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Further Measurements and Observations on the Cromwell Current[1]

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ABSTRACT

The Cromwell Current was observed in the eastern Pacific during the Scripps Institution of Oceanography SWAN SONG Expedition, 5 September–1 December 1961, employing hydrographic stations and direct current measurements. The velocity structure in 1961 at 140°W was similar to that observed in April 1958 except that the transport in 1961 was only 22×10^6 m^3/sec—55% of the transport observed in 1958. It is suggested that part of this difference may be accounted for by the difference in strength of the South Equatorial Current during the two expeditions. The Current structure in 1961 at 118°W was similar to that observed at 140°W, but at 96°W the Current was apparently beginning to dissipate. The breakup was more pronounced at 93°W. A small flow was tracked around the north side of Isabela Island in the Galapagos and observed again east of the Galapagos. East of the Galapagos the water in the Cromwell Current was slightly heavier and about 150 m deeper than that to the west.

From the velocity observations and the distribution of properties there is evidence of a convergent meridional flow. An isolated high-salinity core, south of the equator, is thus explained. Estimates of the meridional and vertical-velocity components are 5 cm/sec and 10^{-3}cm/sec, respectively. The "residence time" of a particle within the Cromwell Current has been estimated to be 10^6–10^7 sec.

Estimates of the magnitude of the terms in the east-west equation of motion suggest that all terms except the local acceleration term may be important in the balance of forces. A second possibility is that vu_y and wu_z are several times larger than the others, and thus the Cromwell Current may be characterized as a "free inertial current." An important driving force for the Current is the pressure-gradient force $(-\alpha p_x)$. Where this term was approximately 2×10^{-5} dynes/g, the Cromwell Current was present. Eastward from about 108°W the pressure-gradient force was reduced; eastward from 95°W the sign was reversed. It is here that the Current began to break up.

Previous investigators have indicated that the balance of forces in the north-south direction is essentially geostrophic. On SWAN SONG the Cromwell Current was not in geostrophic balance and the nature of the balance of forces is unclear.

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INTRODUCTION

The Cromwell Current is a thin, swift flow having a maximum speed of 100–150 cm/sec (two to three knots) and a transport of $20–40 \times 10^6 m^3/sec$. It flows eastward beneath the surface and has been reported to be centered on, and symmetrical about, the equator. The core of the Current in the eastern and Central Pacific is between 50 and 100 m deep. The Current is found along most, if not the entire, equatorial line of the Pacific. An analogous equatorial undercurrent has been found in the Atlantic (Metcalf et al. 1962), and an equatorial undercurrent is present at least part of the year in the Indian Ocean (Knauss and Taft 1964, Swallow 1964).

Current measurements in April 1958 in the region of the equator, 140°W, showed the Cromwell Current to be well developed, with a width of 400 km, a maximum velocity of three knots, and a transport of $40 \times 10^6 m^3/sec$. Observations in May 1958 from 140°W eastward along the equator showed the speed and general structure of the undercurrent to be remarkably similar over a distance of 5000 km, but at the Galapagos Islands the undercurrent seemed to disappear (Knauss 1960).

The specific purpose of the Swan Song Expedition (5 September–1 December 1961) of the Scripps Institution of Oceanography was to determine, if possible, what happens to the Cromwell Current as it moves eastward toward and beyond the Galapagos Islands. There appeared to be four possible explanations for the apparent disappearance of the undercurrent during the 1958 study.

(i) The width of the Cromwell Current decreases as it flows eastward, thus decreasing the transport of the undercurrent, even though the high-speed core along the equator remains unchanged. It should be noted that all measurements in 1958 east of 140°W were at the equator; i.e., there were no cross sections of the undercurrent except at 140°W.

(ii) The Cromwell Current maintains its high velocity and large transport but veers away from the equator as it approaches the Galapagos Islands. Isabela Island in the Galapagos straddles the equator.

(iii) Strong and violent mixing takes place in the vicinity of the Galapagos; water is entrained in the undercurrent, and its speed was so reduced as it moved through these Islands that it could not be measured. The discussion of the results of the 1958 expedition was limited to those observations that indicated speeds of 25 cm/sec (0.5 knot) or greater.

(iv) The Cromwell Current sinks as it moves through the Galapagos and was thus undetected. The depth of the current observations in 1958 was limited to 250–300 m.

As will be demonstrated in later sections, the explanation of what happens to the water in the Cromwell Current can be found in a combination of all four of these alternatives. Water is lost from the undercurrent as it moves eastward. The undercurrent becomes thinner and the transport is reduced to less than 30% of that in the Central Pacific. Mixing and entrainment do occur as the water flows eastward through the Galapagos Islands. The water on the east side of the Galapagos is flowing more slowly (approximately 10–25 cm/sec) and at a greater depth (160–250 m). Finally, the maximum speed of the undercurrent beyond the Galapagos is found north of the equator.

METHODS

Cruise Plan. The SWAN SONG Expedition aboard the Scripps R. V. ARGO was divided into three legs. Four meridional cross sections from 5°N to 5°S were made. Sections at 140°W and 118°W were made on the first leg; sections at 96°W and 87°W were made on the second leg. The third leg was devoted to making observations in and around the Galapagos Islands.

Each of the four sections included hydrographic stations at 110-km intervals (1° of latitude) from 5° to 3°, and at 55-km intervals (0.5° of latitude) equatorward of 3°. Thus hydrographic casts were made at 17 points along each section from 5°N to 5°S. (The one exception was the 118°W section on which the 5°S station was omitted.) The number of hydrographic casts along each section was always more than 17 since casts were often repeated at buoy stations.

Buoys were anchored on each section, usually at 2°N, 1°N, 0°, 1°S, and 2°S, and current measurements were made with a propeller-type current meter (a modified Roberts meter) lowered from the ship. Additional current measurements were made with Swallow neutrally buoyant floats.

The station distribution for the three legs of the SWAN SONG Expedition is shown in Fig. 1. Stations near the Galapagos Islands are shown in Fig. 5.

Hydrographic Stations. Ninety-one hydrographic casts were made in this study. Eleven were to a depth of 200 m, the remainder to 1200 m. All employed 20 or 21 Nansen bottles and paired protected reversing thermometers. Eleven of the bottles were equipped with unprotected thermometers. Salinity was determined with a conductivity salinometer. The tabulated data are available from the National Oceanographic Data Center and in a technical report of the Scripps Institution of Oceanography (Anonymous 1965). The 95% confidence limits for the observed data are believed to be: temperature, ± 0.02°C; salinity, ±.01‰; depth, 5 m or ± 1%, whichever is greater; oxygen, ±.05 ml/l. The limits on the oxygen data refer to internal consistency. There is the possibility of an even larger systematic error in all the oxygen data (Carritt, personal communication).

Roberts-meter Measurements. It was planned to use a newly designed current meter for this work, but the meter was lost on its first lowering. Hence

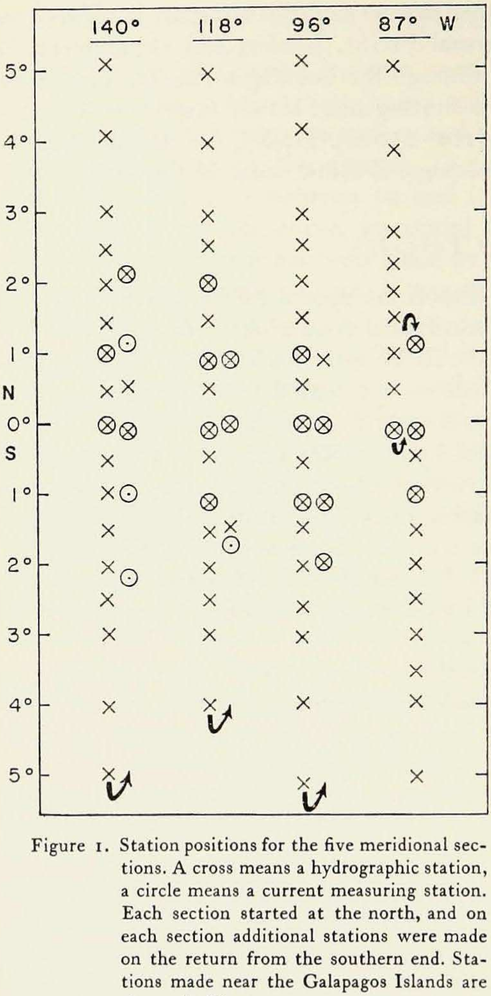


Figure 1. Station positions for the five meridional sections. A cross means a hydrographic station, a circle means a current measuring station. Each section started at the north, and on each section additional stations were made on the return from the southern end. Stations made near the Galapagos Islands are shown in Fig. 5.

all work was done with the same modified Roberts meter used in the previous work on the Cromwell Current in 1958.

Current observations were made by lowering the modified Roberts meter and a depth gauge from the ship. The Roberts meter contains a magnetic compass. The meter recorded on deck the speed and direction of the water flowing past the meter. True velocity at any depth was determined by vector addition of the ship's velocity and the velocity recorded by the meter. The movement of the ship over the ground was determined by measuring the ship's position by radar from a "taut-wire" anchored buoy. The method has been described in some detail by Knauss (1960).

In an attempt to make the ship-drift velocity a constant for any given set of observations, the ship steamed slowly through the water during the period of measurement. With this technique the crab-like movement usually exhibited by a ship while lying-to was eliminated. The current meter was lowered to a certain depth, an observation was made, and then the current meter was lowered to the next depth. The period of observation at any depth was from two to seven minutes. Measurements were made at approximately 20 levels in the top 350 m. After the instrument reached its greatest depth, the measurements were repeated as the meter was brought to the surface. Approximately three hours were required to complete a set of observations.

It is difficult to arrive at an estimate of the standard error in these observations. In the 1958 work the 95% confidence limits were put at ± 25 cm/sec. Although the technique has been refined since 1958, subsequent work with a new current meter suggests that the greatest error in the SWAN SONG data may be in the assumption that the ship movement is identical to the current-meter movement. This is certainly true on the average, but at any given moment the current meter may be swinging on the cable and may have a velocity over the ground that is different from that of the ship. This independent movement is more pronounced in the first few minutes after a current meter reaches a given depth and is more pronounced with a high wire angle than with a low wire angle. Although I believe that, with the proper current meter, measurements with this technique can be made with an accuracy of ± 10–15 cm/sec, I also believe that the 95 % confidence limits in the SWAN SONG data are closer to ± 20 cm/sec.

During the first section of SWAN SONG, difficulty was encountered with the anchored buoys. Several of them drifted at speeds in excess of 10 cm/sec. The anchoring system was modified, and I believe there was no appreciable buoy drift on the last two sections of the cruise. Corrections for buoy drift were applied at the following stations: 140°W, 1°N and 0°; 118°W, 2°N, 1°N, and 0°; and 96°W, 1°N.

The current data for each buoy station are a composite of several sets of measurements averaged in the following way. The east-west and north-south components for each station were plotted against depth. A curve was first drawn to all the points of "down" observations, and a second curve was drawn to all the "up" observations. A single curve was then fitted to the station and an attempt was made to maintain all of the small-scale variations that appeared on both the up and down lowerings. Two to five current-measuring stations were made at each buoy over a period of from 24 hours to five days. The individual speed-vs.-depth curves for each station were overlain and a composite curve was drawn for each buoy station. Again an attempt was made to retain minor variations in the velocity-vs.-depth curves if they appeared on most or all of the stations, even if they did not occur at exactly the same depth. All fitting of curves was done by eye and the averaging process invariably resulted in a smoothing of the data. An example of the various steps in the averaging process is shown in Fig. 2. The current-meter data are on file at the National Oceanographic Data Center and have been made available in a technical report of the Scripps Institution of Oceanography (Anonymous 1965).

