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Observations of near-equatorial flows in the eastern Pacific

by Ants Leetmaa[1]

ABSTRACT

Direct measurements were made in 1980 and 1981 of the near-equatorial flow field along sections at 110, 102.5, 95, and 85W. The Equatorial Undercurrent weakens as it approaches the Galapagos. Most of the transport is lost from the warmer, upper part of the current. In June 1981, the transport at 110W was 26 Sv (1 Sv = 10^{12} gm/sec) and at 95W it was 13 Sv. However, further to the east at 85W only a trace of eastward flow was present above 150 m and most of the flow was westward. To the west of the Galapagos the bulk of the eastward flow lies asymmetrically south of the equator. In the surface layers eastward flows extends southward to 3S. This appears to be distinct from the Undercurrent. It is argued that this shallow eastward flow is driven by the curl of the wind stress. At 110W the net transport within 3° of the equator was close to zero. The eastward transport of the Undercurrent was compensated for by westward transport in the South Equatorial Current north of the equator.

1. Introduction

Since the discovery of the Equatorial Undercurrent in the Pacific Ocean in 1952, a number of expeditions have explored its meridional structure and zonal extent (Knauss, 1960 and 1966; Taft and Jones, 1973). The Undercurrent is strongest in the central ocean and weakens abruptly just west of the Galapagos Islands (92W). Little is known about where the transport goes and to what extent the current continues to the east of the Galapagos. Knauss (1966) suggests that some flow goes north of the Islands and sinks to a deeper level by 85W. Stevenson and Taft (1971), on the other hand, measured some subsurface eastward flow at 84W at about 75 m just south of the equator. This level coincided with a high-salinity core which to the west of the Galapagos is found south of the equator and is transported eastward in the Undercurrent. They concluded that the flow they observed was an eastward extension of the Undercurrent and that part of its transport passes south of the Galapagos.

Large-scale interannual sea surface temperature (SST) anomalies in low latitudes have been shown to be associated with global climatic variations. This has led to an increased interest in equatorial circulations and how these might cause

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changes in the surface temperature. As part of the Equatorial Pacific Ocean Climate Studies (EPOCS), a NOAA program to study the origin and effect of these SST anomalies, measurements were made of near-equatorial currents in the eastern Pacific. In March and April of 1980, profiles were taken every 5° along the equator from 125W to 159W on the NOAA Ship *Oceanographer.* A discussion of that data appeared in Leetmaa and Spain (1981). Later that year during August and September short meridional sections were taken across the equator at 95, 102.5, and 110W from the NOAA Ship *Researcher.* During June 1981 sections were occupied at 110, 95, and 85W from the *Oceanographer.*

The velocity profiles were obtained with a free-falling acoustically tracked profiler, PEGASUS. This is described by Spain *et al.* (1981). Velocity profiles are computed from the trajectory of the instrument which is tracked relative to two expendable bottom-mounted beacons. The relative positions of the beacons were ascertained by shipboard survey. The depth of the instrument and the travel times from the two beacons suffice to fix the position of the profiler, provided it stays to one side of the beacons. The trajectory, determined from position fixes over 3-6 m in the vertical, is smoothed with a seven point least squares fit, and differentiated to compute velocities. The instrument is tracked on the way up and down. The down and up profiles usually agree to within a couple of cm/sec. Hence, the absolute accuracy of the system is of this order. Baseline orientations are determined to a couple of degrees. There is evidence for this in that the meridional velocity field in the vicinity of the Undercurrent where the zonal velocities are large does not look like the latter. A few of the velocity profiles were made from the ship using a profiling current meter (PCM) (Düing and Johnson, 1972). These were referenced by assuming that the average velocity below 300 m approached zero. The hydrographic measurements were taken with a Neil Brown Instruments System Mark III CTD. This was calibrated by water samples collected simultaneously with a rosette multisampler.

2. Observations

During 1980 in August and September meridional sections were taken across the equator at 110, 102.5 and 95W. In August highest speeds in the Undercurrent of 130 cm/sec were found on the equator (Fig. 1a). However, the bulk of the current was located further south since the velocities at 30′S were stronger than those at 30′N. The highest velocities lay just beneath the strongest part of the thermocline at a temperature of 16° or 17°C. Eastward velocities extended to about 900 m. Surface currents at and just north of the equator were to the west. South of the equator they were weakly eastward. The isotherms in the thermocline were spread apart the most just south of the equator (Fig. 1b). Coldest surface temperatures were located on the equator. Normally during this time of the year

