Development of the Subsurface Currents of the Northern Somali Current Gyre from March to July 1979

Abstract. *Measurements from March to July 1979 by current meters moored between the shelf and the deep sea from 5° to 8°N show that there was shallow (< 150-meter) coastward and northward circulation between 6° and 8°N long before the onset of the southwest monsoon. After the onset, a powerful coastward flow developed offshore around 6°N, branching into northward and southward flows at the continental rise while the current deepened to more than 250 meters. There seemed to be a separate circulation on the shelf with some counterflow to offshore. All current records show that there were strong fluctuations with periods of 3 to 6 days.*

Recent work has shown that the Somali Current, at least in the early stages of the southwest monsoon, is not a continuous boundary current from south of the equator to 10°N, as is presented in the textbook maps of ocean currents. Instead, the circulation along the East African coast is characterized by a sequence of two gyres that can differ in size from year to year (*1*). During the Indian Ocean Experiment (INDEX), the development of the shoreward part of the northern gyre and the zone separating both gyres were studied at depths ranging from 80 to 720 m by an array of six current-meter moorings (M1 to M6) deployed at the shelf and continental slope off Somalia in March 1979 and retrieved in July by the *Columbus Iselin* (Fig. 1a). The water depths at these stations ranged from 180 m (M5) to 2500 m (M4). One mooring (M6) was put on the top of a seamount, which extended from a water depth of 4000 m up to 1800 m. An additional mooring (M7) was deployed at 2°20′S in 1000 m of water off Kenya, at a site where we already had a mooring in 1976 (*2*). Besides the current-meter moorings, two wind-recording buoys (W1 and W2) (Fig. 1a) were moored in shallow water, and one additional temperature recorder was installed at Ras Hafun.

In addition to this array, four moorings were deployed between 17 and 28 May from the *Discovery*. Three of the positions (273 to 275) are shown in Fig. 1a; the fourth was located farther to the south. Each was moored for about 1 month. However, the joint recording interval was only about 3 weeks. The depths of these instruments were about 300, 600, 900, and 2200 m (*3*).

The wind recordings at W1 and W2 were only partly successful in the rough environment. The northern station (W2) yielded a good record until 8 June (Fig. 2a) and showed that, although the direction of the wind stabilized after 8 May, its speed remained low until early June. At the southern station (W1), the direction sensor was lost in early May and the whole instrument mast on 10 June. The wind speed record there shows two phases of stronger winds around 16 and 26 May and then a gradual increase after 5 June. Hence both wind records suggest a "multiple onset" of the monsoon but are too limited to reflect the complete development of the monsoon. Also, local effects (for example, sheltering through high coastal cliffs) may be of importance in judging these records from near the coast (*4*).

The development of the northern gyre from March to July 1979 is shown in Fig. 1, b to k, for three depth ranges. To eliminate a substantial fraction of the powerful fluctuations (Fig. 2b), we present 20-day averages and then 10-day averages.

Currents at 80 to 130 m. In March, long before the onset of the monsoon, there was a quite steady northward current at 80 m at M2 (Fig. 1b and Fig. 2a); but 50 m deeper the currents were much weaker and fluctuated more, with a small net coastward component. Overall, in the months before the monsoon's onset, there was a clear change in the current pattern at 110 to 135 m between 5° and 7°30′N: the two northern stations (M3 and M4) recorded no southward flow at all (*5*). At the southern end of the coastal array (M1), there were prolonged phases of northward or southward flow. At M6, the flow was mostly coastward or northward; M2 recorded a rotation from northward at 80 m to mostly coastward at 135 m.

After the monsoonal onset (Fig. 1, g to k), the current at M6 increased in velocity to about 50 cm/sec coastward (*6*). At M4 the northward current strengthened, and at M1 the current was south to southeast; that is, it had an offshore component. At M2 the current turned toward the coast at 80 m, with a southward component in the onshore flow at 135 m. There is also an indication that the zone of onshore flow migrated to the north and reached M4 in late May or early June (Fig. 1, f and g), but moved back south toward M6 as the monsoon progressed.

