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.

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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.
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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).
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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.
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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

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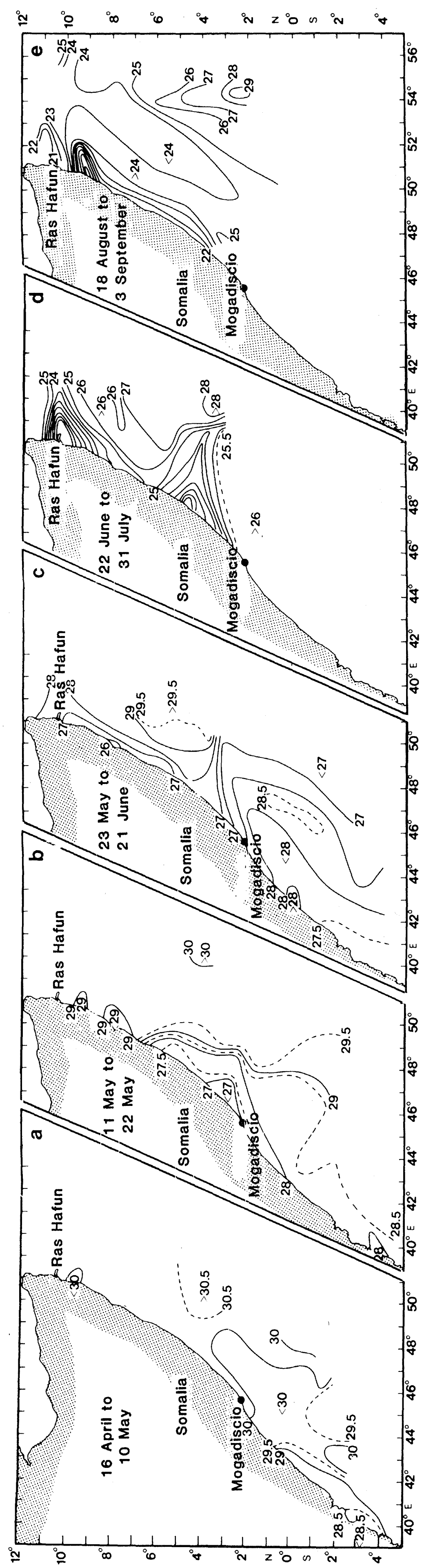

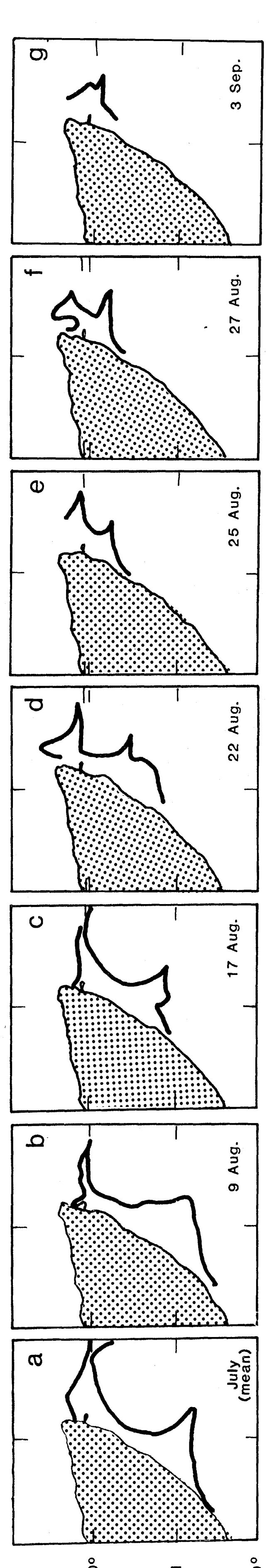

Fig. 1 (top). Time sequence of ship-observed SST fields showing the oceanic response to the southwest monsoon of 1979. Fig. 2 (bottom). Time sequence of satellite-observed frontal locations for northern translation of the southern wedge of upwelling water.

ship observations from April through August 1979, is mapped in Fig. 1, a to e. In late April (before the onset of the southwest monsoon), water warmer than 30°C was found near the coast as far south as 2°N (Fig. 1a). Here the equatorial water, which extended along the coast as a narrow, cool band from the south, was separated by a weak front. Interior temperatures were above 30°C.

By mid-May, cooling of coastal water between 2° and 7°N was evident (Fig. 1b), with weaker frontal development between 7° and 10°N. The thermal gradient in the southern frontal region was 0.02°C per kilometer, with highly variable temperatures between 28° and 26°C along the coast of southern Somalia. Gradients in the northern region (8° to 10°N) were weak, and the average temperature was still around 30°C.

By late May a strong thermal front had developed at 3°N (Fig. 1c). Its position and thermal gradient features were clearly observed in the ship and satellite results. Simultaneous current measurements (*14*) show that the front was associated with strong offshore flow of the Somali Current. Temperatures in this region were about 26°C near the coast, with a thermal gradient in early June at 0.025°C per kilometer. By this time cooling in the northern region had begun, with temperatures down to 25.9°C near the coast at 8°N. A large thermal front 50 to 100 km offshore and concave toward the coast had become established.

