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

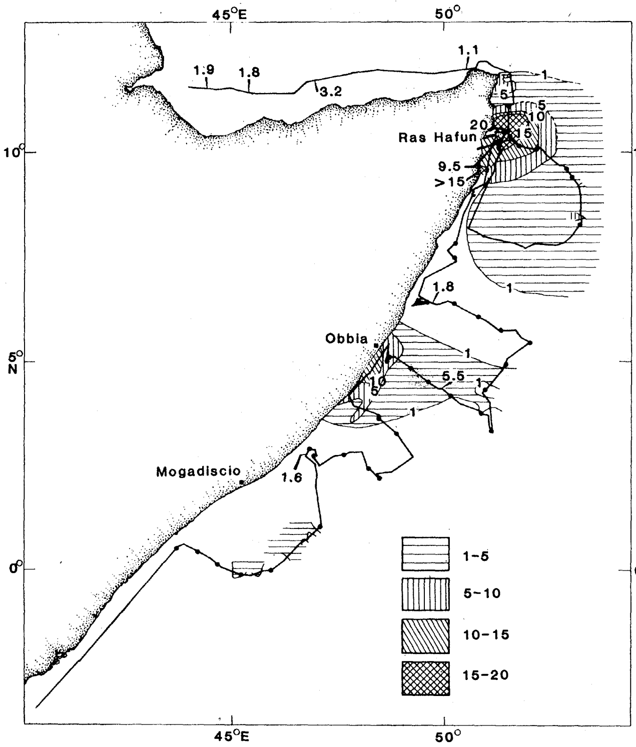

Fig. 1. Surface nitrate concentrations (micromoles per liter) observed off Somalia during leg 3 (7 July to 4 August 1979). Closed circles indicate positions of hydrographic stations.

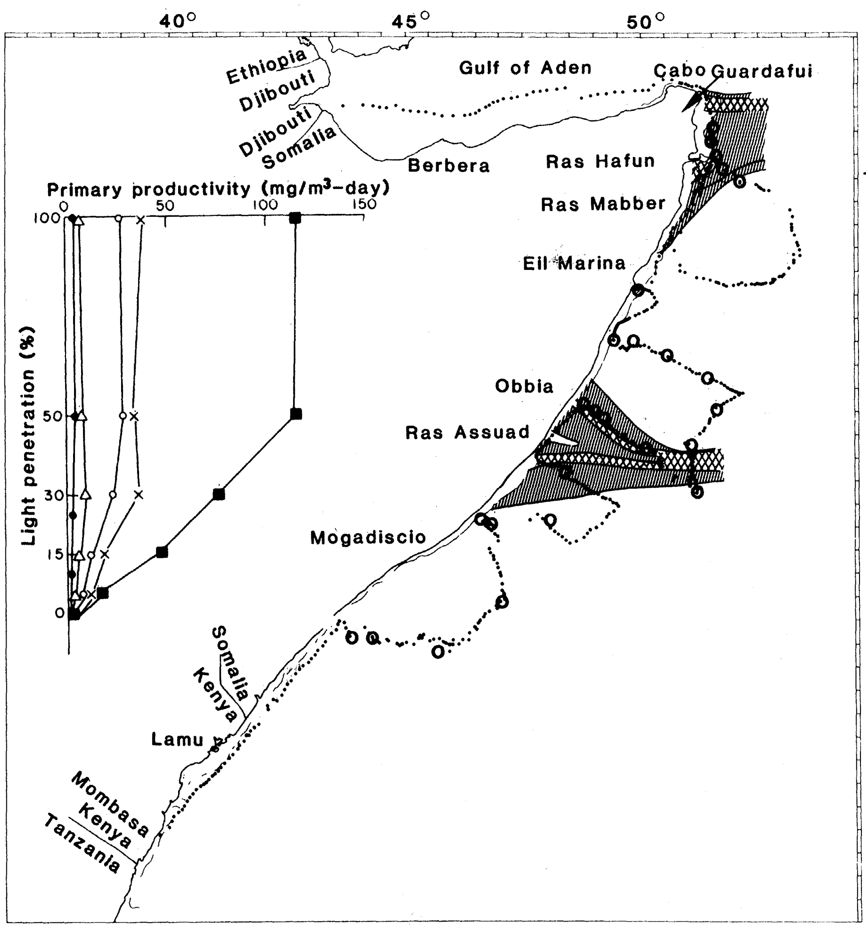

Fig. 2. Surface chlorophyll a concentrations (milligrams per cubic meter) observed off Somalia during leg 3 (7 July to 4 August 1979). Dots indicate positions where samples were taken while under way; circles indicate positions of stations where primary productivity was measured. Hatched areas are those where surface concentrations of chlorophyll a were between 0.4 and 1.0 mg/m^3; crosshatched areas, those where the values were between 1 and 5 mg/m^3. Inset shows profiles of primary productivity in terms of carbon from three regimes during the southwest monsoon in areas of upwelling (■), in areas of shoaling thermocline (X), and in areas where sea surface temperatures were greater than 25°C (O); during the northeast monsoon (△); and in the Sargasso Sea (●) (*13*).

