# Some observations of the coalescing of Somali eddies and a description of the Socotra eddy

Somali current
Indian Ocean eddies
Southwest monsoon
Eddy coalescence
Courant de Somalie
Tourbillons de l'Océan Indien
Mousson Sud-Ouest
Rencontre de tourbillons

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ABSTRACT

The eddy circulation pattern in the Somali Basin was observed to shift during the latter part of the 1979 southwest monsoon. Measurements were obtained from research vessels and from tankers taking repeated XBT sections along the standard offshore sea lane. Initially the current turned strongly offshore between 4°N-6°N forming a loop or eddy to the south of the northern eddy which turned offshore at about 10°N. This pattern resulted at the surface in two wedges of relatively cold and fresh upwelled water along the coast similar to the type of circulation observed during a 1970 survey. However by late August the location of the southern turn off point had shifted northward and the coastal boundary current then merged and flowed into the northern eddy. This flow pattern produced a relatively fresh and cold cell in the near surface water on the western portion of the northern eddy. By October the circulation appeared to have reverted back to a pattern somewhat similar to that observed during the earlier (June, July) part of the monsoon. Observations of the Socotra eddy circulation indicate that it develops each southwest monsoon approximately between 10°N-14°N and during some years its horizontal and vertical scale approaches that of the northern Somali eddy.

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RÉSUMÉ

Observation de la rencontre de tourbillons océaniques dans le bassin de Somalie et description du tourbillon Socotra (Océan Indien)

Un changement de la circulation tourbillonnaire dans le bassin de Somalie a été observé en 1979 à la fin de la mousson Sud-Ouest. Les données proviennent des sections XBT effectuées par des navires de recherche et des pétroliers le long de la route maritime normale. Au début, le courant se détachait brusquement de la côte entre 4° et 6°N, en formant un anneau ou tourbillon situé au sud du tourbillon Nord, ce dernier se détachant de la côte vers 10°N. Cette situation avait pour résultat deux remontées d'eaux froides et peu salées jusqu'en surface le long de la côte, comme il avait déjà été observé lors d'une campagne effectuée en 1970. A la fin août, cependant, la position du point méridional où le courant se détache de la côte s'était déplacée vers le Nord, et le courant limite côtier se fondait alors dans le tourbillon Nord. Cette nouvelle situation créait une cellule d'eau dessalée et froide dans les couches superficielles de la partie ouest du tourbillon Nord. En octobre, la circulation semblait être retournée à un état proche de celui observé au début de la mousson (juin-juillet). Les observations de la circulation du tourbillon Socotra montrent qu'il se développe à chaque mousson du Sud-Ouest, approximativement entre les latitudes 10°N et 14°N et que, certaines années, son extension horizontale et verticale est voisine de celle du tourbillon Nord de Somalie.

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## INTRODUCTION

The seasonal variations in the structure of the upper layers (0-500 m) of water off the Somali and Arabian coasts have been observed for a period from October 1975 through December 1979 by a series of fifty-five temperature sections from expendable bathythermograph (XBT) probes along the regular tanker sea lane (Bruce, 1979; 1981; Fig. 1). Fifteen of these sections (Fig. 2) were obtained during the 1979 FGGE observational period when several cooperative studies were made of the Somali current circulation during the southwest monsoon. Many of these have been reported in *Science* (*see* Swallow, 1980). All XBT sections presented in Figure 2 along the sea lane are within approximately 15-20 n mi of each other. The tankers were equipped with satellite navigation, and the strong east-west set by currents across the lane could be corrected relatively quickly (est. of 2 to 3 hours). Although the major observational period for the research vessels involved in FGGE was during the initial phase of the monsoon (April-June), data were also collected later in the monsoon and after it ceased by the tanker XBT program and by USNS *Wilkes*.

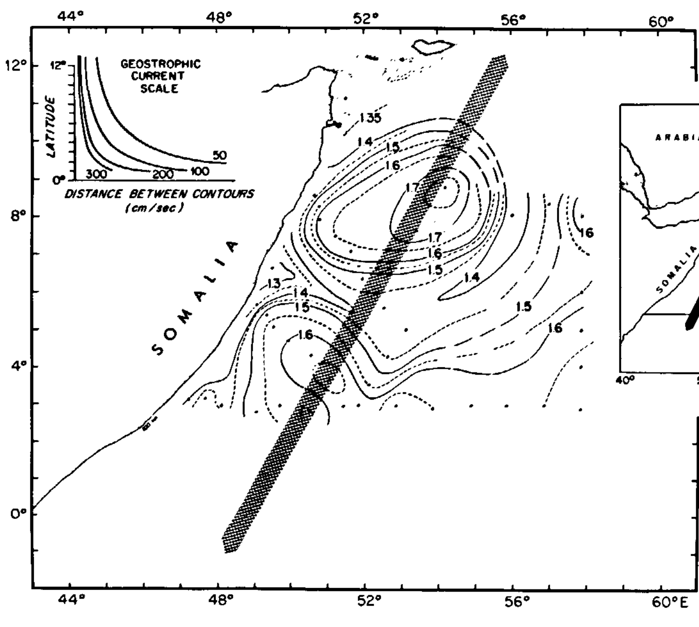
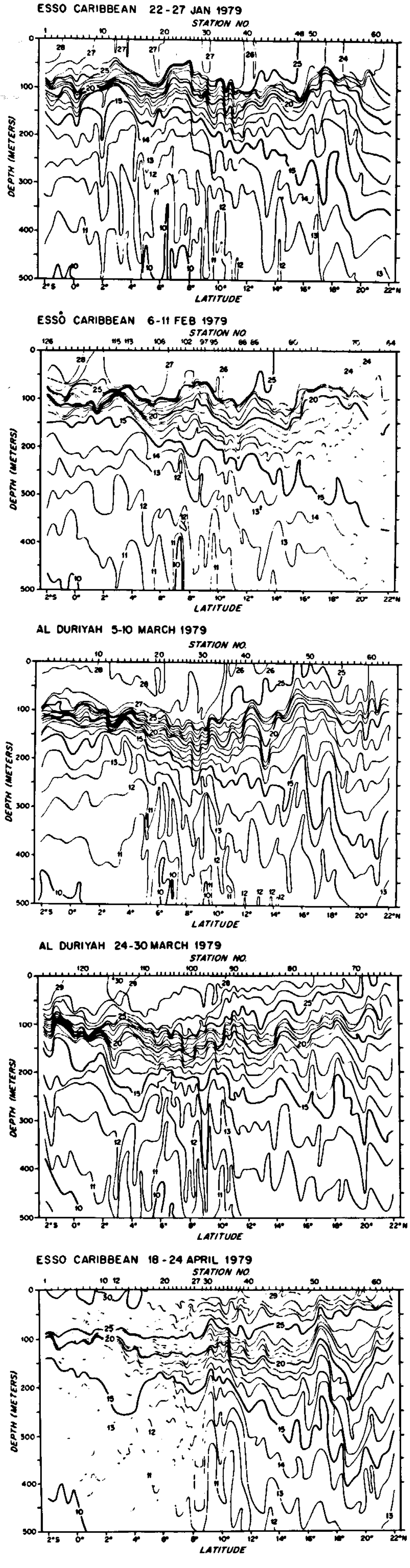



Figure 1

*Portion of sea lane used by tankers passing through Somali Basin along which XBT sections (Fig. 2) were obtained. Surface dynamic topography (rel.* 1 000 *dbar) from* 4-20 *August* 1970 *(Bruce,* 1973) *shows how sea lane is situated relative to the eddy field during the southwest monsoon. Inset shows entire section,* 2°*S to* 22°*N.*



