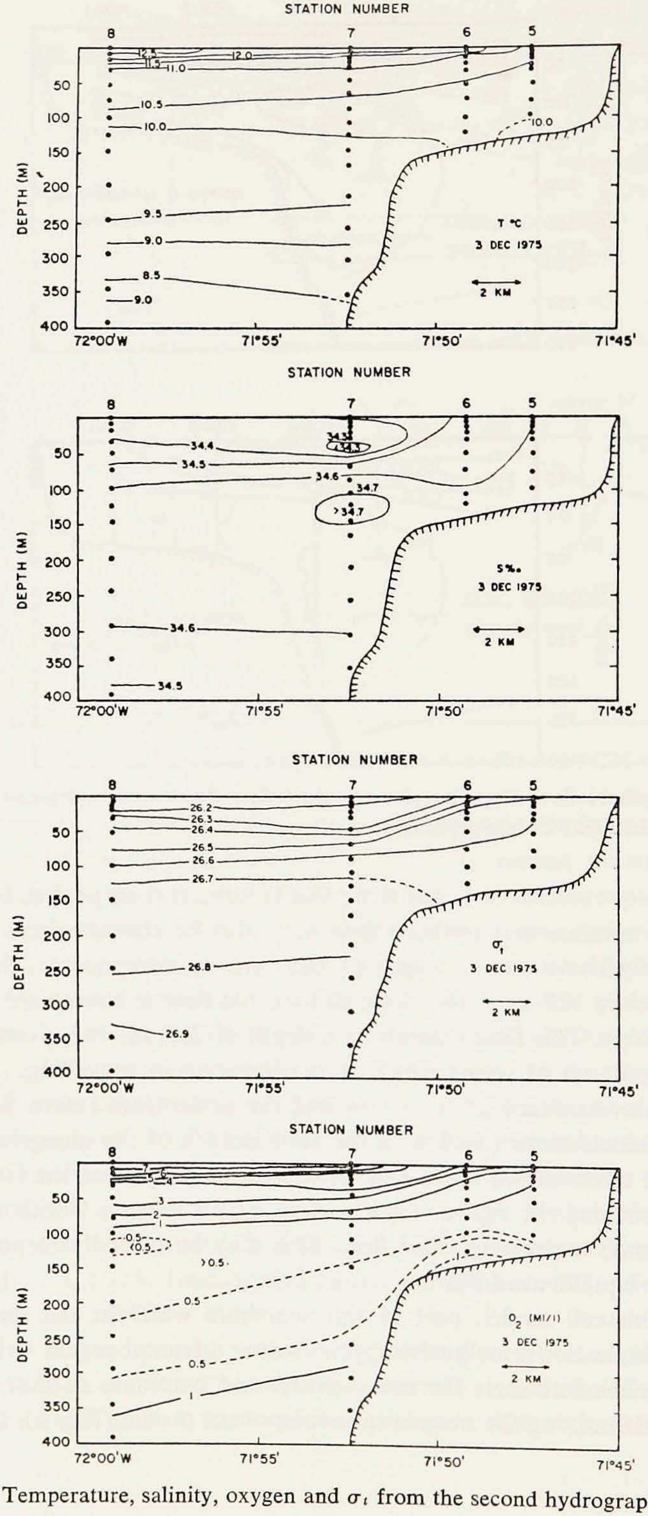

Figure 7. Temperature, salinity, oxygen and σ_t from the second hydrographic section.

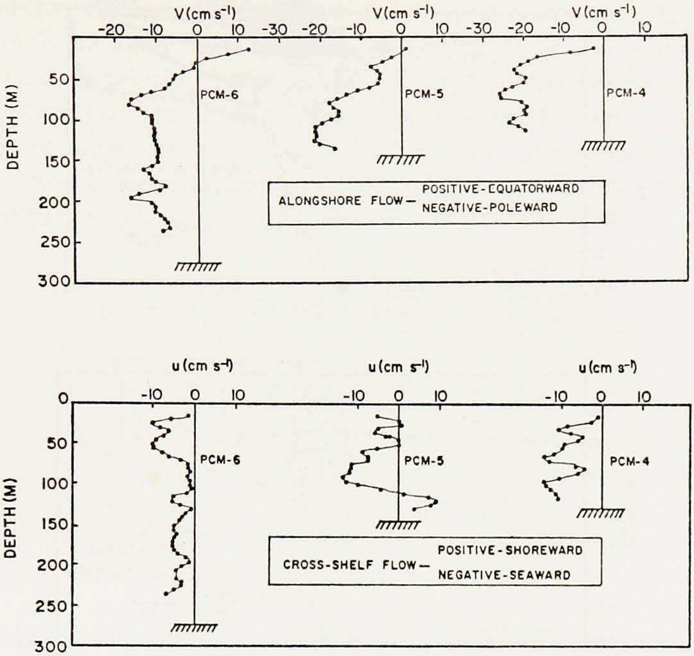

Figure 8. Profiles of current velocity components from the second PCM section.

