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L'OCEANOGRAPHIE PHYSIQUE DE LA MER ROUGE

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des Sciences Physiques de l'Océan (I.A.P.S.O.)

Laboratoire d'Océanographie Physique du Muséum
Paris, 9 - 10 octobre 1972

PUBLICATION DU

CENTRE NATIONAL POUR L'EXPLOITATION DES OCEANS

(C N E X O)

L'OCEANOGRAPHIE PHYSIQUE DE LA MER ROUGE

"L'OCEANOGRAPHIE PHYSIQUE DE LA MER ROUGE"

SYMPOSIUM DE L'ASSOCIATION INTERNATIONALE DES SCIENCES PHYSIQUES DE L'OCEAN

(IAPSO)

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Organisé

par le Laboratoire d'Océanographie Physique

du Muséum National d'Histoire Naturelle

Paris, 9 - 10 Octobre 1972.

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SYMPOSIUM IAPSO - UNESCO - SCOR

OCEANOGRAPHIE PHYSIQUE DE LA MER ROUGE

Programme détaillé des travaux

LUNDI 9 OCTOBRE 1972

Séance du matin : Président H. LACOMBE

9h 00 - réception des participants
10h 00 - ouverture du symposium par le Professeur H. LACOMBE
10h 20 - communication de D.E. PEDGLEY : "An outline of the weather and climate of the Red Sea"
11h 30 - pause
11h 50 - discussion sur la communication de D.E. PEDGLEY
12h 05 - communication de M.K. ROBINSON : "Seasonal variation in temperature of the Red Sea"
12h 45 - discussion
13h 00 - fin de la séance du matin.

Séance de l'après-midi : Président P. TCHERNIA

14h 40 - communication de W. PATZERT : "Seasonal reversal in Red Sea circulation"
15h 10 - discussion
15h 30 - communication de S.A. MORCOS : "Circulation and deep water formation in the Northern Red Sea"
15h 45 - communication de C. MAILLARD : "Eaux intermédiaires et formation d'eau profonde en Mer Rouge"
16h 00 - discussion
16h 20 - pause
16h 40 - communication de K.WYRTKI : "On the deep circulation of the Red Sea"
17h 10 - discussion
17h 35 - communication de D. ANATI : "Water transports in the Gulf of Aqaba"
18h 05 - discussion
18h 10 - fin de la séance.

MARDI 10 OCTOBRE

Séance du matin : Président K. WYRTKI

9h 10 - communication de C. MAILLARD : "Circulation hivernale en Mer Rouge"
9h 30 - discussion
9h 45 - communication de W. PATZERT : "Volume and heat transports between the Red Sea and Gulf of Aden and notes on the Red Sea Heat budget"
10h 00 - discussion
10h 05 - communication de J.M. GORMAN : "New measurements of circulation across the sill between the Red Sea and the Gulf of Aden"
10h 40 - discussion
10h 50 - pause
11h 10 - lecture par J.M. GORMAN de la communication de H.M. VAN AKEN et L. OTTO : "Observations of the exchange of water in the Strait Bab-el-Mandeb in 1967"
11h 45 - communication de S.A. MORCOS : "Circulation and mean sea level in the Suez Canal"
12h 15 - discussion
12h 20 - communication de S.H. SHARAF EL DIN : "Further studies on tides and hydrography of the Suez Canal and its Lakes"
12h 30 - discussion
12h 35 - communication de A.R. MILLER : "The Bitter Lake salt barrier"
13h 05 - discussion
13h 10 - allocution de clôture par H. LACOMBE
13h 20 - fin du Symposium.

LISTE ALPHABETIQUE DES PARTICIPANTS ET AUDITEURS

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ALLOCUTION D'OUVERTURE DU SYMPOSIUM

En 1970, le Professeur Paul TCHERNIA, soulignant l'intérêt scientifique de la Mer Rouge et l'opportunité de faire le point de nos connaissances dans cette mer à la suite des nombreux travaux effectués en liaison avec l'Expédition Internationale de l'Océan Indien, proposa à IAPSO l'organisation d'un Symposium sur l'Océanographie Physique de cette Mer.

La Commission d'Océanographie Physique de IAPSO retint cette suggestion et le Comité Exécutif de l'Association décida en 1971 de tenir ce Symposium. En son nom, je remercie le Professeur TCHERNIA de son initiative.

Le sujet retenu est volontairement limité aux aspects physiques et dynamiques, à l'exclusion de ceux relevant de la géophysique et de la géochimie (notamment sur les saumures sursalées des ombilics du fond, qui ont fait l'objet d'ouvrages synthétiques récents).

Par contre, les travaux portant sur la physique et la dynamique de cette mer n'ont pas suscité de confrontation entre spécialistes ni de publication d'ensemble : c'est ce que ce symposium a l'ambition de faire.

Cette étendue marine a des caractères particuliers du fait de la climatologie qui règne sur sa surface ; c'est un bassin de concentration où la surface marine a un bilan d'eau négatif : c'est par suite un bassin où se forme une eau profonde typique.

Voilà pourquoi il paraissait indiqué que ce Symposium fît suite au Colloque International CNRS-CNEXO sur la formation des eaux profondes qui s'est tenu ici même la semaine dernière.

Au seuil de nos travaux, je voudrais exprimer les remerciements des organisateurs aux Scientifiques distingués qui ont bien voulu venir jusqu'à nous ; ma reconnaissance va aussi à IAPSO, à l'UNESCO et au SCOR pour l'aide qu'ils ont fournie en vue de faire venir ici nombre d'entre vous.

La triste nouvelle que nous avons apprise mercredi dernier du décès de notre éminent collègue, le Professeur Günter DIETRICH, Directeur de l'Institut für Meereskunde de l'Université de Kiel, nous prive de la participation d'un océanographe mondialement connu, que nous aimions et respections tous et qu'aujourd'hui nous pleurons, mais aussi de celle de ses collègues allemands retenus à Kiel.
Le concours qu'ils nous auraient apporté grâce à leurs récentes études sur la Mer Rouge est profondément regretté.

Je vous propose d'observer une minute de silence à la mémoire de notre Collègue et ami disparu.

Je déclare ouvert le Symposium de IAPSO sur "l'Océanographie Physique de la Mer Rouge".

H. LACOMBE

AN OUTLINE OF THE WEATHER AND CLIMATE OF THE RED SEA

D.E. PEDGLEY *

Abstract

In the area of the Red Sea the wind flow is dominated by the persistent subtropical anticyclones, but below an altitude of about 3 km winds are strongly modified by the topography of Africa and Arabia, particularly by the presence of a north-south oscillating convergence zone from about October to May. Transient troughs moving eastward to the north of the anticyclones during this part of the year occasionally weaken the static stability usually present, thus allowing the development of rare outbreaks of thundery showers, sometimes heavy and widespread. Scattered daytime showers occur more commonly along the escarpments bordering the southern Red Sea. The south-west monsoon from Africa is distorted to a north-westerly and brings widespread showers to the mountains from July to September.