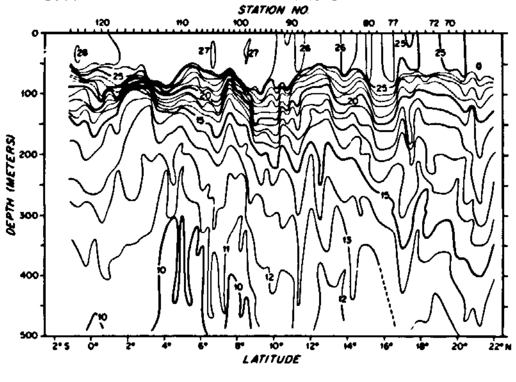
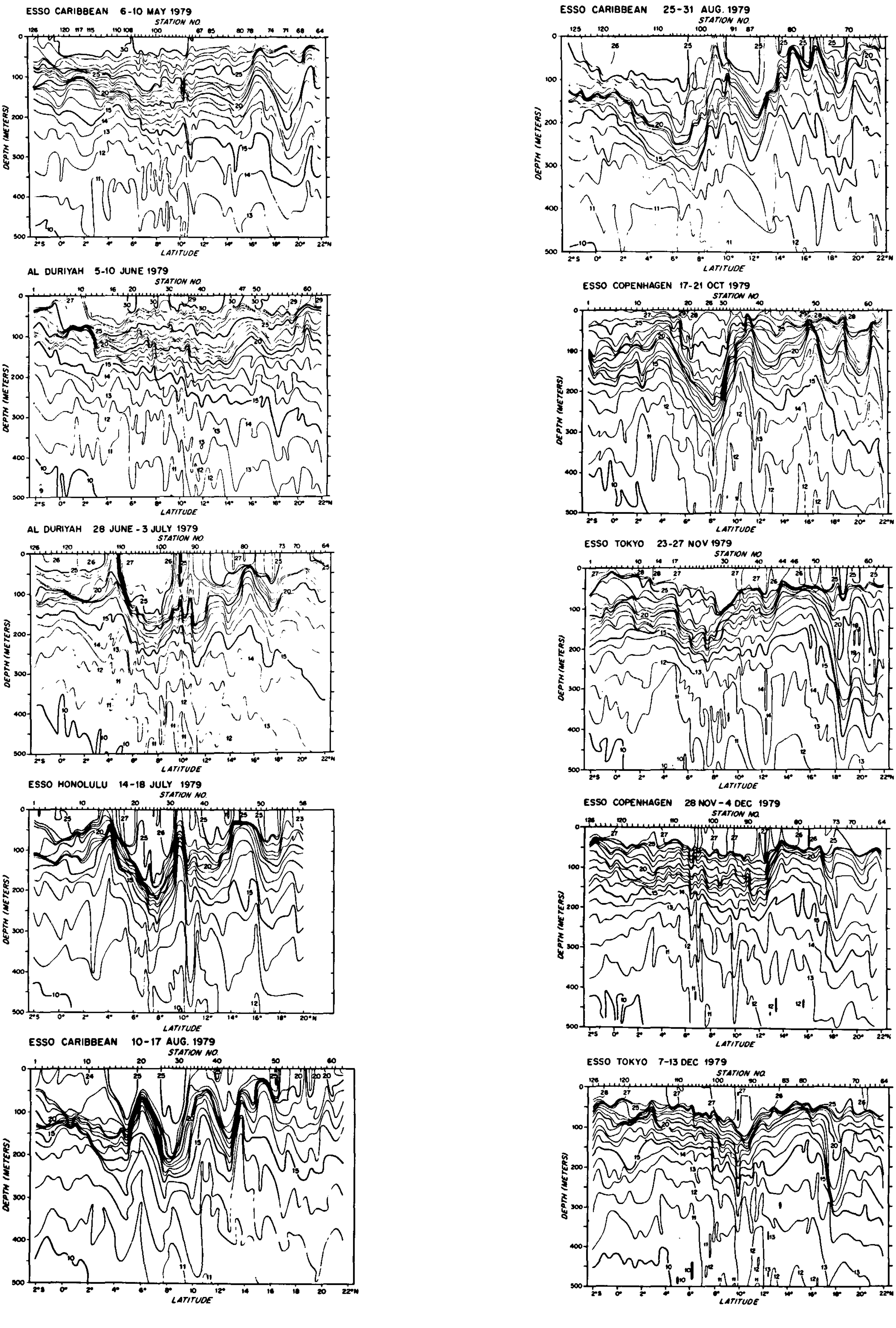




Figure 2

*Temperature (°C) sections along tanker sea lane (Fig. 1) from 2°S to 22°N (see Bruce, 1979) using XBT data.*


ESSO CARIBBEAN 6-10 MAY 1979
AL DURIYAH 5-10 JUNE 1979
AL DURIYAH 28 JUNE - 3 JULY 1979
ESSO HONOLULU 14-18 JULY 1979
ESSO CARIBBEAN 10-17 AUG. 1979
ESSO CARIBBEAN 25-31 AUG. 1979
ESSO COPENHAGEN 17-21 OCT 1979
ESSO TOKYO 23-27 NOV 1979
ESSO COPENHAGEN 28 NOV - 4 DEC 1979
ESSO TOKYO 7-13 DEC 1979
STATION NO.
DEPTH (METERS)
LATITUDE

From earlier observations (Bruce, 1973; 1979; Swallow, Fieux, 1982) it was found that during certain years such as 1970 and 1976 the northeastward coastal (Somali) current turned strongly offshore to the east at about 4°N-6°N. During 1976 a series of satellite tracked drifters set in this current and drogued at 10 and 80 m were reported by Regier and Stommel (1976) to have clockwise trajectories suggesting an eddy motion between about 4°N-3°S from the coast out to about 54°E. Part of the flow after turning offshore during 1970 and particularly during June 1979 was observed to extend southward toward the equator (Leetmaa *et al.*, 1982; Swallow, Fieux, 1982; Swallow *et al.*, 1983; Duing *et al.*, 1980). From the observations it appears that some of this flow was probably recirculated back into the coastal current. This circulation pattern was observed to the south of the large northern eddy which has been observed to develop each year of observation between 5°N-12°N (Bruce, 1979). A wedge of cold water at the surface to the left of the current occurs in the region where the flow turns offshore both at ~5°N and ~10°N. The surface dynamic topography associated with this mode of Somali Basin circulation which was observed during the first part of August 1970 (Bruce, 1973) is illustrated in Figure 1. Throughout the latter part of August, during that year, the location of the southern turn-off position shifted northeastward along the coast commencing from ~5°N and proceeding northeastward to ~8°N-9°N. By September the current system which had comprised the southern eddy had merged in part with the northern one. The major portion of the coastal current now continued to flow along the coast with only a relatively small flow turning offshore at 5°N-6°N. The coastal current to the north was entrained in the northern eddy and turned offshore at ~10°N. The surface salinity maps (*see* Fig. 3 of Bruce, 1973) for August and September illustrate the changes in the surface circulation pattern as this redirection of flow took place. Because of the northward transport of relatively fresh water (~ <35.2‰) in the coastal current, it is possible to trace the changing circulation pattern of surface and near surface water by quasi-synoptic mapping.

## 1979 Southwest monsoon

During 1979 a similar shift in the southern circulation was observed. The sequence of temperature sections from the XBT stations along the tanker sea lane (Bruce, 1979) between 2°S to 22°N (Fig. 1) presented in Figure 2 was obtained at intervals throughout 1979. As many sections as could be scheduled were obtained within the period of the southwest monsoon. During the first half of the year (to June) the main vertical temperature gradient occurred generally between 80-175 m in the Somali basin region (2°N-12°N) and although there were small features imbedded within the structure, there did not appear to be any large scale feature noticeable from one section to the next from December 1978 through the 5-10 June 1979 section. The upper layer is seen to be relatively well mixed vertically and tended to be isothermal through late

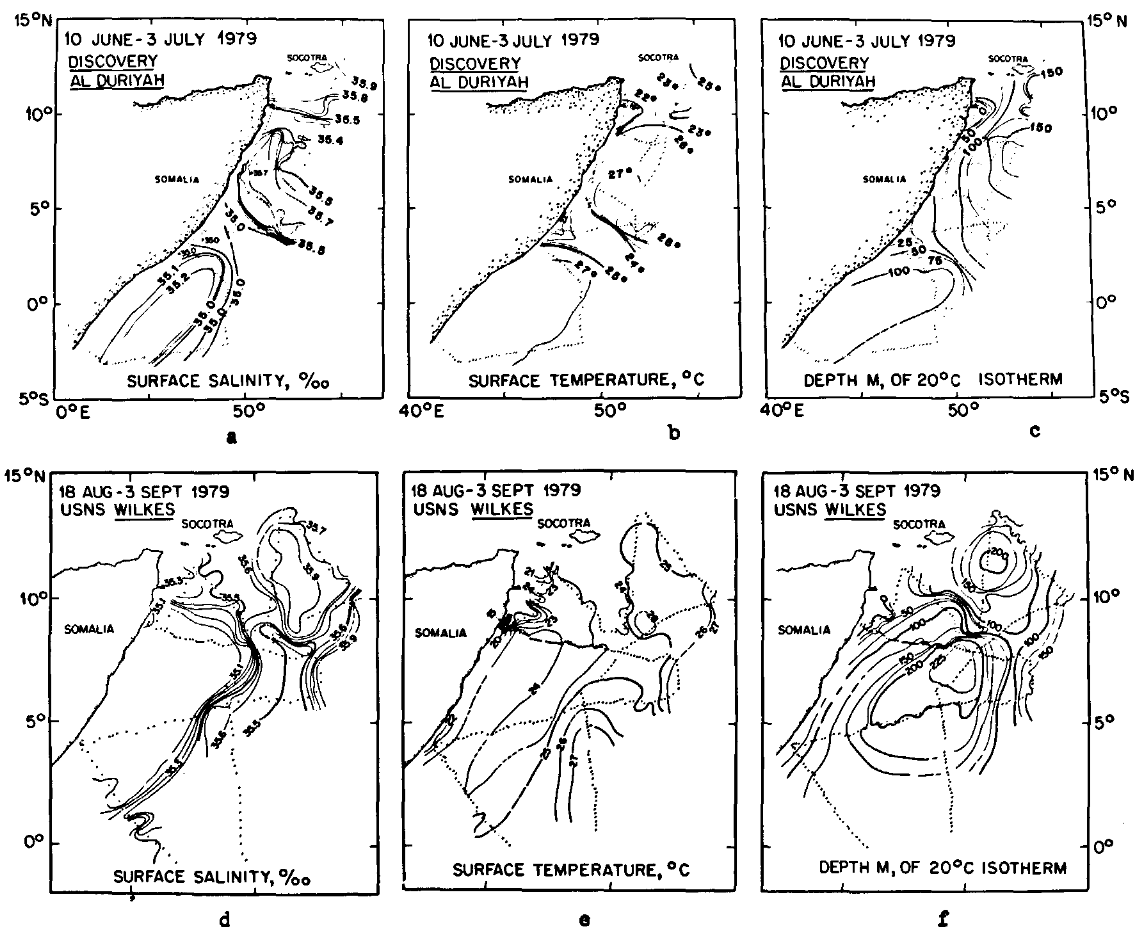



Figure 3
*a) surface salinity; b) surface temperature; and c) depth of 20°C isotherm, 10 June-3 July 1979. d) surface salinity; e) surface temperature; and f) depth of 20°C isotherm, 18 August-3 September 1979.*

March. By this time the mixed layer temperature had increased with the spring warming. By the 18-24 April section near surface temperatures had approached 29°-30°C and a noticeable vertical temperature gradient occurred in the 25-100 m layer, this persisting into early June. Such a gradient might be expected under conditions of weak wind. Although the wind switched to a northward direction all along the coast by early May (Schott, Fernandez-Partagas, 1981), they were relatively weak until mid-June when the southwesterly winds picked up with speeds to 20 m/s.

