northeast monsoon, the winds are from the northeast; however, a northeast current flows to the northeast.

During the northeast monsoon, the zone separating northeastward oceanic flow from southwestward oceanic flow is located, on the average, at 2°S (*2, 3*). At about 1°S, the reversal from southwestward to northeastward flow has typically been observed in mid-April (*4, 5*). In these earlier studies, the northern extent of the reversal was not observed. We found that the flow to the northeast extended to at least 1°N by the end of April 1979 (Fig. 1A). Thus the current was in the transition period between the northeast and southwest monsoon conditions.

The reversal of the Somali Current along the African coast did not occur as a continuous intrusion of northward flow to more northerly latitudes. The salinity field suggests that the separation zone migrated back southward some 100 km to the equator during late April. Then, about 2 weeks later, the northeast current continued northward and separated at about 3°N (Fig. 1B). The separation zone remained there through the end of May (Fig. 1C). The rate of northward movement of this zone was about 24 km/day during early May. Further northward movement to 4°N occurred by June or July (Fig. 1D). The offshore flow was characterized by unusually high current velocities, which increased from 200 cm/sec in mid-May to 350 cm/sec in mid-July. At a location 350 km offshore, the *Iselin* measured current speed at 370 cm/sec. The nearshore region north of the separation zone had abnormally low sea surface temperatures and a very high content of nutrients and plankton.

The Somali Current advects low-salinity surface waters. The boundary of surface waters with salinities < 35 per mil moved north and east as the separation zone of the current moved north. The eastern boundary of the low-salinity water was observed at 45.5°E during late April (Fig. 1A), suggesting that after separation from the coast near the equator, most of the Somali Current turned clockwise southward.

In mid-May, only a portion of the low-salinity water turned south, at 47.5°E (Fig. 1B). Another portion continued northeastward to north of 2°N. The late May (Fig. 1C) current vector and salinity distributions are similar to those of mid-May near the equator, and suggest that not all of the Somali Current flows to the northeast after separation—some recirculates back to south of the equator in a clockwise turn, as in April (Fig. 1A).

In late May, salinities > 35 per mil were measured along the southeastern boundary of the low-salinity region (Fig. 1C). The flow along this boundary was to the east and south. The trajectory of a buoy launched at 0°30′S, 49°E on 13 May (Fig. 1B) indicates that the southward motion extended to at least 6°S before reversing (Fig. 1C). The surface salinities and buoy trajectory in June and July (Fig. 1D) show that a large portion of waters with salinities > 35 per mil is entrained into the boundary current. Prior to June, the boundary current salinities were < 35 per mil.

The temporal evolution of the clockwise gyre north of 6°N was observed for the first time in 1979. The flow between 5° and 9°N was to the north in mid-May (Fig. 1B). Data collected earlier showed northeastward flow at these latitudes in February and March 1979. This flow has been observed during other periods of northeast monsoon flow (*6*).

Offshore of the coastal currents between 6° and 10°N, the flow in mid-May was predominantly to the east. There is no evidence of a strong circulation pattern (Fig. 1B). By late May, some onshore flow was observed at 6°N (Fig. 1C). A well-developed gyre was established only by late June (Fig. 1D), with onshore flow at 5°N and a separation zone at 10°N.

The four charts show the one constant feature of the wind field, a wind speed maximum north of 4°N. Although weak in April, it strengthened continuously, reaching 30 knots in July—up to 40 knots near 8°N, 51°E. Since the northern eddy spin-up paralleled the evolution of the wind maximum, it is likely that the gyre is generated by the local wind. There is no indication that it drifts to this position from the south, as predicted in some numerical models (*7, 8*).

The two separation zones observed in 1979 occurred at different latitudes from those seen in 1964 (*9*) and 1975 (*10, 11*). These year-to-year differences may be related to differences in the wind field, but at present the relation is not clear. During 1979, wedges of cold water were observed inshore of the separation zones at 4° and 10°N. Similar wedges at different latitudes were seen in satellite images in 1966 (*12*), 1969 (*13*), and 1976 (*13*), but apparently not in 1977 and 1978 (*13*). Further study of historical sea surface temperatures and a modest program of monitoring the current should clarify these year-to-year differences in the ocean's response to the monsoon.