Résumé

Aperçu du temps et du climat de la Mer Rouge

Dans la région de la Mer Rouge, le régime des vents est dominé par les anticyclones tropicaux persistants ; cependant au-dessous de 3 km d'altitude environ, les vents sont fortement influencés par le relief de l'Afrique et de l'Arabie, en particulier en ce qui concerne l'existence, d'octobre à mai, d'une zone de convergence oscillant du Nord au Sud. Des dépressions transitoires se déplaçant vers l'Est, au Nord des anticyclones, affaiblissent parfois à cette époque de l'année, la stabilité statique habituellement présente, permettant aussi l'éclatement d'averses orageuses, parfois fortes et étendues. Pendant le jour, des averses locales se produisent le plus souvent le long des escarpements qui bordent le Sud de la Mer Rouge. La mousson de S.W. de l'Afrique est déviée et se transforme en vent de N.W. et apporte aux montagnes des averses étendues de juillet à septembre.

* Centre for Overseas Pest Research, London.

INTRODUCTION

In this account, we shall consider the synoptic meteorology of the Red Sea, and discuss the nature of atmospheric disturbances on the scale of hundreds or thousands of kilometres. We shall also include meso-scale disturbances, with dimensions of 10-100 km. The word 'climate' will be used in the sense of the cumulative effects, for a given place and period of time, of a sequence of such disturbances. These effects may be expressed in terms of means and deviations of such descriptive parameters as wind, temperature and rain (what some are now calling 'climatography'), or in terms of the frequency of occurrence of various synoptic types ('synoptic climatology') with some discussion of their physical causes and frequency variations in space and time ('dynamic climatology').

It is not possible to give a comprehensive account of either the meteorology or the climatology of the Red Sea ; not enough is yet known about them. Nor is it necessary to dwell on the climatography, except to note that, as regards surface parameters, there exists an excellent atlas based on numerous ship reports (Royal Netherlands Meteorological Institute 1949), and narrative accounts (such as Meteorological Office 1951).

As regards higher levels in the atmosphere, there are few wind and temperature sounding stations ; hence only broad patterns can be given, based partly on interpolation between nearby countries. There have been very few published synoptic studies (Ashbel 1938, El Fandy 1952, Beau, Bourhis and Berges 1965, Pedgley 1970, Zohdy 1970) ; and fewer meso-scale studies (Flohn 1965 a and b, Pedgley 1966). To this sparse literature will be added studies from Egypt and the Sudan, as well as some comments based on personal experience of the area. Emphasis will be on patterns of wind and rain.

Patterns of wind

Near the sea surface, the broad-scale wind-flow is simple. On almost all days, winds are north-westerly in the north, whereas from about October to May south-east winds in the south replace the north-westerlies present during the remainder of the year. From October to May the two opposing streams meet in the Red Sea Convergence Zone (RSCZ - see Fig.1). Wind speeds are usually less than 10 m sec^{-1}, the principal exception being near the Bab el Mandeb, where the south-easterlies are often stronger, sometimes more than 20 m sec^{-1}, and perhaps in the from of a jet. The RSCZ tends to lie north-south, rather than directly across the Red Sea, perhaps a result of Coriolis forces acting on a fluid constrained to flow in a rift (Rao and Simons 1970). At its northernmost, from November to January, the RSCZ lies near Port Sudan and Jiddah. In summer, north-westerlies usually cover the whole length of the Red Sea, but on a few days southerlies spread across the south, probably derived from the south-west monsoon of Somalia and eastern Ethiopia.

Figure 1 also shows schematic flow patterns for higher levels in the winter atmosphere. At 1 500 m, the pattern is similar to that at the surface, but the RSCZ is further north. At 3 000, winds are dominantly westerly in the north, but variable in the south, and much the same occurs at 5 500 m. The change in pattern between 1 500 and 3 000 m reflects the removal of the barrier effect of the plateaux of Ethiopia and Yemen.

