Equatorial Current Observations in the Western Indian Ocean in 1975 and 1976

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ABSTRACT

Vertical profiles of current, temperature and salinity were taken in the upper ocean from 3°S to 2°N along 55°30′E in the Indian Ocean during February–June in 1975 and 1976. During both years a strong O(80 cm s^{-1}) equatorial undercurrent was present throughout the measurement period in the vicinity of the equator. A second region of eastward flow above the thermocline was observed at 3°S. During May and June the undercurrent moved southward and merged with the southern region of eastward flow. The meridional flow field was dominated by transients that during strong events were antisymmetric about the equator and had a vertical wavelength of ~180 m. The transient events strongly affected the zonal flow field; during strong events the undercurrent was almost eliminated. This is in contrast to the GATE observations where the undercurrent was advected back and forth across the equator.

1. Introduction

From mid-February to the end of May in 1975 and late February to mid-June in 1976, repeated velocity and temperature sections were occupied approximately bi-weekly from 3°S to 2°N along 55°30′E in the Indian Ocean. These were taken from La Curieuse, a 68 ft native design schooner which we chartered in the Seychelles. We added for our work a generator, a hydrographic winch and a satellite navigator, which was borrowed from the Office of Naval Research. The basic measurements consisted of profiles of relative velocity and temperature made with a Profiling Current Meter (PCM) (Düing and Johnson, 1972). For some cruises in 1975 a Plessy 9060 STD was available. In 1976 a conductivity sensor was added to the Aanderra in the PCM and gross information was collected about the salinity field.

This program was one of several INDEX pilot studies that took place in the western Indian Ocean during this time. Our primary objective was to obtain an expanded time and space coverage of the equatorial undercurrent. Previous measurements were not adequate to describe during what seasons the undercurrent was present. In fact, it was not until the International Indian Ocean Expedition in the early 1960's that even the existence of an undercurrent in the western Indian Ocean was established.

The observations of the *Argo* in 1962–63 (Taft and Knauss, 1967), the *Discovery* (Swallow, 1964, 1967), the *Vityaz* (Ivanov, 1964) and the *Meteor* (Düing *et al.*, 1967) gave the first observations relating the seasonal change of wind stress to the presence of the undercurrent. These observations indicated that a somewhat weaker and more variable undercurrent than found in the Pacific is present late in the northeast monsoon. With the onset of the southwest monsoon north of the equator it becomes variable and weaker and finally disappears. Measurements by Knox (1976) at Gan (73°E) in 1973 gave a similar picture. There the undercurrent appeared in March and was present for only one or two months. During that year an easterly wind stress began at Gan in early February. In 1974 no undercurrent was observed at Gan.

In addition to the undercurrent, another type of eastward flow develops along the equator in the Indian Ocean. During the transitions between the southwest and northeast monsoons in May and October a narrow current flows eastward at high speed along the equator (Koninklijken Nederlands Meteorolgisch Instituut, 1952). This coincides with the occurrence of westerly winds along the equator. The measurements of Knox (1976) and Taft and Knauss (1967) show strong shears across the thermocline at these times with eastward flow at the surface. Wyrtki (1973) relates the occurrence of these wind-induced flows with a decrease in the thickness of the mixed layer off Africa and an increase off Sumatra. O'Brien and Hurlburt (1974)

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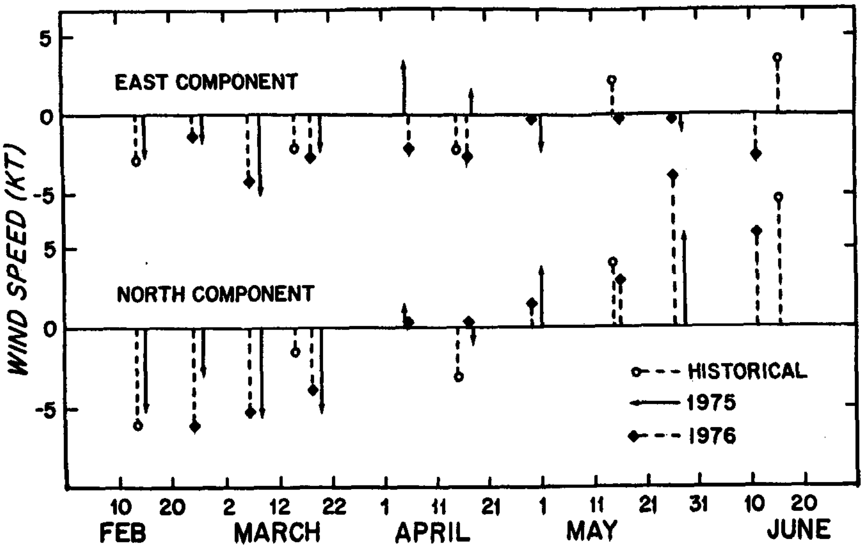


FIG. 1. Cruise averaged winds observed in 1975 and 1976.

have modeled this phenomenon and obtained about the proper width and strength for the jet.

Deep vertical profiles of horizontal current taken by Luyten and Swallow (1976) along 53°E in late May and June of 1976 indicated that the short vertical-scale jet-like structure normally associated with the undercurrent was present throughout the water column. Hence the flow at the base of the mixed layer that is usually called the undercurrent is only one of several undercurrents. Unfortunately, our instrumentation limited our sampling primarily to the uppermost one of these.

2. The data

Stations were occupied at every 30′ of latitude from 3°S to 2°N. In 1975 eight sections and 122 profiles were taken. In 1976 because of instrumentation problems only six complete sections and two partial sections were completed. A total of 150 profiles were taken. The raw data have been depth averaged. Data from all scans between the sea surface and 5 m were averaged and assigned a depth of 0 m. All data between 5 and 15 m was averaged and assigned a depth of 10 m, etc.

No calibrations, other than those which came with each Aanderaa current meter, have been applied to the temperature or velocity data. Comparisons between surface bucket temperature readings and surface values of the temperature from the PCM indicate that they agree in most cases to about ±0.2°C.

