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SOMALI EDDY FORMATION DURING THE COMMENCEMENT OF THE SOUTHWEST MONSOON, 1978

by

J.G. Bruce, D.R. Quadfasel
and
J.C. Swallow

July 1981

TECHNICAL REPORT

Prepared for the Office of Naval Research under Contract N00014-74-C-0262; NR 083-004 and N00014-79-C-0071; NR 083-004.

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Department of Physical Oceanography

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Somali Eddy Formation During the Commencement of the Southwest Monsoon, 1978

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An early stage of the Somali eddy circulation was mapped in the period May 29 to June 13, 1978, using expendable bathythermograph data at closely spaced stations. By this time the SW monsoon had been blowing at 5°N for about 4 weeks and the large anticyclonic eddy in the northern Somali Basin was clearly discernible between 3°N and 10°N. It is estimated that the offshore transport at this time was approximately half of that occurring during the period when the eddy reaches maximum size and strength during August and September. A smaller southern eddy was observed just offshore between the equator and 3°N.

INTRODUCTION

Of the two monsoons regularly occurring each year in the northwest Indian Ocean, the southwest monsoon from April through September is much the stronger [*Hellerman,* 1967, 1968]. During this monsoon the Somali Current flows northeastward along the east African coast commencing by late April south of the equator [*Leetmaa,* 1972, 1973], progressing northward during May and reaching full strength during July and August [*Swallow and Bruce,* 1966]. In the vicinity of the Somali Basin at this time, large anticyclonic eddies are formed [*Bruce,* 1968]. The largest of these (diameter 400–600 km) is termed the prime eddy [*Bruce,* 1979]. From existing evidence it appears to occur each year between approximately 4°N to 12°N and the Somali coast and 58°E. An adjacent smaller eddy to the northeast off Socotra also seems to develop each year. During certain years an eddy forms adjacent to and to the south (~0° to 5°N, Somali coast to 53°E) of the prime eddy [*Bruce,* 1973, 1979]. The Somali Current is part of the eddy field of the prime and southern eddies. As the current turns offshore, its relatively fresh (~35.0–35.2‰) and cool water serves as a useful tracer for mapping the flow. In the region of upwelling on the left of the current as it diverges from the coast, near-surface temperatures range from roughly 12° to 25°C.

Previous surveys reported in the literature of the Somali Current and associated eddies have taken place during or slightly after the stage of maximum eddy strength during the southwest monsoon (August, September). The monsoon winds which drive the current system normally intensify from May through July and decline after this through September. A fortuitous set of near synoptic observations enables us in part to describe an earlier stage of the eddy development off the Somali and southeast Arabian coasts. Temperature sections were obtained during late May and early June 1978 from expendable bathythermographs (XBT's) by the Exxon tanker *Al Duriyah* and United Kingdom naval vessels *HMS Hydra* and *HMS Hecate.* The station positions were relatively closely spaced (15–30 n. mi. (25–50 km)) in order to study the small-scale features that occur in this region during the southwest monsoon. The *Al Duriyah* observations were part of an on-going program for monitoring the characteristics of the eddy structure off the Somali and Arabian coasts from a time series

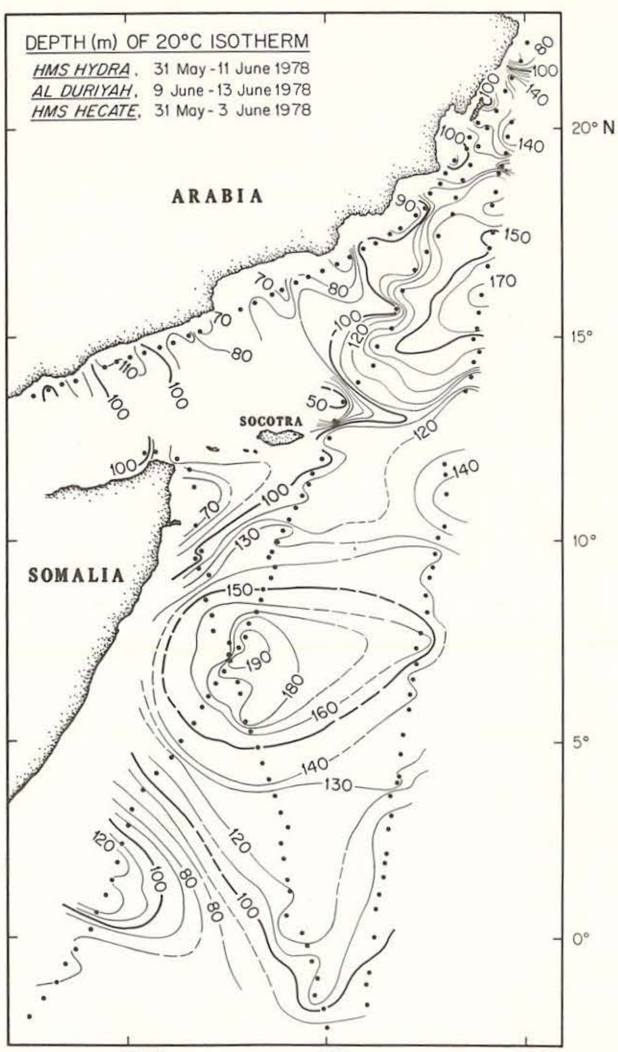

Fig. 1. Depth in meters of 20°C isotherm, May 29 to June 13, 1978.