By late June (*Al Duriyah*, 28 June-3 July) the temperature structure between 5°N-10°N along the section indicates that the northern eddy had clearly developed, the mixed layer depth (6°N-8°N) now being greater than 150 m. The strong horizontal temperature gradient in the upper 100 m near 4°N-5°N indicates where the westward flow of the northern eddy and the eastward flow of the southern circulation had developed. This general pattern persists in July (*Esso Honolulu*, 14-18 July) and is similar to the tanker sections obtained during 1976 (Bruce, 1979) when a southern turn off was indicated in all the XBT sections obtained during the southwest monsoon that year. The late June-early July 1979 near surface circulation pattern, mapped from observations of *Discovery* and the Exxon tanker *Al Duriyah*, is indicated in part by Figure 3 *a*, *b*, and *c* (*see* Swallow *et al.*, 1983). At this time the surface salinity was a particularly good means of tracing the relatively fresh ($<35.2^0/_{00}$) coastal water turning offshore in the southern flow. By mid-August (Fig. 2, 10-17 August) the northern boundary of the southern flow was observed at approximately 6°N which is nearly 200 km to the north of its mid-July location. Then by the end of August (*Esso Caribbean*, 25-31 August) a further shift northward of the boundary occurred (to about 9 1/2°N) giving evidence for a coalescence of the southern circulation with the northern one (*see* Brown *et al.*, 1980; Evans, Brown, 1981). Further data collected at this time from USNS *Wilkes* (Fig. 3 *d*, *e*, *f*) shows the resulting circulation by maps of surface salinity, surface temperature and the depth of the 20°C isotherm (Swallow *et al.*, 1983). Estimates of current strength from ship's set (Fig. 4) during this cruise indicate speeds of 250-300 cm s$^{-1}$ toward the northeast in the near coastal region (9°N). Farther offshore the current is to the east and then to the southeast to the east of 55°. A strong onshore component occurs at ~5°N, 54°-56°E and to the east of this an offshore surface current associated with the front mapped in Figure 3 *d* and 3 *f* is shown. The relatively fresh near surface water (Fig. 3 *d*) ($<35.2^0/_{00}$) is contained west of 55°E, however, the deep eastern boundary of the northern eddy as suggested by the 20°C isotherm depth map (Fig. 3 *f*) extends east as far as approximately 57°E. Thus at the time of this survey the near surface relatively fresh water mass extended only over the western and central portion of the northern eddy. The T-S characteristics of this water are shown in Figure 5, stations 10 and 15.

Station 10 (5°01'N, 51°52'E) is near the eastern boundary of the fresh layer which is about 100 m deep (*see* Fig. 3 *d*). Farther north this layer is over 150 m deep at station 15 (8°27'N, 51°42'E).

By the 17-21 October (Fig. 2) section the circulation appears to have returned to one somewhat similar to that found in July, having a relatively strong horizontal near-surface temperature gradient occurring near 5°N. Note that again during the October interim period

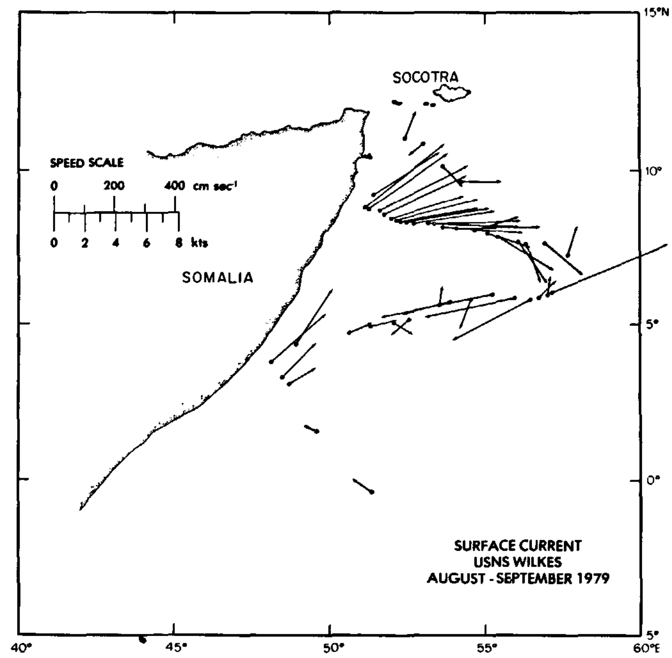



Figure 4
*Surface current as determined from ship's set.*

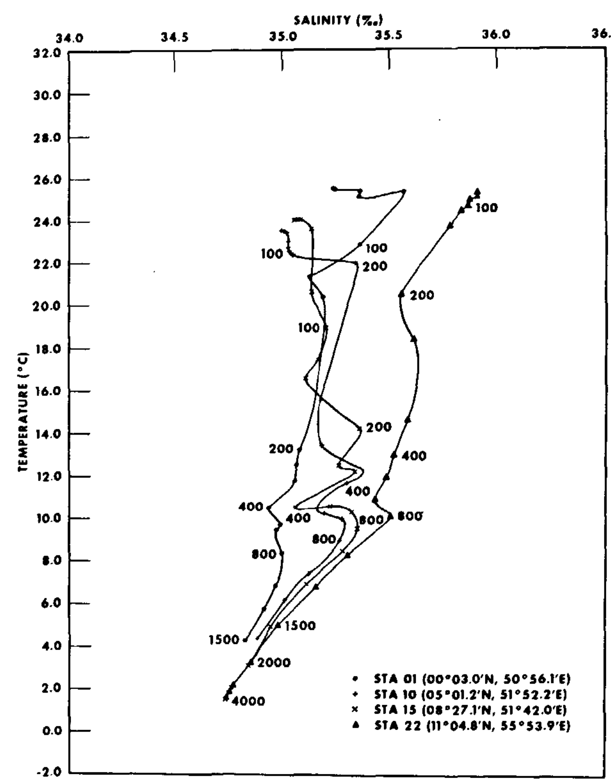



Figure 5
*T-S relationships from* 1979 *USNS Wilkes STD station* 1 (18 *August*), *station* 10 (21 *August*), *station* 15 (25 *August*), *and station* 22 (29 *August*). *Depths in meters given at intervals along T-S curves* (*Beatty* et al., 1981).