Swallow Floats. Eighteen neutrally buoyant floats were tracked successfully for periods ranging from 4 to 29 hours. All floats were placed between depths of 200 and 500 m. Positioning was done by taking successive bearings on the floats, either by the methods outlined by Swallow and Worthington (1961) or by listening with a highly directional hydrophone. (ARGO is equipped with a U. S. Navy AN/SQS-4 sonar.) The movement of the float was measured relative to the anchored buoy.

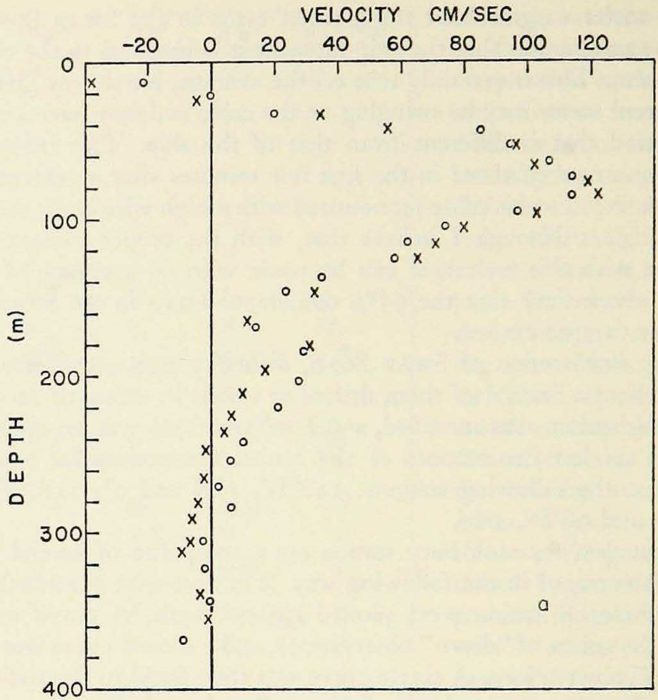
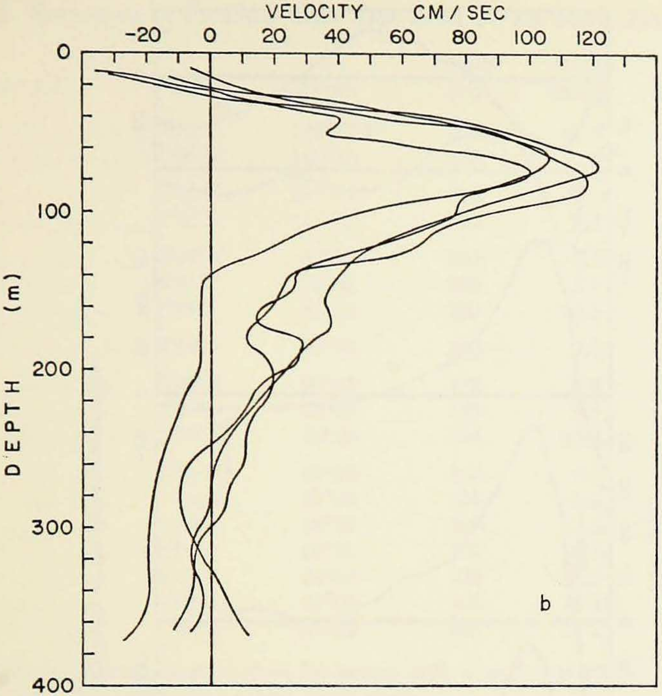


Figure 2. The averaging process for drawing a velocity profile. (a) A single lowering; the circles represent readings as the current meter was lowered, the crosses, the readings on the return. (b) The curves drawn through four sets of readings. (c) The smooth curve representing the east-west velocity component at 0°, 118°W. Minus values are to the west.

The method outlined by Swallow and Worthington (1961) for deriving an independent estimate of the depth of the floats is less reliable when the floats are shallow than when the floats are deep. Near the end of the cruise a pair of hydrophones was rigged in conjunction with a Vibroton pressure gauge, and a depth estimate was obtained by lowering the hydrophones to the depth of the float. This technique has also been described by Swallow. Of the three floats whose depths were checked in this manner, two agreed with the predicted depth to within 4 m, and the third was deep by 73 m. The discrepancy in the latter was probably the result of an undetected air bubble attached to the transducer during the initial balancing. I believe that most, if not all, of the floats reached the predicted depth, and the rest were deeper than the predicted depth by 50–150 m. Since we have no very good way of checking the depth of the first 14 floats, I have assumed that each reached its predicted depth. The mean velocity, relative to the anchored buoy, has a precision of 2 cm/sec. I believe that there are no important systematic errors. The results are summarized in Table I.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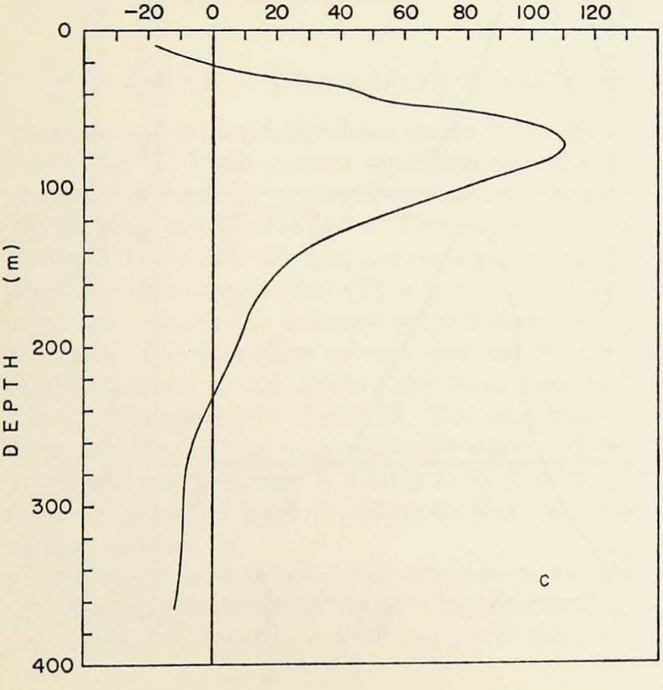
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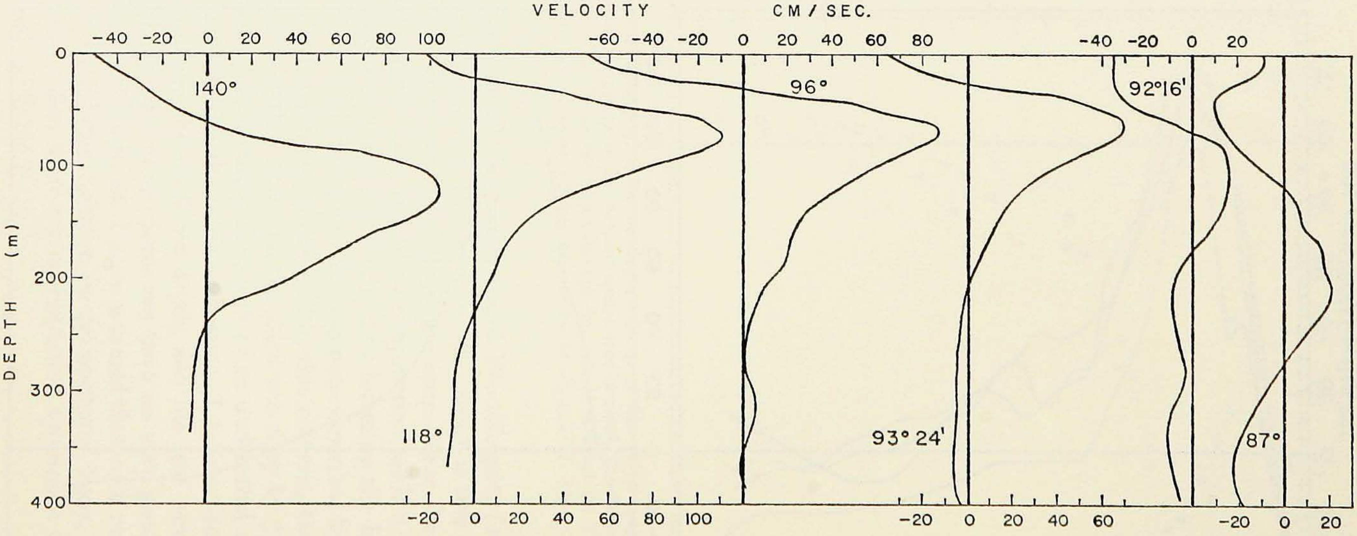

Figure 3. East-west velocity components at the six equator stations.

Table I. Summary of Swallow float data from Swan Song Expedition.

Float no.	Lat.	Long.	Depth (m)	Hours tracked	Speed (cm/sec)	Dir. (°T)
1	0°02′S	139°57′W	400	12.2	3	337
2	1°00′S	140°02	250	7.0	21	036
3*	1°59′N	118°04	300	9.0	18	063
4*	0°04′S	118°00	500	8.5	30	296
5*	0°57′N	95°55	500	4.3	11	110
6	0°01′S	96°02	200	9.7	15	065
7	1°09′S	95°59	200	12.3	4	130
8	0°00	93°30	200	9.2	15	040
9†	1°00′N	90°45	273	8.8	18	115
10†	1°00‘N	90°45	196	9.5	38	065
11†	1°43′S	90°29	204	28.7	3	138
12	1°05′N	87°00	500	9.5	13	226
13	1°05′N	87°00	200	8.8	25	102
14	0°07′S	86°55	200	7.3	41	065
15	0°07′S	86°55	200	8.4	22	087
16	0°07′S	86°55	500	16.6	9	050
17	1°02′S	87°03	500	15.3	12	035
18	1°02′S	87°03	200	14.7	8	170

* Float velocities adjusted to allow for known drift of anchored buoy.

† Floats 9, 10, 11 had independent depth check.

EASTWARD TRANSPORT (140°W–93°W)

The composite east-west velocity-depth curves for the six equatorial stations are shown in Fig. 3. These current measurements agree with those made along the equator during May 1958 in that a marked decrease in the maximum velocity did not occur until east of 96°W. There appears to be a slight thinning of the Cromwell Current to the east, and consequently there is a decrease in the transport per unit cross section ($T'_x = \int u dz$). A similar thinning of the undercurrent and a decrease in transport per unit cross section can be seen in the 1958 results. The maximum velocity and the transport per unit cross section for the equatorial stations of the 1961 Swan Song and 1958 Dolphin expeditions are summarized in Table II. The maximum velocity and the transport per unit cross section were uniformly higher in 1958 than in 1961, but the variation with longitude is similar in both cases. The similarity is shown in the last column of Table II, where the data are plotted as percentages of the values at 140°W.

The composite east-west velocity field observed on the four cross sections west of the Galapagos is shown in Fig. 4. The cross sections at 140°W and 118°W are similar, but between 118°W and 96°W there is a sharp decrease

Table II. The maximum transport of the Cromwell Current per unit cross section at the equator ($T' = \int udz$) and the maximum volocity (u_m) during the 1958 (Dolphin) and 1961 (Swan Song) expeditions.