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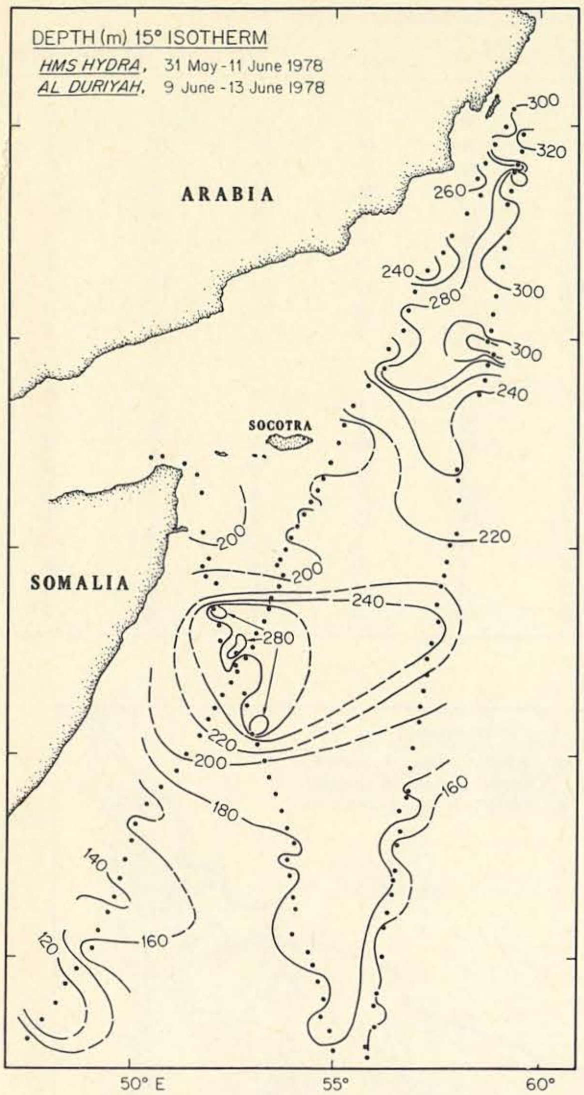

Fig. 2. Depth in meters of 15°C isotherm, May 29 to June 13, 1978.

of temperature sections made from Exxon tankers on approximately the same sea lane [*Bruce*, 1979].

DATA

The data consist of four XBT (Sippican Corp., T-4, 460 m probes) sections.

1. *HMS Hydra*, 55 stations from May 29, 20°08′N, 59°38′E to June 3, 2°59′S, 55°45′E.
2. *HMS Hydra*, 40 stations from June 8, 3°39′S, 55°10′E to June 11, 12°06′N, 50°30′E.
3. *Al Duriyah* (Exxon tanker), 63 stations from June 7, 22°00′N, 60°05′E to June 13, 2°00′S, 47°33′E. Surface salinity, wind velocity, and ship's set by currents.
4. *HMS Hecate*, 35 stations from May 31, 20°32′N, 59°10′E to June 3, 13°18′N, 46°52′E.

Further data discussed here but not used in the horizontal maps were obtained earlier by *Esso Osaka* May 19 to 21, 1978, and consist of 24 stations along the tanker sea lane which are located approximately 20–25 mi. (35–45 km) east of those of *Al Duriyah*. Additional data obtained when the eddy was further developed are presented from an *Esso Atlantic* July 6–8, 1978, section, 31 stations. Maps of the mean depth of the 20°C isotherm for May and June, used data from the following sources: NODC, Hydrographic Office of the Navy (United Kingdom), EAMFRO (Zanzibar), WHOI (*Atlantis II*, 1976), *La Curieuse* (H. Stommel, WHOI), *Hydra* (this paper), and Exxon tankers (J. Bruce, WHOI). The coastal wind observations were provided by the Somali Meteorological Service.

