Reports

The Indian Ocean Experiment: Introduction

The following six reports summarize the results of the Indian Ocean Experiment (INDEX), an oceanographic survey of the Somali Current and western equatorial Indian Ocean during the onset of the southwest monsoon in 1979. In this region, surface currents change dramatically with the annual cycle of monsoon winds in a qualitatively well known manner (*1*). Off the east coast of Africa the Somali Current follows each seasonal wind reversal within 1 month, reaching speeds of 7 knots (3.5 m/sec) during the southwest monsoon. Previous studies of the width and shape of the current and its water properties were all made in mid-monsoon, with the current fully developed in one direction or the other (*2*–*4*). The transition seasons have generally been avoided because of the practical problem of mapping rapid changes over a large area. Such observations as have been made then (*5*, *6*), although significant, were limited in extent.

A more detailed description of the way the Somali Current changes in response to the onset of the southwest monsoon would be useful for comparison with dynamic models of the process (*7*–*9*). Such a study was considered timely in view of the Global Weather Experiment, which offered the prospect of frequent satellite-derived maps of sea surface temperatures and greatly improved surface wind observations. An earlier experiment (*10*) had suggested that the velocity field along the equator has a complex vertical structure of mainly zonal jets. At the surface, the eastward equatorial jet appeared to be closely related to the occurrence of eastward winds there during the change of monsoon (*11*). The Global Weather Experiment offered an ideal opportunity for extending the observations of the distribution of these phenomena in space and time and relating them to the variable wind field and possibly the Somali Current.

Proposals for oceanographic work in these two areas were coordinated by the INDEX group and linked to international plans for other observations in the Indian Ocean through the Scientific Committee on Oceanic Research working group 47 (oceanography in the Global Weather Experiment). A composite program of shipboard work and satellite-derived observations ran from February to August 1979. None of the ships were continuously involved through that period. Specific contributions are detailed in the reports on separate topics that follow.

The Somali Current did not grow continuously but appeared to extend itself northward in a series of steps. For much of the early part of the southwest monsoon, it separated from the coast near 4°N. A clockwise eddy evolved in situ to the north of that latitude in late May or early June, and was swept away by the main current migrating through to the northeast in August. There was evidence of a deep countercurrent under the southern part of the Somali Current, connected to a westward equatorial jet centered at 700 m. Along the equator to the east of 50°E, satellite-tracked drifter buoys moved intermittently eastward in qualitative agreement with mathematical models of behavior of the equatorial surface jet. None of these observations has yet been related in detail to the wind field.

A driving force behind INDEX and these reports was Dr. Walter Düing, who died on 24 March 1980. To acknowledge Dr. Düing's inspiration and many contributions, we dedicate these reports to his memory.

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12. Financial support for INDEX is acknowledged in the reports that follow.

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Somali Current: Evolution of Surface Flow

Abstract. *The transition of the Somali Current from northeast monsoon conditions to southwest monsoon conditions was observed from April through August 1979. The northeastward flow associated with the Somali Current of the southwest monsoon progressed from the equator in April to 4°N in August. The separation of the current from the coast, as observed at the northern boundary of the northeastward flow, did not intrude north continuously, but rather in distinct steps. South of 4°N, the circulation was characterized by the incorporation of increasing amounts of somewhat more saline water from the south and east into the boundary current. A clockwise gyre with northeastward flow along the coast developed between 6° and 10°N during June.*

The equatorial Indian Ocean along the east coast of Africa provides an excellent setting for studies of the response of the sea to atmospheric forcing. The atmospheric forcing signal is large because of the monsoonal wind, and the ocean response is dramatic. In the northern winter, the Somali Current flows from north of the equator to about 2°S. In the northern summer, the current reverses direction and flows north.

Our experiment encompassed the transition period between the northeast monsoon and the southwest monsoon. During this time, the flow of the Somali Current changes from southwestward to northeastward. Our findings include important spatial and temporal data about this transition, and provide a conceptual framework for many of the results of previous studies.

Data were collected from three ships: the *Discovery* of the British Institute of Oceanographic Sciences, the *Columbus Iselin* of the University of Miami, and the *Researcher* of the U.S. National Oceanic and Atmospheric Administration. The courses of the ships were coordinated to obtain maximum spatial and temporal coverage of the area while permitting individual programs to be conducted. Meteorological data were also collected on all the cruises.

Surface current charts were constructed for four time periods from three different types of data (Fig. 1, A to D).

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Drift vectors were computed on board the *Discovery* from satellite fixes and dead reckoning. Vertical profiles of horizontal current relative to ship drift were obtained with profiling current meters deployed from the *Iselin* and *Researcher*. The absolute velocity at 10 m was obtained by monitoring the *Iselin*'s drift relative to an acoustic beacon placed on the ocean floor (*1*). The *Researcher* data show currents at 15 m relative to currents at 600 m (the current vector observed at 600 m is subtracted from the 15-m vector). No intercalibration of the three data sets was performed. Therefore, particularly in regions of weak flow, individual current vectors should be viewed only in the context of the large-scale circulation pattern, rather than as quantitative estimates of the flow.

