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THE THREE LAYER STRUCTURE OF WATER EXCHANGE IN-BAB-EL-MANDAB STRAIT.

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ABSTRACT

The current observations recorded in the Strait of Bab-El-Mandab during the summer season of 1982 showed the existence of an intermediate layer flowing into the Red Sea with an average speed of 25 cm/sec and temperature of 18°C. The maximum speed observed was 36.0 cm/sec and the minimum temperature was 15.8°C in August. This layer extends vertically from about 50 m to more than 150 m depth. A strong inversion has been obseved at about 50 m from the surface. The minimum oxygen content was found at 70 m depth. Due to the summer monsoon which dominates during that time of the year, thin outflow layer exists in the Strait at the surface. In addition the deep water of the Red Sea continues to flow out at the bottom. while a thick intermediate layer into the Sea. The cold low saline water was traced to about 18°N in the Red Sea.

INTRODUCTION

The water structure through Bab-el- Mandab is still an unresolved question and needs more attention to estimate accurately water movements between the Gulf of Aden and the Red Sea. Several investigations have been made to study the water circulation in the Red Sea and particulary along the main channel (Luksch, 1901; Vercelli, 1925 and 1931; Thompson, 1939; Neumann and McGill, 1961; Boisvert, 1966; Siedler, 1969; Morcos, 1970; Maillard, 1972; Morcos and Soliman, 1972; Robinson, 1972; Wyrtki, 1972; Patzert, 1972; Soliman, 1979; Wassif et al., 1983; Maillard and Soliman, 1985a, & b), as well as the water exchanges between the Red Sea and the Gulf of Aden (Vercelli, 1925 & 1931; Siedler, 1968 & 1969; Morcos, 1970; Jones and Browning, 1971; Bogdanova, 1972; Gorman et al., 1972; Patzert, 1972; Van Aken and Otto, 1972; Khimitsa and Bibik, 1979; Bruce, 1981; Murty and El-Sabh, 1984; Poisson et al, 1984; Swallow, 1984; Maillard and Soliman, 1985 a & b.

In winter, the wind blows from SSE on the southern part of the Red Sea. The water structure during this time is definetly two layers as maintained by all the previous investigators The warm and low saline upper layer is directed toward the Red Sea mainly under the action of the SSE winds. Meanwhile, the lower layer, which is relatively cooler and higher in salinity, is flowing out the sea over the sill. Generally, Patzert (1972) and Jones and Browning (1971) have given the main factors which induced motion between the Red Sea and the Gulf of Aden.

During the transitional seasons, the winds change their direction and a state of stability is provided at the surface. According, the water movements across the Strait of Bab-el-Mandah are influenced by the gravity currents caused by the density difference in Red Sea and Gulf of Aden waters. Taking this fact into consideration, cyclic motion can be expected, which means the existance of in-and out-flow water at the upper surface layer as well as at the lower one in agreement with Khimitsa and Bibik (1979).

It is assumed that the occurrence of cold water in the Gulf of Aden can be traced to the upwelling phenomenon in the Arabian Sea and along the Somali coast. In summer, the prevailing wind is NNW. The SW monsoon months in the Arabian Sea are dominated by upwelling along the Arabian coast and the cold water plumes and wedges extend eastward (Quraishee, 1984). The intensity, extent and duration of upwelling depend on different detailed aspects of the wind field and in different ways in different areas (Swallow, 1984). The frequency of storm surge occurrence in the Arabian Sea appears to be increased in the last few years (Murty and El-Sabh, 1984), and accordingly the upwelling in this area seems to be more pronounced. The cold water in the Gulf of Aden, which is streaming into the Red Sea across the sill as intermidiate layer, may be due to the upwelling in the Somali basin (Warren et al., 1966) and along the southern Arabian acoat (Tunnel, 1963).

Generally speaking, the inflowing current in winter is traced to the upper layer of the Gulf of Aden water, while in summer the intermediate layer flowing into the Red Sea is mainly due to the upwelling water from the deep water in the Arabian Sea and the Gulf of Aden.

This structure was investigated during summer 1982 through two cruises (MEROU I in June and MEROU II in October) carried out on the French R/V "MARION DUFRESNE" across the Strait of Bab-el-Mandab and the western part of the Gulf of Aden. Moreover, a mooring of fourrecording current meters was fixed on the western side of the Strait during the period July - September 1982.

RESULTS AND DISCUSSION

The Hydrographic Structure of the Area (Strait of Bab-el-Mandab)

The area under investigation has been surveyed using CTD- device at a number of stations located in (Fig. 1). The results have been represented graphically in charts and discussed.