Long.	No. of observ.	T'	u_m (cm/sec)	$T'/T'(140°)$ (°/o)
1958 Results				
140°	9	18.2×10^5 cm²/sec	132	1.00
131°–137°	3	13.4	121	.74
122°–128°	3	12.6	143	.70
110°–119°	4	12.8	154	.70
101°–107°	3	11.2	124	.62
92°– 98°	3	7.3	110	.40
1961 Results				
140°	5	10.2	105	1.00
118°	4	9.4	111	.91
96°	4	7.7	87	.75
93°	5	5.6	70	.55
92°16′	3	1.3	16	.13

in the total transport, and the Current develops a marked asymmetry about the equator at 96°W. In none of the four cross sections is the symmetry as good as that observed in the 1958 cross sections at 140°W (Knauss 1960: fig. 3), but there is approximate symmetry at 140°W and 118°W. The lack of symmetry is very noticeable at 96°W, and even more so at 93°W. In all four cross sections, however, the maximum velocity was found at the equator.

Data on the eight floats tracked in conjunction with these four cross sections suggest that there are no very strong currents between 300 and 500 m (Table I). The exception is the 30 cm/sec flow toward 296° at 500 m, observed over an 8.5-hour period with float 5. Although the tracking time was short there is no reason to doubt the value, nor is there any reason to suspect that the float was shallower than indicated.

The kinetic energy and volume transport of the Cromwell Current measured on these four cross sections are given in Table III. The transports at 140°W and 118°W are nearly the same, but the transport at 96°W is less than half the value at 140°W. The volume transport in the undercurrent decreases at the rate of 8×10^5 m³/sec/degree of longitude between 96°W and 93°W and at a rate of 5×10^5 m³/sec/degree of longitude between 118°W and 96°W.

An alternate way of considering the decrease in volume transport of the Cromwell Current is to calculate the loss per day. Although the maximum velocity of the undercurrent is about 100 cm/sec, the Current as a whole moves with a mean speed of about 30 cm/sec. Thus, the decrease in transport is at a rate of 1.8×10^5 m³/sec/day between 96°W and 93°W and 1.2×10^5 m³/sec/day between 118°W and 96°W.

Table III. The volume transport and the kinetic energy per unit length of the Cromwell Current as observed in 1961.

Section	Dates (1961)	Volume transport	Kinetic energy
140°W	Sept. 4–22	22×10^{12} cm³/sec	6×10^{14} ergs/cm
118°W	Sept. 27–Oct. 6	20	6
96°W	Oct. 18–27	10	2
93°W	Nov. 17–23	8	2
87°W	Oct. 31–Nov. 8	4	1

There is of course no reason to believe that the transport begins to decrease exactly at 118°W. It may begin, and in all probability does begin, some distance farther east. If the transport of the Cromwell Current were to remain steady to 108°W, the mean rate of decrease from 108°W to 96°W would be identical with that observed between 96°W and 93°W; i.e., 5×10^6 m³/sec/degree of longitude.

The four cross sections at 140°W in April 1958 give transports between 34 and 42×10^6 m³/sec. The transport measured at 140°W and 118°W in October 1961 was about 55 °/₀ of that observed in 1958. One possible explanation for the lower velocity and transport values in 1961 as contrasted with those in 1958 may be found in the association of the Cromwell Current with the westward-flowing South Equatorial Current. The Cromwell Current is more or less embedded in this South Equatorial Current, which, in the spring of 1958, was flowing very weakly in the region 2°N to 1°S. It was found to have appreciable surface speeds at only 2°S. In the fall of 1961 the South Equatorial Current was very much in evidence from 2°N to 2°S. Westward surface speeds of 35–120 cm/sec were recorded.

Since the Cromwell Current is embedded in the South Equatorial Current (although there must certainly be some type of nonlinear interaction between these two currents), it might be reasonable as a first approximation to consider the observed flow of the Cromwell Current as a simple vector sum of these two currents, and thus subtract the velocity field of the South Equatorial Current from the observed velocity field. A reasonable velocity-versus-depth curve that may be assumed for the South Equatorial Current is one having a nearly constant velocity through the mixed layer, the velocity then dropping to nearly zero as it passes through the thermocline. Even a rather conservative estimate of the flow of the South Equatorial Current will, when "subtracted" from the observed velocity distribution, increase the volume transport of the Cromwell Current by at least 50 °/₀. Whether this difference in flow of the South Equatorial Current is indeed the explanation for the difference in transport in the Cromwell Current during the two expeditions is certainly questionable, but it seems possible that it might be at least part of the explanation.

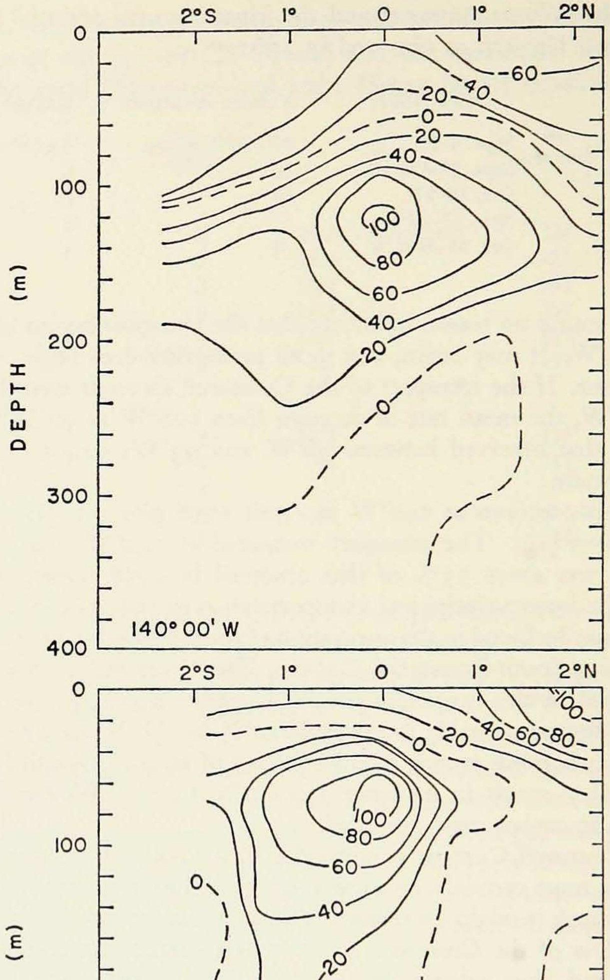

Figure 4. The east-west velocity cross sections on the four crossings west of the Galapagos Islands. Units are cm/sec. Plus values are eastward velocities.

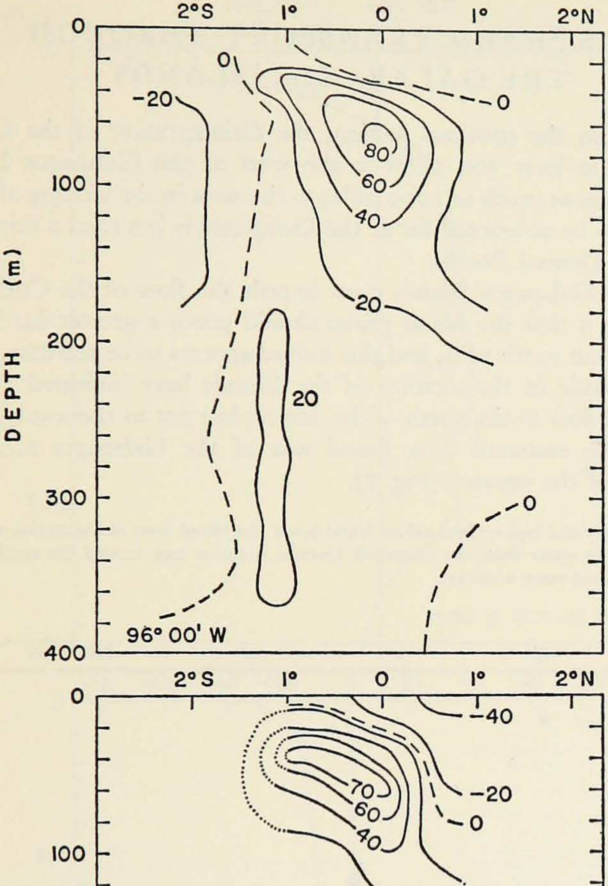

Figure 4. The east-west velocity cross sections on the four crossings west of the Galapagos Islands. Units are cm/sec. Plus values are eastward velocities.

EASTWARD TRANSPORT THROUGH THE GALAPAGOS ISLANDS

As indicated in the previous section, the disintegration of the Cromwell Current begins at least 300 miles to the west of the Galapagos Islands at 96°W and perhaps as much as 1000 miles to the west in the vicinity of 108°W. The transport to be accounted for at the Galapagos is less than a third of that observed in the Central Pacific.

Although the Galapagos Islands must impede the flow of the Current, it is apparent in Fig. 5 that the island group should prove a greater barrier south of the equator than north of it, and this indeed appears to be the case. Current measurements made in the vicinity of the Islands have indicated that there was an eastward flow to the north of the Islands but not to the south (Fig. 6).[2] Furthermore, the eastward flow found east of the Galapagos at 87°W is centered north of the equator (Fig. 7).

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[2] The high-salinity and high-oxygen values found below the mixed layer at the station south of the Galapagos suggest that water from the Cromwell Current finds its way around the southern end of Isabela Island on at least some occasions.

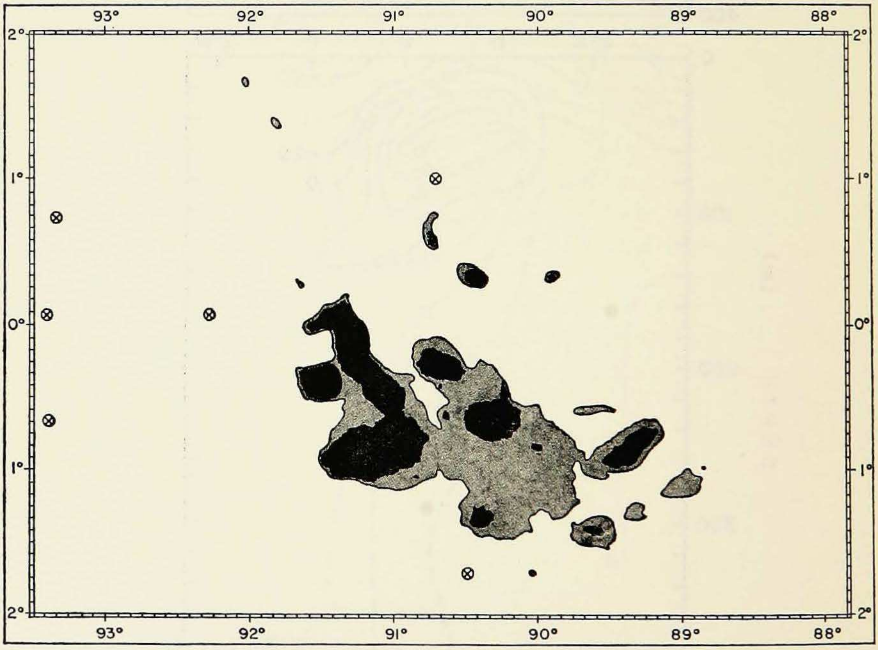

Figure 5. The Galapagos Islands. The black areas are above sea level. The hatched area represents water shallower than 200 m. The six hydrographic current-meter stations are indicated.