No wire angle corrections have been made to the velocity data. In regions with strong shear, hence large wire angles, experience has shown that these corrections can be of the order of tens of centimeters per second. Thus, the peak speeds that are reported for the undercurrent in this paper are probably underestimated. Estimates of the drift vectors for the profiles used in the velocity sections were made by averaging all the data from a deep level to the bottom of each profile. This vector was then subtracted from each profile. The depth below which the averaging was performed was 250 m for all the cruises in 1975 and cruises 1 and 2 in 1976 and 300 m for the remainder of the cruises in 1976. In 1976 a number of stations had two satellite fixes occur during a cast. Comparisons of the drift vectors derived from the satellite data with those obtained by using a deep average velocity as previously defined gave the following results. If eastward and northward drifts can be considered independently, 72 comparisons were available. In 37 cases the difference was 5 cm s^{-1} or less. Sixty out of the 72 lay within ±15 cm s^{-1} of one another. In such a comparison error exists in both techniques. Thus a gross estimate of the error in these velocity sections is about ±20 cm s^{-1} except where the shears are large and there the error is probably of the order of ±30 cm s^{-1}.

Two data reports have been produced which contain listings and plots of all of the depth-averaged profile data for 1975 and 1976. These can be obtained from the authors.

3. Wind observations

Historical wind data are almost nonexistent in this area (KNMI, 1952). To illustrate the transition from the northeast to the southwest monsoon (southeast south of the equator), average winds were determined for each cruise. These were obtained by vector averaging the wind observations taken at each of the stations for a given cruise. The average winds for each cruise in 1975 and 1976 are presented in Fig. 1. The times that the various cruises took place can be determined by noting the location of the wind arrows along the abscissa. Generally, a cruise took 5–6 days and the time indicated is when the equator was crossed on the northward leg.

From February through most of May the winds were light, less than 10 kt most of the time, and predominantly meridional. Winds from the north lasted until late March and southerly winds began in early May. April is the transition month between the two regimes. The winds tended to be easterly. Only in April 1975 were light winds from the west observed. Historical wind data indicates that during the transition westerlies are more persistent further to the east. In 1976 there was a strong increase in the southerly component of the wind during the last part of May. As will be seen, this seemed to have a major effect on the currents at that time. Strong northerly winds also occurred between the first and second cruises in 1975 (which we experienced in the Seychelles and hence are not apparent in Fig. 1) and similarly affected the currents.

Basically the wind fields during both years were rather similar and conform with what little historical data exist in this area.

4. Zonal velocities

a. Measurements in 1975

The first cruise took place in mid-February. At that time the large-scale structure of the zonal flow consisted of westward flow north of the equator and eastward flow south of it with westward flow at the surface extending as far south as 2°S (Fig. 2). A well-defined, rather narrow undercurrent was at ~1°S with peak speeds of ~80 cm s^{-1}. The region of eastward flow at 3°S probably represents the northward extent of the south equatorial countercurrent (KNMI, 1952). The westward surface flow just north of the equator was as strong as the undercurrent. A subsurface westward maximum O(60 cm s^{-1}) was found at 1°N at about 150 m.

The undercurrent almost disappeared between the first and second cruise (28 February). Only weak eastward flow was observed in the thermocline in the vicinity of the equator. The distribution and strength of the westward flow north of the equator remained as before. Eastward surface flow was still present between 2.5 and 3°S.

By the third cruise (9 March) a strong and relatively broad undercurrent was again observed. It extended from the equator to 2.5°S and appeared to connect to the surface eastward flow at 3°S. Its maximum lay at ~100 m which was deeper than it was during cruise 1. The strongest westward surface flows are now confined north of the equator.

Two weeks later during cruise 4 strong westward surface flows again extended southward to 2°S. The undercurrent shifted northward to the vicinity of the equator. The deep westward flow north of 1°N and the eastward flow south of 2°S appeared to be basically the same as during cruise 3.

By the fifth cruise, the meridional component of the wind was almost zero. A weak zonal component blew from the west. The undercurrent shifted back to ~1°S. Despite the westerly winds the surface currents were still to the west from 2°S to 2°N. However, their magnitude was reduced by ~20 cm s^{-1} from what was observed on the previous cruise. By cruise 6 (18 April) westward surface flow was only observed between 0 and 2°N. A subsurface maximum still existed in the eastward flow from 2°S to 1°N. The undercurrent which comprises the major part of this maximum was still centered at ~1°S. However, a band of eastward flow with velocity over 40 cm s^{-1} extended from the surface at 3°S to the undercurrent. A subsurface maximum had developed in the westward flow north of 1.5°N.

The velocities during cruise 7 were similar to those during cruise 6 except that eastward surface flow extended to 2°N and the subsurface maximum in the westward flow at 2°N had weakened. By the end of May (cruise 8) the gross flow pattern off the equator was not much different than was found during the first cruise. North of 1°N the flow from the surface to 250 m was still to the west, albeit weaker than in February. The big difference was in the surface currents. The strong westward flows from 2°S to 2°N were gone. Only weak westward flow was present from 1 to 2°N. A subsurface maximum still existed in the eastward flow south of the equator. It, however, was rather broad and extended from 3 to 0.5°S.

b. Measurements in 1976

Because of difficulties with instrumentation only a partial section from 3 to 1°S was run during survey 1 in late February. Two subsurface maxima were evident in the eastward flow (Fig. 3). One was at 2.5°S and the other at 1°S. The surface flow was westward as far south as 2°S. The flow beneath the undercurrent was westward and had a maximum at ~225 m. This maximum appears to be centered about the equator as can be seen from survey 2. During this second survey (10 March) the undercurrent was located on the equator and had peak speeds of ~80 cm s^{-1}. The surface flow was westward from 2°N to 1.5°S and had maximum values that exceeded 100 cm s^{-1}. Beneath this at 2°N the deep flow appeared to be eastward. A region of surface eastward flow was present south of 2.5°S. Cruise 3 was aborted after the first station because of winch failure. During cruise 4 a continuous band of strong eastward flow extended from the surface at 2°S to the undercurrent which was located just south of the equator. The surface flow was westward north of the equator with strong vertical shears between it and the undercurrent. The maximum in the deep westward flow beneath the undercurrent was still present.