INTERPRETATION OF SYNOPTIC MAPS

In the Somali Basin the 20°C isotherm reaches its greatest depth of over 190 m in the region around 7°N, 53°W (Figure 1) about which a closed circulation is indicated by the depth contours between 150 and 190 m. The strongest gradients extend from this region northward to 11°N and to the south to about 4°N. The circulation as contoured turns offshore at approximately 8°N–9°N across the *Hydra* track, proceeds toward the east, and then turns southward between 54°E–57°E. A return flow toward the west is indicated between 7°N and 0° east of 52°E. The isotherm shoals to less than 70 m just off northeastern Somalia. It should be noted that the stations obtained in the center of the circulation all were obtained within a 2-day period (June 10–12) and it is expected that time aliasing would be relatively small here. The circulation appears to be that of the prime eddy [*Bruce*, 1979] in its early stage of development during the SW monsoon. There is also a deepening of the isotherm around 2°N with depths exceeding 120 m. An offshore flow is suggested in the region 3°N–4°N.

Another large-scale feature appears between 14°N and 18°N off the Arabian coast. Close to the coast (*HMS Hecate*) considerable variation in isotherm depth suggests the presence of several small-scale features.

Of these three depressions in the depth of the 20°C isotherm, only the one at 7°N (prime eddy) is clearly discernible in the map of the depth of the 15°C isotherm (Figure 2). Evidence of isotherm deepening appears in the three tracks, with

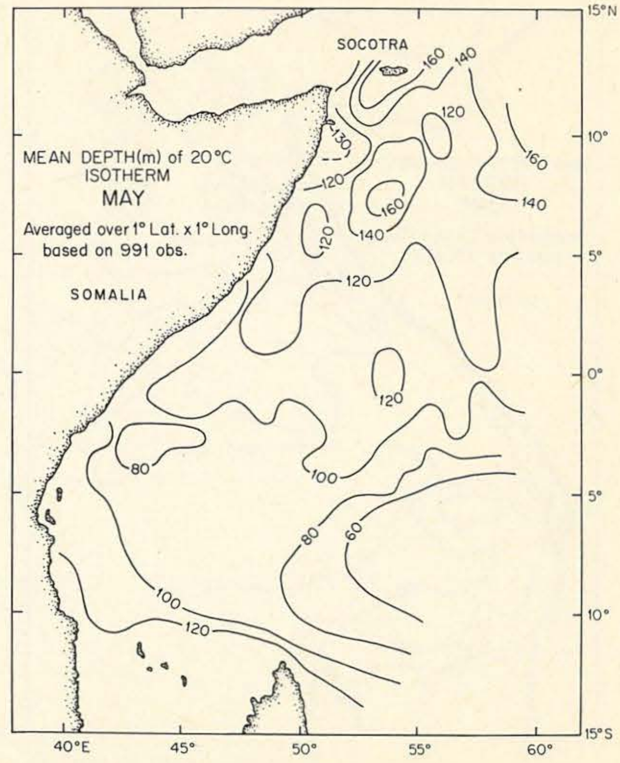

Fig. 3. Mean depth in meters of 20°C isotherm for May (see text for data sources).

TABLE 1. Number of Observations in Somali Basin Used for Construction of Figures 3 and 4

	38°–40°E	40°–42°	42°–44°	44°–46°	46°–48°	48°–50°	50°–52°	52°–54°	54°–56°	56°–58°	58°–60°E
					May						
12°N–14°N							6	1	9	3	0
10°N–12°N							6	14	30	19	1
8°N–10°N							12	24	11	3	9
6°N–8°N						2	7	26	4	4	8
4°N–6°N						9	22	9	4	4	11
2°N–4°N					11	2	20	14	5	2	1
0°N–2°N				15	3	11	10	5	37	1	1
2°S–0°		1	12	7	12	35	7	12	34	13	1
4°S–2°S		26	19	11	3	4	11	9	23	1	0
6°S–4°S	4	20	16	11	10	7	11	9	1	2	4
					June						
12°N–14°N								2	7	0	0
10°N–12°N							10	9	15	16	8
8°N–10°N							18	36	13	5	2
6°N–8°N						4	6	35	0	7	0
4°N–6°N						7	22	18	0	6	2
2°N–4°N					5	4	14	15	2	7	11
0°–2°N				8	2	15	4	3	10	10	32
2°S–0°			7	4	7	18	1	0	16	3	25
4°S–2°S		9	10	6	2	0	0	0	16	10	20
6°S–4°S	2	9	6	4	2	0	0	0	0	4	7

the greatest depths being >280 m. The southern feature apparently is not sufficiently deep to produce a recognizable feature.