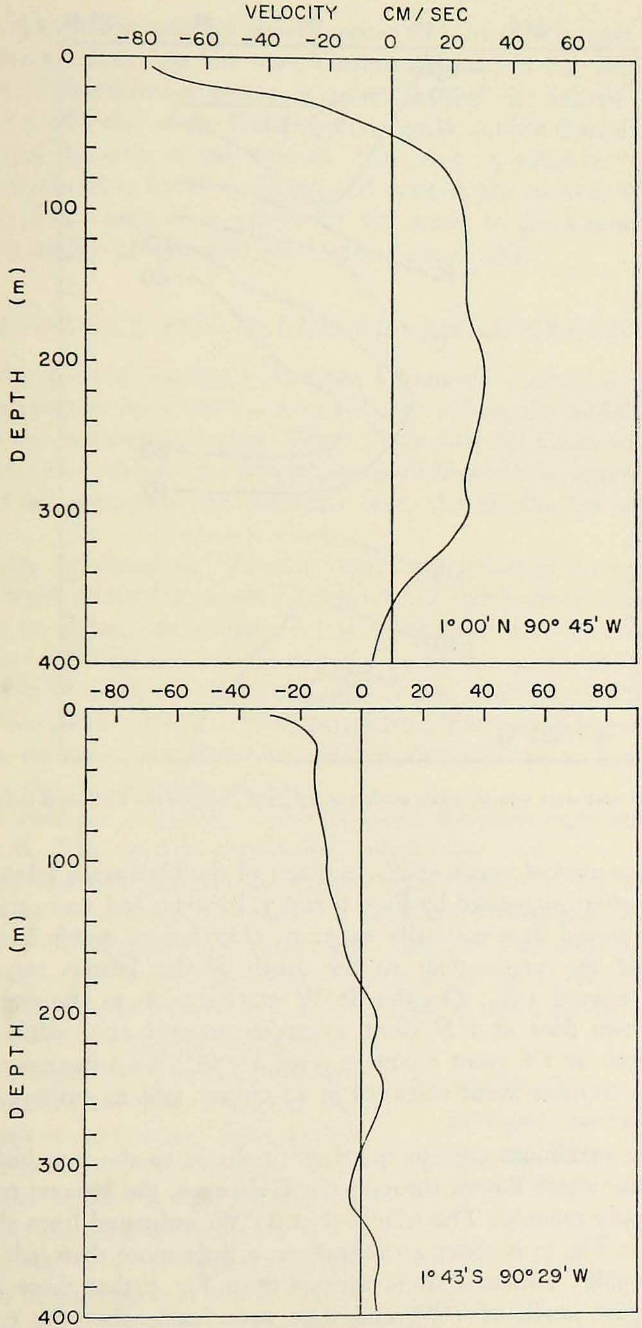

Figure 6. The east-west velocity profile north and south of the Galapagos Islands. Minus values are to the west.

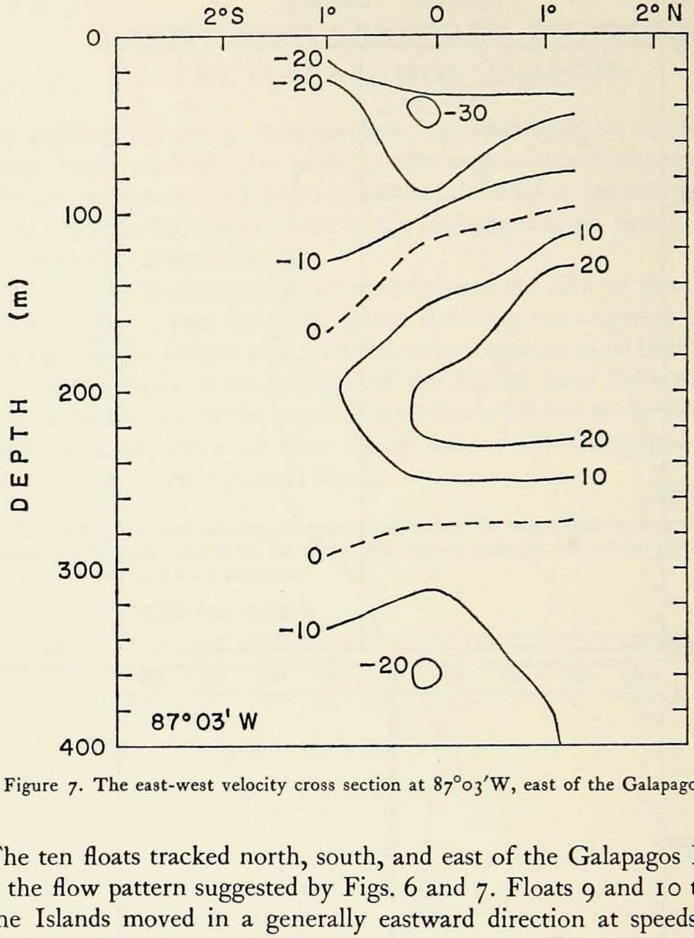

Figure 7. The east-west velocity cross section at 87°03′W, east of the Galapagos Islands.

The ten floats tracked north, south, and east of the Galapagos Islands confirm the flow pattern suggested by Figs. 6 and 7. Floats 9 and 10 to the north of the Islands moved in a generally eastward direction at speeds of 18 and 38 cm/sec while the single float to the south of the Islands traveled at only 3 cm/sec toward 138°. On the 87°W cross section to the east of the Islands, the 200-m float at 1°N went 25 cm/sec toward 102° while a float at the same depth at 1°S went 8 cm/sec toward 170°. Two successive floats at 200 m at the equator went eastward at 41 cm/sec and 22 cm/sec, respectively (Table I).

Although the maximum current speed was reduced to about a third of its peak value as the water flowed through the Galapagos, the volume transport may not be greatly reduced. The transport at 87°W, estimated from the cross section shown in Fig. 7, is about $4 \times 10^6 m^3/sec$, a little more than half of that estimated for 93°W. However, it is obvious from Fig. 7 that there is more eastward transport north of 1°N, and it is conceivable that the transport estimate might be nearly doubled.

The decrease in velocity would appear to be caused in part by mixing with surrounding water. As the undercurrent approaches the Islands it begins to sink, and it continues to sink as it moves through the Islands. The water that emerges to the east of the Galapagos is slightly heavier than that in the undercurrent to the west of the Islands. The mean σ_t value for the water transported eastward at 87°W is 26.35, and most of the water is very close to that density. The range of σ_t values for the water in the Cromwell Current at 93°W is 24.85–26.30, with the mode at about 26.0.

EVIDENCE FOR A MERIDIONAL CIRCULATION

In the Central Pacific, where the Cromwell Current is fully developed, there appears to be a transverse circulation within the undercurrent in addition to the eastward transport. Water flows into the Cromwell Current from the sides. The evidence for this equatorward flow can be seen directly from the current measurements and indirectly from the distribution of salinity.

Velocity Observations. There is some suggestion of an equatorward flow at the depth of the Cromwell Current in the north-south velocity profiles for stations on either side of the equator. Although there is considerable scatter between individual sets of observations, 12 of the 21 lowerings at these eight stations (2°N, 1°N, 1°S, and 2°S at 140°W and 118°W) show marked equatorward flow in the vicinity of the thermocline. The remaining nine observations indicate no strong meridional component. None of the 21 sets of observations shows a significant poleward flow.

The averaged meridional-velocity curves for these eight stations are given in Fig. 8. The average meridional velocity for each of the eight stations, averaged between 30 m and 200 m, is given in Table IV. The mean equatorward flow for the eight stations is 12 cm/sec. For several reasons, however, the exact number must be treated with caution. The average value is of the same magnitude as the uncertainty in any single set of observations. If there is an average equatorward flow at the depth of the Cromwell Current there should be poleward flow at the surface and/or beneath the Cromwell Current. The meridional flow averaged over the depth 0–300 m and eight sections was not zero but 7 cm/sec equatorward. For these reasons it appears that the most that can be said is that the velocity data hint at a convergent meridional flow in the region of the Cromwell Current whose value is in the range of 1–10 cm/sec.

Table IV. The mean value of v, averaged between 30 m and 200 m. $|\bar{v}| = 12$ cm/sec. $|\bar{v}| \times 170 \text{ m} = 2 \times 10^5 \text{ cm}^2/\text{sec}$.

	140°W	118°W
	$\bar{v}$	$\bar{v}$
2°N	−19.6	−23.0
1°N	− 6.5	−21.2
1°S	+12.6	+ 6.8
2°S	+ 5.6	+ 1.8

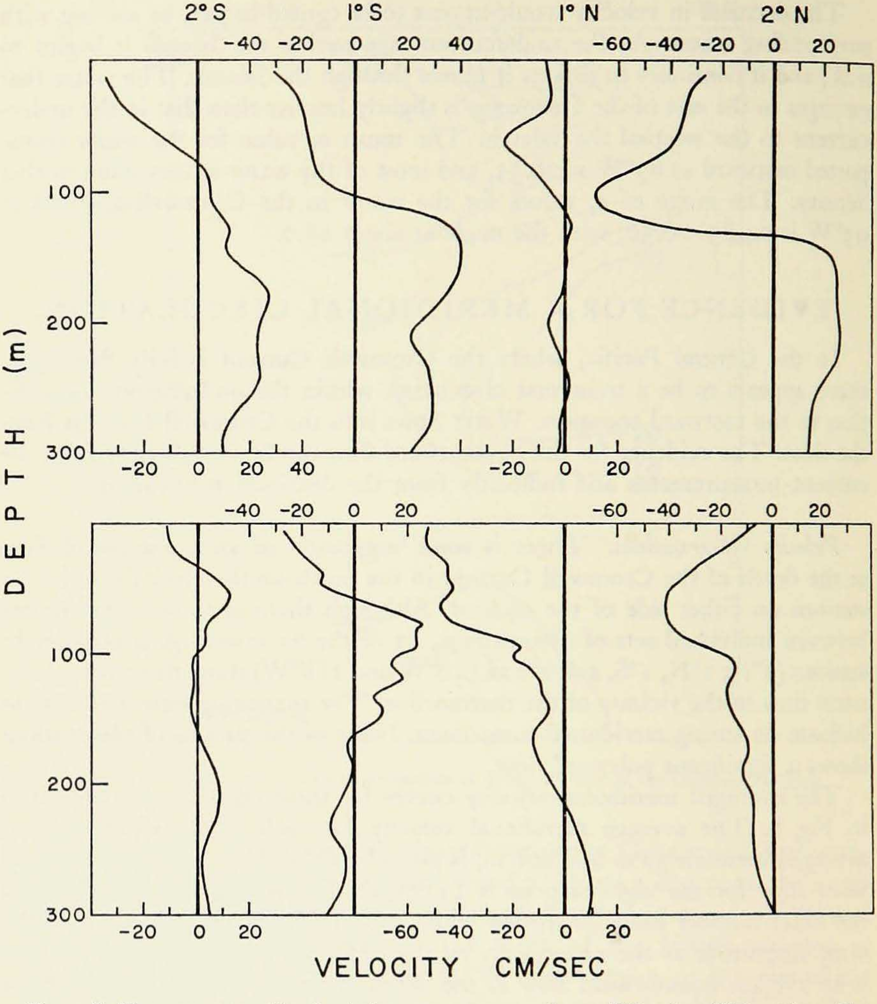

Figure 8. The average meridional velocity components on the 140°W and 118°W sections. Plus indicates a northward component, minus a southward component.