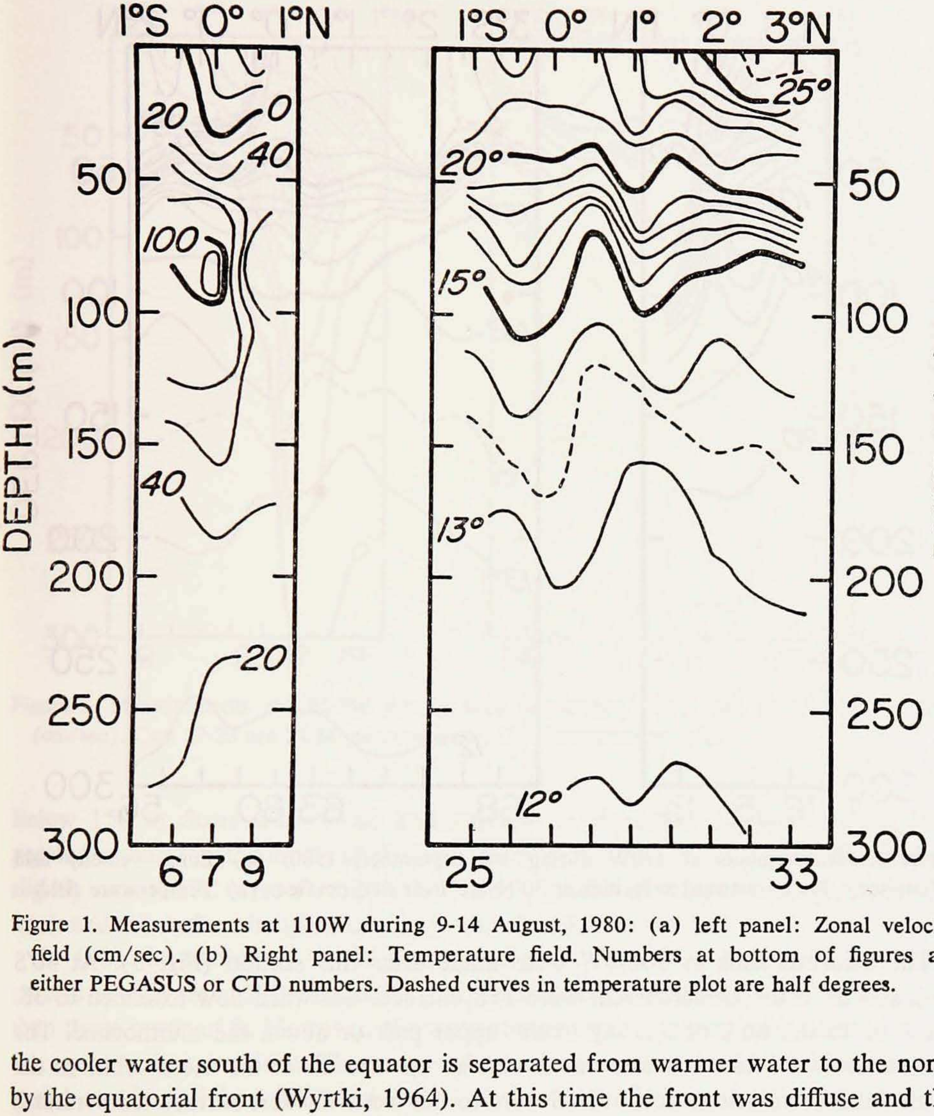

Figure 1. Measurements at 110W during 9-14 August, 1980: (a) left panel: Zonal velocity field (cm/sec). (b) Right panel: Temperature field. Numbers at bottom of figures are either PEGASUS or CTD numbers. Dashed curves in temperature plot are half degrees.

the cooler water south of the equator is separated from warmer water to the north by the equatorial front (Wyrtki, 1964). At this time the front was diffuse and the northward increase of temperature was gradual. About a month later the front had intensified. The 25.5°C isotherm had moved to within 30 nms of the equator (Fig. 2b). Just north of the equator the near-surface temperature changed about 3°C over 30 nms. Associated with this temperature gradient were large westward velocities of over 200 cm/sec (Fig. 2a). Westward flow extended to slightly over 100 m at this location. The Undercurrent was located south of the equator. Peak velocities at 30′S were 116 cm/sec. Throughout the Undercurrent the velocities appeared to be about 10-15 cm/sec weaker than in July. Eastward flow extended to at least 1S and the speed maximum shoaled to the south.