There is evidence of the formation of the prime eddy in the mean maps (Figures 3 and 4, Table 1). During May a region in which the isotherm has commenced to deepen to over 140 m is centered about 7°N, 54°E, however, the only shoaling of the isotherm is along the Somali coast between the equator and about 4°N. By June the deepening has increased over a larger

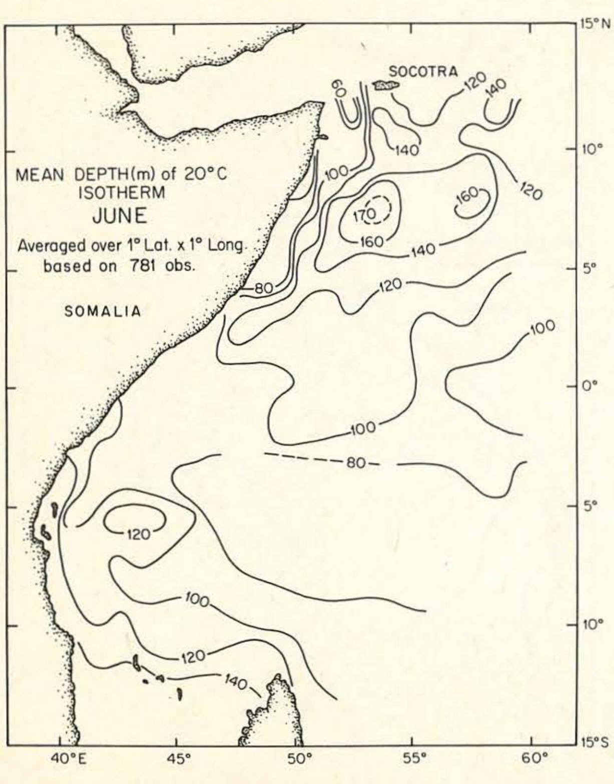

Fig. 4. Mean depth in meters of 20°C isotherm for June (see text for data sources).

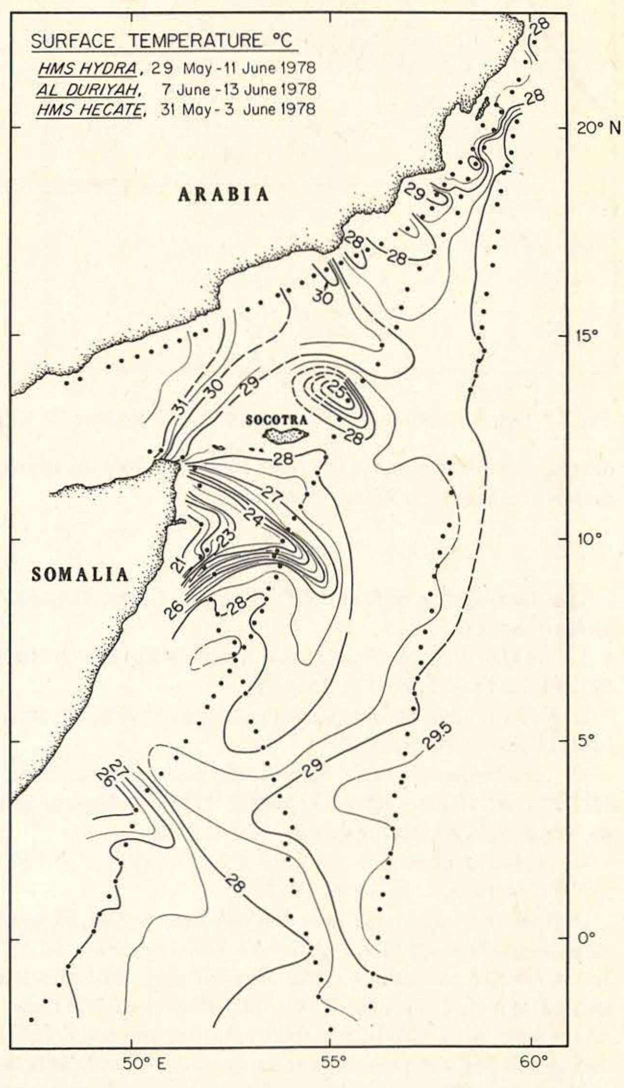

Fig. 5. Surface temperature, in degrees Celsius, May 29 to June 13, 1978.