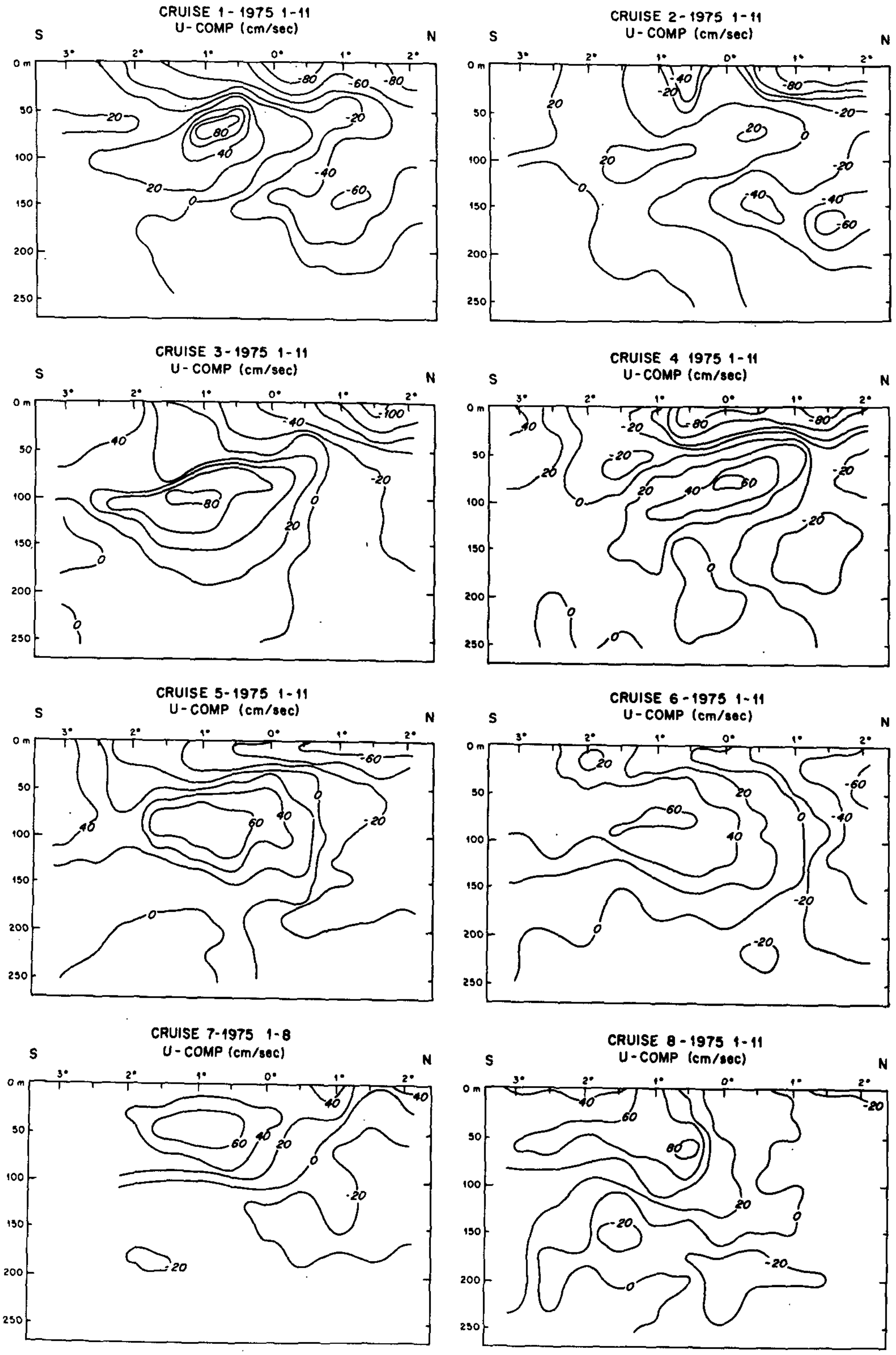
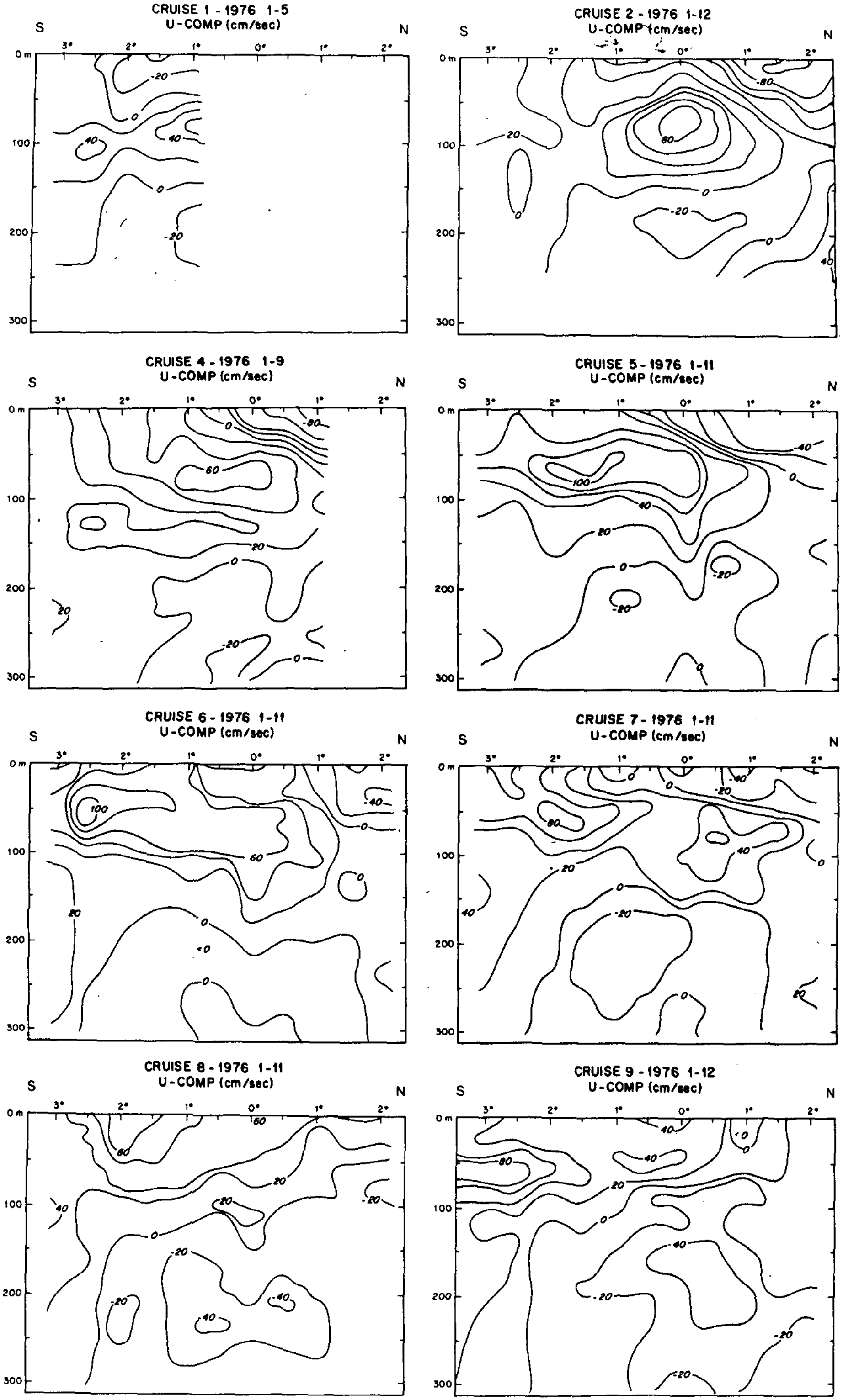