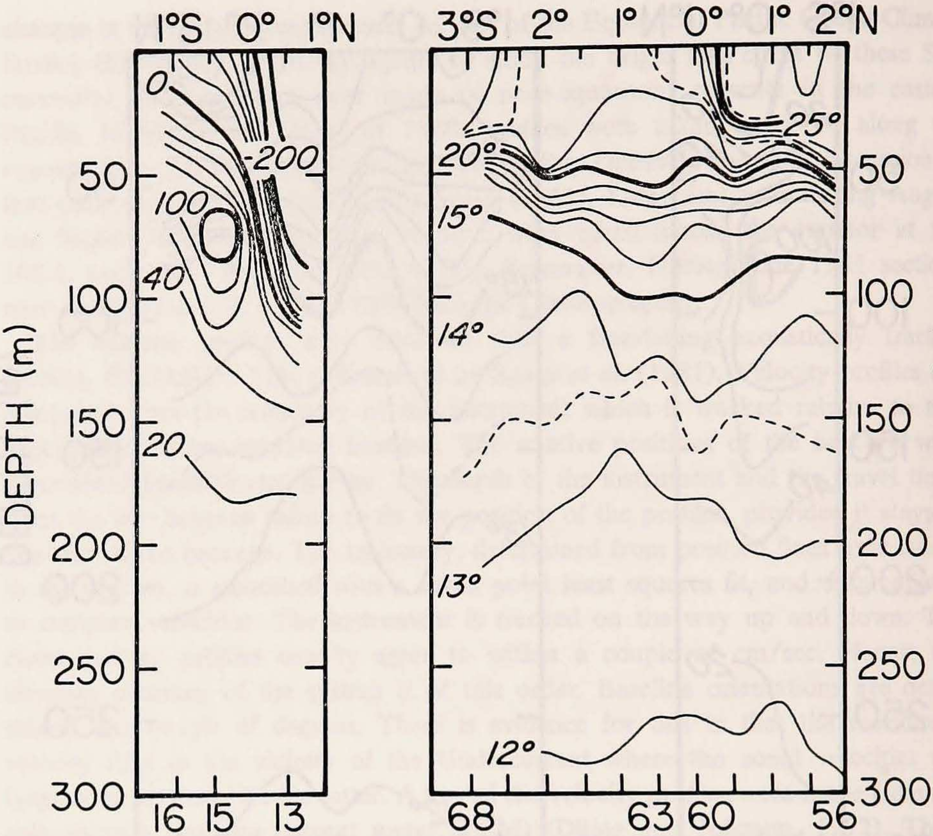

Figure 2. Measurements at 110W during 1-5 September, 1980: (a) Zonal velocity field (cm/sec). Peak westward velocities at 30′N are over 200 cm/sec. (b) Temperature field.

The measurements at 102.5W were made after this section (Fig. 3). At 30′S peak speeds in the Undercurrent were 118 cm/sec. Eastward flow extended to 3S. South of 1S the bulk of this lay in the upper part or above the thermocline. The shallow eastward flow was associated with an upward tilt of the thermocline to the south. Surface velocities north of 1S were to the west. Coldest surface temperatures of 21.1°C were at 1S. Just north of the equator the surface temperature changed from 22° to 24°C over about 60 nms. The thermocline on the average at this section was 10-15 m shallower than it was at 110W.

The section at 95W was occupied in July just before the 110W section. The Undercurrent at this location was weaker than further to the west. On the equator peak speeds were only 49 cm/sec (Fig. 4a). They were located at a depth of 100 m; this speed maximum lay deeper than at 110 or 102.5W. A secondary speed maximum of 40 cm/sec was located at 50 m at 30′S. Surface velocities on and north of the equator were westward. At 30′N these were about 100 cm/sec.

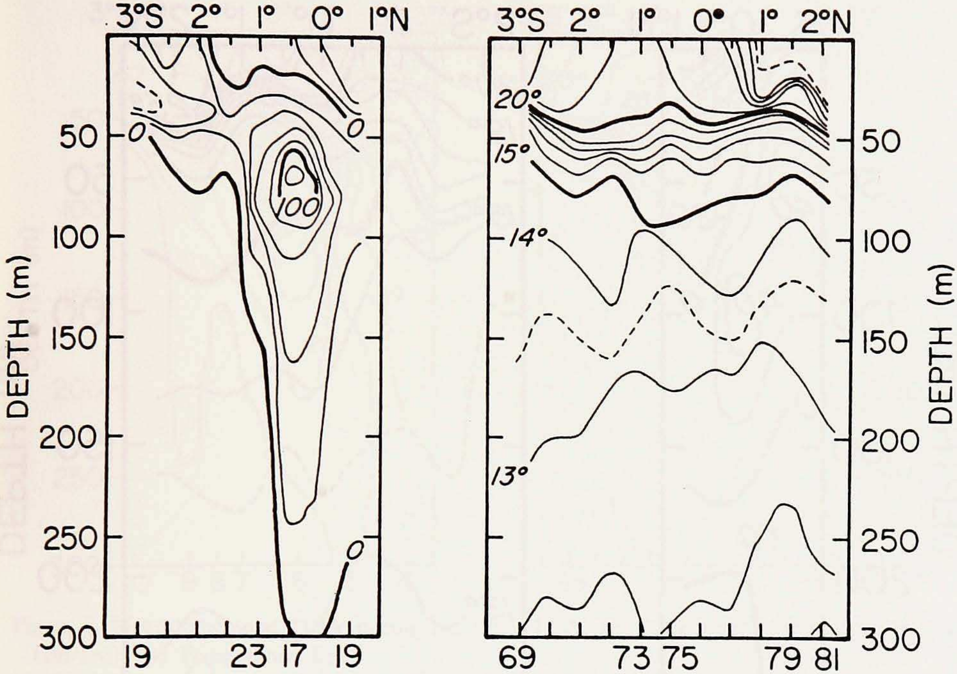

Figure 3. Measurements at 102.5W during 6-10 September, 1980: (a) Zonal velocity field (cm/sec). Cast 19-23 are PCM measurements. (b) Temperature field.

Below 150 m flows were weak and variable in direction. Coldest surface temperatures were located south of the equator between 30′S and 1S (Fig. 4b). Values slightly over 26°C were found at 2N. The meridional temperature gradient was weak and the surface temperature front was absent.

In 1981 the section at 110W was occupied in June (Fig. 5a, b). Peak Undercurrent speeds were 122 cm/sec. Again, speeds south of the equator were greater than those north of it. However, the current was more symmetrically located about the equator than in 1980. The eastward speed maximum shoaled to the south as it did at 102.5W in 1980, and eastward flow extended south of 2°30′S. Large areas of weak westward flow existed below the thermocline. The South Equatorial Current (SEC) north of the equator was well developed. Westward flow extended southward across the equator to 30′S. Speeds of over 100 cm/sec were found in the surface layers between 30′ and 1°30′N. North of 1N westward flow was present below the thermocline.