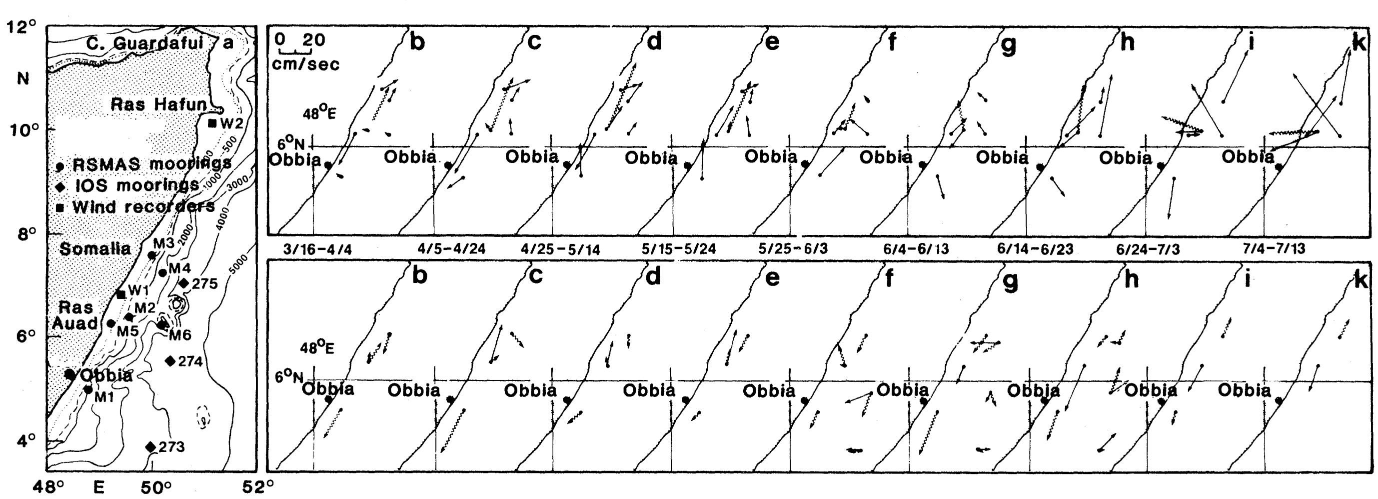

Fig. 1. Current distributions for different time periods and depths. (a) Topography and mooring locations. (Upper panel, b to k) Currents at 110 to 135 m (straight arrows) and at M2 (80 m) (wavy arrows). (Lower panel, b to k) Currents at 230 to 370 m (wavy arrows) and at 700 to 900 m (straight arrows). Acronyms: *RSMAS*, Rosenstiel School of Marine and Atmospheric Sciences; *IOS*, Institute of Oceanographic Sciences.