FIG. 2. Zonal flows observed during 1975. The numbers 1–11 indicate that stations 1–11 were used to contour this figures. Station 1 is at 3°S, etc. On most sections a southward section was also taken.

By cruise 5 eastward flow extended from 3°S to 2°N in the upper part of the thermocline. A strong subsurface maximum was located between 2°S and 0°. It is difficult to distinguish the undercurrent from a possible subsurface maximum in the south equatorial countercurrent. The surface flow from



CRUISE 1 - 1976 1-5 U-COMP (cm/sec)

CRUISE 2 - 1976 1-12 U-COMP (cm/sec)

CRUISE 4 - 1976 1-9 U-COMP (cm/sec)

CRUISE 5 - 1976 1-11 U-COMP (cm/sec)

CRUISE 6 - 1976 1-11 U-COMP (cm/sec)

CRUISE 7 - 1976 1-11 U-COMP (cm/sec)

CRUISE 8 - 1976 1-11 U-COMP (cm/sec)

CRUISE 9 - 1976 1-12 U-COMP (cm/sec)

FIG. 3. Zonal flows observed during 1976.

3 to 0.5°S was to the east. As during cruise 2, the deep flow at 2°N was eastward. Below ~200 m from 1°S to 1°N the flow was still westward.

The profiles from cruise 6 (1 May) were similar to those from the previous cruise. The main difference is that the subsurface eastward maximum was more limited in meridional extent and was located at ~2°S. By cruise 7 (20 May) further fragmentation of this band of eastward flow had occurred. The largest velocities were now found at the surface between 2.5 and 3°S. The velocity maximum then sank to the top of the thermocline as it extended toward the equator. An isolated eastward maximum was located at ~0.5°N at a depth of ~80 m. The deep westward maximum was located at ~1°S.

Major changes took place between cruises 7 and 8. The subsurface maximum in the eastward flow was almost completely eliminated. Instead, eastward velocities were found at the surface and extended from 3°S to 2°N with a maximum at 2°S. Also absent was the deep eastward flow between 1.5° and 2°N. The strength of the deep maximum in the westward flow located between 1°S and 1°N increased. By cruise 9 in early June, the subsurface maximum in the eastward flow returned between 3 and 1.5°S. Whether this was a remnant of the undercurrent or a subsurface intensification of the countercurrent is not clear. The deep westward maximum had further increased in size and westward flow was present at the surface again at 1 and 2°N.

c. *Comparisons between 1975 and 1976*

Although the detailed features of the flow field varied from cruise to cruise, the large-scale distribution and evolution of the zonal flows was similar for both years. Generally, the flow was to the east on and south of the equator, in the upper layers. A well-defined undercurrent was located near or south of the equator. At the southern end of our section there was a persistent eastward flow. A band of eastward flow connected the undercurrent with the countercurrent. During the transition from the northeast to the southeast monsoons the undercurrent moved southward from its position near the equator to merge with the south equatorial countercurrent. Apparently, this eastward subsurface maximum persisted into the southeast monsoon as late as August (Bruce, 1973). Thus it is difficult to state definitely when the undercurrent ceases to exist.

North of the equator the surface flow is westward. It appears to be stronger earlier in the year and frequently extends southward across the equator. Beneath this at the northern end of our section the deep flow in 1976 was to the east until early May. The contour plots of the 1975 cruises do not show this feature and instead persistent flow to the west was present. The flow in the vicinity of the equator below 150 m during both years was to the west. However, this was more symmetrically located about the equator in 1976 than in 1975.

The main differences between the two years appear to be in the magnitude of the flows. In 1976 the flows south of the equator tended to be stronger than in 1975. This was true of the undercurrent and the countercurrent. The westward shear beneath the undercurrent was stronger in 1976. Thus the deep westward flow in the vicinity of the equator at ~200 m was more prominent in 1976. The westward surface currents were stronger in 1975.

5. Meridional velocities

It is difficult to describe the evolution of the meridional velocity fields as was done for the zonal velocities. In general, the velocities are less than our confidence limits. Furthermore, the variability is large and the motion field is dominated by transients which were not resolved by our sampling. Nonetheless, it is instructive to look at a representation of these velocities. In Fig. 4 are shown the individual meridional velocity profiles for all the cruises from 3°S to 2°N in 1976. The small numbers next to each profile indicate which cruise the profile was taken on. This presentation is meant only to depict the gross features of the meridional velocity field and not the details for any individual cruise. The contoured cross sections for each cruise in 1975 and 1976 are shown in the data reports.

The mean flows are clearly small from 3°S to 2°N and not resolvable. This was true for both years.