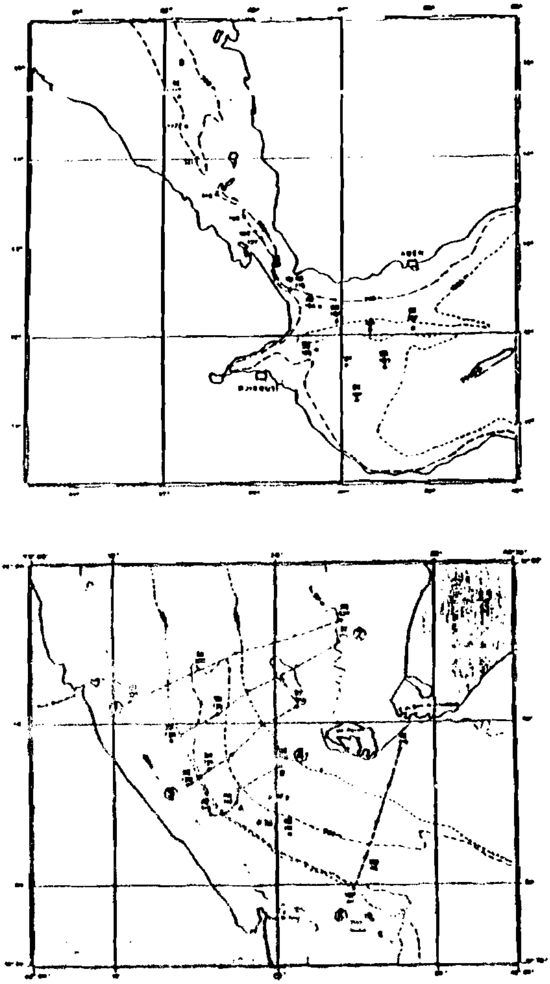


Fig. 1
Location of stations along the main
channel of Bab El-Mandab Strait (upper),
and in the Strait (lower).

The Horizontal Distribution of Temperature in Early Summer (June-July 1982):

At the surface, the water temperature is warmer on the western side (31. 0 $^{\circ}$C) than on the eastern one (30. 4 $^{\circ}$C) with a mean of 30.7 $^{\circ}$C. The water temperature decreases rapidly with depth showing a dercease of 8 $^{\circ}$C at 50 m from the surface temperature (Fig. 2). The water temperature

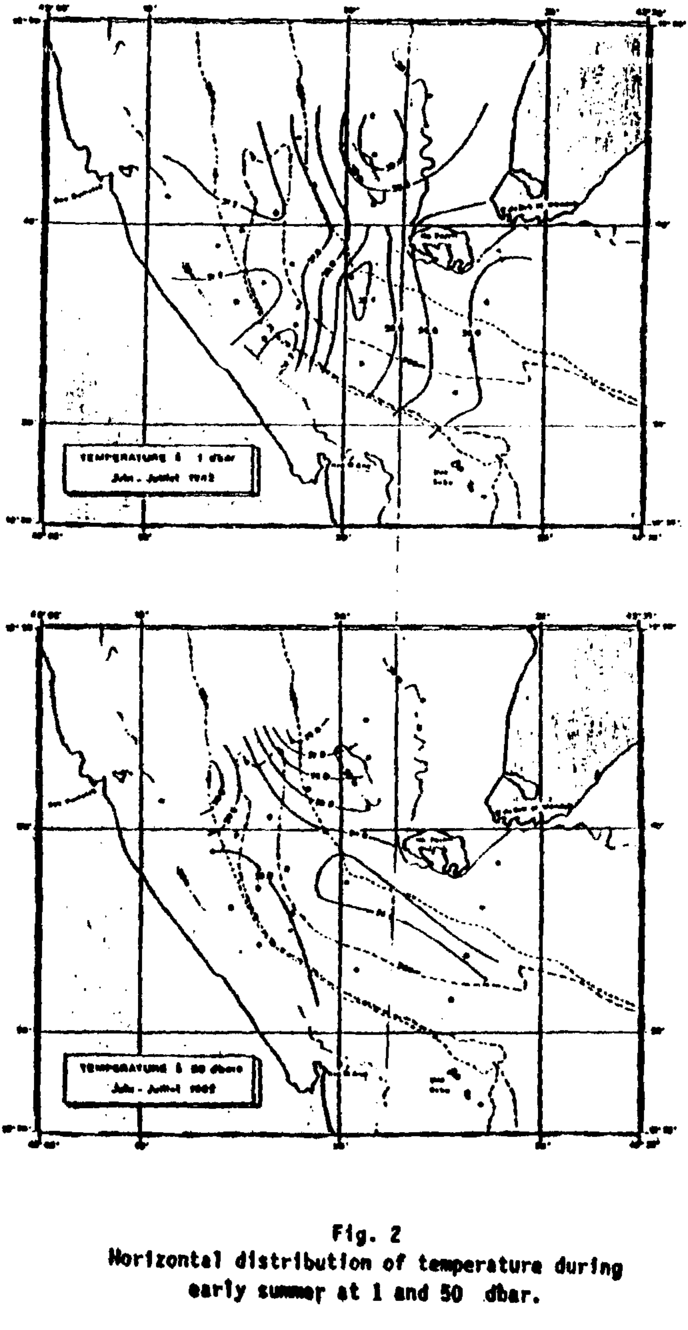


Fig. 2
Horizontal distribution of temperature during early summer at 1 and 50 dbar.

in the Red Sea is 4.5°C higher than that in the Gulf at the same level (50 m depth). At 100 m depth, the cross-sectional area, through which the water flows, is greatly reduced. Thus, during this time of the year, the warm and high saline deep Red Sea water out flowing over the sill to the Gulf of Aden is mixed with the cold and low saline inflowing Gulf water and as a result its temperature and salinity are reduced. At 150 m depth, the water temperature varies greatly between the northern and southern sides of the Strait; at the western coast (23.0°C) is higher than at the eastern one (20.0°C). This indicates that the deep Gulf water enters the Red Sea on the eastern side and the deep Red Sea water flows out of the Sea on the western side (Fig. 3).

The Horizonatal Distribution of Temperature in Late Summer (Septermber-October 1982):

At the Sufrace in the strait, the water is nearly homogenous with an average temperature of 30.75°C. At 50 m depth, the distribution appears to be complicated due to the mixing processes in the horizontal and vertical directions (Fig. 4).