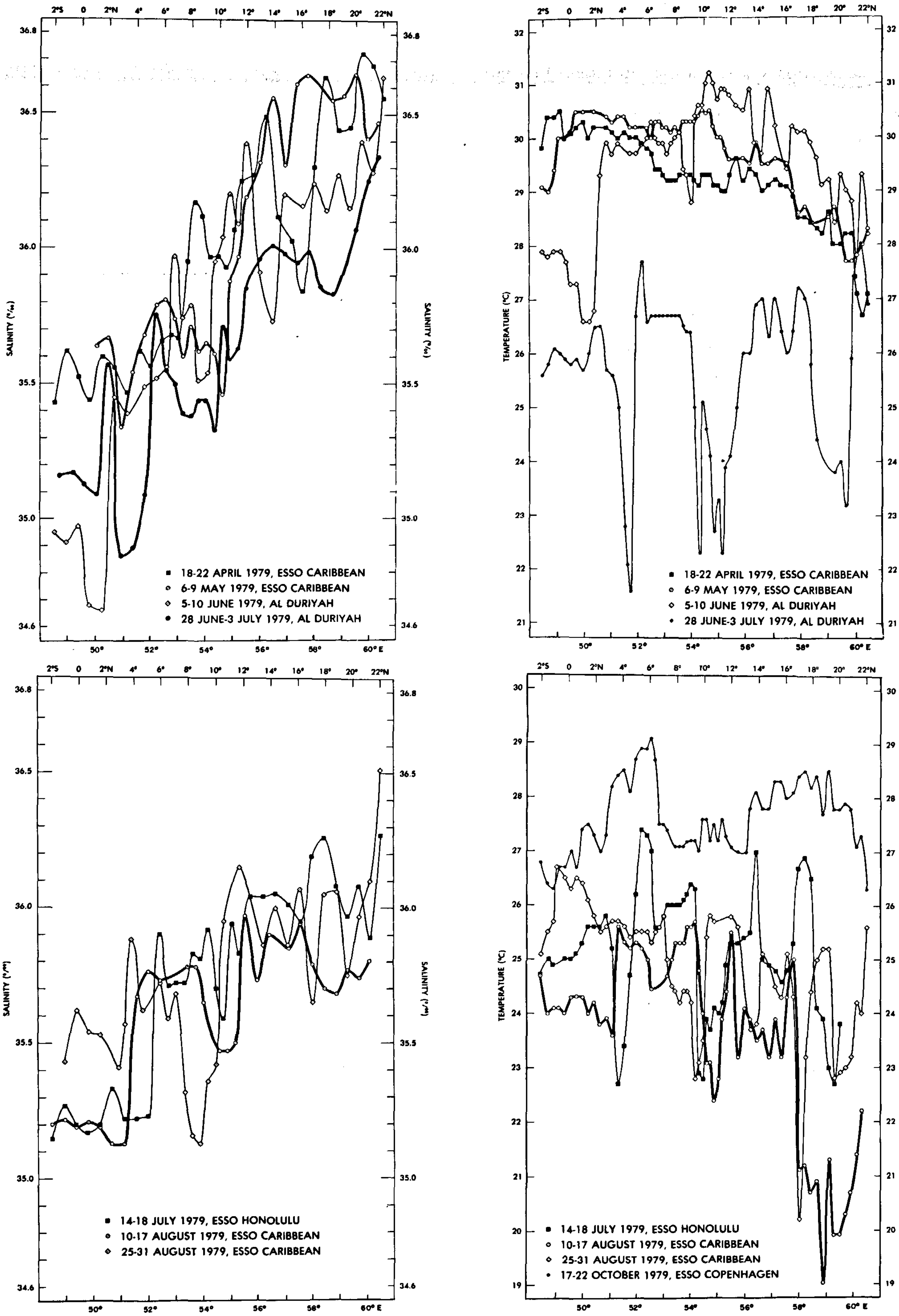



Figure 6
*Surface salinity ($^0/_{00}$) and temperature (°C) along tanker sea lane.*

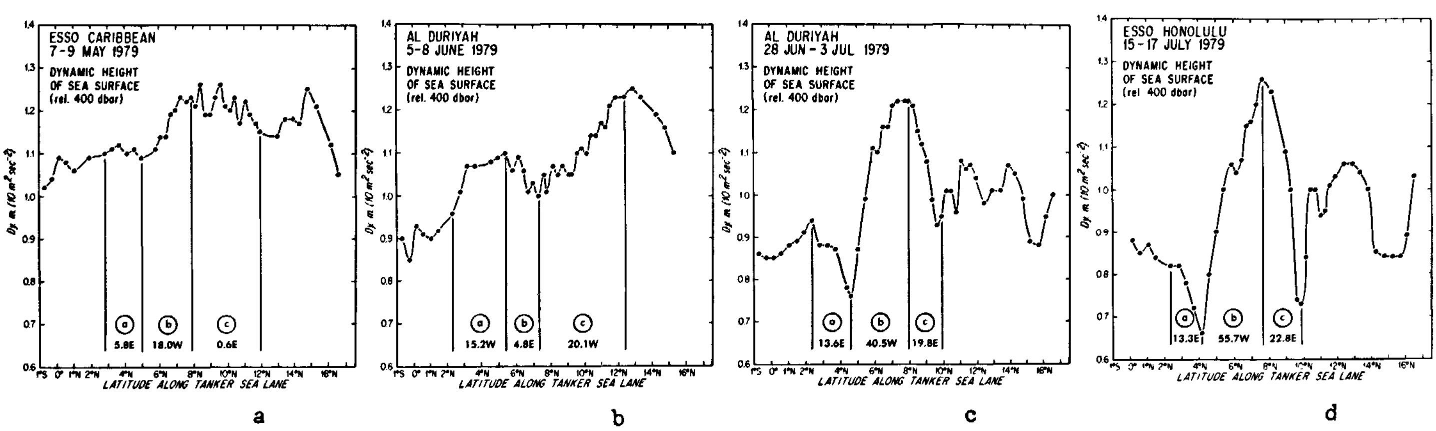
between monsoons when light winds occur (Hastenrath, Lamb, 1979) the upper layer has a vertical temperature gradient similar to that found in April. After October the structure of the northern eddy had weakened, however, the horizontal gradients still give evidence for the existence of the northern eddy (9°N-11°N) in the last section that was run in the series (7-13 December).

The shift of the eddy between July and late August can be seen in satellite imagery for that period (Brown *et al.*, 1980; and Swallow *et al.*, 1983).

**Surface salinity and temperature**

Surface salinity and temperature observations during 1979 obtained with the XBT sections (Fig. 6) on the tanker sea lane often can serve as a monitor of the surface flow patterns in the Somali Basin (Bruce *et al.*, 1980). The eddies formed during the southwest monsoon often extend offshore 400-500 km (Fig. 1). As the monsoon advances, increasing amounts of the relatively cool and fresh water from the coastal current and region of upwelling are advected offshore across the sea lane.

The surface salinity and temperature values for 18-22 April (Fig. 6) were obtained during the transition between monsoons before the wind turned toward the northeast (Schott, Fernandez-Partagas, 1981). Both of these measurements and those during 6-9 May and 5-10 June indicate the relatively high salinity and temperature occurring during the late northern spring warming period. The May surface salinity shows minimums between 3°N-4°N and near 10°N, and the early June values of both salinity and temperature have minimums at 8°N-9°N and particularly at ~1°N as the current turning offshore advected the relatively fresh ($<34.7^0/_{00}$, 5-10 June) and cold coastal water to the east. The near surface direct current measurements (Leetmaa *et al.*, 1982; Swallow *et al.*, 1983) indicate that the circulation pattern at this time was comprised of a strong southern turn-off (~2°N) (the fresh water in this southern circulation is basically South Equatorial Current Water, SECW, *see* Swallow *et al.*, 1983) and the northern eddy developing as shown by Figure 3 *a*, *b*, *c*. The surface dynamic topography (Fig. 7 *a b*) shows the early stage of the weak high of the northern eddy which, as observed along the XBT sea lane, appears to shift from about 7°N-11°N (7-9 May) to 3°N-8°N (5-8 June), then back to a more northerly location of about 5°N-10°N (28 June-3 July). By this time the high had become relatively well developed (Fig. 7 *c*). Also by the end of June (28 June-3 July) the surface signature of the fresh, cold band at 3°N-5°N which had been advected eastward offshore from the southern turn off region of the Somali current is clearly shown in Figure 6. At this time surface temperatures at 10°N-11°N indicate also that cooler upwelled water was brought offshore by the northern eddy. However the surface salinity here was ~$35.3$-$35.4^0/_{00}$ suggesting that much of the low salinity SECW was turning offshore with the southern eddy. Observations of the coastal flow during this time (Leetmaa *et al.*, 1982) suggest that varying amounts of leakage along the coast into the northern eddy can occur. The effects of the leakage is seen by the variation in the surface salinity north of 8°N in Figure 6 during July and August. By the time of the 25-31 August section, however, the translation of the southern eddy northward was occurring resulting in coalescence with the northern



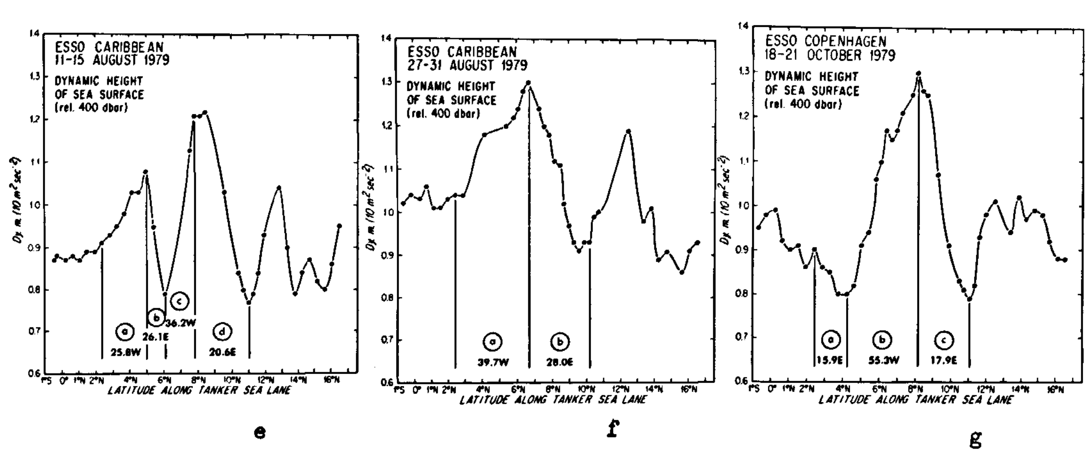




Figure 7

*(a to g) Sea surface dynamic topography (rel. 400 dbar) constructed from XBT data along the tanker sea lane during the 1979 southwest monsoon. Mean salinity from hydrographic data in this region was used to establish a single T-S curve employed for all topography shown here. Volume transport* ($10^6 m^3 s^{-1}$) *across sections is given under circled letters (also see Tab. 1).*

eddy (Fig. 2 and 3). The surface salinity was now lower (~35.1$^0/_{00}$) near 9°N than that found to the south. During August as shown by Figures 2, 6, and 7, and by Swallow *et al.* (1983) relatively large variations can occur in the thermal structure and dynamic topography during the period of coalescence. The observations from the *Wilkes* survey in late August-early September 1979 took place during this period of relatively rapid change as indicated by the satellite imagery (Evans, Brown, 1981) at which time the southern cold wedge propagated approximately 36 cm $s^{-1}$ northeastward along the Somali coast.