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Subsurface Circulation in the Somali Current

Abstract. *Direct velocity measurements were made at intermediate depths along the East African coast from March to July 1979. Strong time-dependent flows with multiple reversals in direction were found in the upper 1000 meters between 3°N and 4°S. At 700 meters, there may be a connection between the southwestward coastal current and an equatorial jet observed at 49°E, the latter turning south near the coast. North of 3°N little spatial organization of the flow can be recognized.*

Little is known about the circulation at intermediate depths (200 to 2500 m) in the western Indian Ocean. Indirect techniques, such as tracing salinity or oxygen on density surfaces, suggest a complicated interleaving of high-salinity, low-oxygen water originating from the north with relatively fresh, high-oxygen water from the south (*1*). Few direct measurements have been made. A small

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number of Swallow float and current meter observations taken by Swallow and Bruce (2) late in the southwest monsoon of 1964 indicated that there are energetic flows at depth. However, their directions were variable and no clear organized circulation pattern was discerned. In contrast, recent observations of vertical profiles of horizontal current along 53°E close to the equator revealed the presence of persistent zonal flows that reversed with depth (3): there was a pronounced westward jet at about 700 m. The role of these equatorial flows in the near-coastal circulation of the Somali Basin is unclear.

During the spring and summer of 1979, an international oceanographic experiment called the Indian Ocean Experiment (INDEX) was conducted in the western Indian Ocean to study the response of the currents to the transition in the monsoonal winds. A special effort was made to observe the structure and evolution of the flow at intermediate depths. The techniques for doing this varied among ships. The *Researcher* measurements reported here were taken with an acoustically tracked dropsonde (4) from the surface to close to the bottom or to 2500 m. The University of Miami investigators on the *Columbus Iselin* used a profiling current meter (PCM) (5). Profiles were restricted to the top 600 m of the water column, and the ship's drift over the bottom was determined by ranging on acoustic beacons deployed at the bottom. Subsurface velocity data from the *Discovery* were obtained by Swallow floats at 700 and 2000 m during May and June and by the PCM (0 to 700 m) during June only. Moored current meter data were also obtained during both months.

Although some velocity data at intermediate depths were gathered from early March to late July, the most complete spatial coverage occurred in May, when all three ships were working simultaneously. Figure 1 shows the velocities at around 700 m for 10 May to 4 June. The *Columbus Iselin* measurements extended to only 600 m, but are included here because there was little shear between 600 and 700 m. In any case, the bulk of the measurements, especially south of 3°N, were made by the *Researcher* and the *Discovery*. The 700-m level was chosen for data analysis for two reasons. Close to this depth throughout the Somali Basin is a salinity maximum from water overflowing from the southern end of the Red Sea (1). This permits traditional tracing methods to be employed in inferring circulation. Second, the westward equatorial jet at this depth was found in May and June 1976 and was expected to be present during INDEX.

Calculations have been made of the transverse correlation length scale of the 700-m velocity field (90 ± 20 km) and the root-mean-square magnitude (18 cm/sec) (6). These values are intermediate between those for the 2000-m velocity field (50 ± 15 km and 10 cm/sec) and those for the surface field (160 ± 40 km and 85 cm/sec). Given the spacing of the observations—varying between 20 and 200 km—one can expect only the surface flow to be well mapped by the data.

Figure 1 shows that at 700 m, the organization of the flow field north of 3°N is indeed poorly revealed by the scale of the observation program. Between 7° and 9°N there may be an anticyclonic circulation such as that found by Bruce and Volkmann (7) in the same region, but measurements in June by the *Discovery* fail to confirm this conjecture. In contrast, south of 3°N a coherent coastal current is evident flowing southwestward at least as far as 4°S. This flow is the most striking feature of the 700-m current measurements, but even within it strong time variability can be recognized.

Superimposed on the velocity measurements in Fig. 1 are the 750-m temperatures measured by expendable bathythermographs and conductivity-temperature-depth probes along the ships' tracks. They mirror the structure of the velocity field. North of 3°N, the temperature shows no mappable feature, but south of this latitude the coastal current is revealed as a band of warm water with temperatures greater than 9°C. It terminates somewhere between 2° and 4°S. The extent and strength of the current, 750 km and 25 cm/sec, which yield a transit time of 30 days, confirm the importance of time variability.