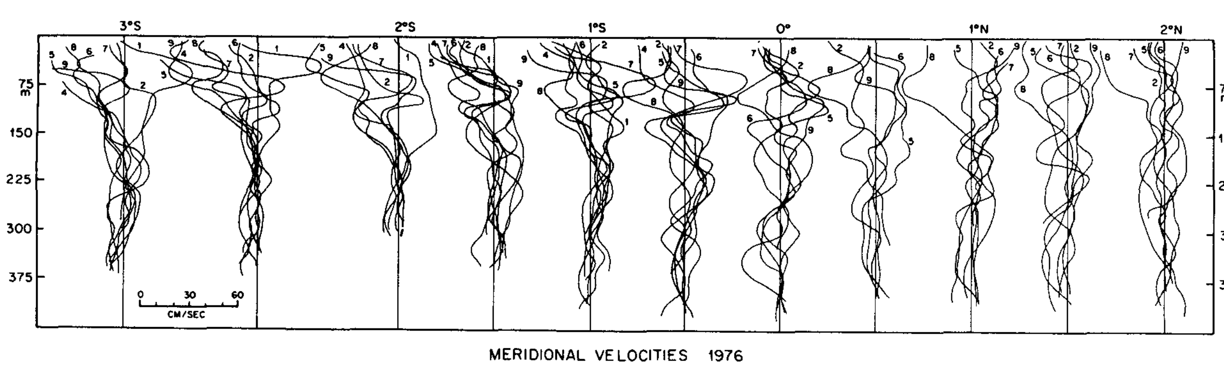


FIG. 4. Meridional velocities observed during 1976. Figure is intended to show the general structure of the flow rather than changes from cruise to cruise. The numbers alongside the curves indicate on which cruise the profile was taken.

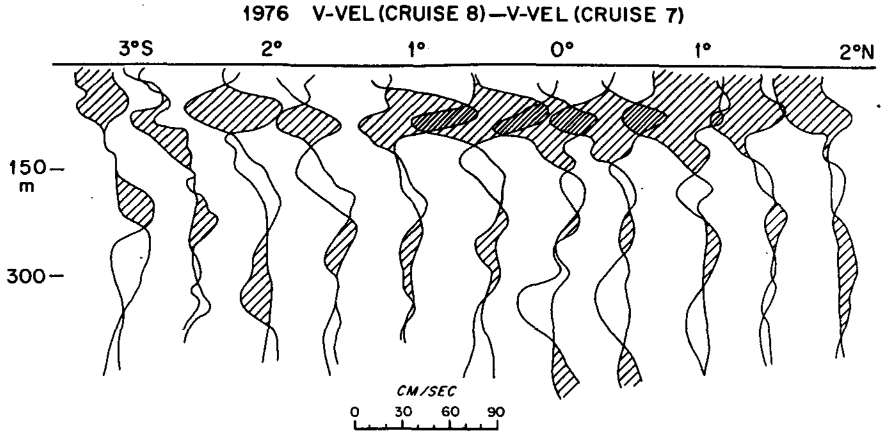


FIG. 5. Vertical structure of the meridional flow during the 1976 transient.

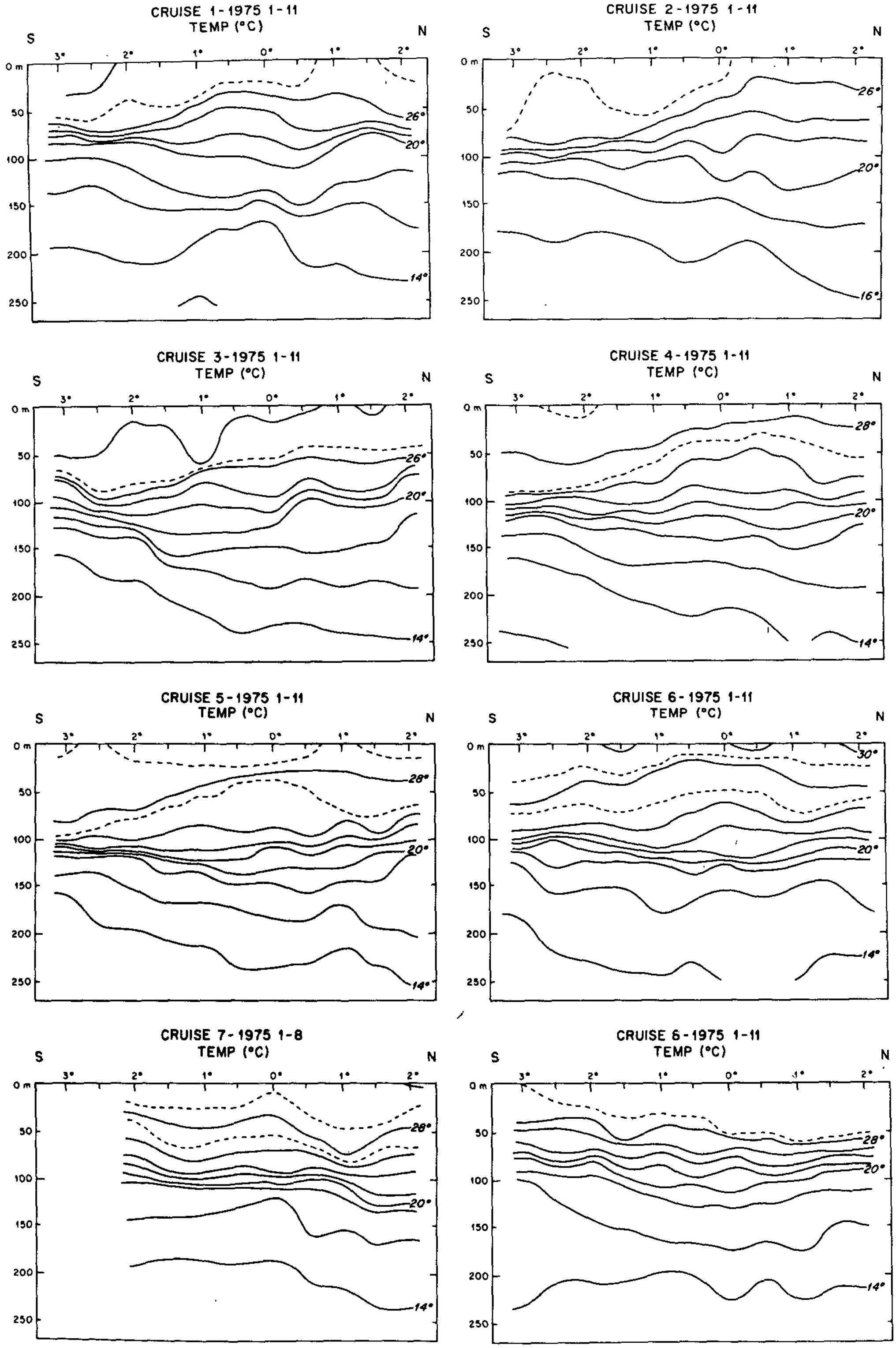
Below ~150 m, the transients have small amplitudes, and their amplitudes increase toward the surface. These tend to be larger south of the equator than north of the equator. During both years there was at least one particularly conspicuous event. In 1976 there was a strong increase in the southerly component of the wind between cruises 7 and 8. This resulted in a strong southward flow at the top of the thermocline during cruise 8. This was part of a more regular structure as can be seen in Fig. 5. Overlain in this figure are the profiles from cruises 7 and 8. The cross-hatched regions indicate where a southward acceleration has taken place and the blank areas where the acceleration is northward. These regions alternate in the vertical. The vertical wavelength is ~175 m, and about two wavelengths are visible. The oscillations are antisymmetric about the equator and appear to change their nature at ~2.5°S. Hence this may represent a node in the horizontal. However, since the Seychelles Bank is at ~3°15′S, this might also represent a topographic effect. By cruise 9 at most latitudes, the jet reversed sign. Thus a "half period" was on the order of 15 days. However, this is poorly resolved by our sampling.