leg 1, 1.0 early in leg 2, 6.0 late in leg 2, and 11.0 in leg 3. During leg 2 no data were taken north of 10°N, but the initiation of upwelling in the northern zone is suggested by a surface nitrate value of 3.4 μmole/liter near the shore at 9°30′N. During leg 1, surface nitrate concentrations were generally less than 1 μmole/liter; data from hydrographic casts also indicate an absence of upwelling.

Surface nitrate concentrations and sigma-*t* (*8*) values during leg 3 (Fig. 1 and Table 1) were higher in the northern area of upwelling than in the southern, suggesting stronger upwelling in the north. The offshore depths of the upwelling waters are in accord with this view. The residence times of waters with maximum nutrient concentrations (Table 1) were short compared to the rates of nutrient uptake, which are based on specific growth rates of phytoplankton and $\Delta C/\Delta NO_3^-$ ratios (*9*). Consequently, we assume that the maximum values for the concentration of surface nutrients are conservative, and have interpolated to the depths at which these concentrations were found outside the upwelling centers. Data from stations between 1° and 5°N suggest that the maximum offshore depth for waters rising to the surface near 5°N was about 100 m, while data north of 5°N suggest a maximum offshore depth of about 200 m for such waters near 10°N. Since the distribution of stations was not ideal, these depths are approximate, but their similarity to those encountered in eastern-boundary upwelling systems is noteworthy.

Variations in water mass composition and uptake by phytoplankton could contribute to differences in surface nutrient concentrations between the northern and southern zones of upwelling. For example, in the northern zone, the highest concentrations of surface nutrients were north of 10°12′N and were associated with relatively high salinity, but the highest surface sigma-*t*'s and lowest surface temperatures were south of this latitude (Table 1). Salinity and nutrient concentrations on any given sigma-*t* surface between approximately 100 and 3000 m increase toward the north off Somalia (*1, 5, 10*), suggesting that variations at the surface may be explained partly by compositional variations in the rising waters. Surface waters of lowest temperature, which were associated with somewhat lower amounts of nutrients (Table 1), were found in or near areas of relatively high concentrations of surface chlorophyll a, suggesting that uptake also influenced the concentration of surface nutrients.

With the 20°C isotherm used as an estimate of the depth of the thermocline

(*11*), it can be seen that areas of cool surface water at 5° and 10°N, where the flow of the Somali Current changes from northeastward to eastward, are areas where nutrient-rich subthermocline water surfaces. Shoaling of the thermocline along the inshore edge of the Somali Current should occur in a continuous manner for several hundred kilometers south of the areas of upwelling (*1, 11*), and the thermocline depth should become less than the depth of the euphotic zone at some point south of the area of cool sea surface temperatures.

Table 1. Selected values from the regions of upwelling near 5° and 10°N.

Number of observations	Location	Temperature (°C)	Salinity (per mil)	Sigma-*t*	Concentration (μmole/liter)		
					NO_3^-	Si	PO_4^{2-}
6	Near 5°N*	18.6	35.3	25.4	13.1	10.8	0.92
4	South of 10°12′N†	17.2	35.4	25.8	16.1	14.6	1.15
7	North of 10°12′N‡	18.7	35.6	25.6	19.9	15.7	1.53

*Surface water with nitrate > 12.9 μmole/liter. †Surface water with nitrate > 15 μmole/liter. ‡‡Surface water with nitrate > 19 μmole/liter.