Researcher measurements made from 10 May to 4 June reveal a systematic weakening of the southwest flow. Indeed, north of the equator the flow reverses. On the eastern side of the section at 2.5°N, the reversal to the northeast begins in early April; the northeastward flow gradually spreads westward until by the end of May the reversal is almost complete. This is shown by the dashed arrows in Fig. 1. South of the equator the southwestward flow weakens with time, but is still well defined at 2°S in mid-June.

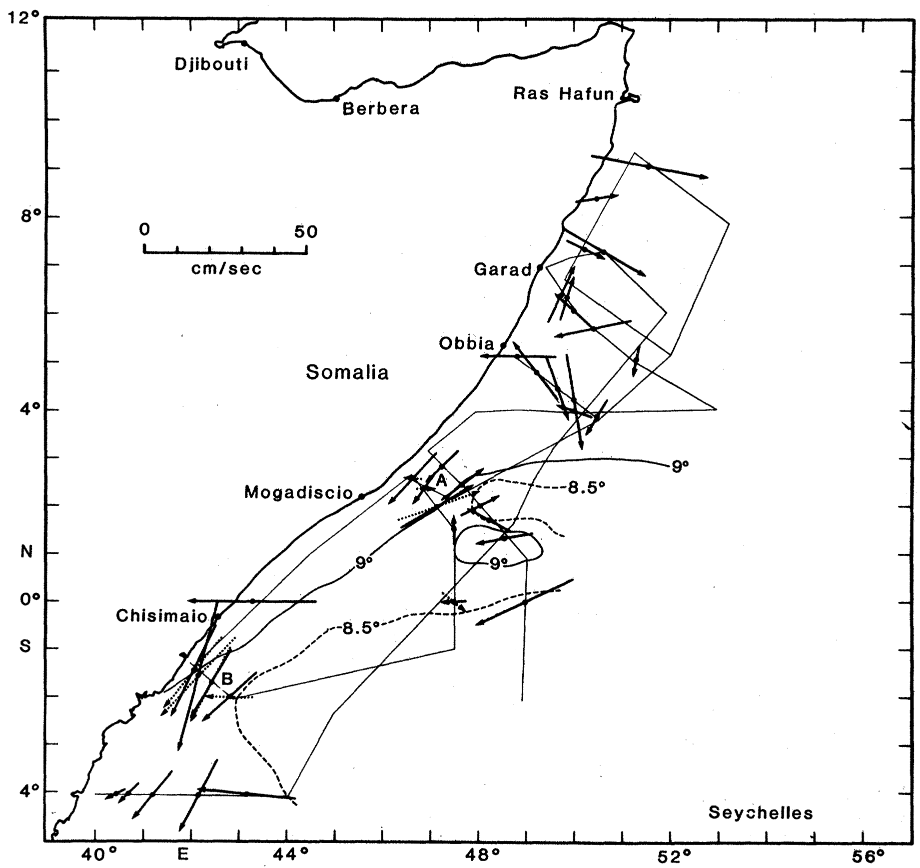

Fig. 1. Flow velocities at 700 m between 10 May and 4 June 1979. The solid arrows at 1.5°S and 2.5°N indicate data taken between 16 and 22 May; the dashed arrows represent data taken between 26 and 31 May. The light line illustrates ship tracks along which temperature data were obtained.