During 1975 a similar event occurred after strong winds from the north after cruise 1. The main signature of this response was a strong northward subsurface flow located at the base of the mixed layer south of the equator. This again was part of a more regular structure which was antisymmetric about the equator and had a vertical wavelength of ~180 m. During this time, as was discussed in the previous section, the undercurrent almost disappeared.

6. Temperature field: 1975 and 1976

The temperature sections for 1975 are shown in Fig. 6. During the first cruise, the isotherms were spread apart in the vicinity of the equator. The region of spreading extended from 1.5°S to ~1.5°N. Hence it encompasses a larger area than the undercurrent which is located just south of the equator. The region around 1°N had the coldest water at the surface, and hence appears to be a region of upwelling. By the second cruise the thermocline became still more diffuse north of the equator. South of the equator it was still intense and deepended by ~20 m. The third cruise was similar to the second; however, there was some spreading of the isotherms at 1°S where the undercurrent had reappeared. The pattern during the fourth cruise was similar to that during the first cruise. The thermocline had again intensified north of the equator and there was a spreading of the isotherms near the equator where the undercurrent was. The patterns during cruises 5 and 6 are similar to that during 4 except that the spreading apart of the isotherms associated with the undercurrent had moved further south and decreased in amplitude. The near-surface temperatures became warmer as they normally do over the rest of the western Indian Ocean during this time (Wyrtki, 1971). By cruise 7 the spreading appeared to be completely gone as the undercurrent became shallower and less intense. During cruise 8 there again was a small amount of spreading associated with the undercurrent maximum at 0.5°S.

The sections for 1976 are shown in Fig. 7. The first section shows the beginning of spreading at 1°S with an intense thermocline to the south of 2°S. Cruise 2 showed a similar pattern south of the equator with strong spreading at the equator associated with the undercurrent. Interestingly enough, as in 1975, the thermocline north of the equator was less intense than it was south of the equator. Cruise 4 showed the thermocline to be spreading further to the south and to be more above the thermocline. The core of the undercurrent at this time was about 0.5°S and at 80 m; i.e., above the strongest thermal gradients. By cruise 5 the temperature gradient in the thermocline had decreased slightly and was


CRUISE 1-1975 1-11 TEMP (°C)

CRUISE 2-1975 1-11 TEMP (°C)

CRUISE 3-1975 1-11 TEMP (°C)

CRUISE 4-1975 1-11 TEMP (°C)

CRUISE 5-1975 1-11 TEMP (°C)

CRUISE 6-1975 1-11 TEMP (°C)

CRUISE 7-1975 1-8 TEMP (°C)

CRUISE 6-1975 1-11 TEMP (°C)

FIG. 6. Temperature sections made in 1975.

almost uniform from 3°S to 2°N with some spreading above the thermocline at 1°S. Cruises 6 and 7 were similar to 5 with perhaps a slightly stronger thermocline south of the equator and a deepening of the isotherms from 3°S to 0°. By cruise 8 the thermocline had uplifted south of the equator and