SCHEMATIC FLOW AT FOUR LEVELS

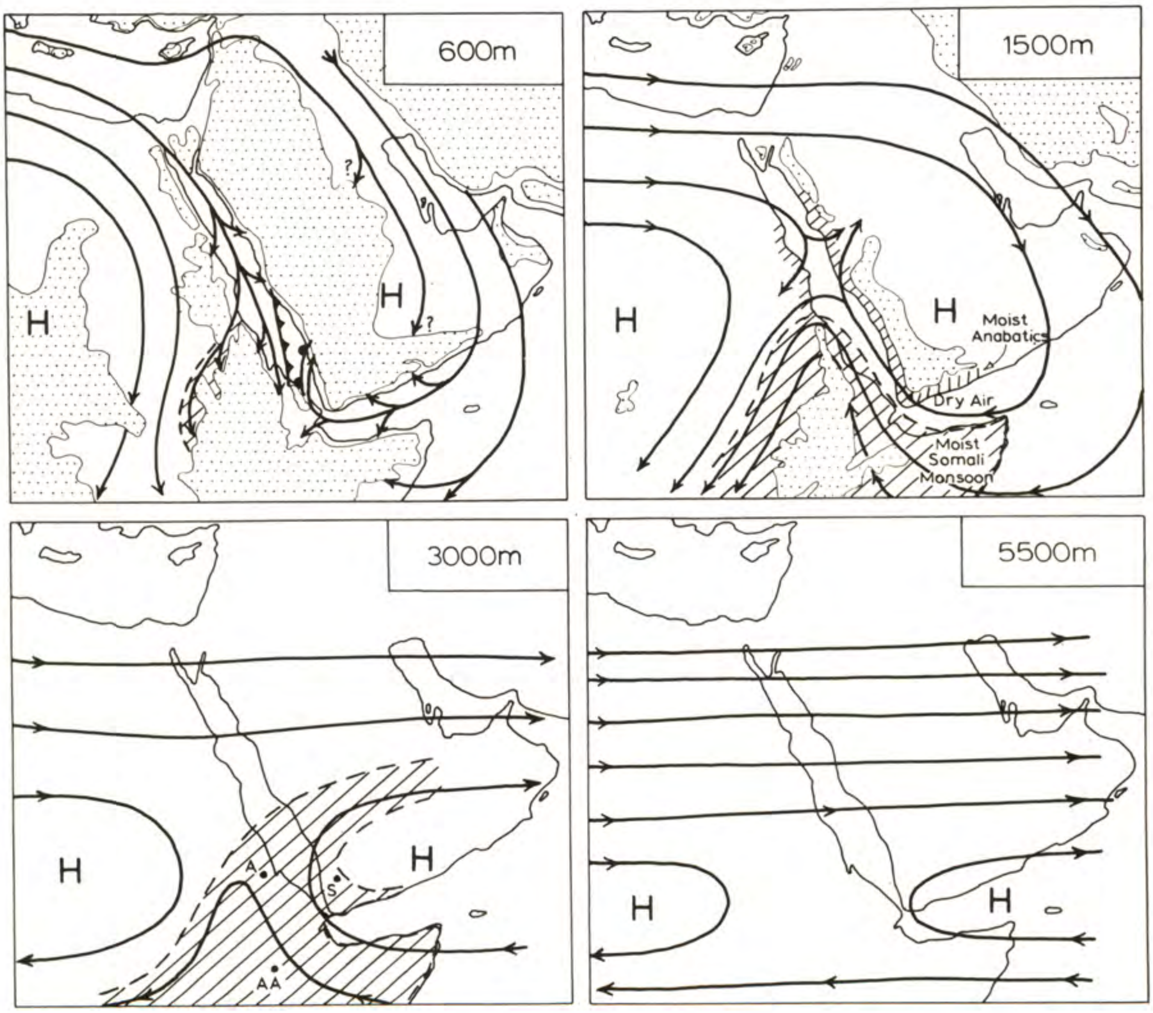


Fig. 1. Schematic wind-flow patterns over the Red Sea in winter at 600 m (2000 ft.), 1500 m (5000 ft.), 3000 m (10000 ft.) and 5500 m (18000 ft.).

Figures 2(a) to 2(d) illustrate flow patterns over the southern Red Sea at three levels in January, April, July and October. In April and October, the subtropical anticyclones at 3 000 m have moved northwards compared with January so that easterly winds occur over the southern Red Sea. By July, the 3 000 m winds have become northerly, and northerly winds are usually present from the surface up to at least 3 000 m, but above that level they veer to easterly (not shown).

Note also that 1 500 m winds in July come from the Sudan ; in fact, they are a recurving branch of the south-west monsoon winds. The northern limit of this monsoon is the inter-tropical convergence zone (ITCZ). Over the Sudan, the ITCZ extends to the ground, but over the Red Sea this is prevented by the presence of a maritime convective layer, consisting of potentially cooler air brought from higher latitudes by north-west winds. On the Arabian side, the ITCZ probably builds down to the ground by day-time heating, and it may well be 'anchored' to the westward-facing escarpment of the plateau south of Jiddah.

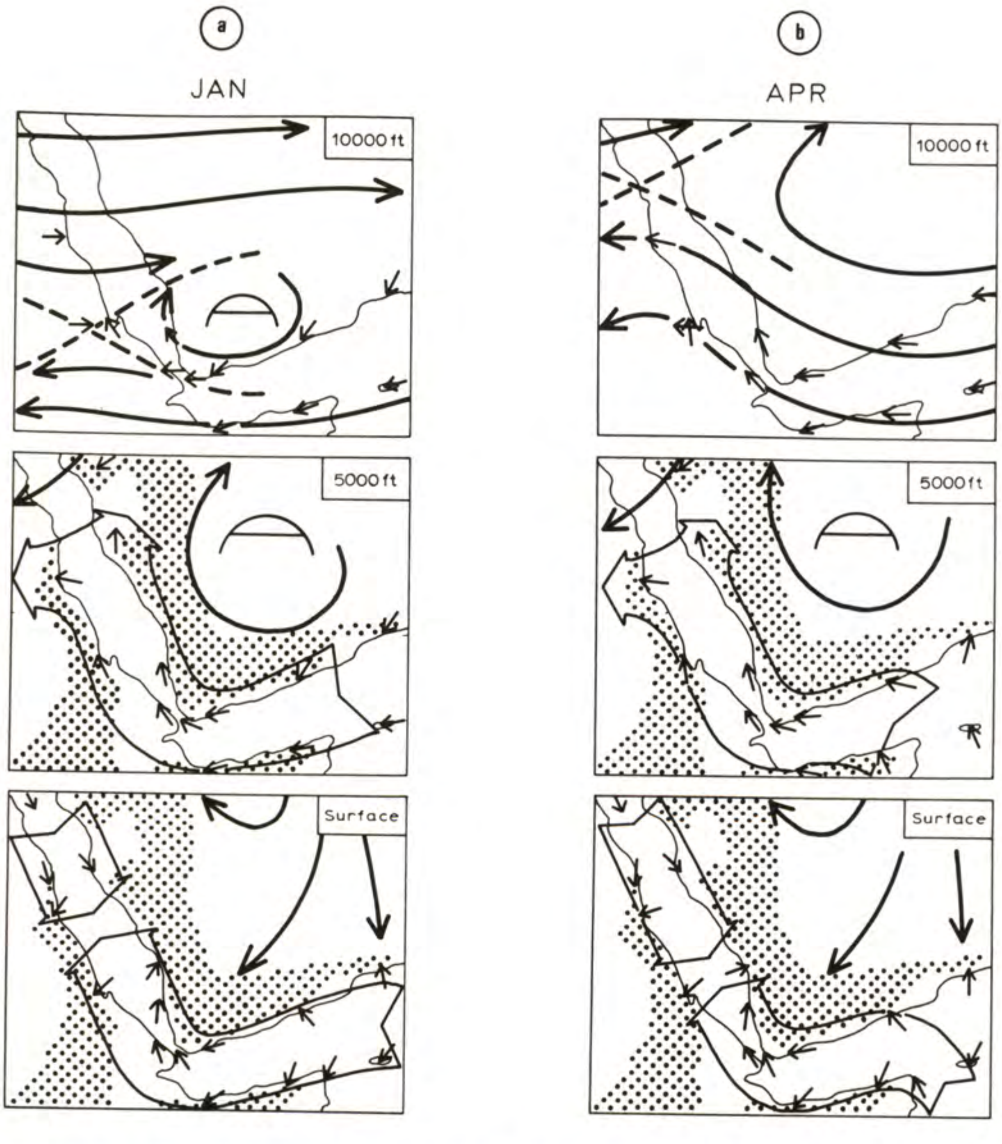


Fig. 2. Schematic wind-flow patterns over the Red Sea at sea-level, 1500 m (5000 ft) and 3000 m (10000 ft) for (a) January (b) April,