is seen that this may be occurring. It is not entirely clear, however, that the seaward flow at station 1 can be connected to the seaward flow at 75 m at station 2 since this must involve crossing isopycnals (compare with Fig. 4, σ_t). Although mixing must be occurring, it is felt that the obvious three-dimensionality is the real problem in an attempt to directly match flows in this two-dimensional representation. In spite of this difficulty, the cross shelf circulation bears a reasonably good resemblance to the double-cell model.

The second hydrographic and PCM sections were made after the area BT survey. In the interim following the first sections, a significant change is noted. From the hydrographic section (Fig. 7), it is evident that the high salinity, low oxygen Gunther water has partially receded from the shelf and is not as marked as in the previous section. In the upper part of the water column, the low salinity tongue has also been displaced seaward and, similarly, is not as distinct as before.

From the PCM profiles (Figs. 8 and 9), which followed this hydrographic section, the *v*-components have the same general features, although the poleward transport at the nearshore station has increased. In contrast, the *u*-components show a distinct alteration. Except for a layer near the bottom at station 5, there is a general seaward flow over the water column which matches the recession from the shelf found in the hydrography. It is interesting to note that such pulsations can produce

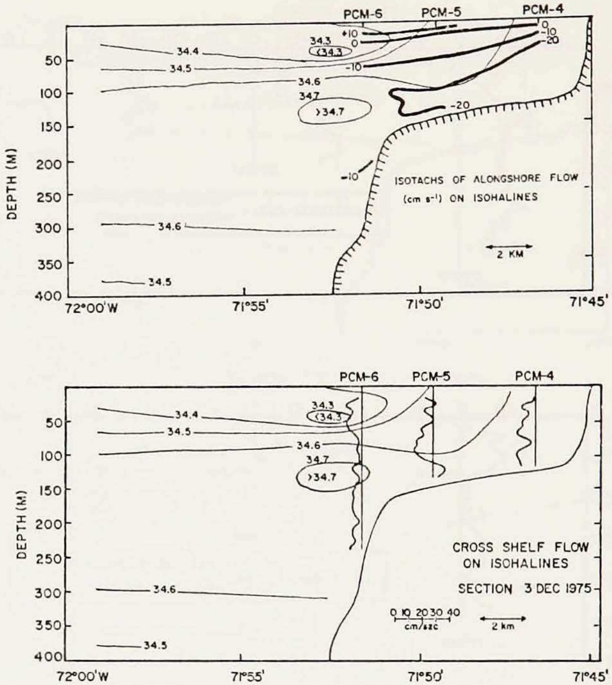

Figure 9. Alongshore flow (upper) and cross-shelf flow (lower) superimposed on the salinity section from the second PCM/hydrographic section.

patchiness of upwelled water, leading to greater stability in ecosystem dynamics (Steel, 1976).

d. Vorticity analysis. Arthur (1965) investigated the acceleration in relative vorticity past a point of land and found an intensification of upwelling equatorward of the point. In the following discussion, Arthur's scaling approach is used with application to Punta Curaumilla, and with an extension to a two layer system. Assuming steady state conditions with wind blowing alongshore, and the usual notation:

$$uu_x + vu_y - fv = -\alpha P_x \tag{1}$$

$$uv_x + vv_y + fu = -\alpha P_y + \frac{\tau_0{}^y}{h} \tag{2}$$

$$w_{-h} = (u_x + v_y)\, h \tag{3}$$

$$v'u'_x + v'u'_y - fv' = -\alpha' P'_x \tag{4}$$

$$u'v'_x + v'v'_y + fu' = -\alpha' P'_y \tag{5}$$

$$w_{-h} = -(u'_x + v'_y)\, h' \tag{6}$$

$$H = h + h' \tag{7}$$

where x is positive east, y is positive north and z is positive up from the sea surface. The primes indicate lower layer variables; the subscripts represent differentiation; w_{-h} is the interface velocity. Internal friction is omitted, hence "upwelling" is due solely to the vertical component of motion along the inclined interface.