In the report on the 1958 work no mention was made of any meridional circulation. In light of the 1961 observations and the importance of the meridional circulation in understanding the dynamics of the Cromwell Current, the earlier data have been reviewed. Although there is some evidence of a weak meridional circulation at the 17 stations made at 2°N, 1°N, 1°S, and 2°S along 140°W, these earlier data do not show the same equatorward flow that was observed in 1961. A possible explanation for the difference between 1958 and 1961 is considered in a later section.

Salinity Distribution. Evidence for a meridional flow can be seen in the salinity distribution. South of the equator, the equatorward flow of water into the Cromwell Current can be seen from the salinity distribution. As suggested by Montgomery and Stroup (1962), there is in the undercurrent an isolated core of high-salinity water that remains south of the equator (Fig. 9). As can be seen in Fig. 10, this core is entirely confined to the region of the Current.

The explanation for this core can be seen in Fig. 11, where the values of maximum salinity between 50 and 150 m are contoured. South of the equator there is a thin layer of high-salinity water. The maximum value in this layer increases to the south, and to the west to approximately 175°W. Plotted on a meridional cross section (Fig. 9), it appears as a high-salinity tongue stretching equatorward.

It is suggested that the water in this tongue flows equatorward. As it reaches the region of the Cromwell Current, this high-salinity water is then swept eastward. This explanation, which is in agreement with the observed velocity distribution, accounts for the salinity distribution in Figs. 9–11.

In the Central Pacific there is no similar high-salinity tongue that can be used as an analogous tracer for the equatorward flow north of the equator. In the western section of the Atlantic, however, there are sources of high-salinity water in the thermocline both north and south of the equator. By an extension of the above reasoning, high-salinity sources on both sides of the equator in the western Atlantic would lead to a high-salinity core more nearly symmetrical about the equator. It is suggested that such a convergent flow might be the explanation for the high-salinity core in the Atlantic Equatorial Undercurrent reported by Metcalf et al. (1962) and Neumann and Williams (1965). However, on the basis of the salinity data presented in this paper, it should be emphasized that there is evidence for an equatorward flow south of the equator but not for a similar equatorward flow north of the equator.

Evidence of Meridional Flow East of 118°W. The data concerning meridional flow for the sections at 96°W, 93°W, and 87°W show no consistent picture. There appears to be no systematic convergence or divergence and, at some of the stations at least, there even appears to be a reversal of direction in the meridional flow within the Cromwell Current. The meridional flows are generally weak, however, and it is difficult to decide what, if any, credence can be given to these particular results.

Evidence of Vertical Motion. Techniques are not available for direct measurements of vertical velocity in the open ocean. However, if the admittedly speculative data in Table IV are accepted and if continuity is considered, an estimate can be made of the vertical motion in the Central Pacific, west of 118°W, where the Cromwell Current is well developed. The average equatorward transport between 30 and 200 m per unit width in the region of the

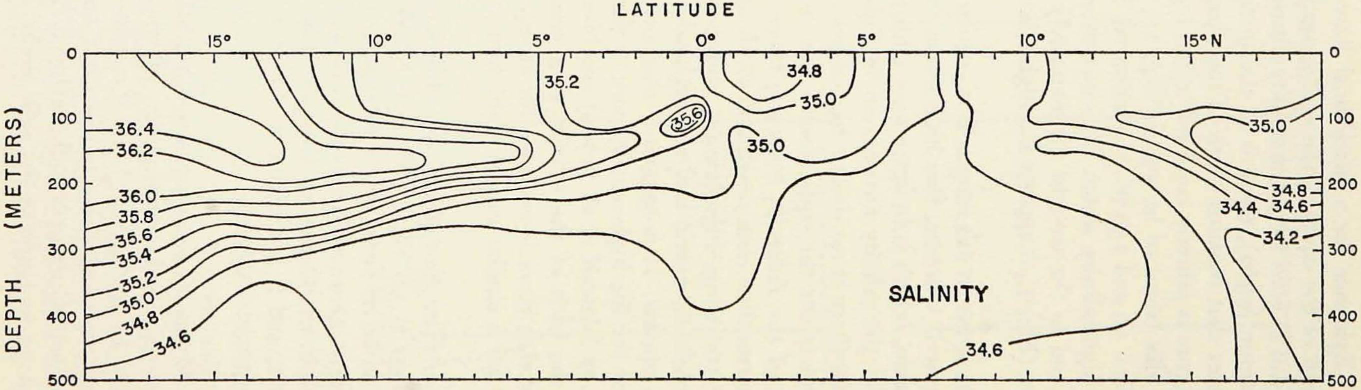

Figure 9. A composite salinity cross section for the Central Pacific. All data taken from stations between 130°W and 155°W.

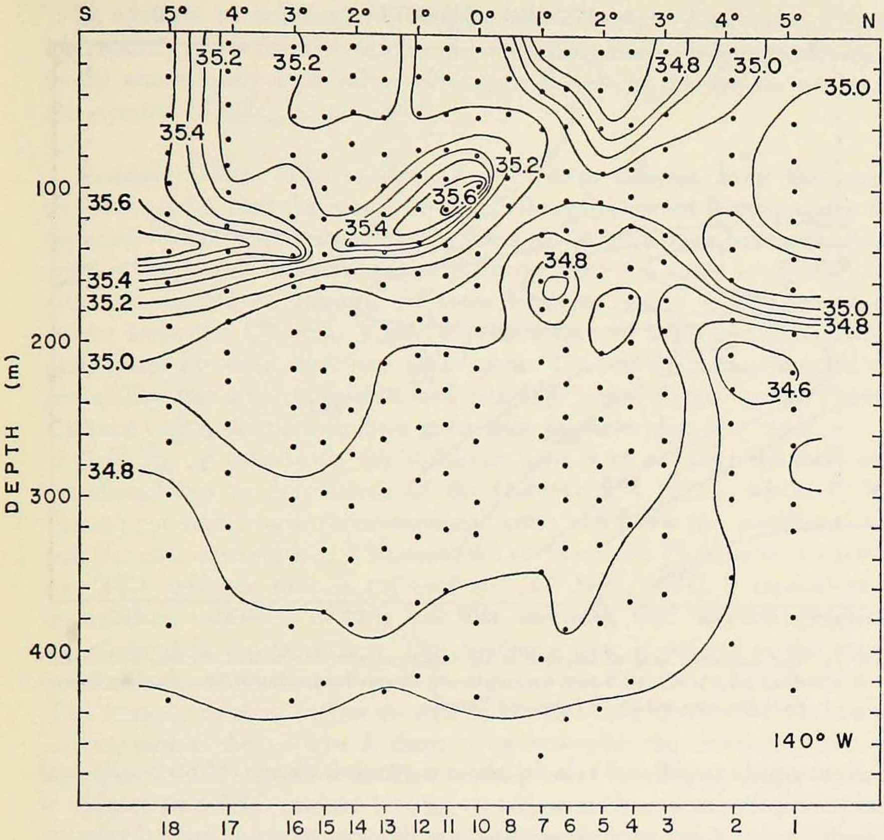

Figure 10. The salinity distribution on Swan Song at 140°W. Dots represent observational points. Station numbers given along bottom.

Current is $2 \times 10^5\,\text{cm}^2/\text{sec}$. Since water is being brought into the undercurrent from both sides, the average entrainment must be twice that figure. In other words, the Cromwell Current is gaining water through meridional transport at the rate of more than $4 \times 10^6\,\text{m}^3/\text{sec}$/degree of longitude. If there were no removal of water through the upper or lower boundaries of the undercurrent, the transport at 118°W should be five times greater than that at 140°W. Since there is no increase in transport downstream in the undercurrent, there must be a vertical transport out of it equal to the observed meridional transport.

The isolated high-salinity center in Fig. 10 appears to be transported upward as well as equatorward. The slope of the isohalines may be a measure of the ratio of vertical-to-meridional velocity. Using this assumption, w/v is calculated to be of order of magnitude 5×10^{-4}. This ratio is identical to that derived from the simplest of scale considerations: vertical velocity times breadth

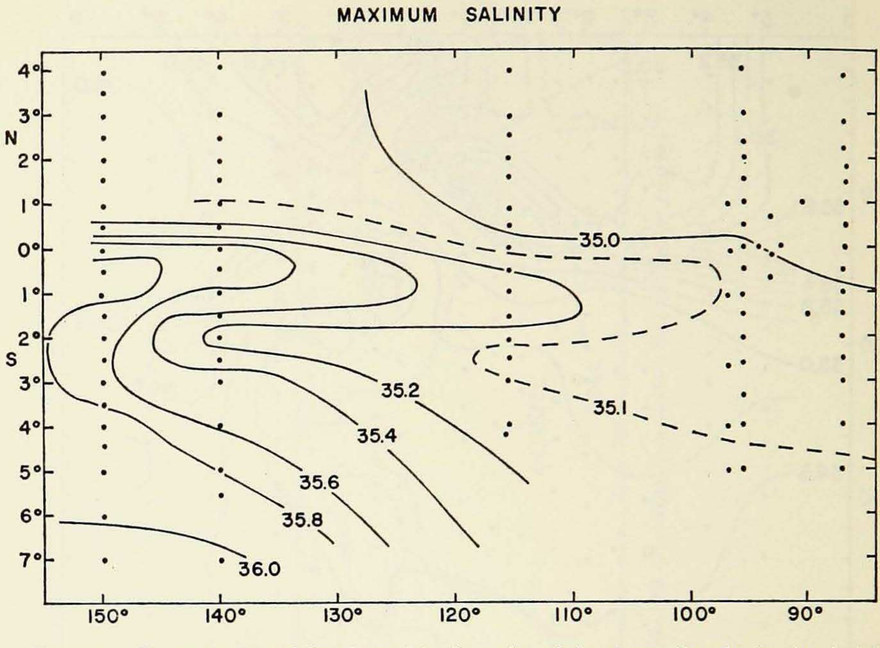

Figure 11. The maximum salinity observed in the region of the thermocline. Station data include those from Hugh M. Smith Cruise 16, and Scripps Institution of Oceanography Expeditions Dolphin and Swan Song, and Step-I.

of current equals meridional velocity times current thickness. If the meridional velocity is 1–10 cm/sec, then $w = 0.5\text{–}5 \times 10^{-3}$ cm/sec. Different models of the meridional circulation obviously produce different values of vertical velocity. I suggest that the above value has the correct order of magnitude.

Since the surface-temperature and surface-oxygen values are lower at the equator than they are a few degrees from the equator and since the surface-phosphate values at the equator are higher than in the surrounding area, an argument can be made for upwelling of water at the equator from below the surface. Furthermore, the higher-than-average temperature and oxygen values and the lower-than-average phosphate values below the core of the Cromwell Current can be used as evidence of descending motion below the core. However, as has been pointed out in the discussion of the 1958 data (Knauss 1960), these distributions can be accounted for by convective motion and/or strong vertical mixing in the region of the equator. That is, the observed distribution may be accounted for by vertical diffusion alone. There need not be any vertical advection in the region of the equator. The indication from the velocity and salinity data of a meridional convergent flow in the region of the Current is less equivocable evidence for a net vertical advection out of the undercurrent.

In addition to temperature, oxygen, and phosphate distributions, Keeling has recently given further evidence for upwelling and/or mixing at the equator in the anomalously high values of carbon dioxide in the surface waters near the equator (Keeling et al. 1965).