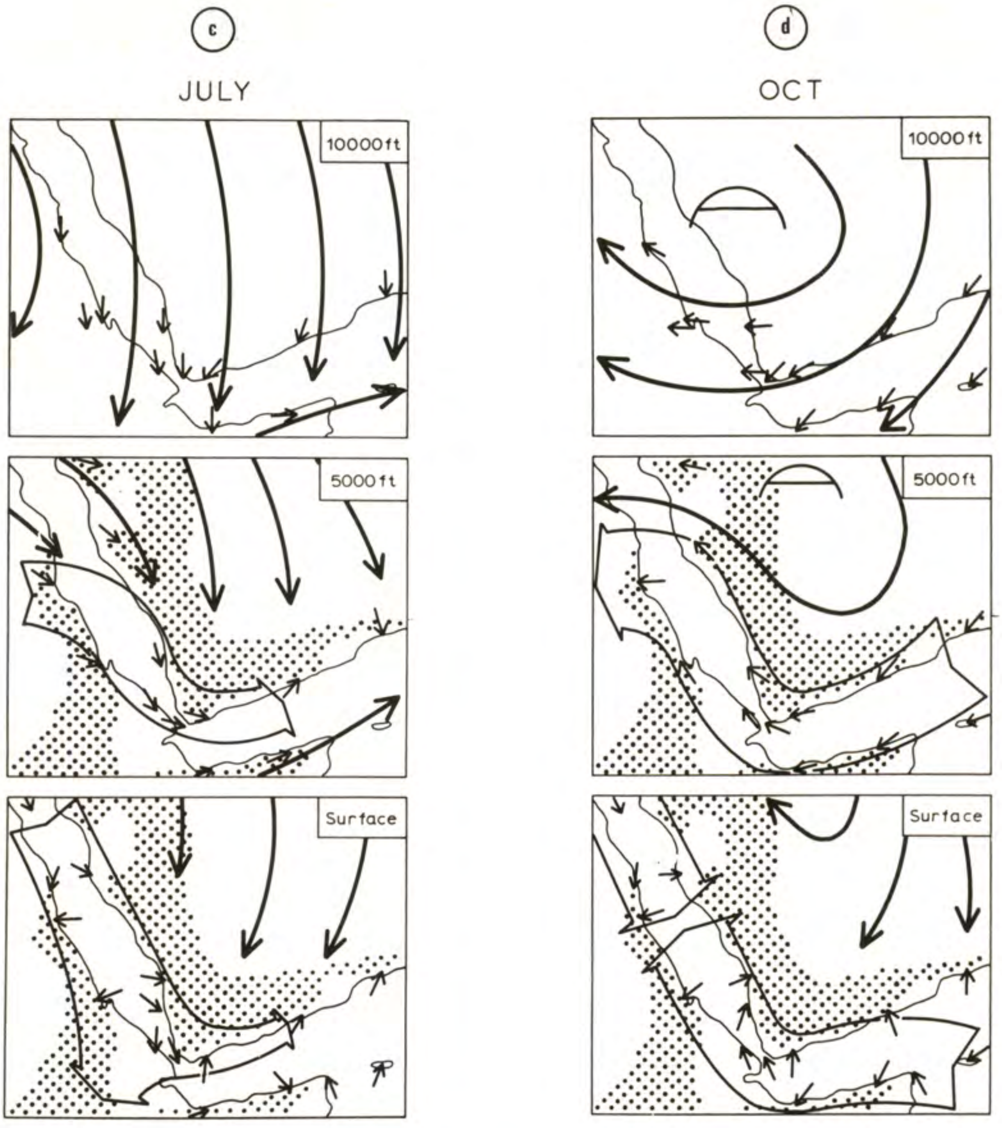


Fig. 2. Schematic wind-flow patterns over the Red Sea at sea-level, 1500 m (5000 ft) and 3000 m (10000 ft) for (c) July and (d) October.

On any given occasion, the patterns given in figures 1 and 2 are distorted by the presence of synoptic disturbances. These may be classified into two types :

a) changes in the 'centres of action' - the position, size and intensity of, for example, the RSCZ, the ITCZ or the sub-tropical anticyclones ;

b) transient waves in the westerlies and easterlies, respectively north and south of the sub-tropical anticyclones.

Both types of disturbance are accompanied by day-to-day changes in the wind at a given place. In particular, the eastward movement of a trough in the westerlies, or an intensification of a ridge, is usually associated with an increase in speed, or surge, in the low-level winds, the leading edge of which may be sharply defined - a wind shift line - with some characteristics of a cold front. Such lines move south-eastwards across the Nile valley at intervals of 2 to 10 days, but they are not so clear cut over the Red Sea. However, north-westerly surges coming from the

Mediterranean temporarily displace the RSCZ southwards so that its position oscillates with a period of a few days (fig. 3). Sometimes these surges have speeds of 15 m sec^{-1}, when they are accompanied by much haze and blowing dust.

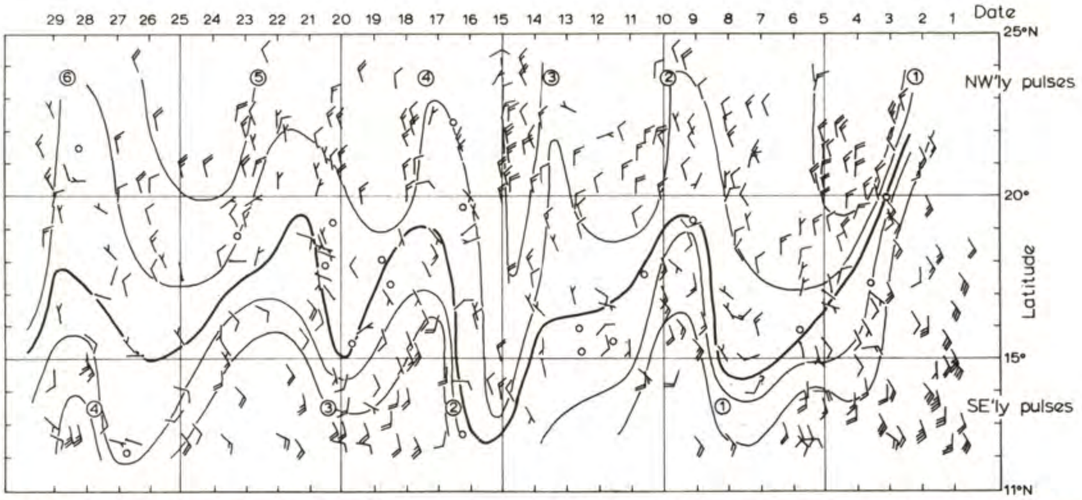


Fig. 3. Horizontal time cross-section along the mid-line of the Red Sea between 11° and 25°N in February 1964, showing winds reported by ships. Isopleths of wind speed are at 10 kt (5 m sec^{-1}) intervals. Successive surges are indentified by circled numbers : north-westerlies at the top, south-easterlies at the bottom. Note the oscillations of the RSCZ.

Above the constraining barrier effects of nearby mountains, winds over the northern Red Sea at 1 500 m, and sometimes even at 3 000 m, tend to veer to east a day or two after a surge has passed. On some days, particularly in spring, these winds veer further to between south-east and south-west. Such an event is likely ahead of a vigorous cold front advancing from the west, or ahead of a 'desert depression' also coming from the west (PEDGLEY 1972). Surface north-westerly winds over the northern Red Sea then become light or they even reverse to south-easterly before the on-coming surge reaches the Gulf of Suez. Such days have surface south-east winds throughout the length of the Red Sea, and they are warmer than normal because the usual north-westerly surface flow from the Mediterranean has been replaced by winds from the Arabian Sea ; at 1 500 m the flow can be from Arabia or Sudan. Following the passage of a wind-shift line, temperatures can fall quickly to below normal. These temperature changes are better defined overland, e.g. along the Nile valley, than over the sea. There is little evidence that westward moving waves are present in the upper easterlies during the monsoon period.