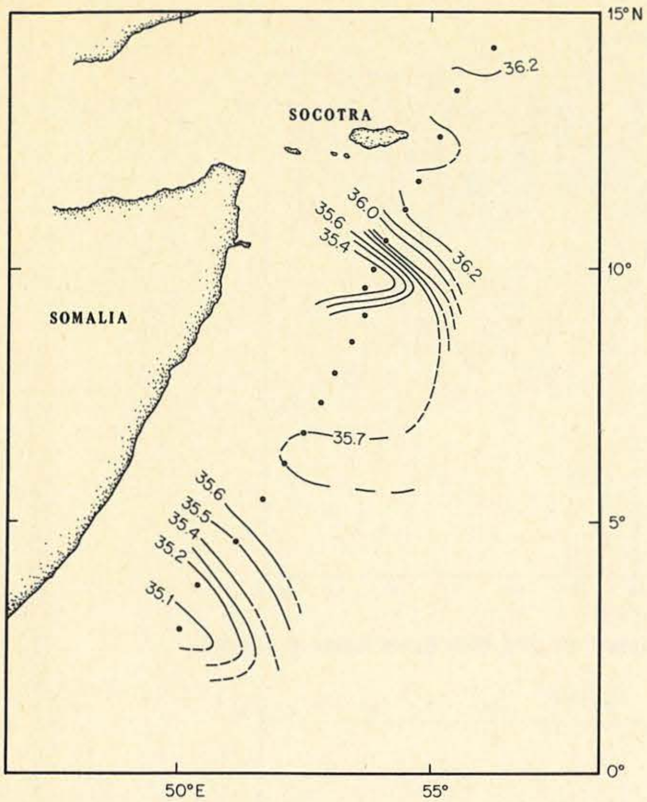

Fig. 6. Surface salinity, ‰, June 9–12, 1978, from Exxon tanker *Al Duriyah*.

area as has the shoaling along the coast north of 5°N to <80 m. However, tanker sections for May and June from previous years show that there is no significant deepening of the 15°C isotherm in this region. Average depths are around 220 m and no uplifting of the deep isotherms toward 10°–12°N was observed. Therefore in 1978 there seems to be an unusually deep development of the eddy at this stage of the SW monsoon.

The relatively cool and fresh characteristics of the Somali Current are evident at the height of the southwest monsoon [*Warren et al.,* 1966; *Bruce,* 1968] and can be useful in preparing maps to help delineate patterns of circulation. Maps of surface temperature and salinity drawn from our May 29 to June 13, 1978, observations (Figures 5 and 6) show that coastal upwelling around 10°N has already developed strongly with horizontal gradients of about 6°C over a degree of latitude and minimum temperatures of <21°C. Past surveys during August have observed water in this region with temperatures of <14°C [*Bruce,* 1974]. As during the period of maximum development of the eddy, the cold and fresh (<35.4‰) water is advected offshore to the east along the northern boundary of the anticyclonic eddy. To the south, the smaller circulation also is advecting the coastal water to the southeast.

The slope of the isotherms and horizontal thermal gradients along the sides of the prime eddy appear between 3°N and 10°N in both *Hydra* and *Al Duriyah* vertical sections (Figures 7 and 8). At the center of the eddy the gradients which appear to be associated with the eddy are present to about 300-m depth in these sections. The *Hydra* section, when compared with an August, 1964 *Discovery* section [*Swallow and Bruce,* 1966] which is on a similar track, shows that the deeper isotherms (15°–20°C) have not yet attained the pronounced slope found later during the monsoon, however, those >20°C are rather similar. The southern feature is relatively shallow appearing to extend from the surface to about 120-m depth at 2°N.

TIME EVOLUTION OF THE PRIME EDDY

The observations along essentially the same tanker sea lane (±20 n. mi. (±35 km)) both before (May 19–21, 1978, *Esso Osaka*) and after (July 6–8, 1978, *Esso Atlantic*) those of *Al Duriyah* may be used to follow the development of the eddy between 4°N and 12°N. The temperature sections of these two ships are shown by *Bruce* [1979]. We have estimated dynamic heights and geostrophic volume transports for the XBT stations along the three tanker and *Hydra* sections (Figure 9 and Table 2). A mean temperature-salinity (TS) distribution was assumed based on data from previous surveys in the western equatorial and Somali Basin region [*Bruce,* 1979]. The major changes in dynamic height during the southwest monsoon are a function of temperature [*Bruce,* 1979]. Errors incurred by assuming a unique TS relationship for all stations are unlikely to exceed ±0.03 dynamic meters (dy. m).

There is an increase of the dynamic height in the central region of the eddy from 1.23 dy. m (*Esso Osaka*) to 1.29 dy. m (*Al Duriyah, Hydra*) in 3 weeks then to 1.36 dy. m (*Esso Atlantic*) after another 3-week interval. Also the trough (10°N–11°N) on the northern edge of the eddy becomes correspondingly lower in value.