## Surface dynamic topography and volume transport

The variation of sea surface dynamic topography along the tanker sea lane during the 1979 southwest monsoon (7 May-21 October) using XBT data is given in Figure 7 *a-g*. The same T-S relationship is used for all determinations of dynamic height with the values of salinity acquired from earlier hydrographic surveys in this region during this time of year (Bruce, 1979; Bruce *et al.*, 1980). In general the larger variations in dynamic height, particularly during the southwest monsoon are mostly a function of temperature. Judging from salinity variations as observed in the upper layers of the Somali Basin during 1979 (Swallow *et al.*, 1983) and from those for the surface salinity between 1°S to 17°N from the tankers (Fig. 6), it is estimated that the resulting errors from assuming a fixed T-S distribution would generally be less than ±0.03 dynamic meters across the fronts of the eddies (also *see* Bruce *et al.*, 1980). The overall change of dynamic height along the sections (1°S-17°N, Fig. 7), where the salinity of the upper layer might change as much as 1$^0/_{00}$, could be about ±0.06 dynamic meters. As indicated by Bruce (1968), the T-S distribution within the boundaries of the northern eddy tends to be relatively tight. Volume transports (0-400 dbar, relative to 400 dbar) across the sections are given for the portion within the Somali Basin eddy field (approximately 2°N-12°N). A more detailed listing of transport values by 50 m intervals is presented in Table 1. Averages for all seven sections show that 66 percent of the transport lies in the upper 100 m and 91 percent in the 0-200 m layer. During the early stage of the 1979 monsoon (7-9 May, Fig. 7 *a*; and 5-8 June, Fig. 7 *b*) there is no clearly distinctive topographic high of mesoscale dimension in the region where the northern eddy historically occurs. However, during approximately the same time period in 1978 the

Table 1
*Southwest monsoon 1979. Volume transport in $10^6 m^3 s^{-1}$ rel. 400 dbr from XBT sections off Somali coast.*

| | | From latitude longitude | To latitude longitude | By 50 m depth intervals | | | | | | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 0-50 | 50-100 | 100-150 | 150-200 | 200-250 | 250-300 | 300-350 | 350-400 | 0-400 |
| *Esso Caribbean* 7-9 May 1979 | *a* | 2°50′N 51°05′E | 5°00′N 52°14′E | 0.1 E | 0.4 E | 1.4 E | 1.9 E | 1.3 E | 0.6 E | 0.1 E | 0.0 | 5.8 E |
| | *b* | 5°00′ 52°14′ | 7°57′ 53°44′ | 4.5 W | 4.6 W | 4.3 W | 2.6 W | 1.2 W | 0.5 W | 0.2 W | 0.1 W | 18.0 W |
| | *c* | 7°57′ 53°44′ | 11°55′ 55°42′ | 1.4 E | 0.9 E | 0.3 E | 0.3 W | 0.6 W | 0.6 W | 0.4 W | 0.1 W | 0.6 E |
| *Al Duriyah* 5-8 June | *a* | 2°22′ 50°32′ | 5°25′ 51°46′ | 7.8 W | 5.4 W | 1.5 W | 0.1 E | 0.1 W | 0.3 W | 0.2 W | 0.1 W | 15.2 W |
| | *b* | 5°25′ 51°46′ | 7°20′ 52°55′ | 2.9 E | 1.8 E | 0.5 E | 0.1 W | 0.1 W | 0.1 W | 0.1 W | 0.0 | 4.8 E |
| | *c* | 7°20′ 52°55′ | 12°25′ 54°47′ | 5.3 W | 4.6 W | 3.6 W | 2.6 W | 1.8 W | 1.3 W | 0.7 W | 0.2 W | 20.1 W |
| *Al Duriyah* 28 June-3 July | *a* | 2°22′ 50°48′ | 4°35′ 51°12′ | 7.8 E | 3.8 E | 1.0 E | 0.1 E | 0.2 E | 0.4 E | 0.2 E | 0.1 E | 13.6 E |
| | *b* | 4°35′ 51°12′ | 7°57′ 53°21′ | 14.7 W | 11.3 W | 7.0 W | 3.6 W | 1.9 W | 1.1 W | 0.7 W | 0.2 W | 40.5 W |
| | *c* | 7°57′ 53°21′ | 9°55′ 53°46′ | 5.7 E | 5.3 E | 4.1 E | 2.4 E | 1.2 E | 0.6 E | 0.4 E | 0.1 E | 19.8 E |
| *Esso Honolulu* 15-17 July | *a* | 2°22′ 50°22′ | 4°10′ 51°22′ | 7.5 E | 4.1 E | 1.3 E | 0.1 E | 0.1 E | 0.0 E | 0.1 E | 0.1 E | 13.3 E |
| | *b* | 4°10′ 51°22′ | 7°40′ 53°15″ | 20.1 W | 15.9 W | 10.1 W | 5.5 W | 2.3 W | 1.0 W | 0.6 W | 0.2 W | 55.7 W |
| | *c* | 7°40′ 53°15′ | 9°55′ 51°24′ | 8.4 E | 6.9 E | 4.2 E | 2.1 E | 0.7 E | 0.4 E | 0.1 E | 0.0 E | 22.8 E |
| *Esso Caribbean* 11-15 August | *a* | 2°22′ 50°44′ | 5°00′ 51°57′ | 8.1 W | 6.9 W | 5.5 W | 2.9 W | 1.5 W | 0.7 W | 0.2 W | 0.0 W | 25.8 W |
| | *b* | 5°00′ 51°57′ | 6°07′ 52°25′ | 9.5 E | 8.4 E | 4.7 E | 1.9 E | 0.9 E | 0.5 E | 0.2 E | 0.0 E | 26.1 E |
| | *c* | 6°07′ 52°25′ | 7°53′ 52°50′ | 11.2 W | 10.3 W | 7.1 W | 4.2 W | 2.0 W | 0.9 W | 0.4 W | 0.1 W | 36.2 W |
| | *d* | 7°53′ 52°50′ | 11°03′ 54°24′ | 7.1 E | 5.9 E | 3.7 E | 1.3 E | 1.0 E | 0.8 E | 0.5 E | 0.3 E | 20.6 E |
| *Esso Caribbean* 27-31 August | *a* | 2°25′ 49°49′ | 6°43′ 52°18′ | 9.5 W | 9.6 W | 8.9 W | 6.4 W | 3.0 W | 1.5 W | 0.7 W | 0.1 W | 39.7 W |
| | *b* | 6°43′ 52°18′ | 10°12′ 53°51′ | 7.9 E | 7.3 E | 5.6 E | 3.9 E | 2.1 E | 0.8 E | 0.3 E | 0.1 E | 28.0 E |
| *Esso Copenhagen* 18-21 October | *a* | 2°25′ 51°03′ | 4°10′ 52°05′ | 6.4 E | 4.8 E | 2.8 E | 1.0 E | 0.3 E | 0.3 E | 0.2 E | 0.1 E | 15.9 E |
| | *b* | 4°10′ 52°05′ | 8°12′ 53°49′ | 16.2 W | 14.3 W | 10.6 W | 7.0 W | 3.9 W | 2.0 W | 1.0 W | 0.3 W | 55.3 W |
| | *c* | 8°12′ 53°49′ | 11°03′ 55°28′ | 5.2 E | 4.4 E | 3.6 E | 2.5 E | 1.4 E | 0.6 E | 0.2 E | 0.0 E | 17.9 E |

higher values of the topography of the northern eddy were already an outstanding feature between 5°N-10°N (*see* Fig. 8 in Bruce *et al.*, 1980). By late June and mid-July (Fig. 7 *c* and *d*) the northern eddy topography had clearly peaked with troughing on both its northern and southern (~4°N) boundary. The general shape of the topography in the basin along the sea lane had not changed conspicuously by 15-17 July, however the troughs near 4°N and 10°N had deepened. The offshore transports (*a*) and (*c*) in Figure 7 *c* and 7 *d* were also somewhat similar. It should be noted that there is agreement here with the offshore transports of the northern eddy (*c*) in both Figures 7 *c* and 7 *d* and those indicated by the transport estimates at this time by Leetmaa *et al.* (1982). They report that the transport in the upper 100 m would be on the order of $20 \times 10^6 m^3 s^{-1}$ during late June-early July. The offshore transports associated with the southern eddy at this time ((*a*) in Fig. 7 *c* and 7 *d*) are low compared to Leetmaa *et al.* It is possible that a portion of the eddy had turned south before reaching the location of the XBT sections along the sea lane. By mid-August (Fig. 7 *e*) the southern trough had shifted to about 6°N and the offshore transport (*b*) was $26 \times 10^6 m^3 s^{-1}$, this being about twice the value of the transport of the offshore flow at 4°N in mid-July ((*a*) Fig. 7 *d*). At the end of August the wedge-shaped region of cold water near 4°N associated with the boundary current had moved northeastward to about 9°N (Swallow *et al.*, 1983). When this occurred the surface topography along the sea lane (Fig. 7 *f*) then resembled our observations during the 1977 and 1978 southwest monsoons (*see* Fig. 5 of Bruce, 1979). The deep trough shown in Figure 7 *d* and 7 *e* (4°N-6°N) had now disappeared along this section. The offshore transport between 7°N-10°N reached $28 \times 10^6 m^3 s^{-1}$ (Fig. 7 *f*) which is comparable also to that of previous southwest monsoons in which the major offshore flow passing eastward through the section was generally between about 7°N-