 0036-8075/80/0801-0593$00.50/0

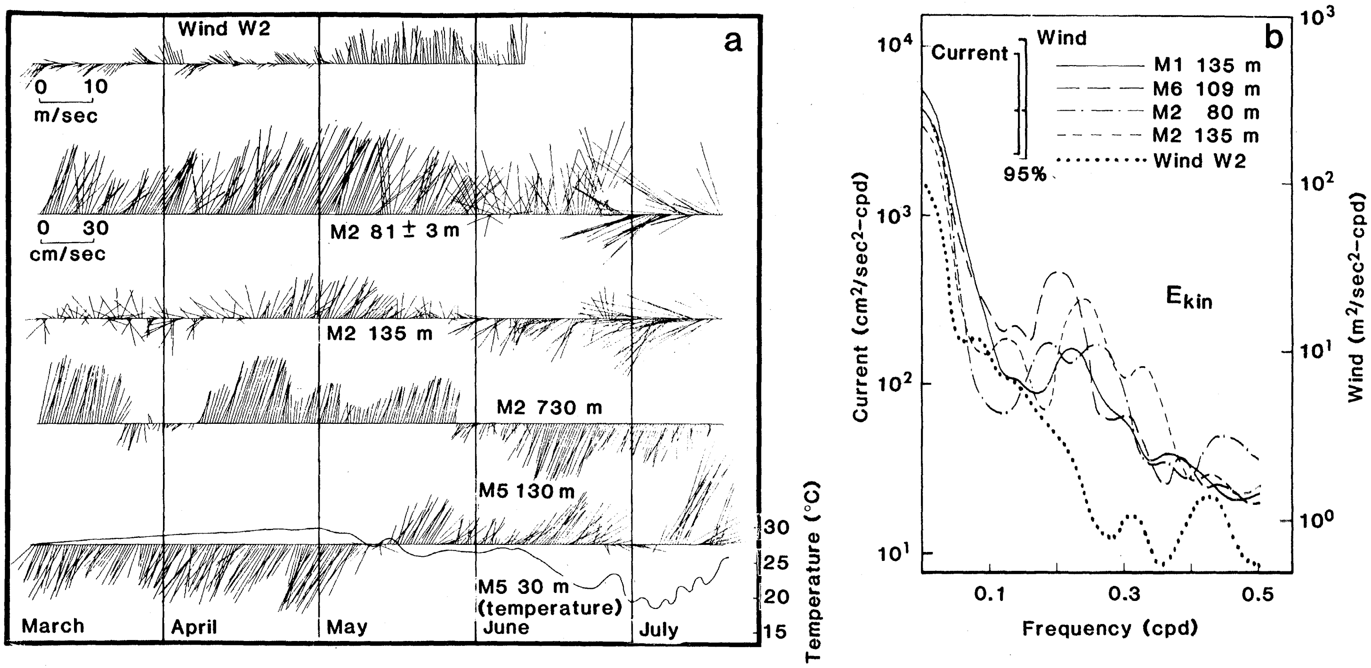

Fig. 2. Current and wind variability. (a) Low-passed vector time series (cutoff period, 2 days) for currents at M2 and M5, wind at W2, and temperature at M5. (b) Low-frequency horizontal kinetic energy (E_{kin}) spectra of currents at several stations and wind at W2; *cpd*, cycle per day.

The currents at 130 m at M5 on the shelf were quite different from those at nearby M2 (Fig. 1 and Fig. 2a). For long periods the flows at these locations were in opposite directions, suggesting that a different pattern may prevail on the shelf. Figure 2a also shows the temperature at 30 m at M5: there was warming when the current flowed southward, and cooling after it turned northward. The cooling was possibly the result of water advected from the divergence to the south of our array (*7*).

Currents at 220 to 370 m. The records from M4, M2, and M1 along the continental slope are puzzling. At M4 the flow at 220 m was southward until about 20 June (*8*), and at M1 the current at 230 m was southward throughout. Yet between these two stations, at M2, the current at 230 m remained northward until the record ended on 10 June. Figure 1, f to h, shows additional current vectors for this level. A consistent pattern is not obvious, perhaps in part because of depth differences of the instruments and the baroclinic structure of the flow. In June the surface layer seemed to deepen: the 135-m current at M2 now had directions similar to those at 80 m (Fig. 2a), and the directions of the current at M1 (230 m) and M4 (220 m) generally agreed with those at the 100-m levels.

Currents at 700 to 900 m. Near the coast, the current at M2 (730 m) flowed northward until 25 May, with only a brief period of weak southward flow in March (Fig. 1, lower panel, and Fig. 2a). After the monsoon's onset it flowed steadily southward at 15 cm/sec, while the flow in the levels above was mainly coastward (Fig. 1, i to k). At instrument moorings 273 to 275, the currents at 700 to 900 m were better correlated with those at higher levels than those at the shoreward station M2. These currents flowed southward to onshore in early June, and then turned northward, with a phase progressing from south to north. By late June we observed northward flow at all three offshore stations, and strong southward flow at M2. We cannot say, however, whether a persistent pattern of deep flow underneath the northern gyre developed that was typical of the fully developed phase. The current vectors at 700 to 900 m (Fig. 1) indicate why there is poor spatial coherence in the maps of current vectors measured at 700 m from ships with profiling instruments (*9*): the ship surveys lasted too long, compared to the kind of temporal variability that exists even after averaging over 10 days, to provide sufficient quasi-synoptic coverage (*10*).

The flow pattern deduced from Fig. 1 agrees well with the ship sea surface temperature observations of Brown *et al.* (*7*), who, in their map for 22 June to 31 July, show warmer open ocean water (> 25°C) converging at the coast around 7°N. Our results for the northern area (Fig. 1, i and k)—especially the coastward flow—also compare well with the surface currents and salinity patterns described by Düing *et al.* (*11*) for 6 June to 30 July, although Fig. 1i suggests that their current pattern should be complemented by a southward flow off Obbia toward the divergence at 4°N during this time (*12*).