Cross differentiating the acceleration equations and eliminating the horizontal convergence terms by use of the continuity equation, the following vorticity equations are formed for each layer:

$$w_{-h} = -\frac{h}{f}\left(\bar{v} \cdot \nabla\xi + \beta\, v\right) + \frac{h}{f}\left(\frac{\tau_0{}^y}{h}\right)_x \tag{8}$$

$$w_{-h} = \frac{h'}{f}\left(\bar{v}' \cdot \nabla\xi' + \beta\, v'\right) \tag{9}$$

where

$$\xi \equiv (v_x - u_y); \qquad \nabla \equiv \hat{\imath}\frac{\partial}{\partial x} + \hat{\jmath}\frac{\partial}{\partial y}\ ;$$

and

$$\xi << f$$

It is assumed that the lower layer flow has the same scale magnitude and curvature as the upper layer flow, but with opposite sign:

$$v' = -v \tag{10}$$

$$\bar{v}' \cdot \nabla\xi' = -\bar{v} \cdot \nabla\xi \tag{11}$$

Adding equations (8) and (9), and making use of assumptions (10) and (11) to eliminate the primed variables,

$$w_{-h} = \frac{H}{2|f|}\left(\bar{v} \cdot \nabla\xi + \beta v\right) + \frac{h}{2|f|}\left(\frac{\tau_0{}^y}{h}\right)_x \tag{12}$$

where $f = -|f|$ accounts for the southern hemisphere location. Parameters chosen for an evaluation of w_{-h} in equation (12) must satisfy both equations (8) and (9) separately (i.e., the parameters are not arbitrarily independent) and must be realistic according to the data presented for Punta Curaumilla. Table 1 provides a set of parameter values which meet these criteria. Using the values given in Table 1, the resultant ascending motion, w_{-h}, from equation (12) is calculated as 1.5×10^{-2} cms^{-1}, a not unreasonable value for an area of relatively intense upwelling (Johnson and Johnson, 1979, calculate $w_{-h} \cong 1.0\text{-}2.0 \times 10^{-2}$ cms^{-1} from convergence measurements off Oregon).

The planetary vorticity term is small in comparison to either the wind effect term or the vorticity acceleration term, and can be neglected from further consideration.

Table 1. Estimated parameters for Punta Curaumilla.

τ	0.7 dynes cm^{-2}
$\Delta\rho$	4×10^{-4} gms cm^{-3}
h	30 m
h'	100 m
f	$8 \times 10^{-5}\text{s}^{-1}$
β	$2 \times 10^{-13}\text{cm}^{-1}\text{s}^{-1}$
v	20 cms^{-1}
R*	20 Km
$\bar{v} \cdot \nabla\xi \equiv \left(\frac{v}{R}\right)^2$	10^{-10}s^{-2}
x — scale**	10 Km
f	$7 \times 10^{-5}\text{s}^{-1}$

* Radius of curvature.

** Shelf width and baroclinic radius of deformation about equal.

Using scaled parameters, the ratio of the vorticity acceleration and the wind effect terms from equation (12) can be written in the following manner:

$$\frac{\text{Vorticity acceleration}}{\text{Wind effect}} = \frac{HV^2\lambda}{R^2\tau}$$

where R is the radius of curvature of flow around the point, τ is wind stress, λ is the offshore scale, V is the current speed and H is the total water depth. Using the parameters given in Table 1, this ratio is 1.86, showing that the vorticity acceleration term is nearly twice the wind effect.

4. Summary and conclusions

From an area BT survey, it seems clear that a zone of relatively intense upwelling surrounds Punta Curaumilla. This zone of intensification is marked by a tongue of cool water which extends seaward and equatorward of the projection of land. The tongue has a surprisingly small ratio (¾) of cross shelf to alongshore dimensions. Using scale analysis of the vorticity equations, it is evident that acceleration of relative vorticity past the point is primarily responsible for the intensification.