Residence Time. The meridional circulation inferred from the previous section suggests that the water in the Cromwell Current is continually being replaced. Water enters the Current from the sides, and as it moves equatorward it is transported eastward; at the same time the water is moving slowly either downward or upward. At some level the water must flow poleward and/or leave the Current. There is no evidence to suggest that any particle participates in more than one such cycle. The evidence does suggest small probability that a given particle will cross the entire Pacific in the Cromwell Current unless the particle does participate in more than one cycle.

One way of calculating the residence time is to consider the ratio of the meridional flux to the volume of the Current: $\tau = V'/T'_y$, where V' is the volume per unit length (cross-sectional area) and T'_y is the meridional transport per unit cross section. V' is about 6×10^{11} cm² and T'_y is about 4×10^5 cm²/sec. The residence time is 1.5×10^6 sec (18 days), which is equivalent to a downstream excursion of only 600 km, assuming that the average speed of the Current is 30–35 cm/sec. The residence time is defined as the time required for the original set of water particles in the Current to be reduced to 1/e. The formula relating inflow to volume is valid only if the time for complete mixing within the volume is short compared with the residence time. It is doubtful if this criterion is fulfilled in the case of an 18-day residence time.

The salinity distribution in Fig. 11 suggests that the eastward excursion for a water particle is closer to 3000 km than to 600 km. Although the high-salinity core is in the high-velocity section of the Cromwell Current, it is difficult to see how the residence time could be less than 3×10^6 sec. This argument may be used as further evidence that the estimate of convergent flow in Table IV is high.

Other assumptions about the meridional paths for the set of particles yield different residence times, but all fall within the 10^6–10^7 second range.

BAROCLINIC PRESSURE GRADIENTS

Precision of Observation. There are several sources of error in determining horizontal pressure gradients from serial oceanographic data. These have been discussed extensively by Reid (1959). Apparently the greatest source of error near the equator is caused by fluctuations in salinity and temperature with time, either because of internal waves or for other reasons.

It is believed that any error inherent in assuming 1000 m as the "level of no horizontal motion" is small compared with the "error" introduced by the

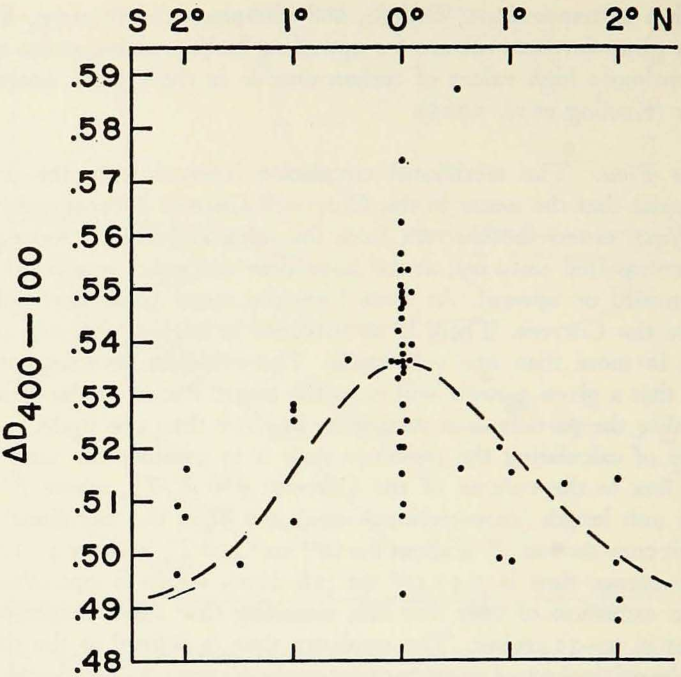

Figure 12. Dynamic height at 100 decibars relative to the 400-decibar surface measured on HORIZON and HUGH M. SMITH from 7 to 24 April 1958 along 140°W. The dashed line represents the required pressure gradient if the velocities observed at 100 m were in geostrophic balance.

temporal variations at a single station. Experience has shown that in this area the horizontal pressure gradient at 500 m relative to 1000 m is very small. In other words, the horizontal pressure gradients calculated for the upper 200 m do not change appreciably whether 500 m or 1000 m are used for the "surface of no motion." The fact that Swallow floats at depths greater than 400 m did not move swiftly is further indication of a lack of an appreciable horizontal pressure gradient between 500 and 1000 m. I believe, therefore, that any uncertainty in the depth of the level of no motion will not cause an uncertainty in the pressure gradient amounting to more than $\pm 2 \times 10^{-5}$ dynes/g (the equivalent of a difference of 1 dynamic centimeter in 5° of latitude).

The force per unit mass exerted by east-west pressure gradients in the vicinity of the equator is of the order of 10^{-5} dynes/g, while the north-south pressure-gradient force is of the order of 10^{-4} dynes/g. (For comparison, the cross-stream pressure-gradient force that balances the Coriolis term in the Gulf Stream is of the order of 10^{-2} dynes/g.) Although the east-west gradient at the equator can be averaged for a distance long enough to determine the

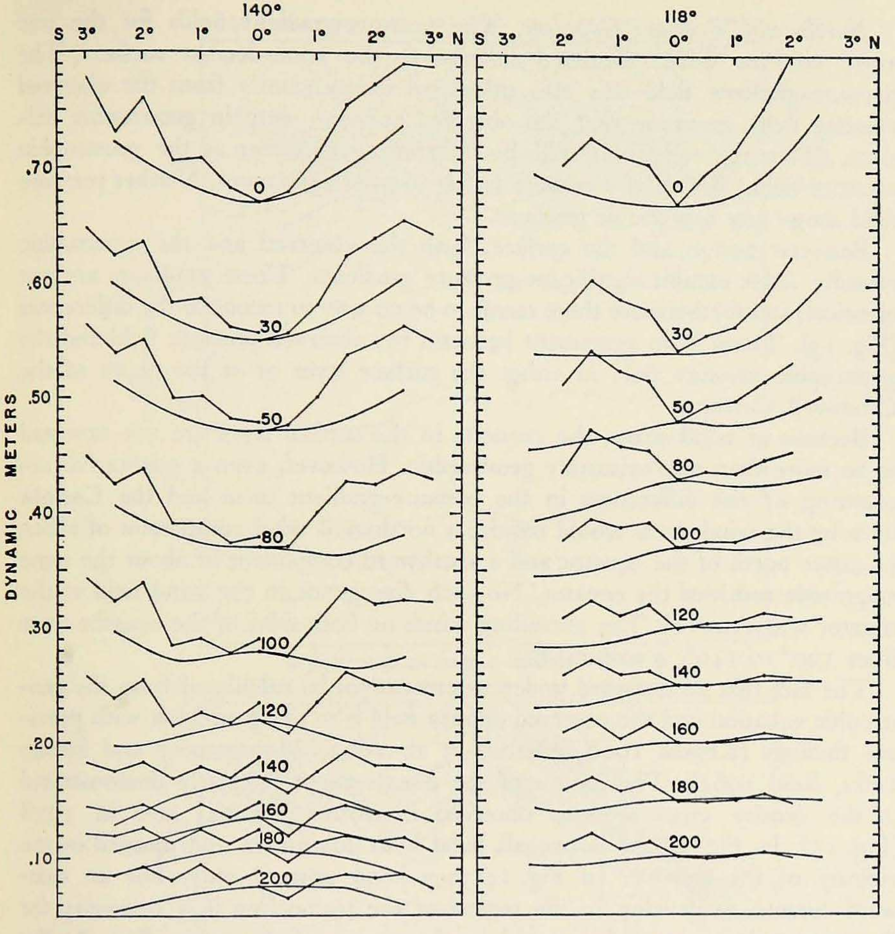

Figure 13. The data and connecting-line segments represent the observed pressure gradient at different levels relative to the 1000-decibar surface. The scale for dynamic height represents relative values. The smooth curves represent the required pressure gradient if the observed velocities (Fig. 3) were in geostrophic balance. The positions of the two curves were made to agree at the equator. At 140°W the two dynamic-height values, shown at the equator, represent the two values observed 21 hours apart (see Fig. 1).

mean gradient, it is very difficult to determine the north-south gradient. The nature of the problem can be seen in Fig. 12, where some of the 1958 data are summarized; these data were collected at 140°W over a 20-day period. Although there is considerable scatter in the observed points, the evidence suggests a symmetrical pressure gradient similar to that required if the Cromwell Current were in geostrophic equilibrium. The dashed line represents the pressure gradient required by geostrophy based on the observed velocity field at 100 m.

North-south Pressure Gradient. The pressure-gradient fields for the five 1961 sections were calculated relative to the 1000-decibar surface. The pressure-gradient field was also calculated independently from the observed velocity field, assuming that the observed currents were in geostrophic balance. (This representation will be referred to hereafter as the geostrophic pressure field.) Below 300 m there is fair to good agreement. Neither pressure field shows any appreciable gradient.

Between 200 m and the surface, both the observed and the geostrophic pressure fields exhibit significant pressure gradients. These gradients are not identical, and furthermore there seems to be no way to reconcile the differences (Fig. 13). There is no agreement between the observed pressure field and the geostrophic pressure field in either the surface layer or at the depth of the Cromwell Current.

Because of wind stress, the currents in the surface layer are not expected to be more than approximately geostrophic. However, even a qualitative accounting of the differences in the pressure-gradient term and the Coriolis term by the wind stress would require a northward wind component of about 10 m/sec north of the equator and a southward component of about the same magnitude south of the equator. No such divergence in the wind field at the equator was observed. The prevailing winds on both sides of the equator were from 120° to 140°, 4 to 6 m/sec.

The fact that an eastward undercurrent cannot be calculated from the geostrophic equation and the observed density field is in sharp contrast with previous findings (Knauss 1960, Metcalf et al. 1962, Montgomery and Stroup 1962, Reid 1964). The nature of the disagreement is clearly demonstrated in the density cross sections observed in 1961 (Fig. 14) and in 1958 (Fig. 15). In Fig. 15 the isopycnals bend both downward and upward in the vicinity of the equator. In Fig. 14 they bend upward only. For an eastward current to develop in the region of the pycnocline it is necessary for the isopycnals to bend downward in the region of the pycnocline. At the level at which they begin to bend upward, geostrophy requires $\partial u/\partial z$ to change sign.

We can imagine that the isopycnal surfaces could be modified by time-dependent fluctuations in the density field. However, it seems unlikely that the results at 140°W and 118°W can be explained in this manner. The fact that the same features were observed north and south of the equator and on both cross sections makes such an explanation rather unlikely. (The same features were observed at 96°W, but the narrowness of the undercurrent at the meridian makes it difficult to draw unambigous conclusions regarding the agreement, or lack of it, between the observed and the geostrophic pressure gradients in the Current.)