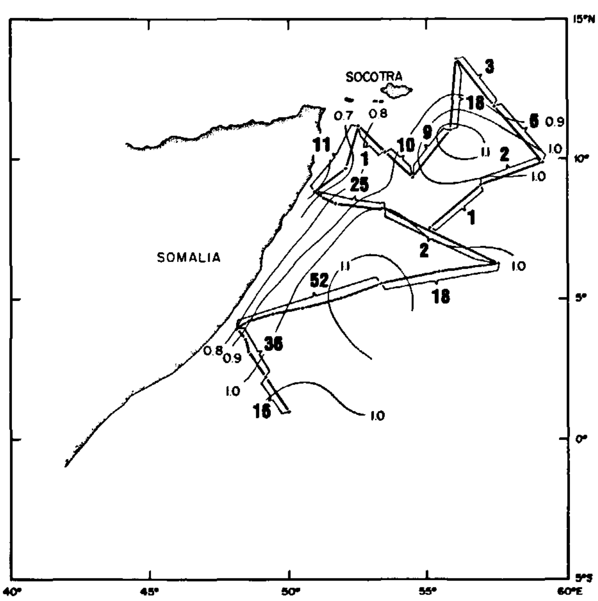



Figure 8
*Surface dynamic topography (dy. m. rel. 400 dbar), 18 August-1 September 1979 from USNS Wilkes STD stations. Bracketed values show volume transport (0-400 dbar) in $10^6 m^3 s^{-1}$ across section.*

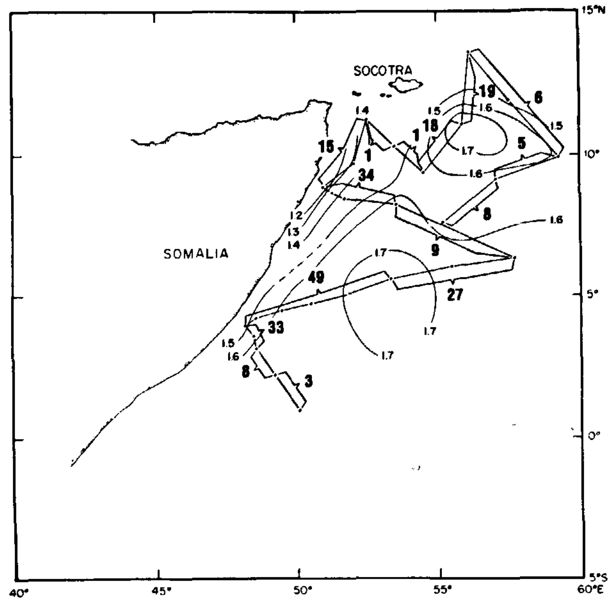



Figure 9
*Surface dynamic topography (dy. m. rel. 1 000 dbar), 18 August-1 September 1979 from USNS Wilkes STD stations. Bracketed values show volume transport (0-400 dbar) in $10^6 m^3 s^{-1}$ across section.*

11°N, with a relatively small eastward flow south of ~6°N. Swallow and Fieux (1982) have shown, however, that during a considerably high percentage of years there was at some time during the southwest monsoon, particularly in June and July, a turning offshore of the boundary current near 4°N-6°N south of the northern eddy. It is felt though that perhaps during 1979 this southern flow may have been particularly energetic in turning offshore strongly eastward (~4°N-6°N) and then extending out as far as the sea lane of the XBT sections. There is evidence, from our observations, for a certain degree of troughing in the dynamic topography at this latitude each year (Bruce, 1981). However with the exception of the 1976 southwest monsoon the troughing is not nearly as pronounced as that observed during 1979. The surface topography from USNS *Wilkes* STD stations (Fig. 8) was approximately contemporaneous with the 27-31 August tanker XBT section (Fig. 7 *f*). Although in some areas station spacing during the *Wilkes* cruise was relatively large, the stations on legs approaching the coast are more closely spaced giving relatively better detail of the coastal dynamic topography and of the determination of geostrophic volume transport. If the alongshore northeast flow of the southernmost section ($36 \times 10^6 m^3 s^{-1}$, 2°N-4°N) continued along the coast, then an onshore flow of $16 \times 10^6 m^3 s^{-1}$ would have been necessary to increase the flow to $52 \times 10^6 m^3 s^{-1}$ at 4°N-5°N. The inflow into the triangular area ($43 \times 10^6 m^3 s^{-1}$) however is greater by $11 \times 10^6 m^3 s^{-1}$ than the outflow, suggesting that the 400 dbar reference level is not as realistic for this region as 1 000 decibars (used for the same *Wilkes* stations, Fig. 9), however the transports estimated from the XBT sections were limited to approximately 460 m and for comparison purposes the 400 dbar level for the *Wilkes* STD stations is used. The flow patterns mapped in both Figures 8 and 9 however suggest some detraining from the northern eddy ~10°N toward the north between Socotra and the northeastern tip of Somalia, as well as some flow into the Socotra eddy to the northeast. *Wilkes* STD station spacing in the eastern portion of the survey region is relatively far apart, and the topography of the offshore fronts as shown by the XBT observations (Fig. 3 *d, e, f*) is not well delineated. Further difficulties occurred because the *Wilkes* survey took place during the rapidly varying coalescence of the eddies, and considerable time aliasing probably occurs in mapping the dynamic topography.

By the time of the 18-21 October XBT section the trough (Fig. 7 *g*) had again deepened near 4°N and the topography along the section resembled somewhat that in July. The offshore transports (*a*) and (*c*) as well were close to those in 7 *c* and 7 *d*.

The geostrophic transports of the northern eddy as shown in Figure 7 generally indicate a deficit when comparing the eastward transport in the northern region of the eddy and the larger westward transport in the southern region. Contributing factors to the transport difference might be a relatively strong centrifugal force associated with the pronounced turning offshore and also alongshore frictional forces associated with the flow of the northern portion of the eddy. Ekman transport resulting from the strong local southwesterly wind might contribute to a relatively large ageostrophic transport offshore in the region of the northern part of the eddy. Swallow and Bruce (1966) compared the directly measured and geostrophic calculations of the Somali current and found that in the upper 100 m (which contains 66% of the 0-200 m total transport), 26% of the total transport was ageostrophic. A westward flow in the southern region of the eddy would occur from 5-20 days after the same water turned offshore in the northern region, which would allow additional time for adjustment of the field of mass at these low latitudes. Thus the calculated westward geostrophic transport might represent a larger percent of the total transport. Another possibility is that some of the water in the northern part of the eddy might continue northward between Socotra and Ras Asir (northeastern point of Somalia), as in fact is indicated by Figure 10 *c* showing that during September 1970 the transport there amounted to $13 \times 10^6 m^3 s^{-1}$.

Also as pointed out earlier, some error is introduced in the transport calculations by using the XBT observations and an assumed salinity from a fixed T-S relation.

**Comparison with 1970 observations**

The 1979 topography from *Wilkes* data is shown also relative to 1 000 dbar in Figure 9, which as previously mentioned appears to be a better reference level than 400 dbar. Leetmaa *et al.* (1982) show a relatively strong (up to 40 cm/s) southwestward alongshore undercurrent at 400 dbar during July 1979 near 6°N which could produce an appreciable error in the transport calculation. Quadfasel and Schott (1983) also discuss the southward undercurrent at this level. This can be compared to that of August and September 1970 (Fig. 10) when a migration northeastward of the cool wedge also was observed in late August (Bruce, 1973), approximately at the time of the 1979 coalescence. Our station spacing for the 1970 observations was considerably closer than during 1979. The figures show the surface dynamic topography and the variation in the flow pattern and transport occurring over the period of transition.