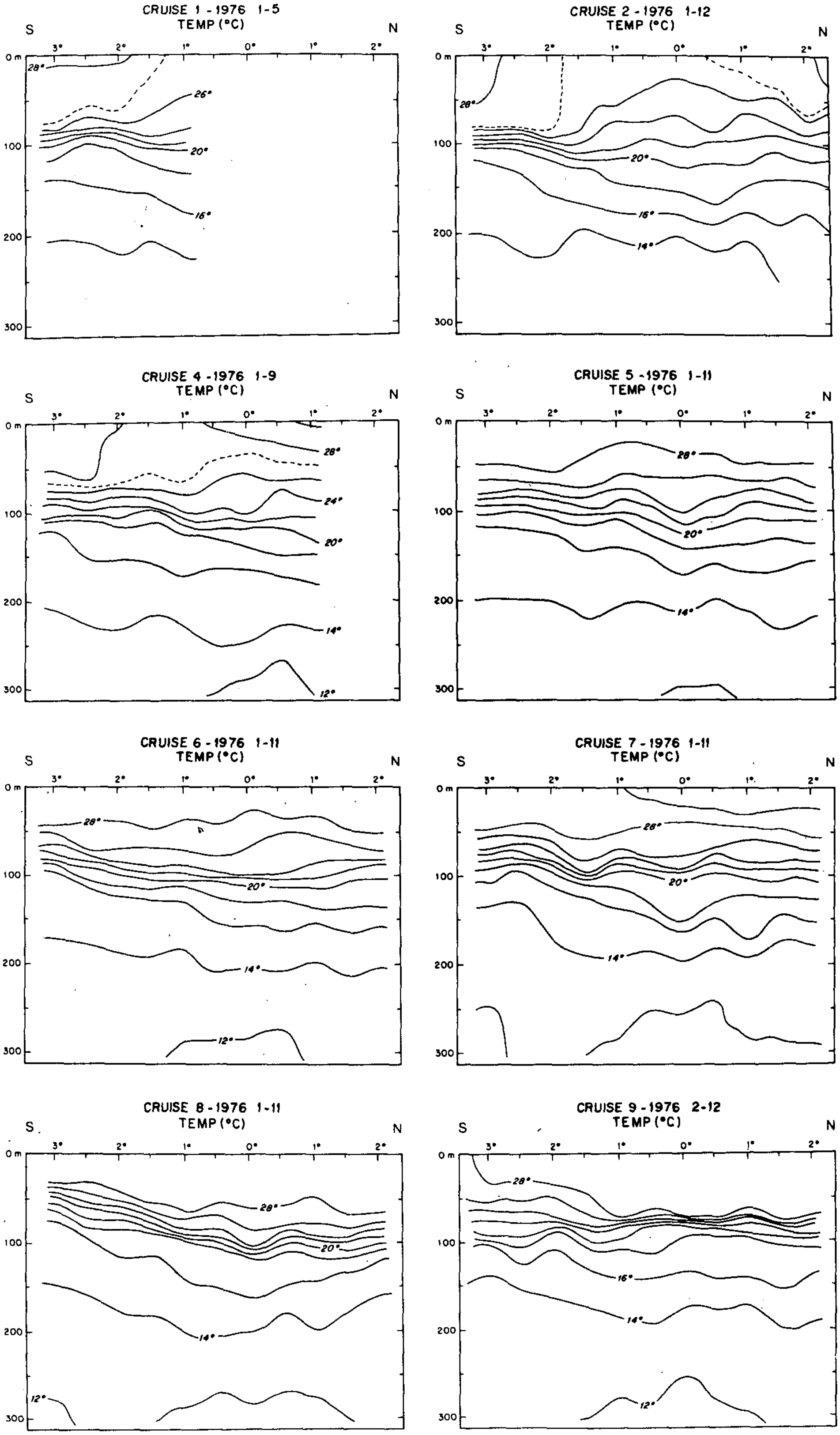


FIG. 7. Temperature sections made in 1976.

further intensified north of the equator. This intensification continued until cruise 9 during which from 1°S and 2°N the thermocline was very strong. There appeared to have been some spreading apart of the isotherms at the southern end of the section. Although there was a spreading apart of the isotherms in the vicinity of the undercurrent, this spreading cannot be used to infer unambiguously the location and/or intensity of the undercurrent. Correspondence between the spreading and the undercurrent core works best during February and March while the latter is best developed and lies in the thermocline. From April onward, when the region of strongest eastward flow moves southward and lies slightly higher in the water column, the correspondence becomes weaker. Even in February and March, the thermocline is much weaker north of the equator (than south of the equator), as is illustrated best by the section for the second cruise in 1975. The reverse of this seems to occur during May and June as is evidenced by the last cruises in 1975 and 1976.

The north–south variation in the intensity of the vertical thermal gradients —away from the undercurrent— might be related to patterns of upwelling and downwelling caused by a meridional wind stress as described by Cromwell (1953). During the northeast monsoon one might expect upwelling north of the equator and downwelling south of it. The reverse of this would be true when the winds became southerly. Downwelling would produce a convergence in the mixed layer and hence deep mixed layers associated with a strong thermocline beneath it. The reverse of this would be true for upwelling.

During the last six cruises in 1976 the 12°C isotherm bows upward symmetrically with respect to the equator. This probably is associated with the westward flow that was observed during this time beneath the thermocline (Fig. 3). Similar temperature structure was not observed during 1975.

7. Discussion

One puzzling aspect about the vertical structure of the transient motions was the large vertical shears in the meridional velocity in the mixed layer, i.e., in the top 50 m (Fig. 5). If these motions represent the transient response of a baroclinic equatorial ocean to an impulsively started wind stress and the response can be described as a superposition of baroclinic modes (Lighthill, 1969), then in regions where the density is uniform there should be no vertical shear. Hence the shear in the mixed layer cannot be ascribed to any of the baroclinic modes. One factor that can support shear in the mixed layer is viscosity. Upon seeing these observations, D. W. Moore (private communication) studied the transient response of a model that has a homogeneous, viscous mixed layer overlying a stratified interior. The response in the mixed layer can be decomposed into two parts: a part, u', in which the velocities are a function of depth, have no net transport, and are confined to the mixed layer, and a u field which is independent of depth in the mixed layer. The solution for the latter field (with a stratified interior beneath the mixed layer) is obtained in the same way that Lighthill (1968) did where the forcing is the stress distributed as a body force throughout the mixed layer. The solution for the u' field is that of a viscous spinup problem with rotation. Off the equator the steady solution becomes Ekman layers with the adjustment time being the local inertial period. On the equator the solution becomes a Couette flow with a viscous diffusion time scale of about $D^2/2\gamma$, where D is the mixed layer depth and γ the vertical viscosity.

The boundary conditions for this solution are the applied stress at the surface and zero stress at the base of the mixed layer. A fictitious pressure gradient of the form τ^y/D must be added to these equations so that when the total solution for the $u' + u$ field is considered this term drops out of the combined equation. The steady solution on the equator is Couette flow in the presence of the pressure gradient τ^y/D. For a northward stress τ^y this solution is

$$V = \left(\frac{\tau^v}{\rho\gamma}\right)\left(\frac{z^2}{2D} + z + \frac{D}{3}\right).$$

For a stress of 0.25 dyn cm^{-2}, a mixed layer depth of 60 m and an eddy viscosity of 10 $\mathrm{cm}^2\ \mathrm{s}^{-1}$, the surface velocity $(\tau^y/\rho\gamma)(D/3)$ is $\sim$50 cm s^{-1}. This was the magnitude of the velocity that was observed. The adjustment time $D^2/2\gamma$ to arrive at this solution is about 20 days which although a bit too long is not unreasonable. The total solution, of course, includes the effects of the baroclinic adjustment which is not considered here. Although this simple model seems to explain some of the features of the observations, it doesn't go far enough. For example, the structure in the mixed layer seems to be only half a wavelength of a motion that penetrates much deeper in the water column. What determines this wavelength? The Lighthill (1968) solution would put most of the energy into the first baroclinic mode that has a much larger wavelength. Does the depth of the mixed layer in fact determine the wavelength of the response?