The thermal structure showed the classical spreading of the isotherms. North and south of the equator near-surface temperatures were about 26°C. Minimum values of slightly less than 24°C were located at 30′S. Temperatures south of the equator were about 2 to 3°C warmer than was observed in 1980. It is not obvious what

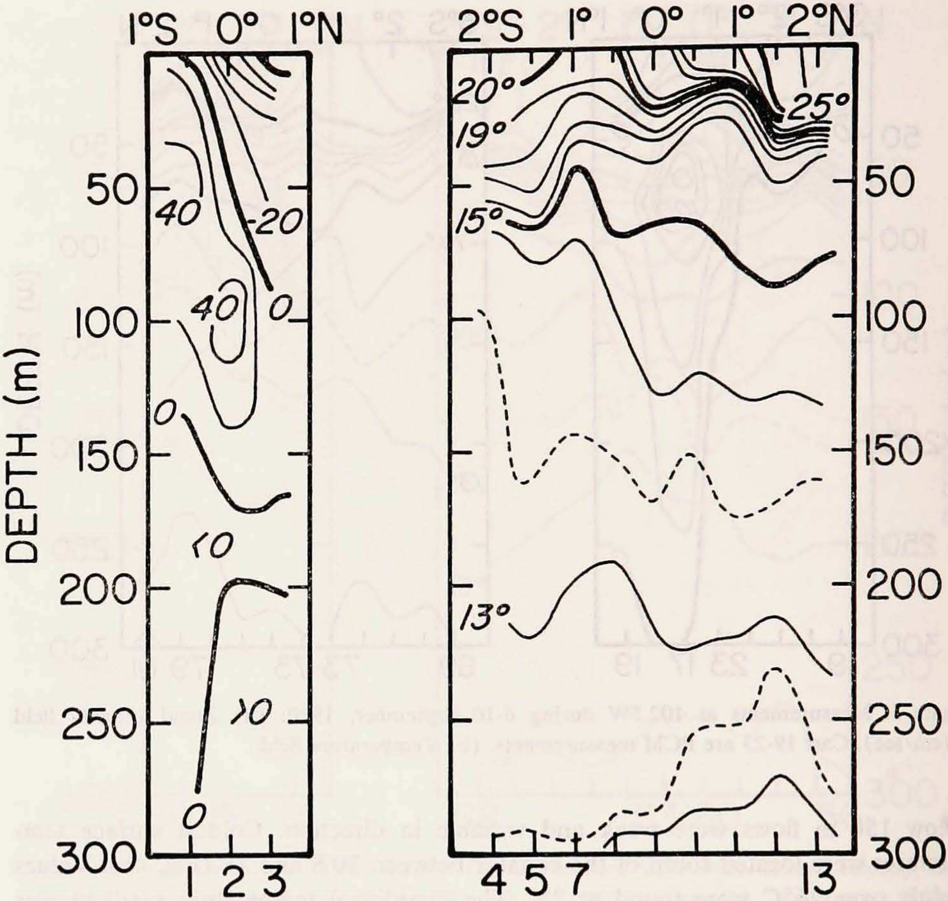

Figure 4. Measurements at 95W during 2-5 August, 1980: (a) Zonal velocity field (cm/sec). (b) Temperature field.

caused this difference because the general pattern of flow was similar both years. The thermocline again shoaled from 30′ to 3°30′S.

At 95W peak speeds in the Undercurrent were about 75 cm/sec (Fig. 6). These were about twice as large as was observed in 1980. There were two speed maxima; one was located at about 70 m on the equator and the other at 50 m at 1S. Eastward flow in and above the thermocline extended to at least 2S. On and north of the equator, surface flow was to the west. At 30′N the westward flow extended below the thermocline. The thermocline, on the average, was about 20 m shallower than it was at 110W. Minimum surface temperatures were about 22°C and these were located at 1S. Temperatures south of the equator were about 2°C warmer than was observed here in 1980.