Apart from these inter-diurnal changes, there are complex diurnal wind changes, details of which strongly - depend on locality. Along coasts, day-time sea breezes and night-time land breezes occur almost daily and in all months. There is some evidence (e.g. DELSI 1967) that the leading edges of both sea and land breezes form meso-scale fronts separating the diurnal circulations from the broad-scale flow. The land breeze front may develop during the night some 10-20 km off-shore, persisting into the morning. The sea breeze front develops during the morning some 10-20 km inland and advances away from the coast, perhaps reaching

100 km by evening. Coastal winds can be considered as being approximate vector sums of the broad-scale flow and the diurnal component. For example, along the west coast, north-west winds become north or north-east by day and west by night, whereas south-east winds become east by day and south or south-west by night. Seawards, land breezes probably extend only 10-20 km ; in contrast, the sea breeze circulation may well reach the middle of the Red Sea by late afternoon, but this has not been studied. Over the coastal plains before the arrival of the sea breeze front, there are diurnal variations in wind that can be ascribed to convective mixing. In the presence of vertical shear of the wind (especially just north of the RSCZ, where surface north-westerlies are overlain by south-easterlies (fig. 4), convective mixing can cause a vertical exchange of momentum whereby the surface north-west wind weakens progressively during the day and may even be replaced by a south-east wind. (In effect, the RSCZ over the coastal plain has a diurnal oscillation in position, similar but in an opposite direction to that of the ITCZ over the Sudan ; in both cases the oscillation is caused by day-time propagation of the zones through the atmosphere rather than simple movement of airstream boundaries). Interaction of the RSCZ with the sea breeze at a place 50-100 km inland from the coast leads to a complex diurnal variation of wind. Near mountains there are added complications due to up-slope (anabatic), and down-slope (katabatic) diurnal winds.

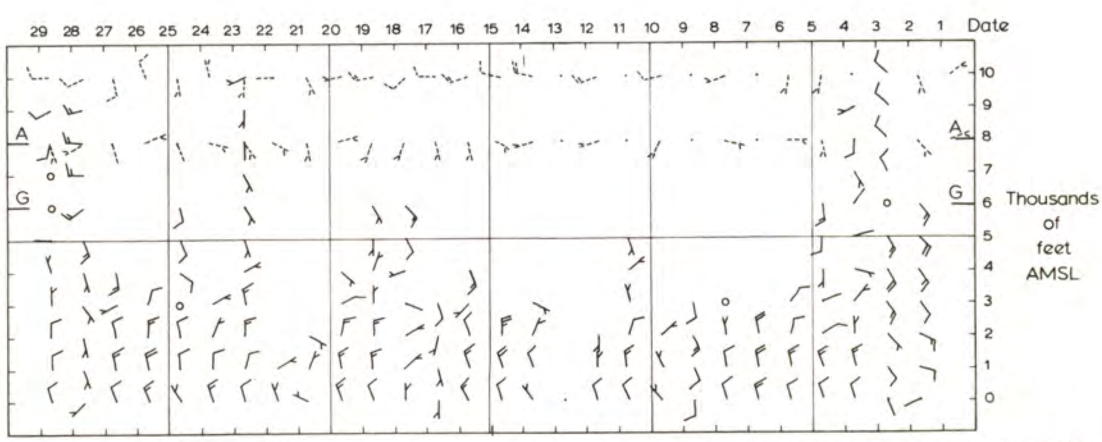


Fig. 4 Vertical time cross-section for Gulbub (c. 17°N 39°E) in February 1964, showing daily winds measured by pilot balloons at 04 GMT between sea level and 3000 m (10000 ft). The broken arrows show winds measured at 06 GMT above Asmara (c. 15° N 39°E on the Ethiopien plateau). A and G indicate the appoximate altitudes of the plateau near Asmara and Gulbub respectively. Note the low-level north-westerlies surmounted by south-easterlies.

Patterns of rain

Rainfall over the Red Sea is sparse and erratic. Judging by records from coastal stations, annual falls are less than 20 mm in the north, and mostly 50-100 mm in central and southern parts. The annual number of days with more than 1 mm varies from about one in the north to 5-10 in the centre and south.

The principal cause of this aridity is persistent subsidence, both on the synoptic scale, as part of the dynamics of the sub-tropical anticyclones, and on the meso-scale, as part of the day-time sea breeze and anabatic circulations. This subsidence brings down low absolute humidities from aloft, and at the same time restricts the depth of the convective layer in contact with the ground. Over the sea, the convective layer is usually only 0,5-1,5 km deep, and is often capped by a temperature inversion (fig. 5), below which the relatively high absolute humidity contrasts with that in the subsided air above. Over the land, the convective layer is usually 2-6 km deep, the depth increasing southwards and from winter to summer.

a

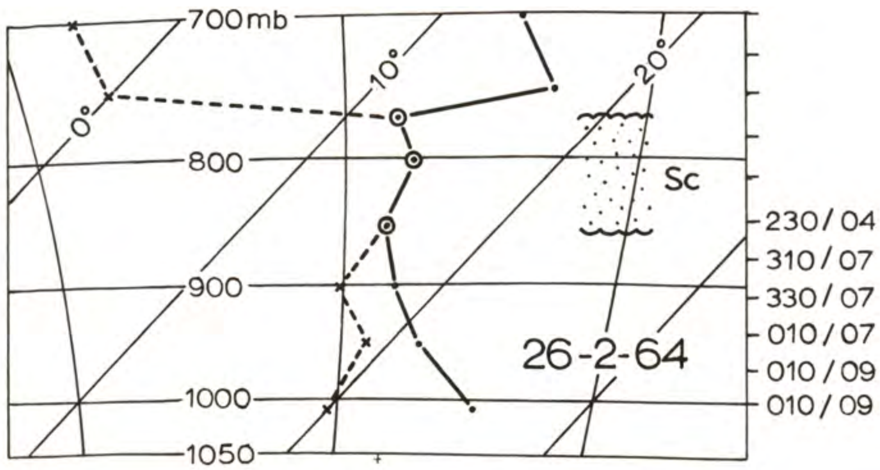
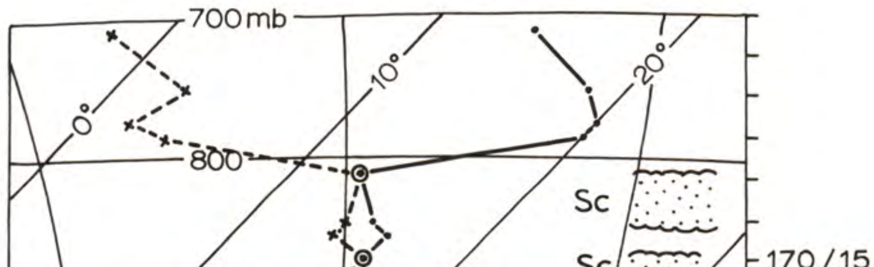


Fig. 5 Examples of aircraft temperature-soundings near Gulbub. Broken lines show dew points. Note the temperature inversions near 800 mb (2 km), with moist air and cloud layers in the maritime layer below, and dry, subsided air above.

b



Moisture necessary for the formation of rain comes from two primary sources :

a) the Arabian Sea, from about October to May, when lower tropospheric south-easterlies cross Somalia and eastern Ethiopia (the sub-inversion, maritime moist layer is then convectively mixed to altitudes of 4-6 km, but a new maritime moist layer tends to form over the southern Red Sea) ;

b) the South Atlantic and the forests of west and central Africa, from about June to September, when lower tropospheric south-westerlies cross Sudan and spill over, and around the northern tip of, the Ethiopian highlands as north-westerlies. (This moist monsoon airstream is typically 2-4 km deep). Moisture within the maritime convective layer over the northern Red Sea does not seem to be a primary source of rainfall.