In the layer of 100-150 m deep, the water temperature is markedly decreased by about 5°C relative to that found in June. The existence of the cold water at this level indicates the depth of the intermidiate water inflowing into the Red Sea during the summer season. This layer may occupy a water column extending from a depth of 40 m from the surface to a few meters above the bottom, leaving only a very thin layer of the Red Sea water to spill out into the Gulf. This deep water may be attributed to the deep Red Sea water, which finds its way out of the Sea through the deep channel, or can be related to the warm deep water existing in the deep holes of the Strait. At a level of 150 m deep, the distribution (Fig. 5) indicates the absence of the warm water (20°C) through the Strait, where the temperature varies between 16°C in the south and 18°C in the north of the Strait. Only at a depth of 200 m, water of relatively high temperature of 20.0°C appears outflowing through the deep channel.

The Horizontal Distribution of Salinity in Late Summer (September-October 1982):

The horizontal distribution of salinity at the different levels (Fig. 6&7), shows a simillar pattern as the temperature distribution. At the surface, the salinity amounts 36.6‰ while in the layer of 100-150 m deep, the salinity shows low values (35.7‰) which characterizes the Gulf of Aden water. At 200 m deep, the salinity is relatively high (38.5‰) which is much lower than the salinity of the water existing in winter. This value represents the average value of both the Red Sea and Gulf of Aden waters.

The Vertical Distribution of Temperature in a Section along The Strait of Bab-el-Mandab:

To understand the hydrographic structure of the water in the Strait during the summer season, it is necessary to know the structure of the

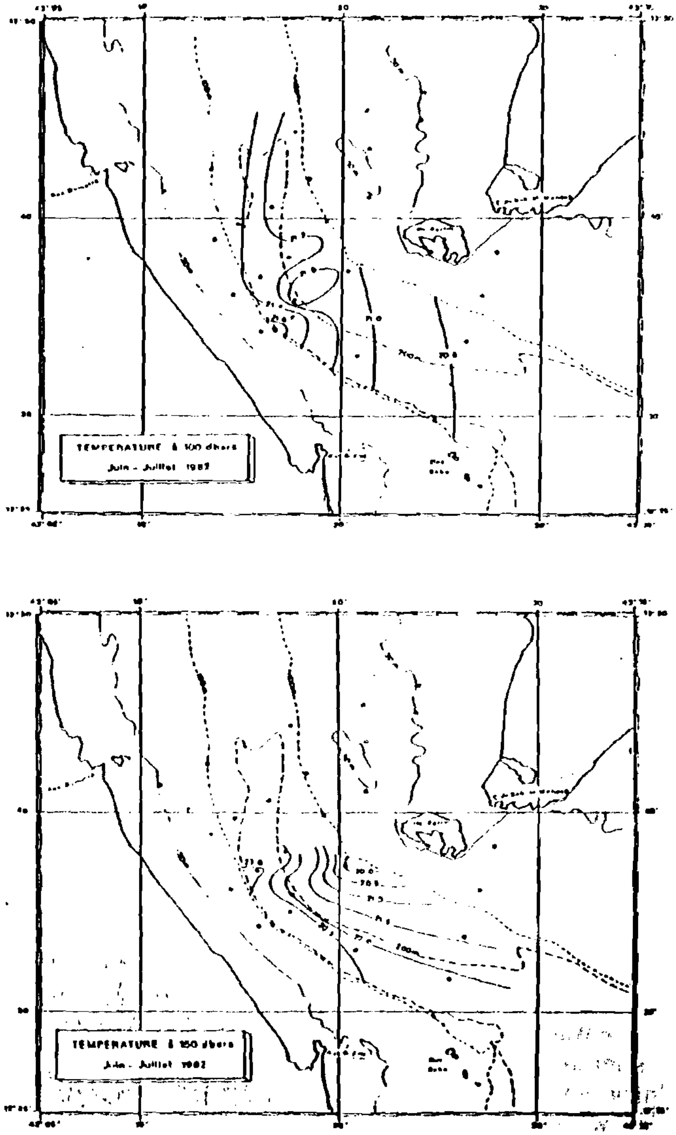


Fig. 3
Horizontal distribution of temperature during
early summer at 100 and 150 dbars.