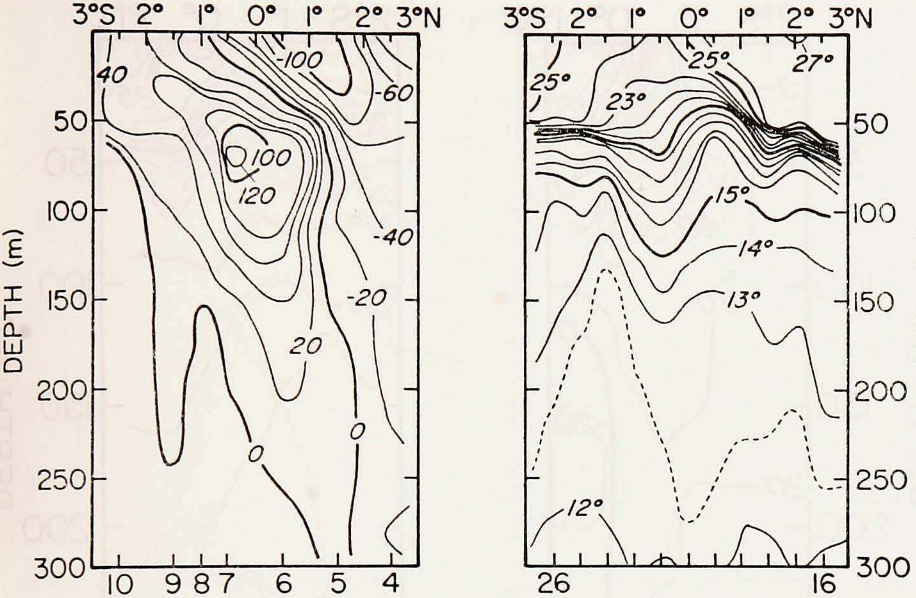

Figure 5. Measurements at 110W during 2-6 June, 1981: (a) Left panel: Zonal velocity field (cm/sec). (b) Temperature field.

By 85W almost all traces of eastward flow in or near the thermocline were gone (Fig. 7). A region of weak eastward flow (velocities < 10 cm/sec) was observed between 2°30′S and the equator at about 65 m. Except for eastward flow in the surface layers at 2.5N, the rest of the flow in the top 150 m was to the west. Within 1° of the equator the flow field was similar to that observed by Knauss (1966). He observed westward flow in the top 150 m at 1N, 0°, 1S. The thermal field showed a spreading of the isotherms, usually characteristic of the Undercurrent, south of the equator (Fig. 7b). This is co-located with a subsurface salinity maximum. The thermal field from 16° to 13°C was deeper at 85W than further to the west.

3. Discussion

These new sections almost double the measurements of the Undercurrent in the eastern Pacific. To see how they fit in with the historical data, the EPOCS data are plotted along with the earlier studies as compiled by Taft and Jones (1973). The eastward transport per unit width was obtained by integrating with depth the velocity profile for all velocities greater than 20 cm/sec (this was the lower limit chosen by Taft and Jones, 1973). The results are shown in Figure 8. Notable is the large magnitude of the short-term variations. At 110W between the August

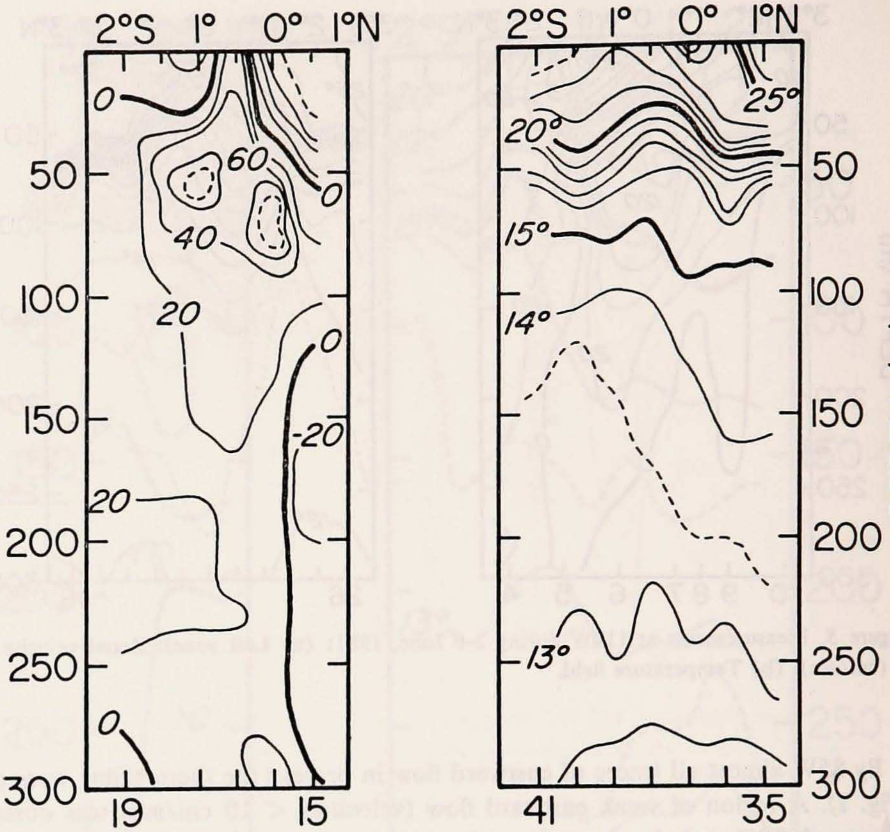

Figure 6. Measurements at 95W during 11-15 June, 1981: (a) Left panel: Zonal velocity field (cm/sec). (b) Right panel: Temperature field.

and September 1980 cruises there was a decrease of 4.4 × 10^5 cm^2/sec or about 20%. During the latter cruise the SEC north of the equator was extremely strong. The transport per unit width at 102.5W was 11.4 × 10^5 as compared to 8.6 × 10^5 cm^2/sec at 110W just a few days earlier. Whether these changes are purely temporal or both temporal and spatial is unknown. However, the SEC was not nearly as strong at 102.5 as at 110W. Variations of similar magnitudes were evident over 3° of longitude during the Dolphin expedition and over 5° during the EPOCS April 1980 cruise. Moored measurements during this latter cruise suggest that the observed spatial variation was in fact an eastward propagating phenomena (Halpern, 1981). Its speed of propagation was about 270 cm/sec and the supposition is that it was a Kelvin wave. This presumably is only one phenomena that can cause short-term variations in the Undercurrent. Because of the large magnitude (of order 5 × 10^5 cm^2/sec) of the short-term variability, it is difficult to say much