Offshore geostrophic volume transport (Table 2) across the tanker lane increases from 14.8 to 33.3 × 10^6 m^3 s^{-1} during this period, whereas maximum values occurring later during the fully developed circulation may reach 42 × 10^6 m^3 s^{-1} [*Bruce,* 1979]. The offshore transport through the *Hydra* section is 7.5 × 10^6 m^3 s^{-1} greater than that of the approximately contemporaneous *Al Duriyah* section and suggests a flow toward the north between Socotra and Cape Guardafui. The return flow to the west across the tanker lane in each case is

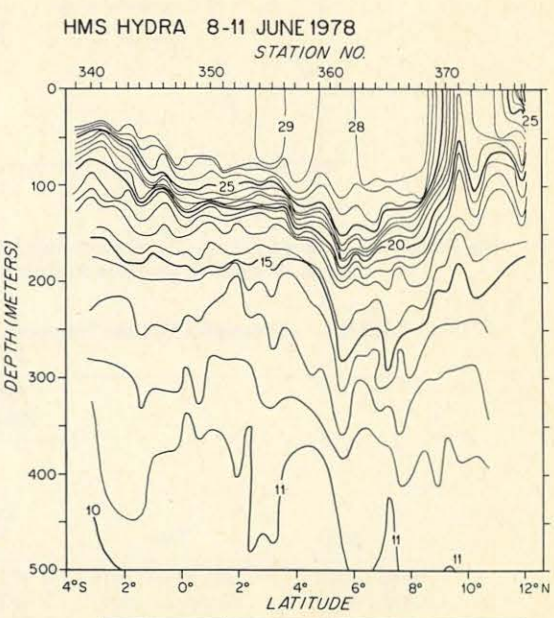

Fig. 7. Temperature section, in degrees Celsius, June 8–11, 1978, from *HMS Hydra*.

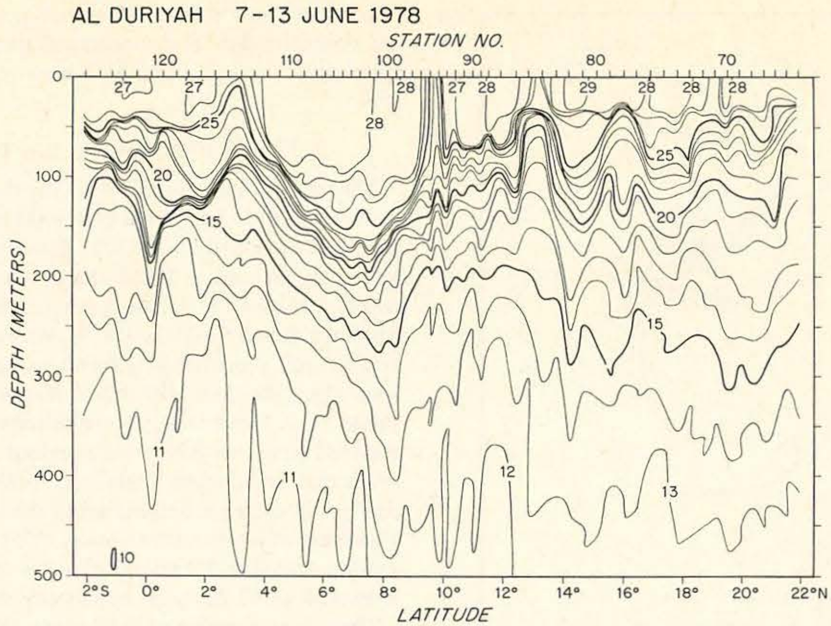

Fig. 8. Temperature section, in degrees Celsius, June 7–13, 1978, from Exxon tanker *Al Duriyah*.

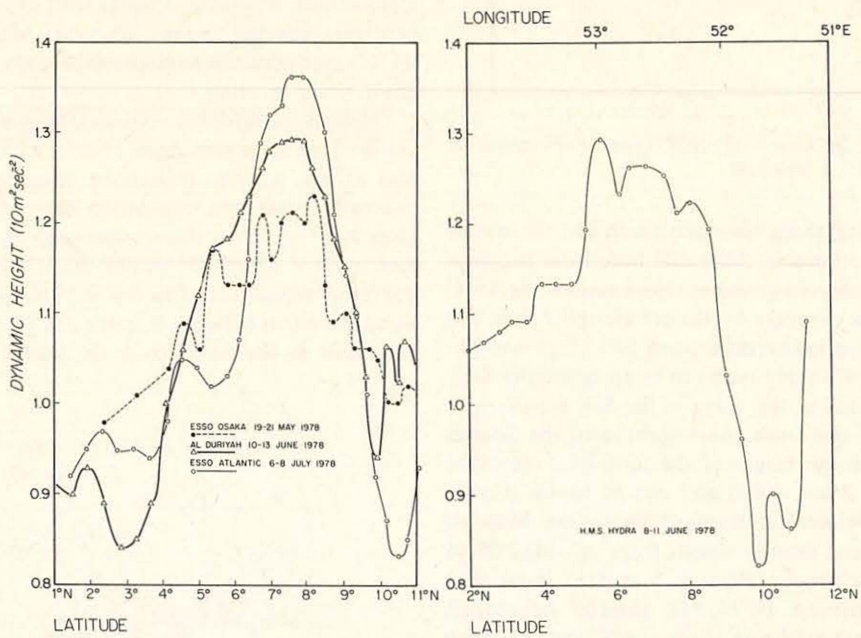

Fig. 9. Dynamic height (10 m^2 s^{-2}) of sea surface relative to 400 dbar along tanker sea lane, 1°N–11°N (left) for *Esso Osaka, Al Duriyah,* and *Esso Atlantic* and (right) for *HMS Hydra* (see Figure 1 for tracks).