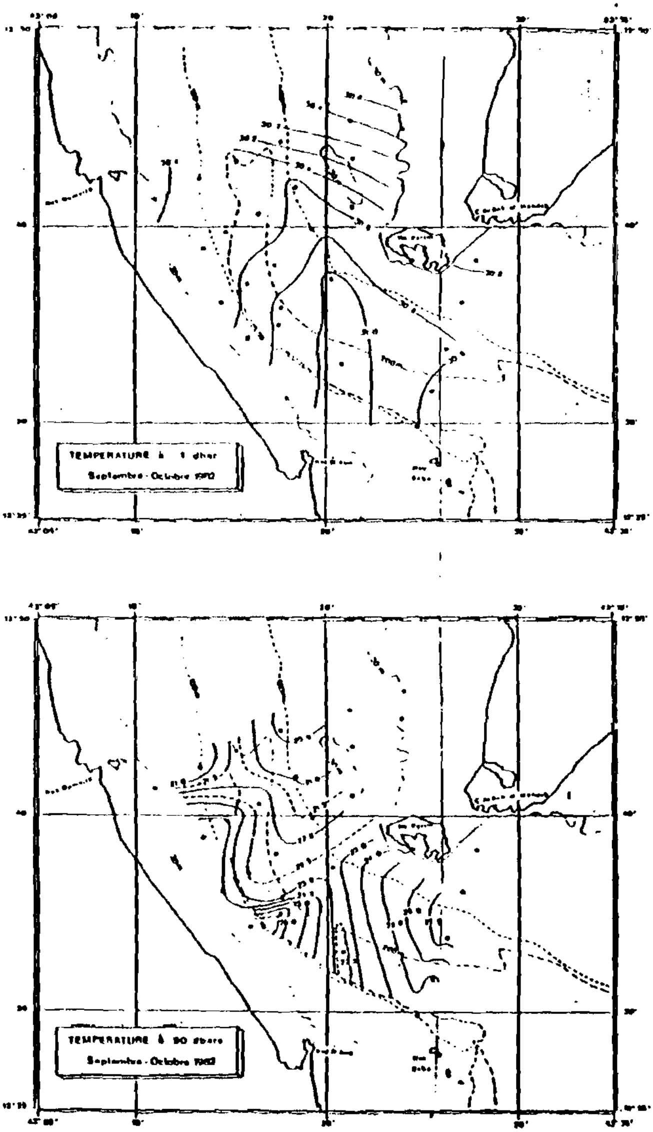
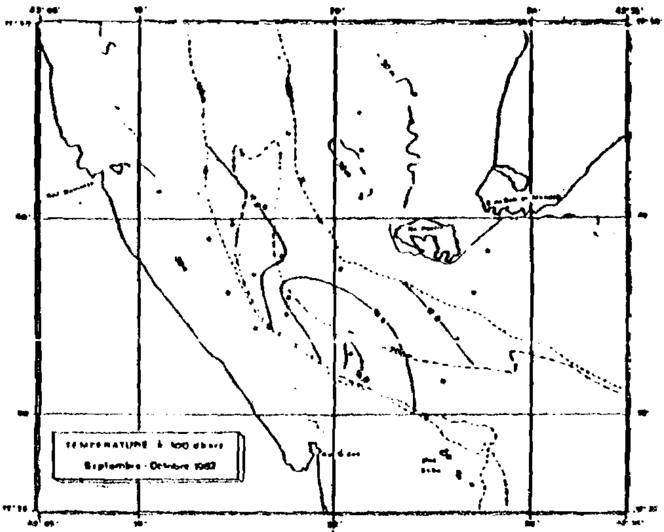


Fig. 4
Horizontal dist-ibution of temperature during late summer at 1 and 50 dbars.



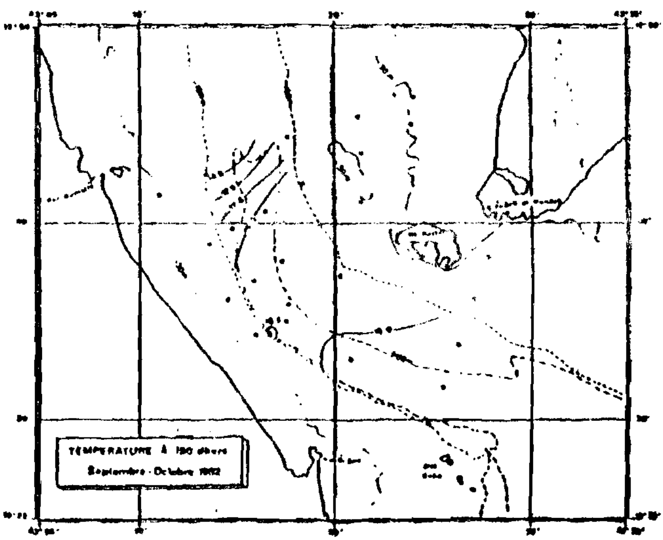


Fig. 5
Horizontal distribution of temperature during late summer at 100 and 150 dbars.