At four stations on the southern edge of the area of upwelling at 5°N (Fig. 2), where the shoaling of the thermocline might act to retain phytoplankton within the euphotic zone and stimulate plant growth, the mean depth of the mixed layer was 23 m less than the mean of the euphotic zone, and primary productivity of carbon was 1.2 ± 0.4 g/m²-day. At nine stations well outside the areas of upwelling (sea surface temperature > 25°C) and the effect of the Somali Current on the thermocline, mean depth of the mixed layer was 15 m greater than the mean depth of the euphotic zone, and primary productivity of carbon was 0.7 ± 0.4 g/m²-day. Ten stations were postioned in the areas of upwelling (sea surface temperature < 22°C) where the depth of the mixed layer was approximately equal to the depth of the euphotic zone. Primary productivity of carbon in areas of upwelling was 1.7 ± 0.8 g/m²-day. Differences in mean primary productivity were significant only between stations in the areas of upwelling and stations well outside the upwellings. Surface samples of phytoplankton from the areas of upwelling were dominated numerically by *Nitzschia delicatissima*, a diatom common in the upwelling off Peru (*12*). The average total number of cells per milliliter was 560. Surface samples from outside the upwellings were dominated numerically by a mixture of dinoflagellates and diatoms, with an average total number of cells per milliliter of 55.

The effect of the shoaling thermocline and enhanced primary productivity was evidenced by increased amounts of chlorophyll a at the sea surface (Fig. 2). The edges of the upwellings at 5° and 10°N contained 0.4 to 1.0 mg of chlorophyll a per cubic meter, corresponding generally to areas where isotherms of sea surface temperature were between 22° and 24°C and closely spaced (*7*). Chlorophyll a at 1 to 5 mg/m³ occurred between bands of 0.4 and 1 mg/m³ (Fig. 2), and at stations along the northerly edge of the upwelling at 5°N, chlorophyll a increased from 0.4 mg/m³ nearshore to 1.6 mg/m³ offshore. The nearshore center of the upwelling at 5°N had low levels of chlorophyll a and high nutrient levels, while offshore (downstream) chlorophyll a increased and nutrients decreased (Figs. 1 and 2), relationships which are similar to those observed off Peru (*12*).

The distribution of chlorophyll a at the surface in the upwelling off Ras Hafun was more complex (Fig. 2), probably because the circulation there includes the influence of warm, saline water from the Gulf of Aden and the effect of Ras Hafun on the Somali Current. We speculate that the chlorophyll a and primary productivity observed in the nearshore part of the upwelling at 10°N extends a considerable distance into the interior of the northwestern Indian Ocean. We base this hypothesis on previous observations of enhanced primary productivity at 60°E at the latitude of northern Somalia (*10*) and on the gyre-like circulation, extending to 60°E, found during the southwest monsoon of 1970 (*5*).

During the northeast monsoon (leg 1), primary productivity of carbon at 12 stations from Ras Hafun to Lamu was 0.3 ± 0.1 g/m²-day, or about half that observed at stations well outside the area of upwelling in the southwest monsoon, and similar to previous observations in this area during the northeast monsoon (*10*). Mean depth of the euphotic zone was 57 m, and mean depth of the mixed layer was 68 m. Surface samples of phytoplankton were dominated numerically by nannoplankton and dinoflagellates with an average of two cells per milliliter.

The contrast in primary productivity between the northeast and southwest monsoons is seen clearly in the profiles shown in Fig. 2; mean productivity off Somalia during the northeast monsoon is almost identical to that of the Sargasso Sea off Bermuda (*13*). During the southwest monsoon, primary productivity increased all along the Somali coast, the least productive stations being two times more productive than during the northeast monsoon, and the areas of upwelling being ten times more productive (Fig. 2). Near the end of May, just as the Somali Current was becoming established, primary productivity of carbon near the shore at 3°N was 1.8 g/m²-day. In July, primary productivity at the same station was 1.3 g/m²-day. This suggests that the biological response to the southwest monsoon was established by late May in the upwelling near 5°N, and that it lasted a minimum of 2 months.

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Equatorial Currents in the Western Indian Ocean

Abstract. *Measurements were made in the equatorial Indian Ocean during spring and summer 1979 from the Somali coast to 62°E in the interior of the western basin. The detailed vertical profiles of horizontal current show that the energetic dominance throughout the region of variability was on vertical scales of several hundreds of meters, confined to within a few degrees of the equator, as observed in 1976. The near-surface equatorial circulation responded directly to variations in the wind field, and satellite-tracked drifter buoys showed the equatorial surface jet extending across the width of the ocean. This eastward flow is generated by the eastward winds that appear in the interval between the northeast and southwest monsoons. The zonal velocity fluctuations extended in a consistent pattern over the observation region. The time and meridional scales of the variability were similar to those observed in 1976, suggesting that the velocity field is dominated by long-term, equatorially trapped motions with long zonal scales.*

During spring and summer 1979, observations were made in the equatorial western Indian Ocean between the African coast and 62°E as a component of the Indian Ocean Experiment (INDEX). The focus of the equatorial observations was the oceanic response to the greatly varying winds associated with the monsoons. Pilot observations in 1976 (*1*, *2*) and earlier suggested that the velocity field in the equatorial Indian Ocean is dominated by a variety of equatorially confined motions. The observational program consisted of compiling vertical profiles of horizontal currents, tracking drifter buoys by satellite, and deploying an array of moored current meters. We report here preliminary results from the first two components.