Clouds within the maritime convective layer are either absent or small amounts of shallow cumulus or stratocumulus with a base near 0,5 km ; only rarely are they deep enough to give light but insignificant showers (fig. 6). Near the RSCZ, stratocumulus clouds can become deeper and more extensive ; in winter they can give spells of light rain over the southern Red Sea and along seaward-facing scarps. They are sufficiently frequent in mid-winther months to show as small maxima on maps of average cloudiness based on satellite observations (ATKINSON and SADLER 1970). Overland, daytime cumulus clouds have bases between 2 and 4 km. Vertical growth is deepest over the mountains bordering the southern Red Sea where thundery showers occur on some days, especially from June to September, when the inhibiting effect of subsidence on convection is reduced by the seasonal northward retreat of the sub-tropical anticyclones. The northern limit of these monsoon rains is effectively fixed by the position of the ITCZ ; only rarely do they occur north of 22°N. In winter, decaying showers drift in the upper west winds to give some rain on the western coastal plain, whereas the heavier monsoon showers drift in the upper east winds to give rains on the eastern coastal plain sometimes preceded by dust-storms (DAKING 1932).

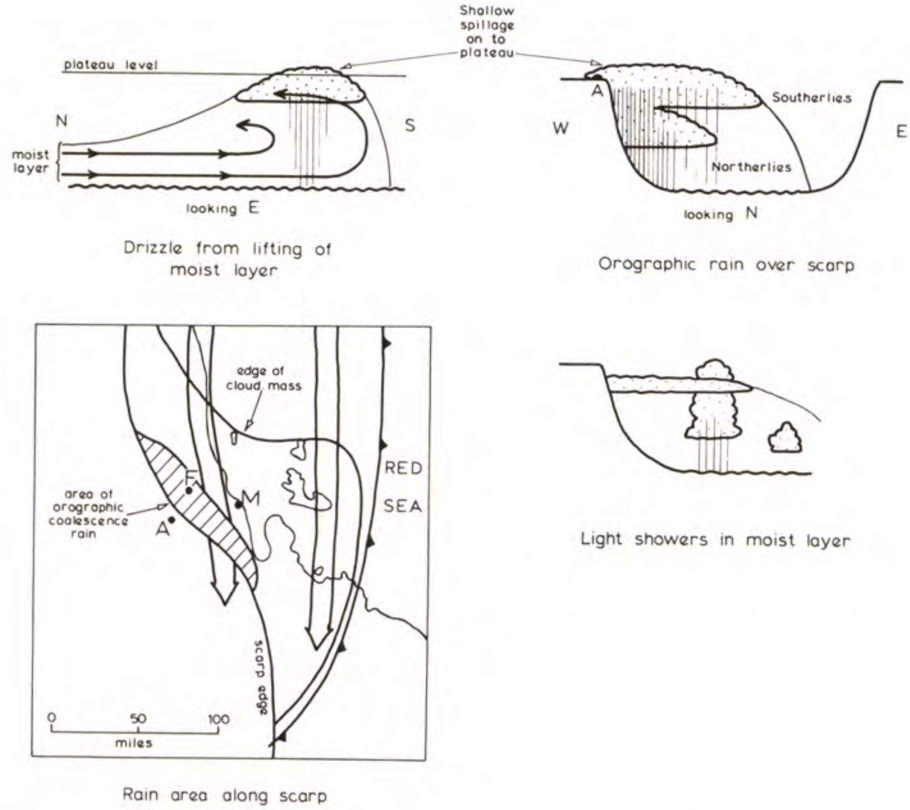


Fig. 6 Schematic representation of formation of rain : I from stratocumulus clouds in the RSCZ and along sea-ward facing scarps, and from moderatley deep cumulus clouds in the maritime layer

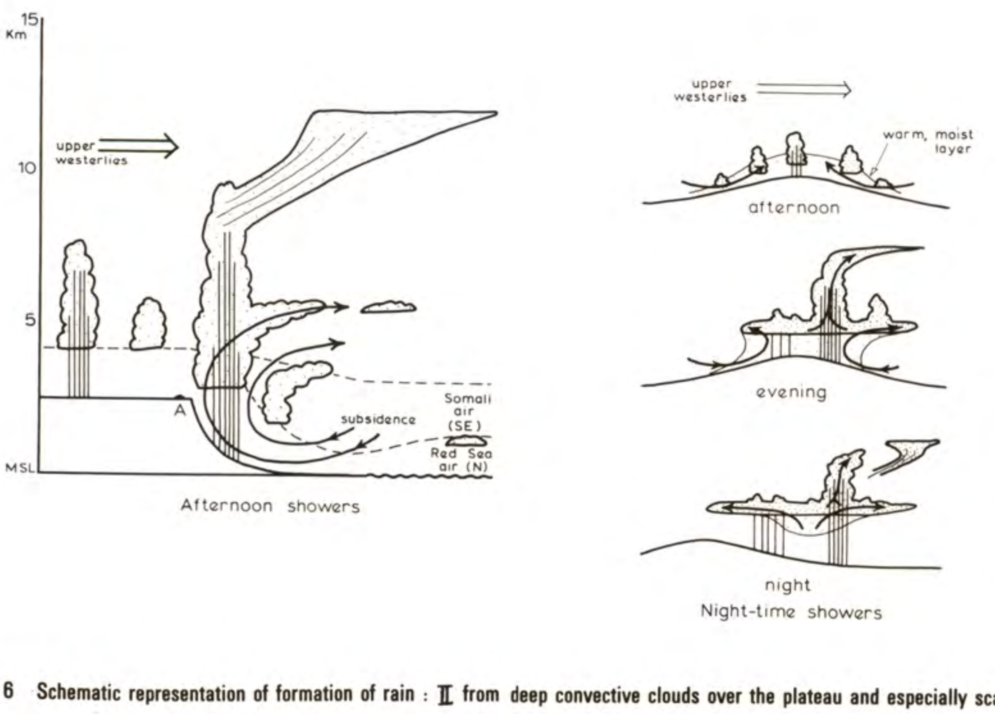


Fig. 6 Schematic representation of formation of rain : II from deep convective clouds over the plateau and especially scarps.