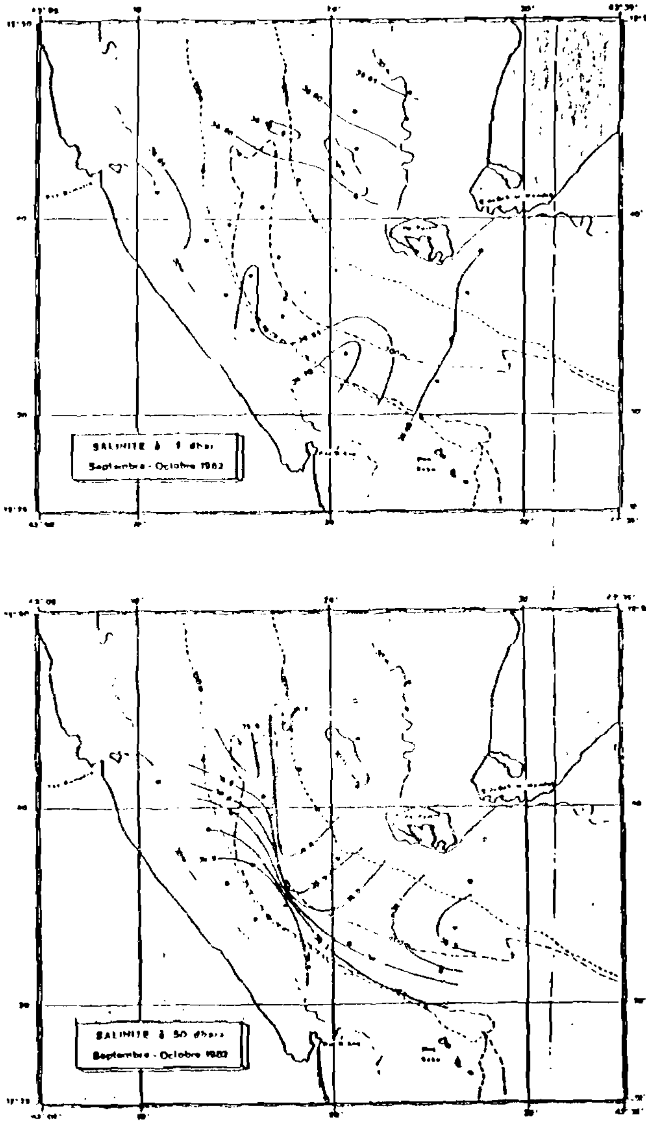


Fig. 6
Horizontal distribution of salinity during late summer at 1 and 50 dbars.

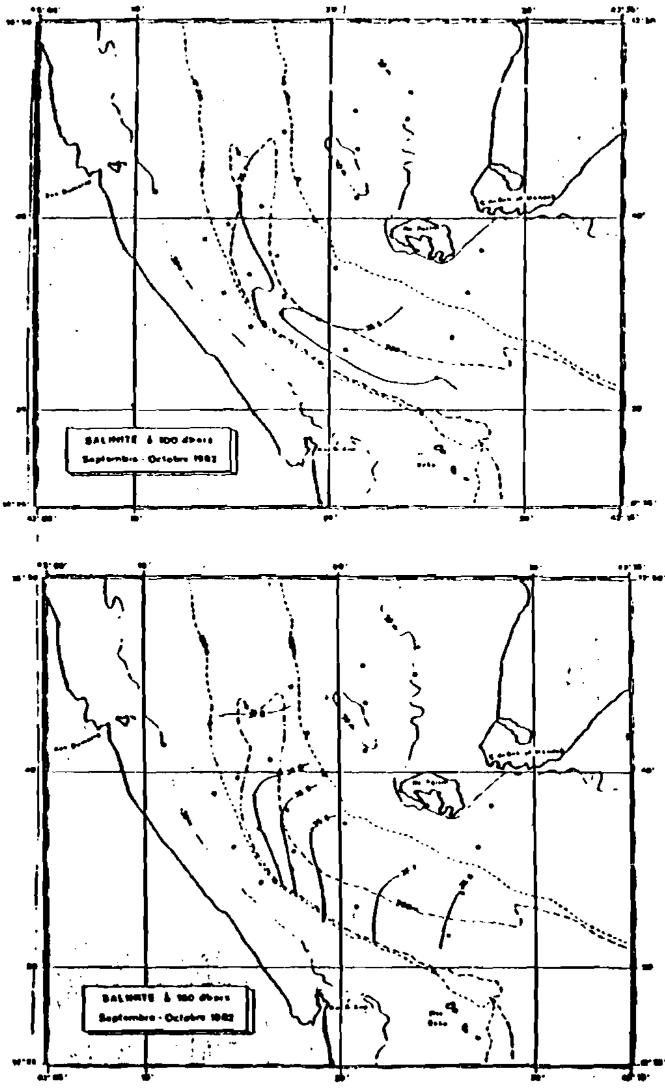


Fig. 7
Horizontal distribution of salinity during
late summer at 100 and 150 dbars.

area during the early summer, i.e. during the transitional period, in which the wind starts to change its direction from SSE to NNW. Figure 8 tepresents the temperature distributjon in the early summer, where the water stratification is clearly shown in the northern part of the section, while in the southern part the summer motion has already developed.

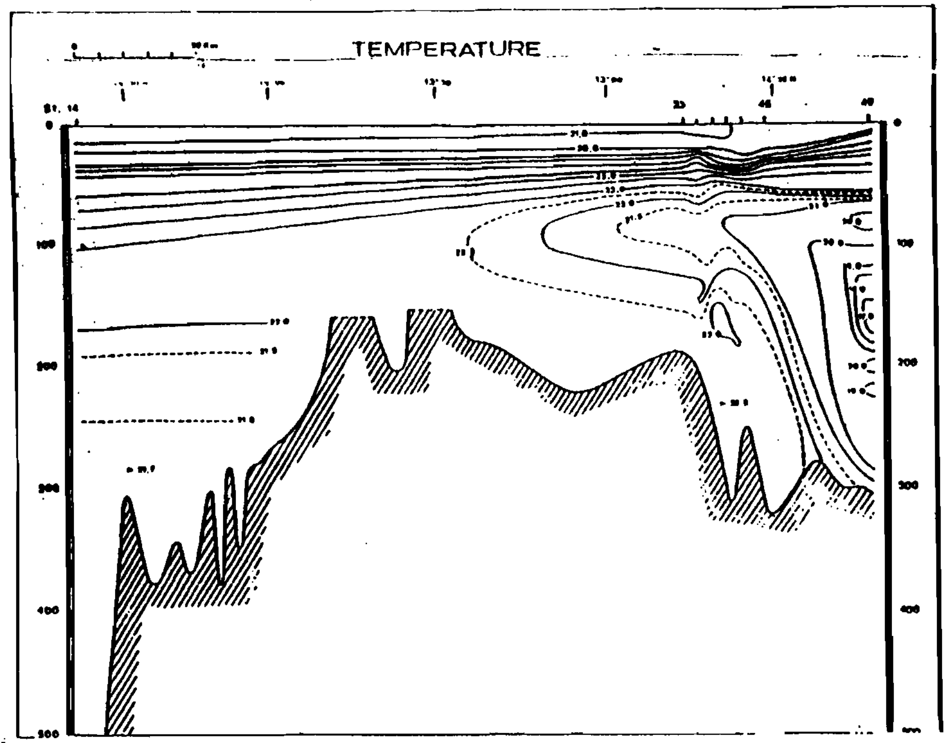


Fig. 8
Vertical distribution of temperature along the main channel of Bab El-Mandab Strait during early summer.