An interesting feature in Fig. 1, f and g, is that the northward migration of the coastward flow to M4 seems to be accompanied by a northward migration of the offshore flow [found by Düing *et al.* (*11*)] to M1.

We do not know whether our later recordings (Fig. 1, i and k) reflected the fully spun-up phase of the northern gyre in late July; but if so, the time series show that the gyre took less than 2 weeks for full development after the circulation pattern recorded in May. The general conclusion from Fig. 1 is that the northern gyre already existed as a shallow circulation in March, long before the onset of the southwest monsoon, and that it was strongly enhanced by the monsoon in June and July. Future numerical models should focus on this behavior of the eddy rather than its generation at the equator and movement north along the coast (*13*).

There is substantial interannual variability in the northern Somali Current system. Two of our stations, M1 at 5°N and M7 at 2°20′S, were moored at sites where instruments were located in previous years during the same time of year. At 2°20′S the M7 records for 1979 (not shown in Figs. 1 and 2) show northeastward currents at 95 and 155 m from 8 March to 7 July, except for 2 days in late March. This northeastward flow is in agreement with that shown in the maps of Düing *et al.* (*11*) and in the current profiles of Leetmaa *et al.* (*9*) at their site B, which was close to M7. The persistent northward flow in 1979 at this depth range was totally different from the flow we measured at this site in 1976 (*2*), which showed many reversals at 84 m until the end of April; the currents at 134 m fluctuated even until the end of May before becoming steadily northeastward. At 5°N three meters recorded basically southward flow between 190 and 590 m from May to August 1977, and showed high correlation of the currents throughout this depth range. In 1979 the flow was much more baroclinic, with long phases of flow at 430 m running counter to that at 230 m.

Strong fluctuations were superimposed on the temporal variations of the gyre development; the horizontal kinetic energy spectra show significant peaks between 3 and 6 days (Fig. 2b). The wind measurements at W2 show energy peaks at shorter periods than the currents and a large diurnal component (filtered out here) due to the sea breeze-land breeze effect. The period range of the current fluctuations shown in Fig. 2b suggests inertial waves (*14*); however, there is no clear tendency for the peak periods to decrease with latitude. Furthermore, at M7 (2°20′S), where the inertial period is 12.8 days, similar energy peak frequencies are seen. Also, in some spectra, second peaks occur at somewhat higher frequencies.

Other possible motions with these periods are stable or unstable topographic waves, and several simple models for analyzing barotropic and baroclinic instabilities (*15*) are now being tested.

F. SCHOTT
Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, Florida 33149

D. R. QUADFASEL
Institute of Oceanographic Sciences, Wormley, England GU8 5UB

References and Notes

1. J. G. Bruce, *J. Geophys. Res.* **84**, 7742 (1979).
2. W. Düing and F. Schott, *J. Phys. Oceanogr.* **8**, 278 (1978).
3. Instruments M1 to M7 were mostly Aanderaa current meters; some were Niskin Wing current meters. Instruments 272 to 275 were all Aanderaa current meters. Most instruments also yielded temperature and pressure records.
4. Wind records from coastal stations (Mogadiscio and Obbia) are being analyzed; wind maps for the area are derived from standard ship observations.
5. We have no explanation for the persistent offshore component in the 120-m record from M3, which was moored in shallower water (500 m) than the other instruments on the slope.
6. Some of the earlier current vectors at M6 suggest that the current might have been trapped along the seamount topography. On the other hand, the fact that there was cross-contour flow (Fig. 1, c, d, and h) and coastward flow at M2 support the deduction that we really observed coastward flow at M6 at times.
7. O. B. Brown, J. G. Bruce, R. H. Evans, *Science* **209**, 595 (1980).
8. At M4 (220 m), only the current direction was obtained. An arbitrary speed of 15 cm/sec was applied to the original time series.
9. A. Leetmaa, H. T. Rossby, P. M. Saunders, P. Wilson, *Science* **209**, 590 (1980).
10. Another aliasing effect (filtered out in Fig. 2a) for the current profiles in (*9*) was the strong semidiurnal tides, which at many instruments had energies close to those of the fluctuations with cycles of several days (Fig. 2b).
11. W. Düing, R. L. Molinari, J. C. Swallow, *Science* **209**, 588 (1980).
12. The vigorous current changes we recorded in June and July (Fig. 2a) indicate that the surface-current chart of Düing *et al.* (*11*) for June and July may include aliasing effects.
13. H. E. Hurlburt and J. D. Thompson, *J. Phys. Oceanogr.* **6**, 646 (1976); M. D. Cox, *ibid.* **9**, 331 (1979).
14. The period of inertia ranged from 3.8 days at M3 to 5.6 days at M1 (Fig. 1a).
15. L. Mysak and F. Schott, *J. Geophys. Res.* **82**, 2087 (1977).
16. We thank the Institut für Meereskunde, Kiel University, Kiel, West Germany, for assisting us with some of the moored instruments, and we thank J. Samuels, P. Diaz, and H. Ho for their help in processing the data. Supported by NSF grant ATM78-24585 and ONR grant N00014-75-C-0173.