When a trough in the upper west winds moves eastward across the Red Sea, cirrus clouds tend to increase ahead of the trough's axis, and sometimes sheets of altocumulus and altostratus with bases at about 6 km give cloudy spells of a day or two, especially in the north (ALPERSON and ZANGWILL 1966). On rare occasions these cloud sheets give light rain (fig. 7). When an upper trough is deep and extends well south, divergence in the wind-flow ahead of it induces a vertical stretching of the lower atmosphere and the convective layer is deepened. Tall clouds can then grow out of the convective layer, resulting in thunderstorms and torrential rain (ASHBEL 1938, EL FANDY 1952, PEDGLEY 1970, ZOHDY 1970). Daily falls can exceed 20 mm, but they are rare in the north ; falls exceeding 50 mm sometimes occur over central and southern parts (fig. 8). This release of moisture from a lower tropospheric south-easterly airstream by the action of a deep upper tropospheric trough is the principal cause of the erratic rains over the sea and coastal plains from about October to May. During that period it occurs about five times each year, but only a small part of the Red Sea is affected on any one occasion.

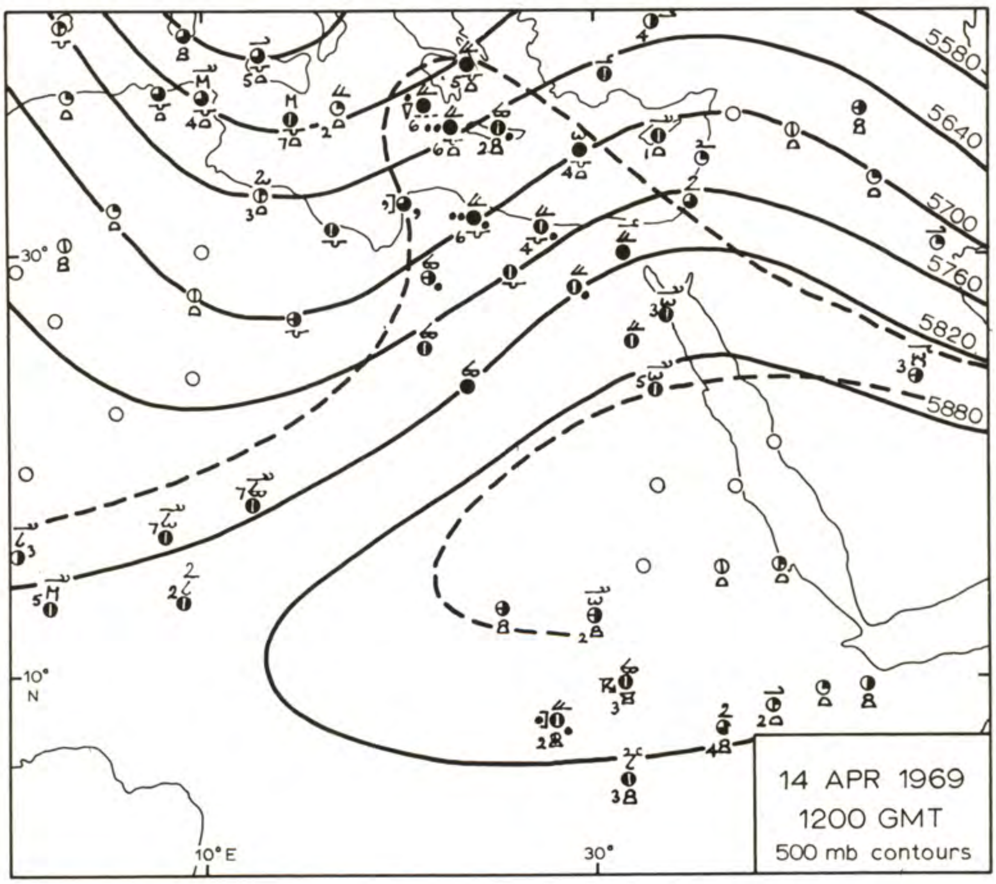


Fig. 7 Example of extensive mid-tropospheric cloud sheets (approximate boundary shown by broken line) ahead of a trough in the upper west winds. Such sheets can give local light rain over the Red Sea.

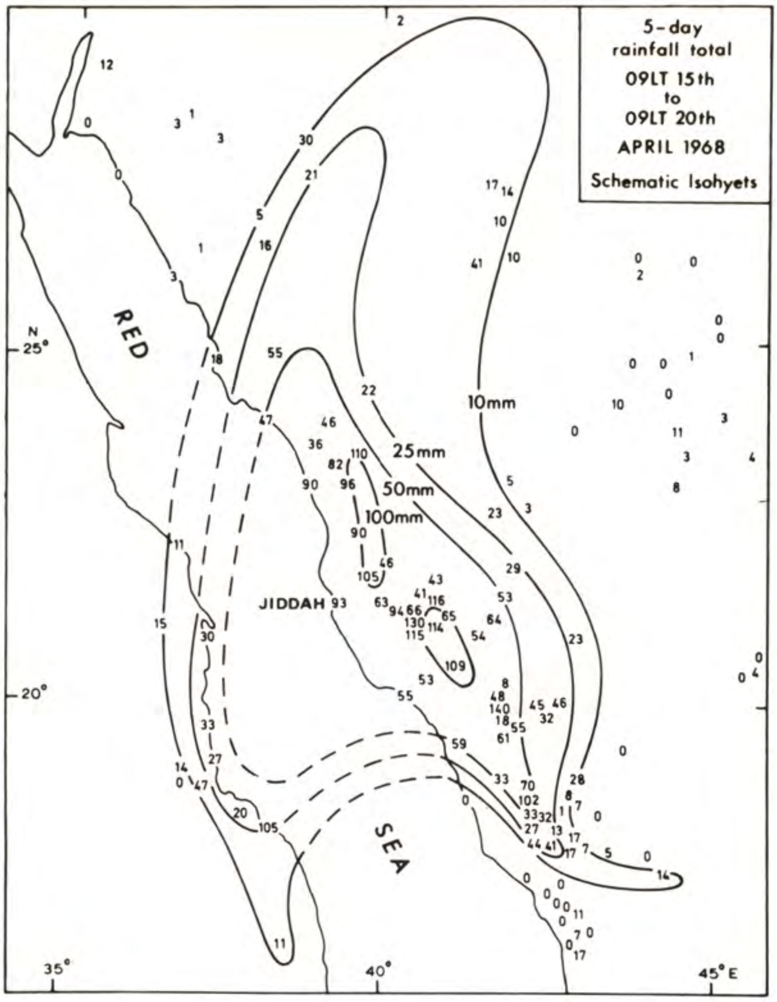


Fig. 8 5-day rainfall totals, 09LT 15 th tou 09LT 20 th April 1968. Most of this rain fell in 24 hours ending 09LT on 18 th.