Since the wind is nearly calm, and the air temperature is relatively high, the surface water receives heat from the atmosphere, raising its temperature and then through convection and advection processes, the temperature will be transferred to the lower layers, and the gradual decrease will appear from the surface to the bottom. The distribution shows a peculair picture of the winter condition and a developing summer structure at the same time. The cold Gulf water of temperature 15.0°C starts to trap the warm Red Sea water (23.0°C), which results in the reduction of its temperature and salinity. This process of mixing creates a water mass having the character of the mixed Red Sea and Gulf of Aden waters, which indicates the origin of this water. With the lapse of time, the deep water from the Gulf continues to flow through the Strait into the Red Sea due to the developing of upwelling in the Arabian Sea (Murty and El-Sabh, 1984), and as a result an increase of the thermocline gradient is observed. The water tempereature of the cold water core is inversly propotrional to the amount of water transported across the Strait. The inflow of this type of water, which is very low in tempertaure (< 15 °C), between the surface and deep water of the Red Sea creates a kind of instability in the water structure, initiating internal waves, which can be easily seen in the sections of temperature, salinity and density distributions along the Red Sea (Maillard and Soliman, 1985a &b).

At the end of this season, the amount of the Intermediate water transported to the Red Sea begins to decrease, and accordingly the Red Sea water strats to trap the cold Gulf water, and through the mixing processes it becomes lighter and rises to the surface, till the stable conditions are attained (Fig. 9). To accomodate these conditions, a lapse of time will be required which explains the existence of the cold (19 °C) and low saline Gulf water (37.0‰) to the north of latitude 17 °N in October and may be in November, which explains the existence of the cold water tongue observed by Jones and Browning (1971).

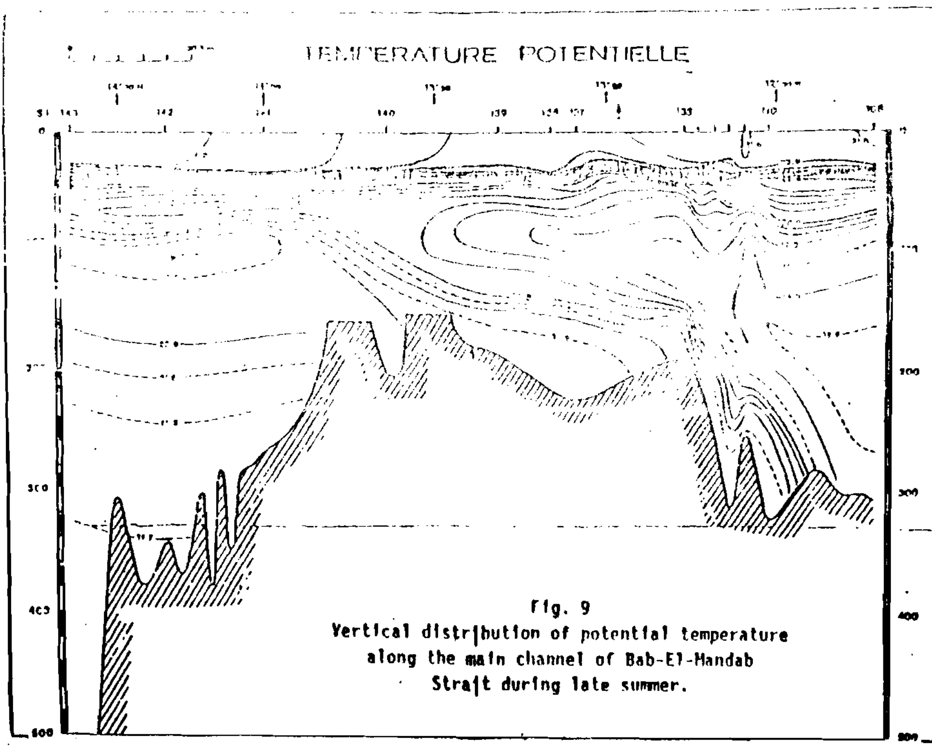


Fig. 9
Vertical distribution of potential temperature along the main channel of Bab-El-Mandab Strait during late summer.

Current And Temperature Observations During The Summer Period (July-September 1982):

Figure 10 shows the variation in the water temperature at the three levels 52, 99 and 140 dbar respectively during the two week period (5-20 July), and at the two levels 99 and 140 dbar during another two periods (20 August - 5 September).