Another interesting aspect about the transients is the strong effect they have on the undercurrent. Both in 1975 and in 1976 the undercurrent was almost completely eliminated during these events. In the Atlantic during GATE the transients appeared basically to advect the undercurrent back and forth across the equator with a period of about 16 days

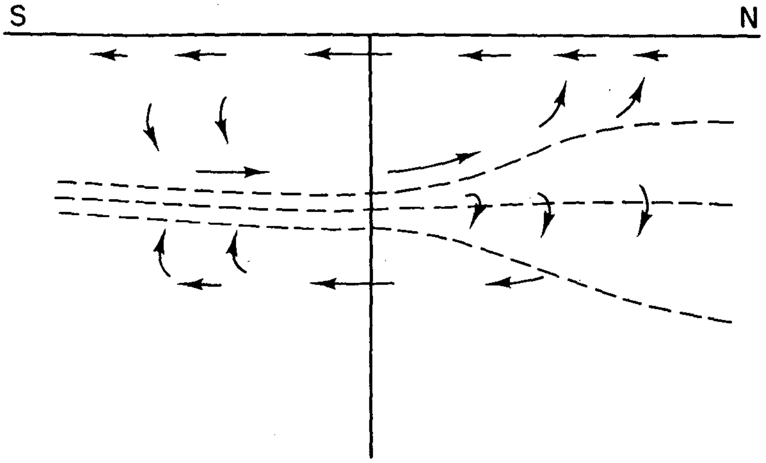


FIG. 8. A schematic illustration showing the relationship between the meridional motion field of a transient caused by wind from the north and the temperature field which is represented by the dashed lines.

(Hallock, 1977). This suggests that the waves in the Atlantic were basically horizontal nondivergent, whereas in the Indian Ocean $\partial w/\partial z$ might be of importance. There is some evidence from the temperature field that $\partial w/\partial z$ was important during events that were observed. If the divergence were solely in the meridional plane, then for northward flow in the thermocline north of the equator the vertical velocity field is such as to spread apart the thermocline. South of the equator the temperature gradient would be enhanced. A schematic illustration of this is presented in Fig. 8. For southward flow in the thermocline, the reverse of this would be true. In 1975 the first of these cases was observed, and in 1976 during cruise 8 the reverse was observed. Between cruises 1 and 2 in 1975 the isotherms spread apart north of the equator. South of the equator, however, there was no obvious strengthening of the thermocline. In 1976 between cruises 8 and 9 the thermocline north of the equator was enhanced and there was some tendency for spreading apart of the isotherms south of the equator. Thus the temperature observations qualitatively support this divergence pattern.

The persistent flow pattern during both years consisted of eastward flow south of and westward flow north of the equator. The eastward flowing undercurrent was present near the equator during the end of the northeast monsoon and it moved southward with the onset of the southeast monsoon to merge with the south equatorial countercurrent. Beneath the thermocline at the equator the flow tended to be to the west. This westward flow was more persistent and stronger in 1976 than in 1975. The reason for this is unclear. However, the undercurrent appeared also to be a bit stronger in 1976 so that if the westward flow beneath it is part of a general zonal current system then it might also have been expected to be stronger in 1976.

Wyrtki (1973) describes the presence of a surface eastward jet that appears along the equator during the transition between the northeast and southwest monsoons. At the location of our measurements, during neither year were there persistent or strong westerlies during this transition. Although eastward surface flow did develop close to the equator, it is clear from Figs. 2 and 3 that this resulted more from a weakening of the shallow westward surface flow close to the equator and a gradual increase in the eastward flow south of the equator than the development of a new jet along the equator. The "Wyrtki" jet might develop further to the east where historical data show the westerlies to be stronger.

It has been suggested that the equatorial undercurrent is driven by a west-to-east pressure gradient along the equator (see, e.g., Philander 1973). This presumably owes its origin to easterly winds in the equatorial zone. During February and March of both years the wind had an easterly component. Historical data suggest that the magnitude of this increases further to the west of 55°E. During the Northern Hemisphere summer, the winds south of the equator continue to have an easterly component (north of the equator they develop a westerly component). Perhaps this is why the undercurrent moves south of the equator during the southeast monsoon. Nonlinear numerical computation by Cane (1975) and Charney and Spiegel (1971), which are forced by a southeast wind, indicate that in the steady state the undercurrent moves southward or "upwind." However, an analogous upwind shift to north of the equator was not observed during the end of the northeast monsoon in February and March. Throughout this time the undercurrent was located primarily south of or on the equator.

A consistent picture emerges about the existence and location of the undercurrent in the western

Indian Ocean between February and September. The undercurrent appears to be well established in the vicinity of the equator by the end of the northeast monsoon. Our measurements at 55°30′E in mid or late February confirm this as well as those of Swallow (1967) at 58°E during late March 1964, Ivanov (1964) in February 1961, and Taft and Knauss (1967) at 61°E during mid-March 1963. The exception is the measurements of Düing *et al.* (1967) at 58°E during the end of January 1965. They found no evidence of eastward flow above 100 m from 3°S to 2°N. Thus either the undercurrent sets up extremely quickly (from mid-January to mid-February) or 1965 was an unusual year.

During the transition to the southeast monsoon the undercurrent shifts southward. At 58°E during early June 1964 Swallow (1967) found a strong undercurrent located between 1°S and 2°S. The present measurements indicate that a similar shift occurred in 1975 and 1976. Taft and Knauss (1967) found an eastward jet at 1°S during mid-August 1962 at 62°20′E. However, no eastward flow was present in their direct current measurements at 53°E in early August 1962 between 2°S and 2°N. Evidence from their hydrographic measurements that eastward flow might have been present between 2 and 4°S at this location during this time is presented by Bruce (1973). Bruce also finds the undercurrent shifted south of the equator in two other sections in late August and early September. In 1964 at 55°E it was located between 1 and 2°S while in 1970 at 51°E it was located at 2°S.

The observations pose an interesting question. At what latitude does an undercurrent cease to exist and become a countercurrent? Is there an essential difference in the physics of these two phenomena?

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