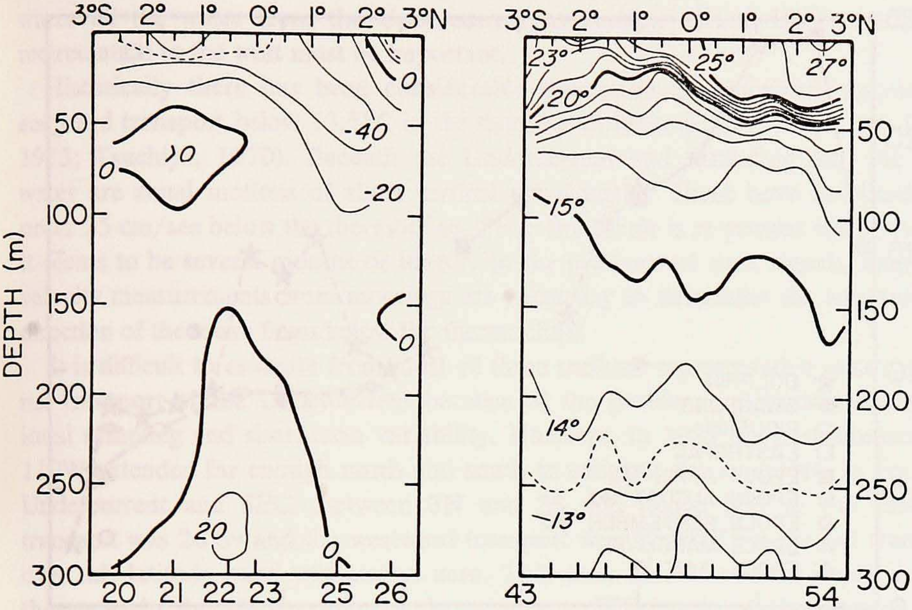

Figure 7. Measurements at 85W during 17-21 June, 1981: (a) Left panel: Zonal velocity field. (b) Right panel: Temperature field.

about cruise to cruise variations. However, some of the previous conclusions still seem to be true. The transport per unit width and presumably the total transport of the Undercurrent is largest in the central Pacific. Transports decreases rapidly close to the Galapagos.

It was suggested by Stroup (1969) and Taft and Jones (1973) that as the Galapagos are approached from the west the transport shifts to deeper levels. To examine this suggestion the EPOCS transport were broken down into two temperature classes. The dividing isotherm was chosen to be 16°C. This lies at the base of the thermocline and at 95W the core of the current lay below it. The lower limit was chosen to be 13.5°C because at 95W in 1981 the flow was to the west at colder temperatures. An isothermal surface because of mixing processes is not a material boundary. However, it is not clear how to evaluate the effects of mixing on this computation.

In 1980 at 110W between 1N and 1S, the transport for temperatures warmer than 16°C was 5.7 Sv (1 Sverdrup = 10^{12} gm/sec). Between 13.5° and 16°C it was 10.4 Sv. At 95W in 1980 the transports above and below 16° were 0.7 Sv and 3.6 Sv respectively. This represents a decrease in the upper layers of 88% and in the lower ones of 65%. In 1981 at 110W the transports above and below 16°C between 2S and 1N were 11.6 Sv and 8.6 Sv respectively. At 95W over the