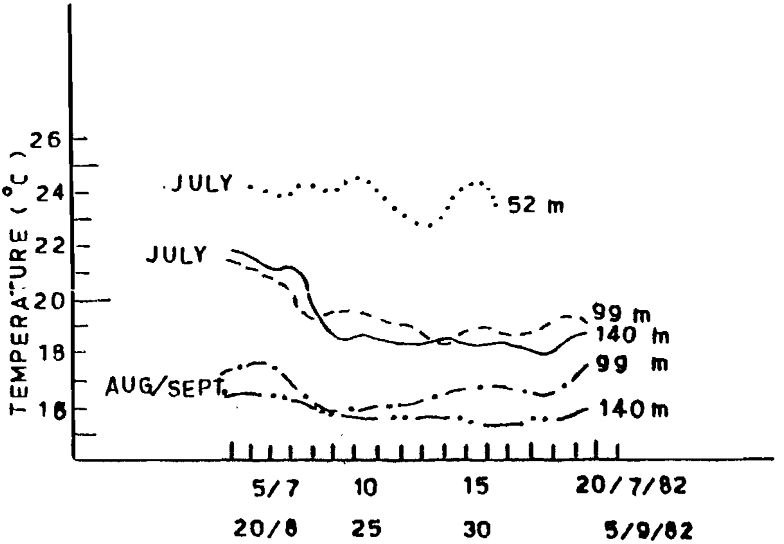


Fig. 10
Time variation of water temperature at 52,99 and 140 dbars during the periods 5-20 July and 20 August-5 September, 1982.

During the first week of July the water temperature at 140 dbar was about 21-22°C. Few days later, the current speed increased from 3 to 10 cm/sec towards the north, resulting in a rapid decrease of the water temperature from 21° to 18°C. Although the current speed decreased in the next two weeks, yet the temperature decreases gradually from 18° to 17.5°C. During the last week of July and the whole time of August (Fig. 11), the current speed increased again amounting 10-15 cm/sec., led to a great reduction in the water temperature at this level. The water temperature remained nearly constant at about 15.5°16.5°C during this period. It is important to mention, that during the first week of September, the current suddenly changed its direction towards the southeast with

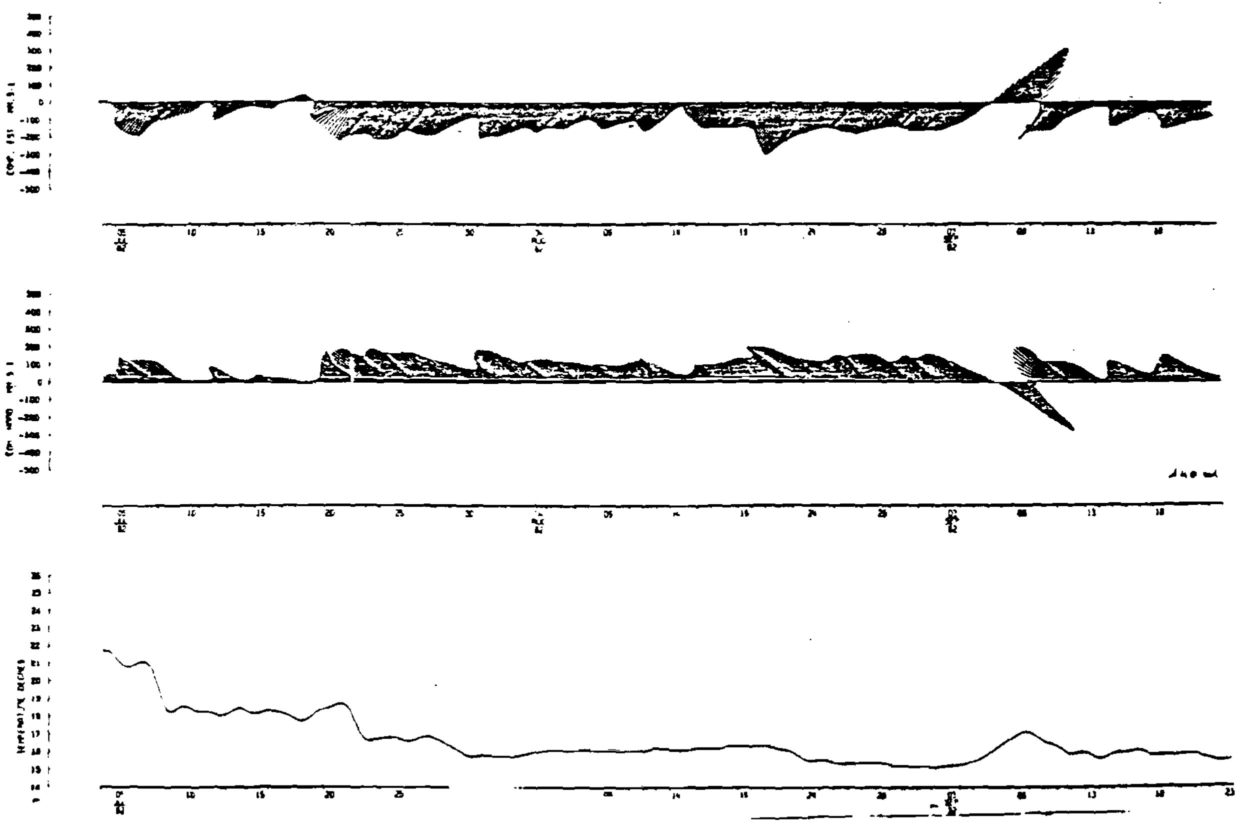


Fig. 11
Water temperature and residual current at 140 m
during the period 5 July-23 September, 1982.

speed 30-45 cm/sec, resulting in a sudden increase in the water temperature of about 2°C, which means a southward outflow of the deep Red Sea warm water to the Gulf of Aden. Few days later, the current inversed its direction again towards the north-west but fluctuating in magnitude and direction, with the temperature fluctuating also about 15.5°C.