By mid-July the southwest monsoon reached maximum strength; Fig. 1d shows the strong northern and southern frontal regions that developed, and clearly depicts the wedge-shaped regions of cold upwelled water. The alongshore length of both wedges was approximately 300 km, and they extended more than 400 km offshore. Temperatures as cold as 18°C in the southern region were found near the coast at 4°30′N, with the cold water extending seaward. Thermal gradients reached 0.1°C per kilogram in both frontal regions. In the northern region the lowest temperatures (17.7°C) were off Ras Hafun. The concave pattern of the front between 5° and 10°N is apparent. Concurrent satellite imagery (not presented here) shows that the ship-derived frontal features illustrated in Fig. 1d were quasi-stationary during this period.

Figure 1e shows the thermal field observed from the ships during late August and early September. The southern frontal system had dissipated. The northern system, however, remained, although the separation region had moved south by ~ 100 km. Near-coastal temperatures were about 3°C cooler than in the previous month.

Figure 2 illustrates the temporal evolution of the southern frontal region observed by satellite for the months of July and August. The frontal position was relatively stationary through the end of July; Fig. 2a outlines its extent. By 9 August the southern wedge (~ 4°N) tended to widen somewhat, although no separate frontal feature appeared (Fig. 2b). The next observations, made on 17 and 18 August, show that the front shifted 150 km north (Fig. 2c). On 22 August the front was located more than 400 km north of the 9 August position. Coalescence with the northern region front was observed in early September. Interpretation of the consecutive positions of this front as a northward translation yields speeds of 15 cm/sec in early August and 30 cm/sec in late August (mean rate, ~ 25 cm/sec). These rates are considerably greater than the 9.8 cm/sec reported for northern eddy translation in 1970 (*10*). However, Düing (*11*) found a rate of 35 cm/sec for a 1975 event he interpreted as a northward-propagating eddy. These satellite measurements correctly mirror the directly observed gradients over the entire period. There is good correspondence between frontal position data obtained by the two methods.

The direct current measurements (*14*) obtained concurrently with most of our 1979 SST observations indicate that the northern and southern separation regions during late May, June, and July are associated respectively with the northern and southern eddy systems in the Somali Basin. This is similar to Bruce's (*10*) finding in early August 1970. Our temperature measurements show merging of the southern eddy with the northern circulation in a manner similar to that observed in late August of 1970, but with a more rapid northward translation. Our results are qualitatively in agreement with the modeling results of Cox (*15*), which show essentially stationary eddies for increased wind stress (or increased vertical mixing), whereas for decreased wind stress (as occurs during late August and early September during the southwest monsoon) there is a tendency for northward propagation.

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Southwest Monsoon of 1979: Chemical and Biological Response of Somali Coastal Waters

Abstract. *In 1979 two areas of upwelling were observed off Somalia, one near 10°N and one near 5°N. The areas of upwelling were characterized by sea surface temperatures between 17° and 22°C, high concentrations of surface nutrients (5 to 20 micromoles of nitrate per liter) and surface chlorophyll a (0.4 to 5.0 milligrams per cubic meter), primary productivity averaging 1.7 grams of carbon per square meter per day, and a phytoplankton assemblage dominated numerically by the diatom* Nitzschia delicatissima.

In contrast with textbook upwelling systems in regions of eastern boundary currents, the upwelling off Somalia during the southwest monsoon is in a western boundary region and is embedded in or closely related to a strong western boundary current (*1, 2*). Although intensive multidisciplinary studies of some of the eastern-boundary upwelling regions have been completed in recent years (*3*), investigations of the nutrient and biological regimes off Somalia ceased after the conclusion of the International Indian Ocean Expedition in 1965. However, the 1979 Indian Ocean Experiment obtained nutrient and biological data from this region before the southwest monsoon (leg 1, 26 February to 15 March), during its onset (leg 2, 24 May to 24 June), and at its peak (leg 3, 7 July to 4 August) (*4*). The most complete suite of biological and chemical data was taken during leg 3, when the placement of instrument stations was guided by sea surface temperature data obtained from satellites. Usually only one region of intense upwelling is encountered off Somalia during the southwest monsoon (*5*), but sea surface temperatures have revealed the occasional presence of a second upwelling near 5°N (*6*). During leg 3, we observed centers of upwelling near 5° and 10°N; to our knowledge, this is the first chemical and biological description of dual upwelling in this region.

The data on nitrate concentrations obtained during leg 3 clearly demonstrate the areas of intense upwelling near 5° and 10°N (Fig. 1). Maximum concentrations of dissolved silicon and reactive phosphorus were also encountered in these areas (Table 1). Consistent with previous studies (*6*), the areas of intense upwelling were immediately north of regions where the flow had a strong offshore component (*7*), and were easily identified by their low sea surface temperatures (17° to 22°C). The offshore areas with nitrate concentrations between 1 and 5 μmole/liter that were observed close to the equator have been noted before (*5*); they probably arise from processes other than coastal upwelling, since satellite data show no upwelling to the south of 5°N during leg 3.

The nitrate data for leg 2 suggest weak upwelling at a few locations. In the coastal zone at about 2°30′N, the maximum concentration of surface nitrate was 3 μmole/liter, and there were large increases in nutrient concentrations at 20 to 100 m compared with those measured during leg 1. Upwelling at this site may subsequently have weakened, since the nutrient values here during leg 3 were intermediate between those of legs 1 and 2. Although surface nitrate concentrations at 5°N were less than 1 μmole during leg 2, subsurface data suggest that upwelling may have begun there in that period. For example, four stations in the coastal zone near 5°N recorded a continuous increase in nitrate concentration at 50 m between legs 1 and 3 (μmole/liter): 0.4 in