TABLE 2. Geostrophic Volume Transport, 0–400 dbar, Relative to 400 dbar of Prime Eddy in Somali Basin (4°N–12°N)

		Offshore Transport, Northern Part of Eddy		Azimuth of Section, deg	Onshore Transport, Southern Part of Eddy	
Ship	Date	Latitude Range	Volume Transport, $\times 10^6$ m^3 s^{-1}		Latitude Range	Volume Transport, $\times 10^6$ m^3 s^{-1}
Esso Osaka	May 19–21, 1978	8°10′N–11°15′N	15	030	4°10′N–8°10′N	23
HMS Hydra	June 8–11, 1978	5°40′N–9°50′N	27	345	4°00′N–5°40′N	28
Al Duriyah	June 9–13, 1978	7°50′N–9°50′N	19	030	4°10′N–7°50′N	39
Esso Atlantic	July 6–8, 1978	7°30′N–10°30′N	33	030	4°10′N–7°30′N	45

Data from XBT stations with same TS distribution assumed for each station (TS are mean values determined from past surveys).

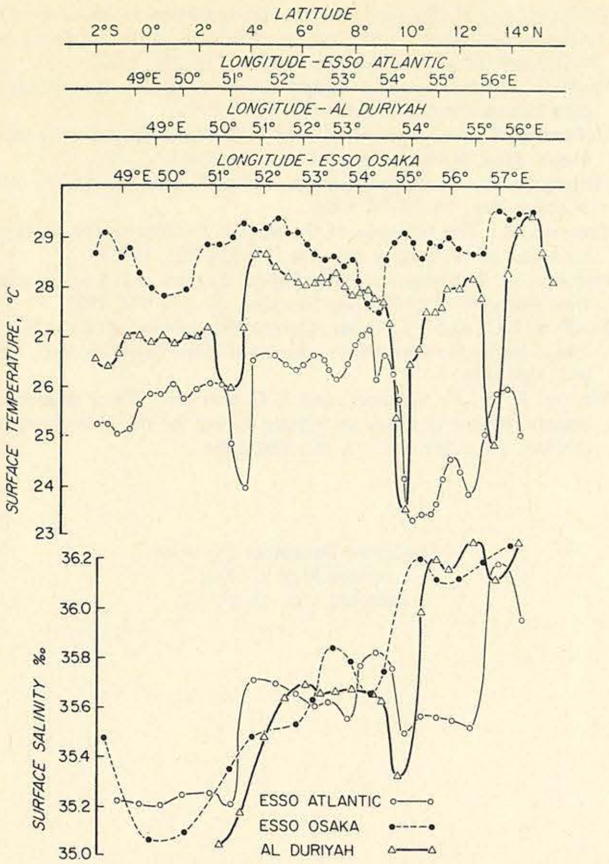

Fig. 10. Surface temperature, degrees Celsius (top), and surface salinity, ‰ (bottom), along tanker sea lane (2°S–15°N) for *Esso Osaka,* May 18–22, 1978; *Al Duriyah,* June 9–13, 1978; and *Esso Atlantic,* July 6–9, 1978.

larger than the offshore value and may in part be due to additional water advecting into the eddy from the southeast.

Surface temperature and surface salinity along the tanker sections from 2°S to 15°N for *Esso Osaka, Al Duriyah,* and *Esso Atlantic* further serve to follow the development of the Somali Basin eddies (Figure 10). The increase in the signal of the relatively cold, fresh surface water originating in the South Equatorial Current and in the upwelling regions which is advected offshore along the northern edge of both eddies as the southwest monsoon progresses is apparent at 10°N and 2°N–4°N. In May the salinity increases roughly linearly toward the north while in the later stages the profiles have sharp gradients at the eddy boundaries. The increased horizontal mixing within the eddies tends to produce plateaus in the surface salinity profiles, e.g., *Al Duriyah,* 5°N–9°N. An overall decrease in the surface temperature with time also may be seen.

Wind Observations

Observations of surface winds along the tanker lane and at three coastal stations in Somalia show the reversal of the wind field over the western Indian Ocean in 1978. In Figure 11 wind vectors are plotted for four different time periods between March and June.