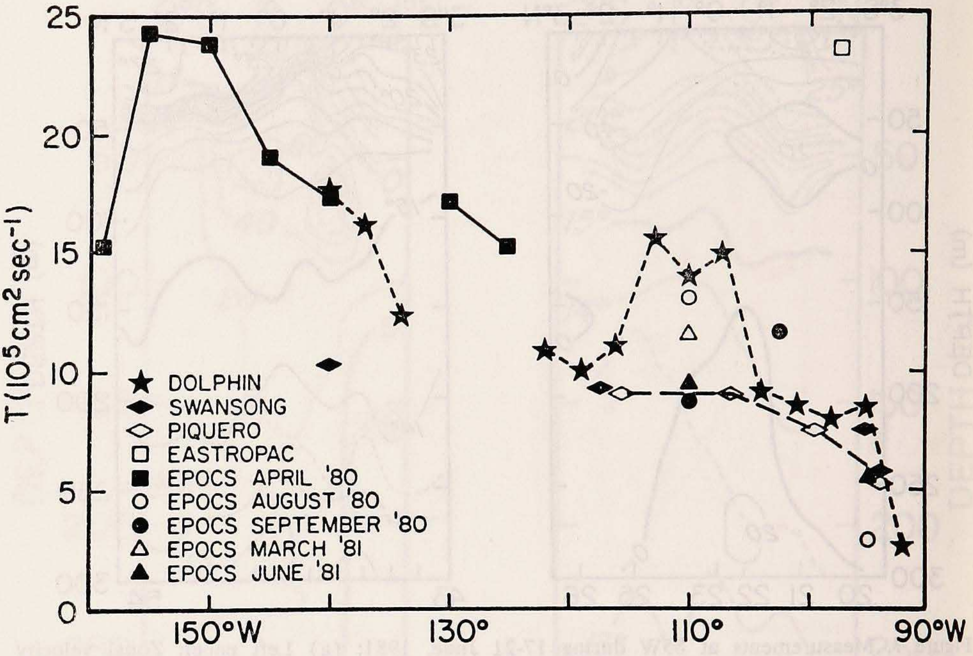

Figure 8. Transport per unit width on stations within 30 nms of the equator from all expeditions. The previous measurements were taken during: Dolphin (April-May, 1958). Swansong (Sept.-Nov., 1961), Piquero (July-August, 1969), Eastropac (April, 1968). For the EPOCS measurements the largest value within 30 nms of the equator is plotted.

same latitude band they were 1.5 and 6.5 Sv. The reduction above 16°C was 87% (almost the same as in 1980) whereas at deeper levels it was only 24%. Thus it does appear that the Undercurrent first loses its warm-water transport as it approaches the Galapagos. At 85W the net transport from 2S to 1N above 13.5°C was 7.3 Sv to the west. Hence, even the deeper transport vanished between 95 and 85W. The question arises as to where the water goes that is lost from the Undercurrent. One possibility is that it gets upwelled into the surface layers. The wind-induced upwelling can be estimated using the zonal stress values of Wyrtki and Meyers (1976). The poleward Ekman transport between 110 and 95W at 3N and 3S is about 5×10^{12} gm sec^{-1}. A comparable amount is lost out of the Undercurrent in this longitude band. However, a simple heat budget computation suggests that this water is not upwelled into the surface layers. The annual mean net heating in this area is about 100 watts m^{-2} (Weare *et al.*, 1981). Thus, the heating between 1N and 1S from 110 to 95W is 3×10^{13} watts. This is capable of heating the 5×10^{12} gm sec^{-1} that is lost out of the upper part of the Undercurrent by about 1.5°C. The bulk of this transport originally is at temperatures around 17-18°C. Surface temperatures are around 22°C. Not enough heating occurs to warm all the water from the Undercurrent to surface values. Hence horizontal recirculation to the west must be important.

Historically there has been considerable discussion of secondary maxima in eastward transport below 13.5°C in the thermostad (Stroup, 1969; Taft and Jones, 1973; Tsuchiya, 1970). Beneath the Undercurrent and extending into the deep water are zonal motions of short vertical wavelengths. These have amplitudes of order 25 cm/sec below the thermocline. Their time scale is at present unknown, but it seems to be several months or longer. In the presence of such signals, long-term velocity measurements from moorings are necessary to determine the amplitude or direction of the mean flows below the thermocline.

It is difficult to estimate from most of these sections representative values of the net transport of the Undercurrent because of the problems of incomplete meridional sampling and short-term variability. However, in 1981 the measurements at 110W extended far enough north and south to estimate the transports in both the Undercurrent and SEC. Between 3N and 3S and above 300 m the eastward transport was 26 Sv and the westward transport was 28 Sv. Thus the net transport over this latitude band was almost zero. This does not, of course, imply that all the water in the Undercurrent ends up in the SEC north of the equator. The transport field is strongly asymmetrical (Fig. 5). Eastward flow is predominantly on or south of the equator whereas the westward flow is north of it. In 1981 at 95W the eastward transport between .25N and 2.25S was 13.8 Sv. The section did not extend far enough north to estimate the transport in the SEC. The Undercurrent during this time lost about half its transport between 110W and 95W.

The shoaling and apparent extension of the Undercurrent to the south was noted by Taft and Jones (1973). Tsuchiya (1974) also discusses previous observations of the ridge in the thermocline around 2 to 4S that is associated with this eastward flow. He suggests that the ridge results from a north-south pressure gradient that is a response to the southerly component of the wind stress. The eastward velocities that pilot atlases seasonally show in this region he attributes to surfacing of the Undercurrent. Not all previous measurements show this ridge; hence, there is some temporal variability. The nonlinear dynamics that are appropriate for the Undercurrent are applicable within about a degree of the equator. Hence, the shallow eastward flow further to the south is not part of the Undercurrent.

A numerical model to study the oceanic response to southerly winds was recently reported on by Philander and Pacanowski (1981). Their results show a shallow eastward flow between 1.5 and 6S. This is related to the north/south pressure gradient that balances the meridional wind stress. The magnitude of the pressure gradient can be estimated from the relationship $h\,\partial P/\partial y = \tau$, where τ is the meridional stress and h is the depth to which it is confined. The quantity, h, is about 50 m in our data since the eastward velocities are confined to the top 50 m. At 3S the meridional stress is about .3 dynes/cm². This is the appropriate value