The conclusion seems inescapable that, during this particular period, neither the South Equatorial Current nor the Cromwell Current were in geostrophic

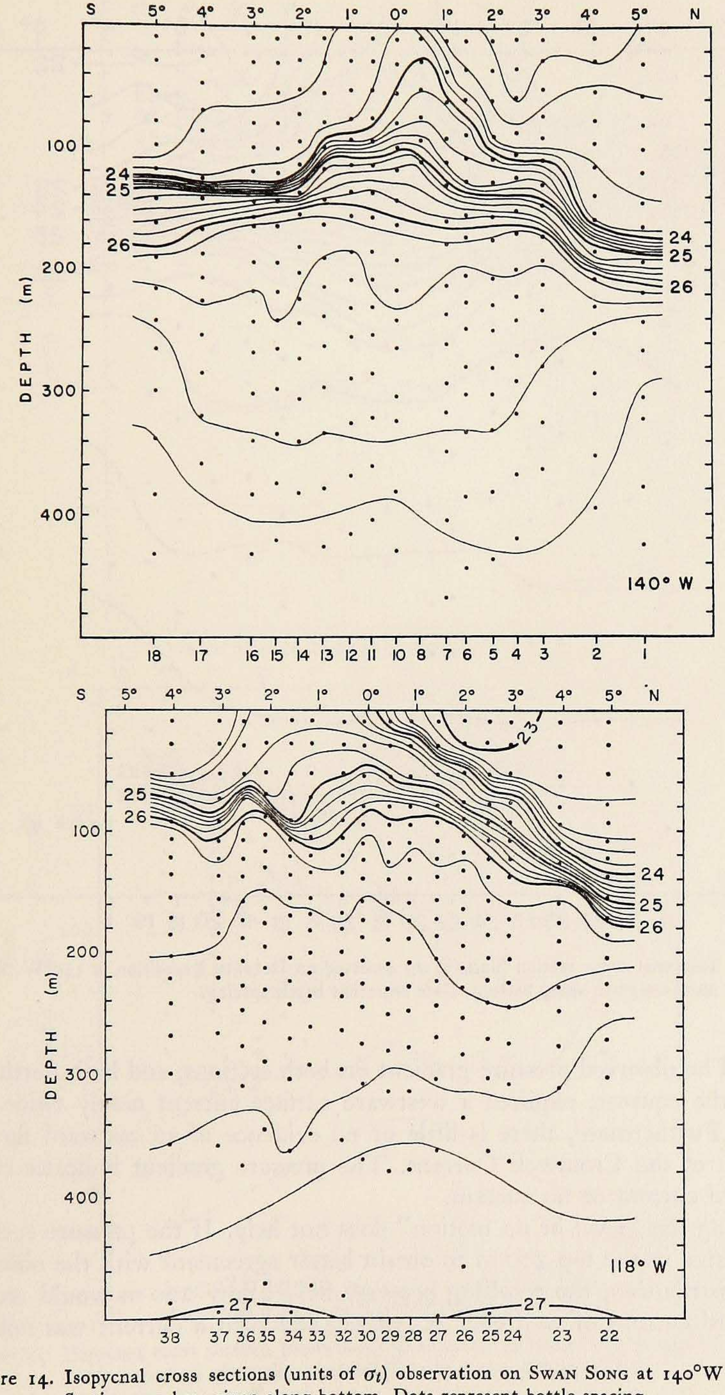

Figure 14. Isopycnal cross sections (units of σ_t) observation on SWAN SONG at 140°W and 118°W. Station numbers given along bottom. Dots represent bottle spacing.

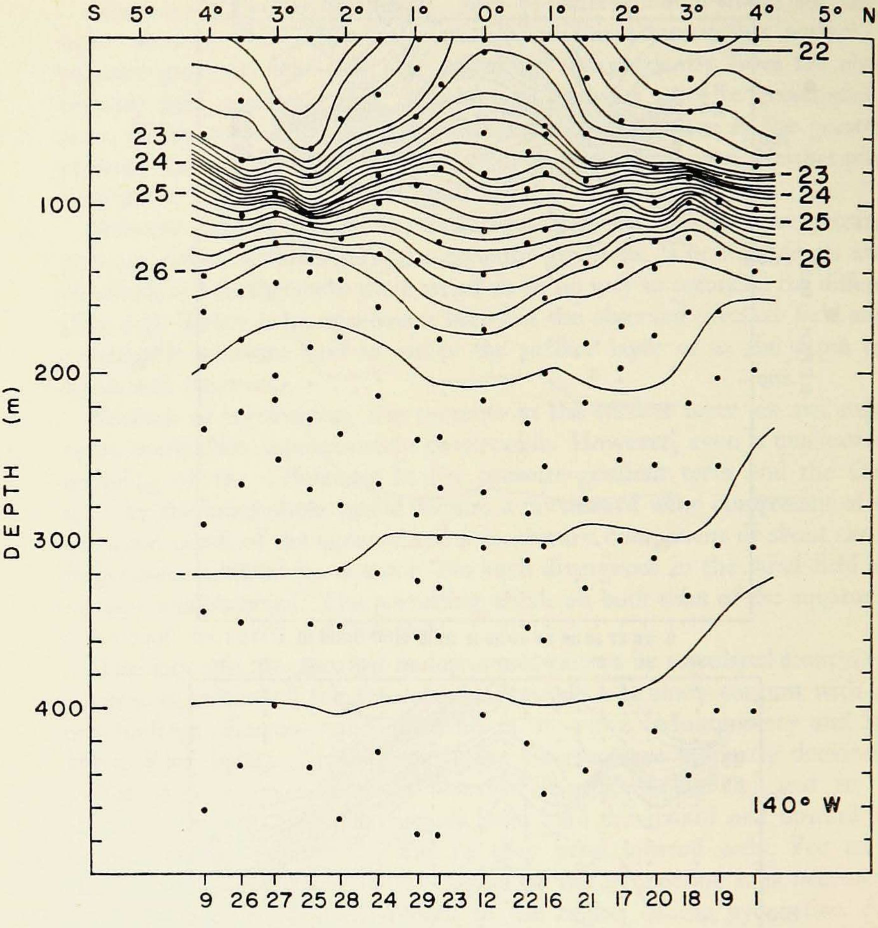

Figure 15. Isopycnal cross section (units of σ_t) observed on Dolphin Expedition at 140°W. Station numbers given along bottom. Dots represent bottle spacing.

balance. The observed pressure gradient on both sections, and both north and south of the equator, required a westward surface current nearly twice that observed. Furthermore, there is little or no evidence of an eastward flow in the region of the Cromwell Current. The pressure gradient indicates either a westward current or no current.

Changing the "level of no motion" does not help. If the pressure surfaces were adjusted in the top 200 m to obtain better agreement with the observed velocity distribution, the resulting pressure field below 200 m would require an eastward current of well over 0.5 m/sec, and such a current was not observed.

East-West Pressure Gradient. Except near the ocean boundaries, the sea surface slopes down to the east along the equator in the Pacific, with an inclination of about -5×10^{-8} (see Knauss 1963: fig. 5), which is equivalent to a pressure-gradient force $(-\alpha p_x)$ of 5×10^{-5} dynes/g. The pressure distribution observed on the equatorial section during the 1958 DOLPHIN Expedition is represented in Fig. 16. The dashed line indicates the core of the Cromwell Current. There is a reversal in the gradient at the depth of the core at about 104°W and at the sea surface at about 98°W. The observed pressure-gradient forces at the surface are: 140° to 98°, $+5.4\times10^{-5}$ dynes/g; 98° to 89°, -10×10^{-5} dynes/g; those at the core of Cromwell Current are: 140° to 104°, $+2.6\times10^{-5}$ dynes/g; 104° to 89°, -3.6×10^{-5} dynes/g.

There were only six equatorial stations in the SWAN SONG Expedition (four of which were at 96° and east), and from these data it is possible only to estimate the gradients or the longitude at which the gradients reverse. The stations do indicate, however, that the same type of gradient was present in 1961. The pressure-gradient forces at both the sea surface and the depth of the core were positive between 140°W and 118°W and negative east of 96°W. In no case did magnitudes of the force appear to differ by as much as a factor of two from those observed in 1958.

On the basis of the 1958 and 1961 data I can conclude that, in the region where the Cromwell Current is well developed, the pressure-gradient force at both the sea surface and the core is positive. East of 96°W, where the flow of the Current is greatly reduced, the gradient is reversed at both the sea surface and the core.

BALANCE OF FORCES IN THE CROMWELL CURRENT

The nature of the forces that drive and maintain the Cromwell Current and other equatorial undercurrents is still uncertain. Thus a discussion of the order of magnitude of the various terms in the equation of motion is appropriate.

$$\frac{Du}{Dt} = u_t + uu_x + vu_y + wu_z = -\alpha p_x + fv + F(x) \quad - w(2\Omega\cos\varphi),$$

$$\frac{Dv}{Dt} = v_t + uv_x + vv_y + wv_z = -\alpha p_y - fu + F(y),$$

where u, v, and w are the velocity components in the east (x), north (y), and up (z) directions, α is the specific volume of seawater, p is pressure, f is the Coriolis parameter and F represents the frictional terms as yet unspecified, Ω is the angular velocity of the earth, and φ is the latitude. The subscripts indicate partial differentiation. The remarks that follow, unless specifically

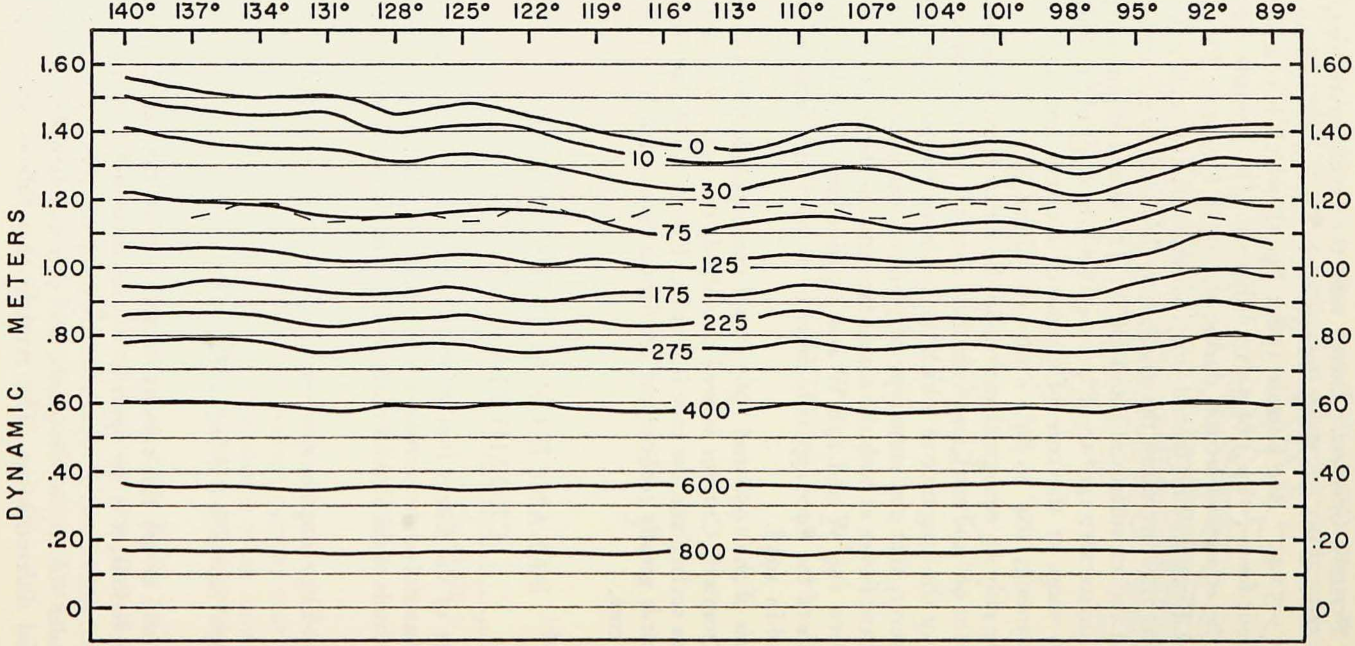

Figure 16. Dynamic height relative to 1000 decibar as measured along the equator on the 1958 Dolphin Expedition. The dashed line represents the observed depth of the core of the Cromwell Current. Hydrographic stations and current measuring stations were made every 3°.

stated otherwise, refer to only the region west of 110°W where the Current appears to be fully developed and stable. Data from both the 1958 and 1961 expeditions have been used to calculate the individual terms.