The migration to the northeastward of the southern wedge of relatively cool water during 1970 also is indicated by maps of the 23°C isotherm depth (also *see* Bruce, 1973) in Figure 11 *a, b, c*. During the first part of August the pattern of flow was somewhat similar to that during June and July 1979 (Fig. 3 *a, b, c*) (Leetmaa *et al.*, 1982; Swallow *et al.*, 1983). The boundary current along the coast was observed to be turning offshore near 5°N-6°N during early August 1970, having a volume transport of 35 to $37 \times 10^6 m^3 s^{-1}$ (0-400 dbar relative to 1 000 dbar; Fig. 10 *a*). The relatively high salinity values (~35.6‰) of the northern eddy (Bruce, 1973) during this phase of the circulation suggest that there was not much leakage of the southern

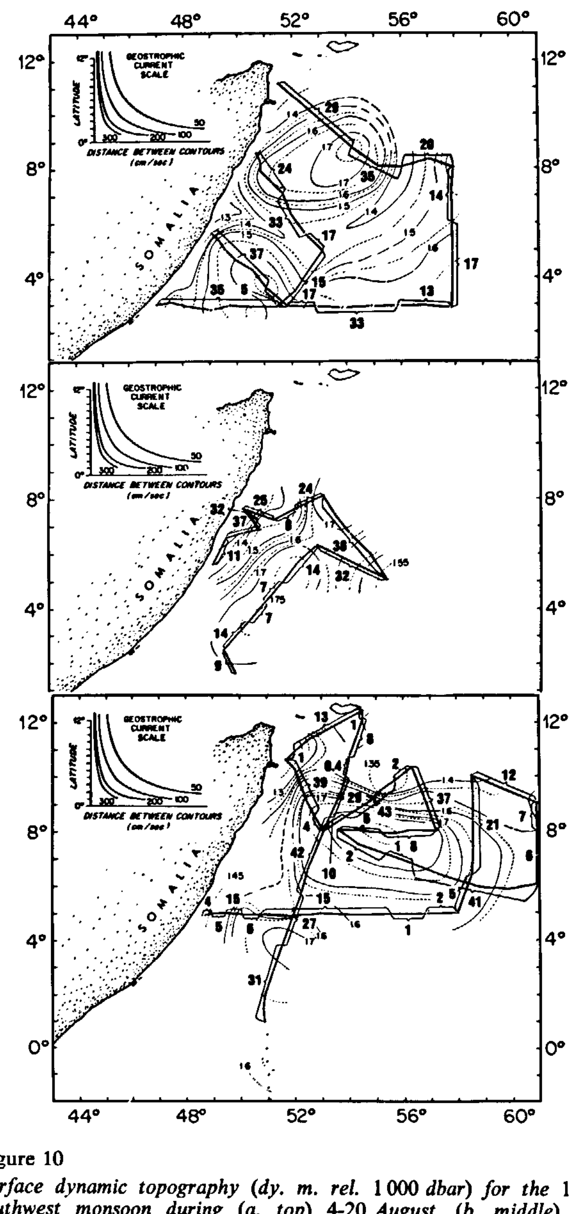



Figure 10

*Surface dynamic topography (dy. m. rel. 1 000 dbar) for the 1970 southwest monsoon during (a, top) 4-20 August, (b, middle) 20-27 August, and (c, bottom) 5-25 September from WHOI R/V Chain hydrographic stations (Bruce, 1973). Bracketed values show volume transport (0-400 m) in $10^6 m^3 s^{-1}$ across section (rel. 1 000 dbar).*

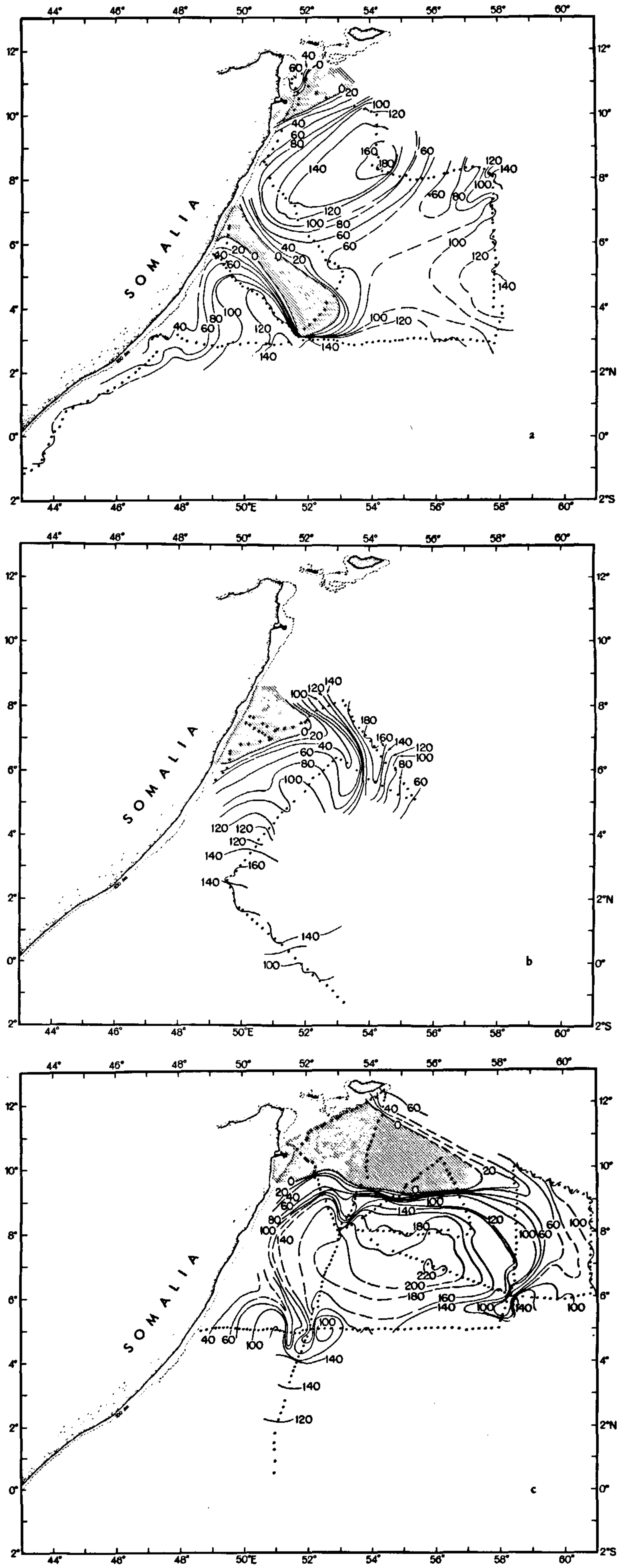



Figure 11

*Depth (m) of 23°C isotherm for the 1970 southwest monsoon during a) 3-20 August, b) 20-28 August, and c) 7-25 September from WHOI R/V Chain BT and XBT stations (Bruce, 1973). Shading shows surface water ≤23°C and represents cold wedge regions associated with coastal current turning eastward offshore.*

coastal boundary current [such as was observed at times during the 1979 measurements (Leetmaa *et al.*, 1982)] into it. The alongshore transports of the northern eddy were 24 to 29 × $10^6 m^3 s^{-1}$. During 1979 in late June transport values measured by Leetmaa *et al.* (1982) in the northern eddy are as high as 20 × $10^6 m^3 s^{-1}$ and in the southern boundary current are as high as nearly 30 × $10^6 m^3 s^{-1}$ (0-100 m layer).

During the late August 1970 migration of the cool southern wedge (Fig. 10*b* and 11*b*) alongshore to the northeastward the transports ranged from 25 to 37 × $10^6 m^3 s^{-1}$. By September as indicated by the surface salinity (Bruce, 1973) the northern eddy had been modified by the relatively fresh near surface water from the southern coastal flow (Fig. 10*c*, 11*c*) by what appears to be a coalescence or mixing of what had been two relatively separate circulations during early August. The boundary current turning offshore near 10°N then amounted to 39 × $10^6 m^3 s^{-1}$, however downstream to the east the transport is 29 × $10^6 m^3 s^{-1}$. 13 × $10^6 m^3 s^{-1}$ is directed between Ras Asir and Socotra. Yet farther downstream the transport is 43 × $10^6 m^3 s^{-1}$ and near 57°E it is 37 × $10^6 m^3 s^{-1}$ suggesting that considerable variability occurs perhaps resulting from complex cross stream advection in the eddy. There appears to be some agreement here with the 1979 values (Fig. 9) which show that a transport of 15 × $10^6 m^3 s^{-1}$ (~10°N, 52°E) inshore toward the northwest which presumably continues northward away from the portion of the eddy turning offshore to the east.

The circulation pattern during September 1970 (Fig. 10*c* and 11*c*) most resembles that observed by *Wilkes* (Fig. 9). During both years the cold wedge of the southern turnoff had shifted northward and merged with the northern eddy. At this time during the monsoon the changes occurring in the eddy circulation are relatively rapid and variable. Since in each case the duration of the survey amounted to over three weeks (5-25 September 1970, *Chain*; 18 August-1 September 1979, *Wilkes*), considerable aliasing would probably occur in an analysis of the transports.

The horizontal circulation of the northern eddy during 1970 (Fig. 10*c* and 11*c*) extended particularly far toward the east to nearly 60°E. Also at this time while a merging of the southern eddy with the northern eddy in part appears to have taken place, there is still a flow directed offshore around 4°N-5°N which amounts to 27 × $10^6 m^3 s^{-1}$ early during the survey (7-8 September 1970). The final section along 5°N was during 24-25 September and suggests that by this time the local flow pattern had changed somewhat with a weakened northward coastal flow.