The first set of vertical profiles of horizontal velocity was made from the *Columbus Iselin* in early April 1979, well before the onset of the southwest monsoon. The second set was made during the period spanning May and June and involved two ships: the French vessel *Marion Dufresne*, which was stationed in the vicinity of 62°E and made vertical profiles of relative current (shear) and deployed the drifter buoys; and the *Columbus Iselin*, which reoccupied the sites at which profiles were made during her first cruise. The profiles were obtained with the White Horse, an acoustically tracked, freely falling instrument. The horizontal velocity profile is inferred from the observed lateral displacement of the instrument as it falls to the ocean bottom and then rises to the surface (*1*, *2*).

The deep equatorial jets in the Indian Ocean (*1*, *2*) were a focus for the INDEX equatorial program. Subsequent observations in the western (*3*) and eastern (*4*) Pacific Ocean have confirmed their existence as a general feature of the equatorial velocity structure in the Indian and Pacific oceans. The observations in 1976 indicated that the zonal component of flow has a time scale on the order of 1 month or longer, whereas the meridional component is variable over periods of 1 week. These motions are confined to within a few degrees of the equator. The most energetic of the zonal jets in the Indian Ocean flowed toward the west, so it was desirable to learn their extension into the interior of the Indian Ocean and, at the western boundary, their interaction with the Somali Current system.

The equatorial profiling program began in early April with the *Columbus Iselin*. A total of 17 velocity and conductivity, temperature, and depth profiles were made at 13 locations between 50° and 59°E. Most of the equatorial profiles away from the coast show eastward flow extending to the thermocline. Below this region there was westward flow, concentrated in structures of relatively short vertical extent, typically 100 to 200 m. The second cruise, in June, extended the spatial coverage from 47° to 62°E, and the 18 profiles made show similar characteristics.

In the latter case, there was eastward flow in the upper layers only to the east of 52°E, and the region of westward flow, extending to 2500 m, intensified. Figure 1 shows the contours of horizontal velocity obtained by the second *Iselin* cruise. The zonal jets are evident in horizontal bands of westward velocity in excess of 20 to 25 cm/sec in the upper 2000 m. The meridional component of flow is smaller in amplitude and generally more spatially and temporally variable. The meridional structure of the flow is similar to that observed in 1976 (*2*). The region of energetic small-scale variability is confined to within 3° of the equator. At 4° from the equator, north and south, the dominance of the large vertical scales typical of mid-latitudes is present. The profile observations from the *Marion Dufresne* confirm this general structure in the upper 500 m at 62°E, although only relative current profiles were made.

The presence of equatorially trapped structures with vertical scales of several hundred meters is consistent with the kinematics of vertically propagating equatorial waves of planetary scale—the equatorial Kelvin and Rossby waves (*2*, *5*). Wunsch (*6*) suggested that monsoonal variations in wind stress can generate a downward-propagating equatorial Rossby wave of annual period whose vertical scale is a few hundred meters. The vertical-phase speed of such a wave is so low that dissipation, together with scattering from the bottom topography, can prevent the formation of standing vertical modes. Cane (*7*) and Philander and Pacanowski (*8*) argued that the response in the upper equatorial ocean rapidly becomes nonlinear, so that the linear radiation mechanism proposed by Wunsch applies only beneath the thermocline. An analysis of the combined moored current meter and velocity profile data in terms of the vertically propagating equatorial wave models is desirable.

During the transition periods between the two phases of the monsoon, there is an interval of eastward wind along the equatorial region of the Indian Ocean. These winds apparently drive the eastward surface jet discovered by Wyrtki (*9*) and documented by Knox (*10*) near Gan Island (70°E). During May 1979, four drogued (20 m) drifter buoys were launched from the *Marion Dufresne* at 0°, 62°E and tracked by the Argos system aboard TIROS-N. Also, two drogued buoys were launched from the *Discovery* at 0°, 48°E, and in June two were de-