East-West Balance.

u_t: The condition of steady state can probably be safely assumed for the Cromwell Current. Measurements made at 0°, 140°W in 1958 over a 22-day period indicate that the local acceleration cannot be more than 10^{-5} cm/sec^2 and is probably considerably less.

uu_x: It is probable that this term cannot be neglected in the balance of forces. The core of the Current slopes upward to the east (Figs. 3, 4, and 15; see also Knauss 1960: fig. 6). The term u_x is positive in the region above the core and negative in the region of the core and below it. Its absolute value is between 1 and 2×10^{-7}/sec. Assuming a value of $u = 100$ cm/sec for the eastward component, $uu_x = 1$ to 2×10^{-5} cm/sec^2, positive above the core and negative in and below the core. The value is reduced by a factor of 2 to 5 poleward of 1°.

vu_y: The term u_y is positive south of the equator, negative north of the equator, and apparently zero at the equator. The gradient is approximately 50 cm/sec between 0 and 1° and is somewhat less between 1° and 2° ($u_y = 5 \times 10^{-6}$/sec between 0° and 1° and $u_y = 1$ to 5×10^{-6}/sec between 1° and 2°). The value of v at the equator, indeterminate at present, is probably zero. On either side of the equator in the vicinity of the core, v is estimated to be 5 cm/sec. The term $vu_y = 2 \times 10^{-5}$ cm/sec^2.

wu_z: The velocity shear (u_z) is of course zero at the core. Above the core it is approximately -2×10^{-2}/sec. Beneath the core the shear is somewhat smaller and is of opposite sign. $u_z = 1 \times 10^{-2}$/sec. The shear both above and below the core may be reduced by a factor of two at 2°. Based on the arguments in the previous sections, with a value of $w = 5 \times 10^{-3}$ cm/sec (positive above the core, negative below the core), $wu_z = -(1-2) \times 10^{-5}$ cm/sec^2 in the region of the equator. For any "reasonable model" the value of wu_z is less poleward of the equator and is reduced by at least a factor of two at 2°.

$-\alpha p_x$: As discussed in the previous section, the pressure gradient force ($-\alpha p_x$) equals 2.6×10^{-5} dynes/g at the depth of the core. At the bottom of the Cromwell Current the gradient is no larger than $\pm 1 \times 10^{-6}$ dynes/g.

fv: The Coriolis parameter is zero at the equator, 1.25×10^{-6}/sec at 0.5°, 2.5×10^{-6}/sec at 1°, and 5×10^{-6}/sec at 2°. It is positive north of the equator and negative south of the equator. For a value of $v = \pm 5$ cm/sec, $fv = 0$ at 0°; -1×10^{-5} at 1°; and -2×10^{-5} at 2°. The sign is the same for both sides of the equator.

$F(x)$: It is not possible to measure the frictional term directly, but following Arthur (1960) we can attempt to calculate it at the core of the undercurrent at the equator where $u_y = u_z = f = 0$:

$$uu_x = -\alpha p_x + F(x),$$

$$F(x) = -3 \times 10^{-5}\ \text{cm/sec}^2.$$

Assuming the derived value of friction, the usual eddy diffusivity coefficients can be calculated:

$$F = A(z)\, u_{zz}.$$

Fitting a parabola to the velocity-depth profile and differentiating twice, $u_{zz} = 6 \times 10^{-6}/\text{cm-sec}$. The vertical eddy diffusivity coefficient is therefore $A = 5\ \text{cm}^2/\text{sec}$.

$w(2\Omega \cos \varphi)$: Within two degrees of the equator, $2\Omega \cos \varphi = 14.6 \times 10^{-5}/\text{sec}$. Assuming a high estimate of $w = 10^{-2}$ cm/sec, this component of the Coriolis force cannot be larger than $2 \times 10^{-6}\ \text{cm/sec}^2$.

Six of the eight terms in the balance of forces in the east-west direction are of the order of magnitude $1-10 \times 10^{-5}$ dynes/g. Only the time variation of u and the second Coriolis term appear to be sufficiently small to be neglected. The magnitude of w is inferred from that derived for v. It should be noted that, if a larger value ($v = 10$ cm/sec) is accepted, the two inertial terms $|vu_y|$ and $|wu_z| = 5-10 \times 10^{-5}\ \text{cm/sec}^2$. They are of opposite sign and tend to cancel. If these higher values are accepted for the meridional circulation, the Cromwell Current might be characterized as a free inertial current, the driving forces being of smaller magnitude.

North-south Balance. Until the meridional circulation is better defined, it is not possible to discuss most of the terms in the north-south equation of motion in the same detail as was done with the east-west terms. Furthermore, the evidence suggests that the nature of the balance was different in 1958 and 1961. In 1958 the Cromwell Current appeared to be in approximate geostrophic balance ($uf = -\alpha p_y = 2 \times 10^{-4}\ \text{cm/sec}^2$). On Swan Song, $uf = +1 \times 10^{-4}\ \text{cm/sec}^2$. The pressure-gradient force was generally smaller and of opposite sign.

The fact that the velocity measurements in 1958 showed no indication of an equatorward flow suggests that the meridional circulation in 1961 might have been considerably stronger during the Swan Song Expedition than during the Dolphin Expedition. Further indirect evidence of a strong meredional circulation during the 1961 cruise can be found in the fact that a "front" was observed on 24 September at about 4°N, 131°W while steaming from the 140°W section to the 118°W section. The front was similar to those from this section described previously (Knauss 1957). South of the front the northward component of the surface current was estimated to be between 75 and 125 cm/sec.

A strong meridional circulation of the type envisaged for the Cromwell Current is not inconsistent with the lack of geostrophic balance. If the pressure gradient does not balance the Coriolis term, it is probably balanced (assuming a steady state) by the combined terms: $vv_y + wv_z$. In both terms the sign is positive north of the equator and negative south of the equator, as would be required if these two terms were to balance the Coriolis term. Using the figures from the previous section, we can estimate $vv_y + wv_z = 3 \times 10^{-6}$ cm/sec². For $vv_y + wv_z = +fu = 1 \times 10^{-4}$ dynes/g it is necessary that v be nearly 30 cm/sec and w of the order of magnitude 10^{-2} cm/sec. The possibility of a meridional circulation of that magnitude cannot be dismissed on the basis of the 1961 observations, but it does seem unlikely.

The significance of the fact that there may be two modes by which the Cromwell Current can maintain a balance in the north-south direction is unclear.

DISCUSSION AND CONCLUSIONS

The velocity structure in the Cromwell Current observed at 140°W in October 1961 was similar to that observed in April 1958. The undercurrent was a thin ribbon about 400 km wide and 200 m thick. The highest speeds were observed at the equator, and the Current appeared to be approximately symmetrical about the equator. The observed transport was 22×10^6 m³/sec—about half that observed in 1958. It is suggested that at least part of the difference in transport is related to the fact that in 1961 the westward-flowing South Equatorial Current was well developed in the region of the Cromwell Current and in 1958 it was not.

The velocity structure at 118°W was similar to that at 140°W, but at 96°W it appeared that the Cromwell Current was beginning to break up. The transport was reduced to half. The undercurrent was no longer symmetrical about the equator. A small eastward transport with considerably reduced maximum velocity was tracked around the north side of Isabela Island of Galapagos and found again to the east of the Galapagos. Considerable mixing apparently takes place around the Galapagos, and the water in the extension of the Cromwell Current to the east of the Galapagos is slightly heavier and about 150 m deeper than it is immediately west of the Islands.

Examination of surface-current charts show that island groups elsewhere usually do not influence a major current as markedly as the Galapagos Islands effect the Cromwell Current. Although currents may be disrupted to some extent as they move through islands, they usually reform on the leeward side. Striking examples are: the Pacific South Equatorial Current as it moves through the Phoenix and Gilbert Island groups, and the Pacific Equatorial

Countercurrent and the Pacific North Equatorial Current as they move through the Gilbert and Marshall Islands, respectively.

It appears that the Cromwell Current is already beginning to break up some 500–1000 km west of the Galapagos. The forces necessary to drive and/or maintain the undercurrent are missing, and the Galagagos Islands supply the *coup de grâce*. The "missing force" appears to be the small negative east-west pressure gradient found in the Central Pacific; this has a value of the order of 10^{-5} dynes/g. This gradient goes to zero and reverses its sign some 1000 km west of the Galapagos.

Velocity observations from the 1961 cruise appear to show an equatorward flow in the region of the undercurrent. No such convergence can be found in the velocity observations from the 1958 expedition. It is difficult to observe the meriodinal circulation with the techniques used on these two cruises, and the apparent difference in the two years may not be real. However, the fact that there was a real difference in the north-south pressure gradients for the two cruises does suggest that the meridional circulation was stronger and more highly developed during the fall of 1961 than the spring of 1958. On the basis of the 1961 data the meridional transport per unit cross section may be as high as 10% and 20% of the east-west transport per unit cross section (Tables II and IV).

Regardless of the velocity observations, the distributions of salinity, temperature, oxygen, phosphate, and dissolved carbon dioxide suggest that there is a convergence at the equator, with consequent upwelling and downwelling out of the Current. Although these distributions might be accounted for by mixing processes without a net mass transport, it seems unlikely at any rate that the salinity distribution is not the result of a convergent flow pattern.

Using the observed velocity data, it has been possible to deduce a vertical velocity and thus calculate all the terms in the equation of motion. However, the uncertainty in the meridional circulation terms (vv_y and wv_z) is such as to prelude any detailed discussion of the north-south balance. Of the eight terms in the east-west balance it would appear that wu_z and vu_y are several times larger than the other four (uu_x, αp_x, fv, and friction), which are of the order of magnitude $1–3 \times 10^{-5}$ dynes/g. Only the time variation of u and the second Coriolis term can be neglected.

The fact that the Cromwell Current was not in approximate geostrophic balance is the most surprising result of the 1961 field work. All other data have suggested that a balance exists. Although the differences are small, they are apparently real, and there appears to be no way to reconcile the observed north-south pressure gradient with the observed east-west velocity components. What does provide the balance is not completely clear; a large meridional circulation could give rise to inertial terms of sufficient magnitude and of the proper sign.

To date it has been common practice to deduce the existence of an undercurrent from the observed density field. If there is a "spreading" of the pycnocline at the equator, with the isopycnals dipping down as well as up, an undercurrent has been presumed. When such a distribution occurs there is no reason to believe that an undercurrent does not exist; however, on the basis of present evidence we must now recognize the possibility that an undercurrent can exist in the absence of such a density distribution.

Although there is more work to be done in describing the Cromwell Current, it would appear, to me at least, that the next significant advance must come from the development of a realistic theoretical model. Hopefully the model will be "realistic" enough so that it can be tested in the field. However, the testing is going to be difficult, since it seems probable that any model will have to depend critically on the distribution of the vertical-velocity component, a variable that cannot be measured but can only be deduced from continuity considerations. There is an additional problem in that equatorial undercurrents are usually "imbedded" in the well-developed south equatorial currents, and it is not obvious what interaction occurs. Any testing of an undercurrent model should be done in those areas and during those periods when the South Equatorial Current is poorly developed along the equator.

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