Although alongshore gradients tend to complicate interpretation of the cross shelf PCM and hydrographic sections, the cross shelf circulation bears some resemblance to the double-cell model of Mooers, Collins and Smith (1976). Similar double-cell types of circulation have been found off NW Africa (Johnson, Barton, Hughes and Mooers, 1975) and off Oregon (Johnson, Van Leer and Mooers, 1976). In the alongshore flow, a thin (~ 30 m) surface layer of equatorward flowing water is found (Humboldt Current), with a relatively strong (25 cms^{-1}) poleward flowing undercurrent (Gunther Undercurrent). This undercurrent water is of subequatorial origin and is characterized by high salt and low oxygen content. Comparing the alongshore flow with the cross shelf flow, it appears that the water which is upwelled onto the shelf and into the surface layer is principally Gunther water. From a current profile on the continental slope, the maximum depth from which water is participating in upwelling is approximately 250 m.

During a later part of the experiment, the equatorward wind stress decreased. The current section at this time shows an increased flow in the nearshore undercurrent and an increase in seaward flow across the shelf. This seaward flow matches a general recession from the shelf of the Gunther water. It is interesting to note that such pulsations in an area of intensified upwelling may lead to patchiness of upwelled water and an increase in ecosystem stability (Steele, 1976). The double-cell cross shelf circulation can lead to enhanced productivity by providing a feedback mechanism for refertilization and reseeding the nearshore area. The strong, relatively shallow undercurrent can provide a feedback mechanism in the alongshore direction for biota that may otherwise be swept from the area. Clearly, Punta Curaumilla is an interesting location, not only for the physical dynamics but for its biological interactions as well.

Acknowledgments. We would like to express appreciation to the personnel of the Instituto Hidrografico de la Armada and students of the oceanographic courses at the Universidad Catolica de Valparaiso for their considerable help in obtaining the data, and to the captain and crew of the AGS YELCHO for their cooperation and enthusiasm during the experiment. Dr. Steve Neshyba and Sr. Guillermo Santis assisted in many aspects, and Dr. Robert L. Smith provided the PCM along with encouragement. Finally, we extend our appreciation to the Chilean Navy for the major part of the expenses.

REFERENCES

Allen, J. S. 1973. Upwelling and coastal jets in a continuously stratified ocean. J. Phys. Oceanog., *3,* 247–257.

Arthur, R. S. 1965. On the calculation of vertical motion in eastern boundary currents from determinations of horizontal motion. J. Geophys. Res., *70,* 2799–2803.

Düing, W. and D. R. Johnson. 1972. High resolution current profiling in the Straits of Florida. Deep-Sea Res., *19,* 259–274.

Gunther, E. R. 1936. A report on oceanographical investigations in the Peru Coastal Current. Discovery Reports, *13,* 107–276.

Johnson, D. R. 1977. Determining vertical velocities during upwelling off the Oregon coast. Deep-Sea Res., *24,* 171–180.

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, D. R. and W. R. Johnson. 1979. Vertical and cross-shelf flow in the coastal upwelling region off Oregon. Deep-Sea Res., *26,* 399–408.

Johnson, W. R., J. C. Van Leer and C. N. K. Mooers. 1976. A cyclesonde view of coastal upwelling. J. Phys. Oceanog., *6,* 556–574.

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. Oceanog., *6,* 3–21.

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

Silva, N. 1973. Variaciones estacionales de temperatura, salinidad y contenido de oxigeno en la zona costera de Valparaiso. Investigaciones Marinas, *4*, 89–112.

Steele, J. H. 1976. Patchiness, *in* D. H. Cushing and J. J. Welsh, (eds), The Ecology of Seas, Saunders Co., Philadelphia.

Wooster, W. S. 1970. Eastern boundary currents in the South Pacific, *in* Scientific Exploration of the South Pacific, W. S. Wooster, ed., National Academy of Sciences, Washington, D.C.,

Wooster, W. S. and M. Gilmartin. 1961. The Peru-Chile Undercurrent. J. Mar. Res., *19*, 97–122.

Wooster, W. S. and J. L. Reid. 1963. Eastern boundary currents, *in* The Sea, Vol. II, M. N. Hill, ed., Interscience, New York,

Wyrtki, K. 1963. The horizontal and vertical fields of motion in the Peru Current. Bull. Scripps Inst. Oceanog., *8*, 313–346.

—— 1964. The thermal structure of the eastern Pacific Ocean. Deutsche Hydro. Zeitschrift, Erq. Reihe A (8°), No. 6, 84 pp.

Yoshida, K. 1967. Circulation in the eastern tropical oceans with special references to upwelling and undercurrents. Japan. J. Geophys., *4*, 1–75.

Received: *28 September, 1978;* revised: *10 October, 1979.*