**Variations of southern gyre**

As has been demonstrated by Swallow and Fieux (1982) from historical ship set observations during the southwest monsoon, a relatively large percentage of years seem to have two anticyclonic gyres formed within the Somali Basin (not including the Socotra eddy). The southern gyre however may vary considerably in size during different years. After turning offshore (~2°N-5°N) it may recurve to the southward to an extent that it would only partially cross the sea lane region of the XBT sections. For example there are no strong gradients between ~2°N-6°N on the 5-10 June 1979 section (Fig. 2) such as appear on the 28 June-3 July 1979 section at ~4°N. Yet observations by Leetmaa *et al.* (1982) show that the coastal current was in fact turning offshore with speeds ~130 cm $s^{-1}$, however at this time it had not yet extended eastward as far as the sea lane. During the first part of the 1978 southwest monsoon (Bruce *et al.*, 1980) the offshore flow of the southern gyre passed through the sea lane at ~2°N-3°N. The horizontal temperature gradients associated with the flow may be seen in the 7-13 June 1978 temperature section (Bruce *et al.*, 1980). Other sections obtained later during that year (Bruce, 1979; 1981) however have relatively weak gradients at 2°N-5°N as compared to those during late June and July 1979 (Fig. 2). Evans and Brown (1981) from satellite IR imagery show a cold wedge associated with the turning offshore of the southern gyre during July (4°N-5°N) and August 1978 (5°N migrating to 9°N). Apparently a portion of this cold water turned southward on the shoreward side of the XBT sea lane because the XBT sections obtained during this time (Bruce, 1979) do not show strong surface gradients such as were observed in the sections during June-August 1979 (Fig. 2). During the years of these XBT observations (1975-1979) the penetration of the southern gyre offshore through the sea lane has showed most clearly in the temperature sections of 1976 and 1979 (Bruce, 1981). The survey of 1970 as shown by the dynamic topography (Fig. 1, 10) (Bruce, 1973) and by the maps of the depth of the 23°C isotherm (Fig. 11 *a*, *b*, *c*) also was a year with pronounced eastward penetration of the southern gyre.

**Socotra eddy**

One feature seen in the 1979 *Wilkes* survey not previously horizontally mapped is the large eddy occurring east of the island of Socotra. The eddy has been observed to develop each southwest monsoon along the tanker sections (Bruce, 1979; *see* Tab. 2). Although our tanker sea lane tended to pass through the central portion of the northern Somali Basin eddy, it would appear that the lane was generally across the western portion of the Socotra eddy (*see* Fig. 3 *d*-3 *f*). Estimates of geostrophic transport from the XBT sections are 9 to $15 \times 10^6 m^3 s^{-1}$ (Bruce, 1979) which are in good agreement with *Wilkes* geostrophic transport values of 9 to $18 \times 10^6 m^3 s^{-1}$ relative to 400 dbar (Fig. 8) although somewhat less than observed by Swallow and Bruce (1966) who report values of 19 to $23 \times 10^6 m^3 s^{-1}$ for 0-200 dbar relative to 1000 dbar. Although there is some exchange along the southern boundary of the Socotra eddy with the relatively fresh water of the northern Somali Basin eddy, still as may be seen in Figure 5 (station 22) the Socotra eddy is generally high in salinity to depths greater than 800 m. The variations of the location of the southern boundary of the Socotra eddy as observed by the tanker XBT sections may range from 9°N to 12 1/2°N as shown in Table 2. Comparing the shift in position of the northern cold wedge as observed from satellite imagery during recent monsoons (Evans, Brown, 1981) and that of the southern boundary of the Socotra eddy (Tab. 2), there tends to be some agreement. Such might be expected because the Socotra eddy generally is contiguous with the northern boundary of the northern Somali eddy. As in the case of the northern eddy, the Socotra eddy can be identified in the thermal structure long after the cessation of a southwest monsoon. For example after the 1975 southwest monsoon the eddy was clearly indicated (Fig. 12) between 10°N-15°N for the period 30 October-2 November, appearing to be approximately the horizontal extent and depth (>400 m) of the northern Somali eddy. During 1976 and 1977 the tanker XBT sections reveal that the eddy structure remained as late as mid-December which was nearly a month after the opposite northeast monsoon had commenced (Tab. 2).

## CONCLUSION

The circulation pattern of the eddies in the Somali Basin and the observed changes in the pattern during 1979 appear to be similar to that found in 1970. During

Table 2
*Location of Socotra eddy as indicated by tanker XBT observations.*

| Date | Southern boundary | Northern boundary | Approximate eddy center |
|---|---|---|---|
| 21-22 October 1975 | 9 1/2°N | 15°N | 13°N |
| 30 October-2 November 1975 | 10° | 15° | 12° |
| 20-21 August 1976 | 11° | 14 1/2° | 13 1/2° |
| 12-13 September 1976 | 11 1/2° | 15° | 13° |
| 26-27 September 1976 | 11° | 15° | 13° |
| 17-20 October 1976 | 12 1/2° | 16 1/2° | 15° |
| 29-30 October 1976 | 13° | 17° | 15° |
| 7-8 December 1976 | 11 1/2° | 15° | 13 1/2° |
| 1-2 July 1977 | 9 1/2° | 12° | 11° |
| 17-18 July 1977 | 10° | 14° | 12 1/2° |
| 30-31 July 1977 | 9 1/2° | 14° | 11 1/2° |
| 1-2 September 1977 | 11 1/2° | 15° | 13 1/2° |
| 21-23 September 1977 | 11° | 15° | 13° |
| 13-15 December 1977 | 10° | 15° | 12° |
| 9-11 June 1978 | 9 1/2° | 13° | 11 1/2° |
| 8-10 July 1978 | 10° | 14 1/2° | 11 1/2° |
| 26-28 July 1978 | 11 1/2° | 15° | 13° |
| 24-25 August 1978 | 9° | 13 1/2° | 11° |
| 30 September 1978 | 11° | 15 1/2° | 12 1/2° |
| (11 October 1978—possible coalescence with Northern Somali eddy) | | | |
| 24-25 November 1978 | 11 1/2° | 15 1/2° | 14° |
| 16-17 July 1979 | 10° | 14° | 12 1/2° |
| 14-15 August 1979 | 11° | 12 1/2° | 13 1/2° |
| 27-28 August 1979 | 9 1/2° | 14 1/2° | 12° |
| 20-21 October 1979 | 11° | 15 1/2° | 13° |
| 25 November 1979 | 11° | 13 1/2° | 12 1/2° |

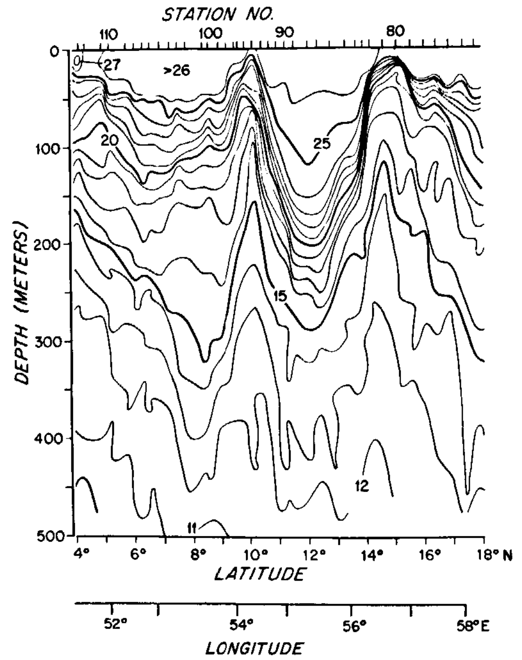



Figure 12
*Socotra eddy, 10°N-15°N, shown in temperature (°C) section from XBT stations along tanker sea lane, 30 October-2 November 1975, Esso Kawasaki.*

both years the southern eddy apparently coalesced with the northern eddy during the late August-early September phase of the southwest monsoon. The 1979 *Wilkes* data suggest that the relatively fresh water from the southern eddy was in rapid transition during the period of the survey (18 August-3 September) because: 1) this water type was found at the surface and near surface (~0-100 m) generally overriding the western portion of the northern eddy (as indicated by the relative positions of the near surface water, Fig. 3 *a* and *b*, compared with that of the contours of the depth of the isotherm showing the approximate configuration of the northern eddy, Fig. 3 *c*); and 2) by October there appears to be a return to the circulation pattern of the early southwest monsoon as observed in June and July with a turn off of the coastal current about 5°N-6°N. Also, the surface current estimates from ship's set during the *Wilkes* survey (Fig. 4) indicate that between 8°N-9°N within the region of relatively fresh surface water (Fig. 3 *a*) the currents are strong (250-340 cm/s$^{-1}$). These data and also those of 1970 (*see* Fig. 3 and 4 from Bruce, 1973) suggest that the coalescing of the southern eddy into the northern one amounts to a penetration by the coastal current associated with the southern eddy into the northern eddy coastal current with a resulting merging of the two water types described by Swallow *et al.*, 1982: BBSW (Bay of Bengal Surface Water) and ASW (Arabian Sea water).

Although the general size and transport associated with the Socotra eddy appear to be somewhat similar during different years from the data available, there are however variations in the location of this eddy both during a single southwest monsoon and interannually.

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