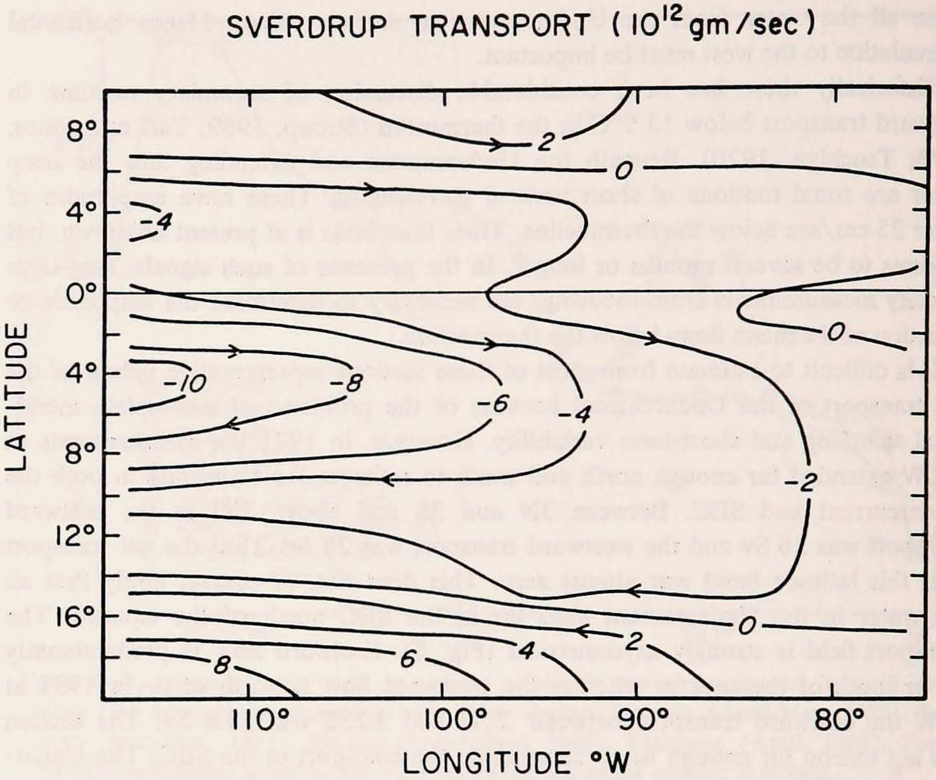

Figure 9. Sverdrup transport streamlines as computed from the Wyrtki and Meyers (1976) mean wind stress. The units are 10^{12} gm/sec.

for the annual mean as well as the monthly mean stress for August/September (Wyrtki and Meyers, 1976). A sea-level slope of .7 cm over 1° of latitude can balance this stress. The *in situ* pressure gradient can be estimated in two ways. Direct hydrographic observations during 1980 show that the dynamic height difference between 2 and 3S is 2-3 dynamic cm. This value is quite uncertain because of aliasing by higher frequency motions. Since the eastward flow is in approximate geostrophic balance, the geostropic relationship gives a second way of estimating this pressure gradient. The observed velocities are about 40 cm/sec. To balance these, a dynamic height difference of about 3.5 cm between 2 and 3S is required. This is about what was directly observed. The pressure gradient required to balance the meridional stress is about a quarter of this, hence it is unlikely that the bulk of the flow is caused by meridional winds. Another possibility is that it is part of the steady circulation caused by the mean wind field. To see if this is possible, the Sverdrup (1947) transport streamlines were computed from the mean wind stress field of Wyrtki and Meyers (1976). The computed streamline pattern shows such a feature (Fig. 9). A clockwise gyre is centered at 5S and 115W. Eastward flow of about 6×10^{12} gm sec^{-1} is located between the equator and about 4S. A rough estimate of the observed transport (see Figs. 3 and 4) is 1 gm cm^{-3} $\times$ 40 cm/sec $\times$ 50 m $\times$ 3×10^{7} cm $= 6 \times 10^{12}$ gm sec^{-1}. The agreement lends support to the idea that this flow could be caused by the curvature of the wind field. The streamline pattern shows that most of the eastward transport turns south and recirculates to the west by 90W. Sverdrup theory does not contain all the correct physics within a degree or two of the equator. Thus the Undercurrent transport of 20 to 30 Sv and how this recirculates to the west is not shown in Figure 9. It is also possible that some sort of transient dynamics might be important in the formation of this eastward flow.

Of interest also in this computation is the general southward flow across the equator. Most of these EPOCS sections show southward flow above the thermocline. However, because of the large variability it is not clear that this is true in the mean. In none of these sections was there any clear evidence for the classical meridional circulation pattern in which poleward flow in the surface layers is compensated for by equatorward flow at depth (Charney and Spiegel, 1971).

These new observations have not markedly changed our understanding of what happens to the Undercurrent as it approaches the Galapagos. As was previously indicated, the current weakens just to the east of these islands. In 1981 no substantial fraction of the Undercurrent was observed at 85W while at 95W there was about 13×10^{12} cm^{3} sec^{-1} flowing eastward. The transport is lost first from the layers above the thermocline. There is considerable short-term variability which makes quantitative statements about expedition to expedition differences impossible. This is especially true below the thermocline in the lower thermostad. The mean flow direction in this region cannot be determined from these measurements.

In 1981 there was as much eastward as westward flow within 3° of the equator at 110W. The measurements also show that a region of shallow eastward flow exists between about 1 and 3S. This is distinct from the undercurrent found further to the south (Tsuchiya, 1975). It is argued that it appears to be a response to the curl of the wind stress.

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