Surface salinity distributions were determined from water samples analyzed on the *Researcher* and *Discovery* and by a continuously recording electronic sensing device deployed from the *Iselin*. The resulting salinity fields were contoured subjectively to delineate areas of high and low salinity (Fig. 1, A to D). Surface wind data collected on the three ships were averaged across 2° bands of latitude for each of the time intervals selected. The surface current and salinity distributions depict the temporal evolution of (i) the northward-flowing Somali Current along the coast, (ii) the separation latitude of the Somali Current, (iii) the incorporation of more saline water from the south and east into the southern part of the boundary current, and (iv) a clockwise gyre between 6° and 10°N. Wind directions are given as the direction from which the wind is blowing; current directions, as the direction to which the current is flowing. For instance, during the

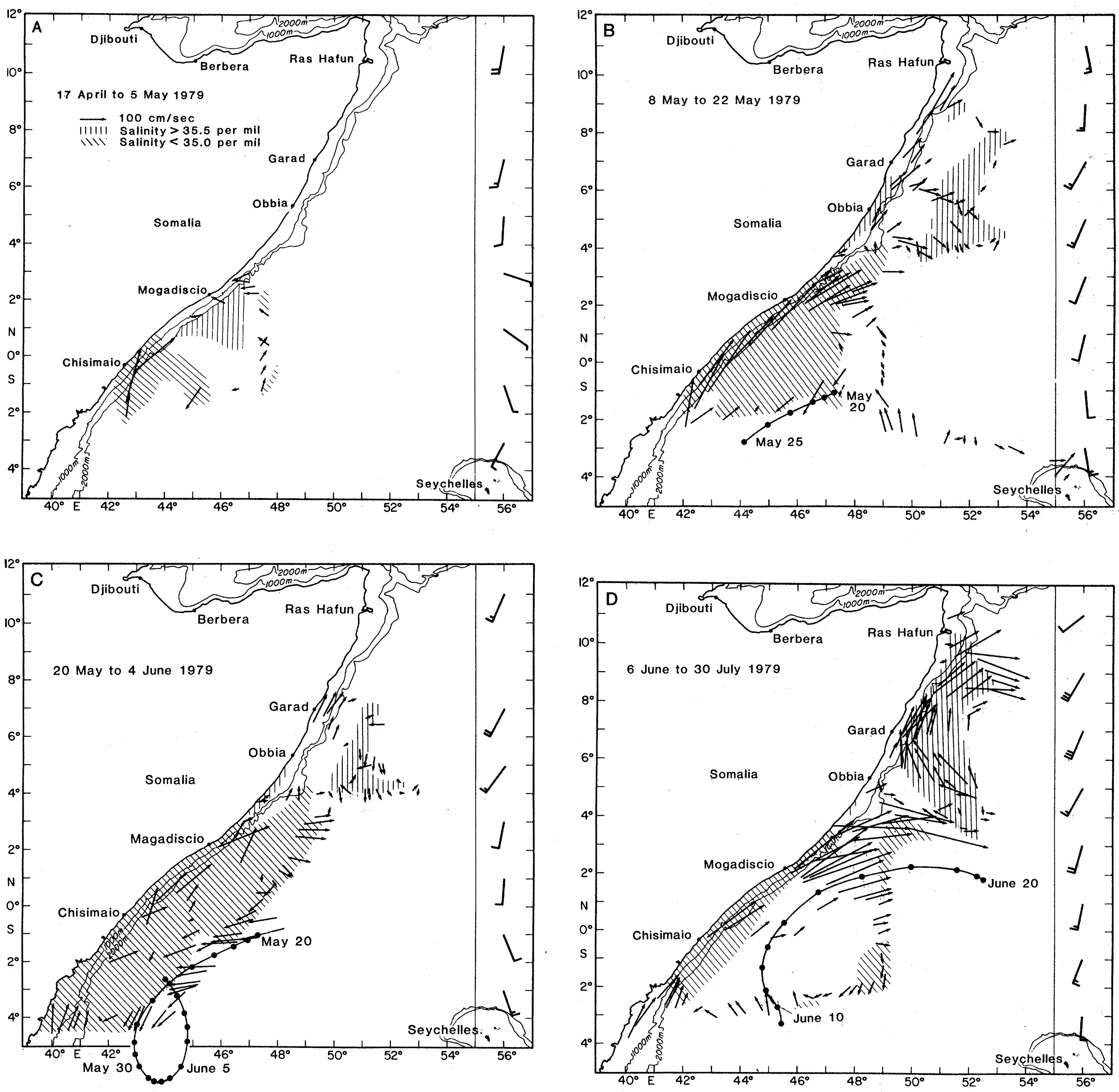

Fig. 1. Distribution of surface currents during the four time periods. Current arrows are centered on the observation point. Wind data collected during this period were averaged across 2° bands of latitude. The heads of the resulting wind barbs are plotted on the center latitude of each band. One half-feather on a barb represents 5 knots of wind. Satellite-tracked buoy trajectories are shown by the lines connecting closed circles (representing days).

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