At the end of March the general airflow was still northeasterly. Two weeks later in April the monsoon reversal started and winds south of 5°N became southeasterly. Speeds, however, were still less than 5 m s^{-1}. The southwest monsoon wind field developed along the Somali coast during April. The actual onset defined by a change in direction of more than 90° and reaching 50% of wind speed of the fully developed southwest monsoon [*Fieux and Stommel,* 1977] progressed northward. The time series of wind observations from the coastal stations indicate an onset at Chisimaio on March 27 and at Obbia on May 1. By mid-May the reversal was completed and wind speeds reached 16 m s^{-1} at 10°N and increased to more than 23 m s^{-1} in early June. By that time the pattern of airflow was similar to that observed in earlier investigations [e.g., *Findlater,* 1971].

At around 2°N–3°N the wind field appears to have a discontinuity after mid-May. The wind developed a strong offshore component and during this initial phase of the southwest monsoon the wind speeds increased from 3 to 10 m s^{-1}. This aspect of the wind field might account in part for the development of the offshore current in this region.

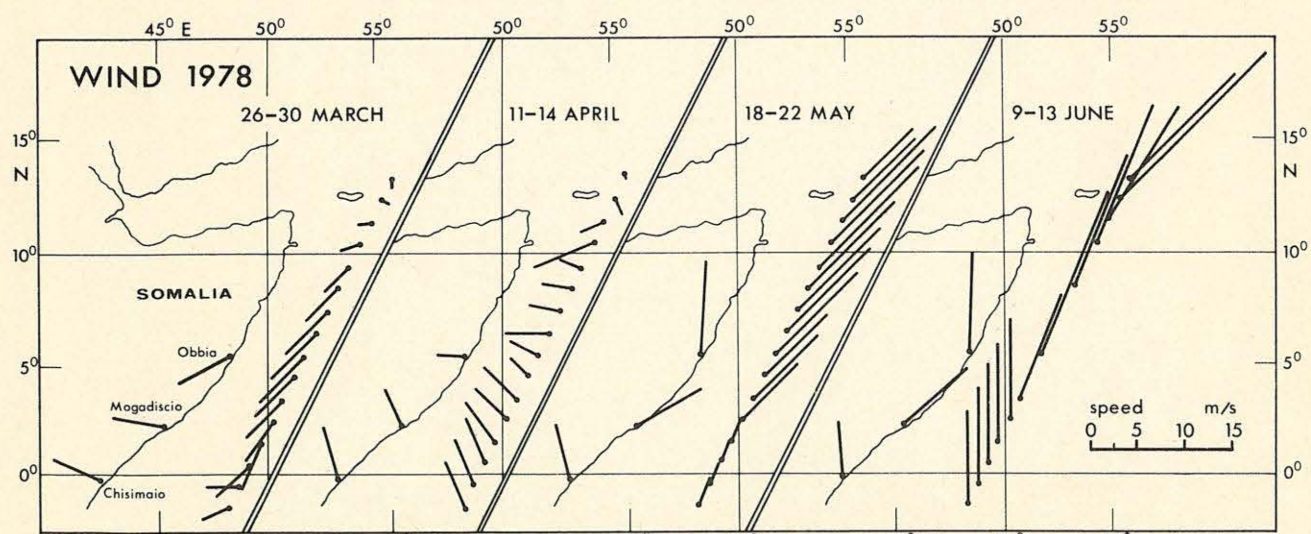

Fig. 11. Surface winds during commencement of southwest monsoon 1978 along tanker sea lane and three shore stations. Note that stick vectors are pointing in the direction toward which wind is blowing.

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2. Southwest monsoon
3. Eddies

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An early stage of the Somali eddy circulation was mapped in the period May 29 to June 13, 1978, using expendable bathythermograph data at closely spaced stations. By this time the SW monsoon had been blowing at 5°N for about 4 weeks and the large anticyclonic eddy in the northern Somali Basin was clearly discernible between 3°N an 10°N. It is estimated that the offshore transport at this time was approximately half of that occurring during the period when the eddy reaches maximum size and strength during August and September. A smaller southern eddy was observed just offshore between the equator and 3°N.

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An early stage of the Somali eddy circulation was mapped in the period May 29 to June 13, 1978, using expendable bathythermograph data at closely spaced stations. By this time the SW monsoon had been blowing at 5°N for about 4 weeks and the large anticyclonic eddy in the northern Somali Basin was clearly discernible between 3°N and 10°N. It is estimated that the offshore transport at this time was approximately half of that occurring during the period when the eddy reaches maximum size and strength during August and September. A smaller southern eddy was observed just offshore between the equator and 3°N.

1. Somali current
2. Soutwest monsoon
3. Eddies

I. Bruce, J.G.
II. Quadfasel, D.R.
III. Swallow, J.C.
IV. N00014-74-C-0262; NR 083-004
V. N00014-79-C-0071; NR 083-004

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