At the level of 99 dbar, the water current increased (40 cm/sec) towards the northwest during the first week of July, and accordingly a huge amount of the deep Gulf water was transported to the Red Sea, resulting in the decrease of the water temperature at that level from 22°to 19°C. On the seventh of July 1982, the total inflowing current amounted 100 cm/sec through the Strait with a residual current of about 45 cm/sec to the north. During the next two weeks, the current speed decreased to 20 cm/sec, resulting in a decrease in the water temperature to 18°C. Again, the current speed increased to the end of August, reaching a maximum value to the north on 24 of August, where the temperature decreased to 15.7°C the lowest value attained at this depth. Later,the temperature began to increase gradually to reach 19°C on the eighth of September, as a result of the decrease of the current speed. Few days later, the current speed increased again, yielding which ields a reduction in the water temperature to 16.6°C and remaind at this value till the end of observations (Fig. 12).

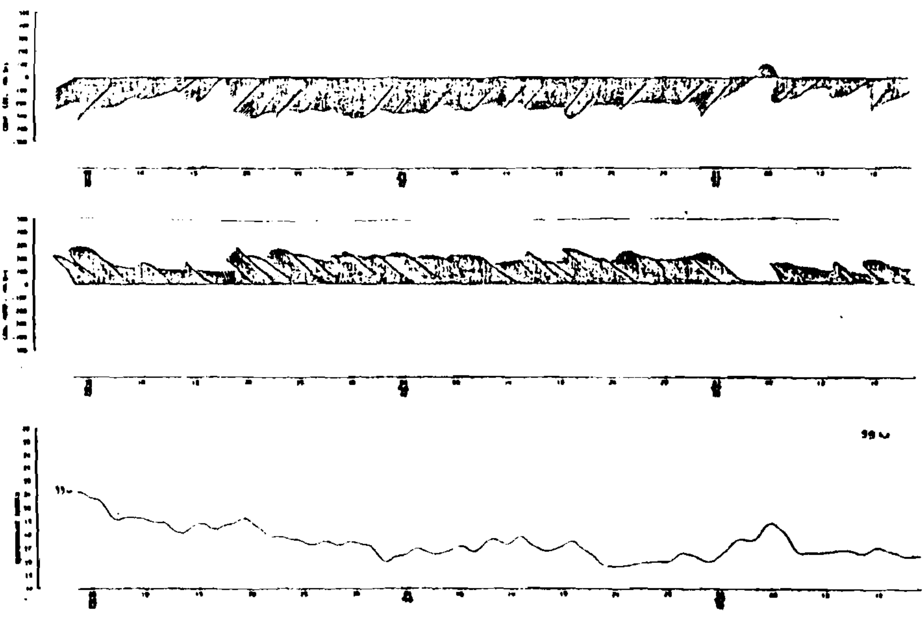


Fig. 12
Water temperature and residual current at 52 and 99 m
during the period 5 July-23 September, 1982.

At a depth of 52 dbar, the current observation was only available for a short period (10 days, 5-15 July). During this period, the water current was also northwards with a speed of about 20-30 cm/sec, and the water temperature fluctuated between 22°-24°C. The surface flow was empirically estimated by Maillard and Soliman (1985b), showing a southward transport of magnitude $0.25 \times 10^6 m^3. sec^{-1}$. From the above, it is clear that in summer, the upper outflow surface water layer occupies the upper 40 m, the intermediate inflow layer extends from 40 t0 160 m; while the third outflowing layer occupies a depth of 10-20 m from the bottom.

SUMMARY AND CONCLUSION

During the summer 1982 two cruises were carried out, MEROU I in early summer and MEROU II in late summer, on the french R/V "MARION DVFRESNE". In between, continuous temperature and current observations were recorded by a mooring four currenmeters on the eastside of the Strait of Bab-el-Mandab. Moreover, the area of the strait has been surveyed. The horizontal and vertical distributions of temperature and salinity have been represented in charts and discussed. The observations of temperature and current speed and direction have been compared at the different levels.

In early summer 1982, the winter pattern of the two layer structure was clearly observed to the north of the Strait, while south of it the summer flow began to develop. In late summer (July-October 1982), the three layer structure became abundantly evident, where a thin surface layer of about 40 m deep was flowing out of the Red Sea, a thick layer of cold and low saline water about 110 m was flowing in the Red Sea as indicated by the well developed temperature inversion at about 80-100 m. This water layer prevailed through the entire summer and part of the fall. The third layer spilling out into the Gulf of Aden over the sill was observed by its relatively high temperature and salinity, and was reduced to a thin layer of few meters above the bottom. The three layer structure hows temperature changes in short period of time compared to the two layer structure. This was clearly observed in one instance for a period of few days (17 September) in the temperature and current observations. The cold water tongue may be traced in the Red Sea to about 18-19°N.

In late summer, the temperaturre and salinity disributions show how the Red Sea water trapping the cold water as a core and then rising to the surface. Patzert (1972), showed that the surface inflow of approximately $0.57 \times 10^6 m^3 sec^{-1}$ occurred in November, January and March, in agreement with Vercelli's (1925) and Siedler's (1968) results. In summer, the intermediate flow reached its highest value of $0.36 \times 10^6 m^3. sec^1$ in Augst, while the surface flow was estimated indirectly as $0.25 \times 10^6 m^3.sec^{-1}$(Maillard and Soliman, 1985b).

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