6 February 1980; revised 19 May 1980

Evolution of Sea Surface Temperature in the Somali Basin During the Southwest Monsoon of 1979

Abstract. *Satellite and research vessel observations of sea surface temperature during the southwest monsoon of 1979 show the development of large wedge-shaped areas of cold water along the Somali coast at both 5° and 10°N during June and July. The cold water associated with the large northern and southern Somali eddy systems could be traced several hundred kilometers offshore. By late August the cold wedge at 5°N translated northeastward as far as 10°N at speeds of 15 to 30 centimeters per second, indicating a coalescence of the systems.*

As the Somali Current system develops each year during the southwest monsoon (May through September), it exhibits a strong thermal signature at the sea surface (*1–3*). This signature results from uplifting of isotherms on the shoreward side of the current and transport of cooler water northward by the current from the equatorial region. The resulting horizontal temperature gradients provide a good means for tracing the surface circulation pattern of the Somali Current and its associated eddies (*4*). Several surveys since 1963 observed that the northeastward-flowing Somali Current is part of the eddy field occurring with each southwest monsoon (*5, 6*). The current normally separates and diverges from the coast about 8° to 11°N (northern separation) (*7–9*) and turns eastward and then southward farther offshore, forming a clockwise eddy. During some years, however, it also turns strongly offshore at about 4° to 5°N (southern separation), this portion of the current being associated with a southern eddy, as observed by Bruce (*10*) during the southwest monsoon of 1970. He described the flow as unstable and conjectured that the pattern was the result of northward propagation of an eddy from the equatorial region. Düing (*11*), utilizing his own moored current meter data and Bruce's (*12*) temperature data from expendable bathythermographs, presented similar arguments for such an event. In both regions of northern and southern separation, intense upwelling of cold water occurs at the sea surface along the coast to the left of the current.

Our observations are of two types: sea surface temperature (SST) measurements from ships and satellite-derived radiometer temperature measurements from the TIROS-N satellite. Observations by participating research vessels were routinely made during the 1979 Indian Ocean Experiment, with close spacing between stations (~ 40 km or less, depending on surface thermal gradients). Measurements were made from the *Columbus Iselin*, *Discovery*, *Wilkes*, and *Researcher* from March through August 1979 with bucket thermometers, continuous flow-through devices, and expendable bathythermographs (accurate to ± 0.1°C). Composite surface thermal maps were produced; ship observations presented here are excerpted from them.

Satellite SST observations were derived from the advanced very high resolution radiometer sensor aboard the polar orbiting satellite TIROS-N. The sensor has a nadir-earth resolution of approximately 1.1 km and a noise-equivalent temperature (a measure of the noise inherent to the instrument) of less than 0.012 K. Thermal data reported here were derived from band 4 (viewing channel, 9.8 to 11 μm). Satellite thermal data were not corrected for atmospheric water vapor effects (*13*) and are used here primarily for identification of patterns rather than absolute temperature. Overall calibration offsets between ship and satellite observations were checked by comparing weekly (or more frequent) ship surface measurements with corresponding satellite data; adjustments to true SST temperature were made when necessary.

Evolution of the SST field, based on

0036-8075/80/0801-0595$00.50/0