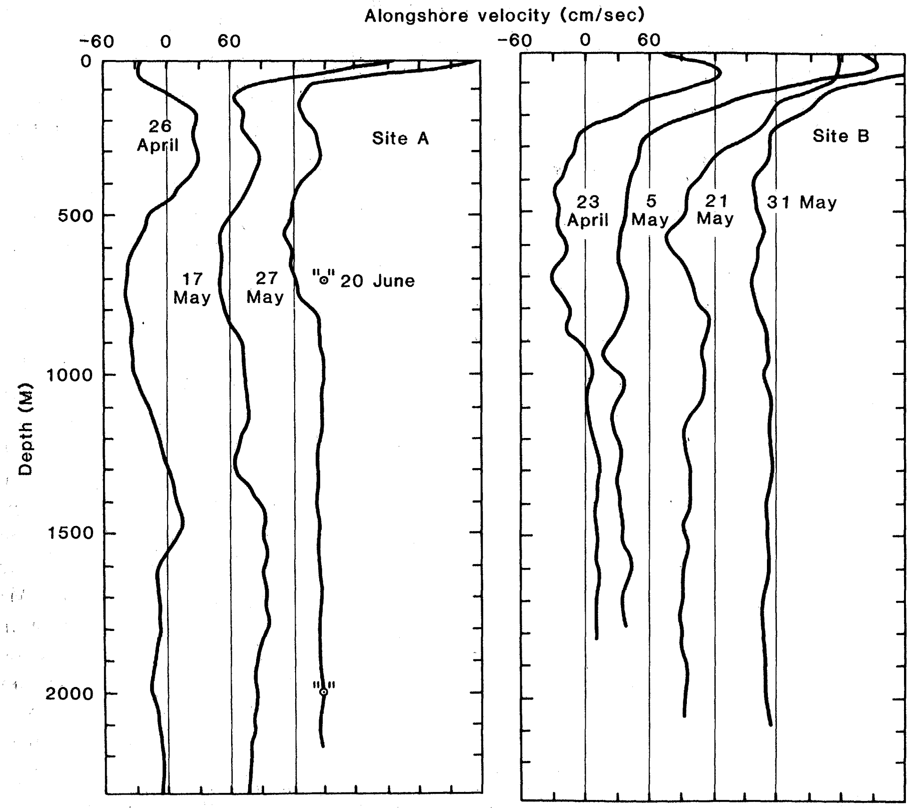

Fig. 2. Alongshore velocity profile data taken at sites A and B (shown in Fig. 1). The zero for each consecutive profile has been shifted 60 cm/sec to the right of that for the previous profile. The dots in A indicate velocity estimates made with Swallow floats. The zero for these data is the same as that for the profile for 27 May. These velocity profiles were obtained by using the Pegasus.

The vertical structure of the flow and its time evolution at sites A and B are shown in Fig. 2. North of the equator at site A in late April the surface flow was to the southwest, as might have been expected from historical data (*8*). Hence the surface Somali Current had not yet reversed at this location. Beneath this shallow southwestward flow, from about 150 to 450 m, was a pronounced northeastward flow. The other stations in this section show it to be concentrated next to the coast. Similar vertical structures were observed by the *Columbus Iselin* in mid-March about 140 km to the northeast of this location, indicating that the structure was present at least during the latter part of the northeast monsoon. Stations farther north did not show this feature. Beneath the northeastward flow (Fig. 2A), the flow was to the southwest with a peak speed of about 40 cm/sec. The horizontal structure of this flow is shown in Fig. 1. As noted earlier, at this location southwestward flow is replaced by northeastward flow during mid-May. The northeastward flow becomes remarkably uniform with depth in the deep water, as seen from the 27 May profile. The points next to this profile indicate the velocities that were measured by the *Discovery* with Swallow floats at 700 and 2000 m about 65 km to the northeast of this location in late June. The amplitude of the flow has remained about constant, but the uniform section extends closer to the surface.

South of the equator at site B, the surface flow was northeasterly at about 2 m/sec in late April (Fig. 2B). It again came as a surprise to find beneath this a flow reversal with depth. Below about 250 m the flow was to the southwest. The remarkable feature of these profiles is that despite the strong surface flow, the integrated transport is to the southwest.

The profiles north and south of the equator are distinctly different. South of the equator, the pronounced subsurface northeastward jet from 150 to 470 m is absent. The northeastward surface flow extends to about 250 m, and the flow reverses to the southwest below this. Also, this southwestward flow is more depth-limited in late April than it is north of the equator. During mid-May the deep northeastward flow that develops north of the equator is absent south of the equator. The northeastward flow develops in late May and even then only at the outermost station.

At 49°E on the equator, PCM measurements by the *Discovery* reveal the structure of the 700-m equatorial jet in June, and floats demonstrate its existence in May (Fig. 1). At times this flow can penetrate to the coast, as evidenced by the strong westward flow measured by the *Columbus Iselin* at 0°, 43°15′E. The water at this depth in the jet has temperature and salinity characteristics during the time that are found nowhere north of 3°N nor along the coast, so the jet must turn south of the equator or, if north, must recirculate south of 3°N. Since the temperature and salinity characteristics of the southwestward coastal current are the same as those of the water north of 3°N, the equatorial jet generally cannot penetrate to the coast. Is the equatorial current steered by the orientation of the coastline? How does the weakening of the coastal flow and its reversal north of the equator fit into this description? And what determines the vertical structure of the coastal current? These and related questions will be explored through the wealth of material gathered in this program, and will, we hope, stimulate theoretical investigations of the response of the deeper ocean.

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