Day-to-day incidence of monsoon rains varies in ways that are not understood. The influence of westward-moving waves in the upper troposphere is probably small. Rainy spells may be associated with changes in position and intensity of the subtropical anticyclones, particularly the one usually present in mid-troposphere over Arabia. A veering of mid-tropospheric winds from east to south-east seems favourable for rain.

Conclusions

Both the weather and the climate of the Red Sea are strongly influenced by the topography of Africa and Arabia. Below plateau-level, the wind-flow is effectively channelled either up-or down-rift, instead of the north-east trade winds that would otherwise be expected (fig. 9). In the south, this influence extends to altitudes of 2-3 km, but in the north it is shallower. Apart from this mechanical barrier effect there is a thermal effect whereby the mountains act as high-level heat sources, inducing day-time anabatic winds. Because the rift is water-filled, there is the added complexity of land and sea breezes.

Above those mechanical and thermal influences, the wind-flow is dominated by the persistent sub-tropical anticyclones with their widespread subsidence leading to prolonged drought, and by the transient troughs in the upper west winds with their rare spells of winter cloud and rain. Deflection of the Arabian Sea trade winds into south-easterlies introduces lower tropospheric moisture that feeds these rains, as well as the thundery showers that occur more frequently over the mountains bordering the southern Red Sea from about October to May. Monsoon rains, mostly over the plateaux, are derived from convection out of the moist. Lower tropospheric, south-westerly air-stream from Sudan and further west.

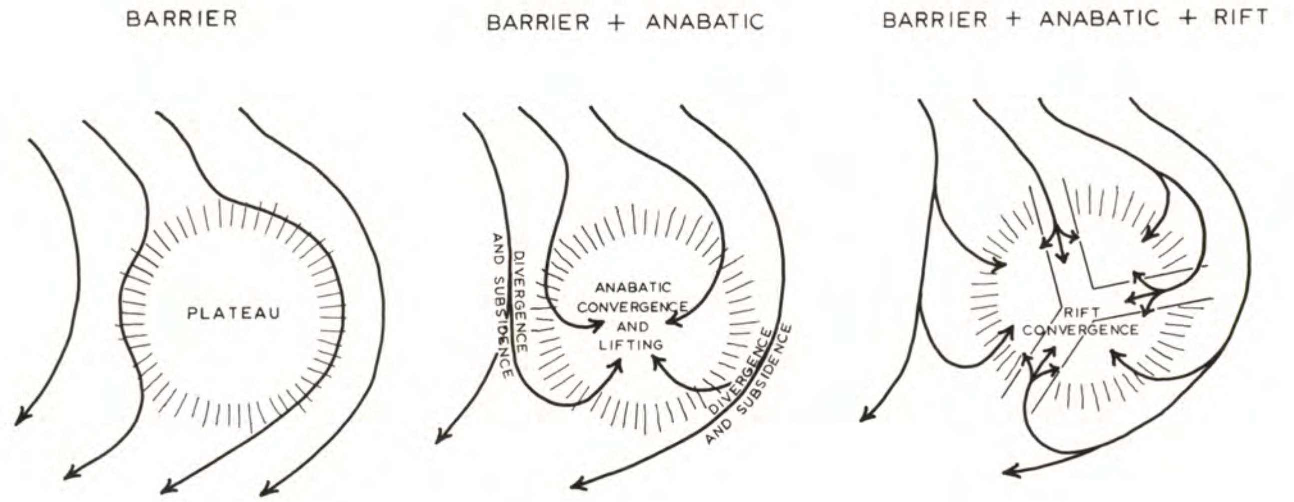


Fig. 9 Schematic representation of broad-scale flow distorted by the plateaux of Ethiopia and Yemen, and by the rifts.

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DISCUSSION AND COMMENTS

Dr. MILLER : The general pattern of wind circulation you have demonstrated shows a curious coincidence with the geographical areas of ocean surface about the Arabian peninsula ; a spiral flow about the Persian Gulf, Arabian Sea, Gulf of Aden and the Southern Red Sea. The juxtaposition with the water distribution is somewhat analogous to hurricane paths, an air-sea coupling phenomenon, off the East coast of the United States. Would you have any comment with respect to the export of moisture flux out of the Arabian area ?

Mr. PEDGLEY : I concentrated, I suppose, on the occasions when important rains fell over the area and we know these are rare events.

Your point about where the moisture normally goes when it doesn't fall out as rain I suppose is of particular interest to you. I would hazard a guess that, on the majority of days during the winter when you have south-easterlies present over the southern Red Sea, particularly at levels rather above that of the surface, the majority of this moisture (I would not want to put fractions into this, I don't suppose anybody has done this) would flow out of the Red Sea rift around the northern end of the Ethiopian plateau inti the Sudan. There is some evidence for this in rather higher dewpoints in the northerly winds over the Sudan North of the inter-tropical convergence zone than there are over southern Egypt. Then, of course the daytime convection will spread this moisture to altitudes of three kilometers or more. If you start with a moist layer which is only one kilometers deep over the Red Sea and spread it by convection to three kilometers over the Sudan, you would not expect a very large increase in dewpoint of the surface.

The other way in which the moisture can be removed is by the diurnal circulations along the escarpments because, particularly during the autumn and the spring (not in the middle of winter which was the time when those pictures were taken of the layer clouds), convection clouds along these escarpments are almost a daily feature. They can go up to typical altitudes of three to five kilometers without producing any showers but nevertheless they will mix moisture into the middle of the atmosphere and then this is carried away by the upper westerly winds. So, although I am really guessing here, I would say that most of the moisture moves out of the Red Sea into the Sudan, on some days perhaps into Saudi Arabia, if the right disturbances are present ; and some of it comes out in the diurnal circulations, i.e. the daytime anabatic wind circulations along the escarpments. It is only on rare occasions that the large scale flow patterns in the winds are conducive to the development of really deep convective clouds with tops up to ten to fifteen kilometers ; it is then that the rare but heavy rains occur.

Dr. MILLER : Would you, in general, say that there is a great export of moisture away from the area ?

Mr. PEDGLEY : Yes, I would have thought so.

Dr. MORCOS : As far as I know there are no published figures available on the average monthly or annual precipitation in the Red Sea. Although the quantities are small, they are important in calculating the term (E-P) in the water balance of the sea. Is the existing information sufficient to calculate these averages ?

Can you differentiate between rainfall originating from the Red Sea itself and rainfall as a result of the transport of moisture from regions outside of the Red Sea ? Can you give any estimates ?

Mr PEDGLEY : That is a difficult question. Let me make another guess. I would have thought that the majority of the moisture which produces rainfall around the Red Sea comes from the Indian Ocean. If you look at that period in April 1968 when there were those heavy widespread rains over Arabia the moisture for those rains was derived from a low level, moist convective layer. You can easily see on daily weather charts that this layer comes all the way from the Indian Ocean, across Somalia, eastern Ethiopia and through the rift (not just the Bab-el-Mandeb Strait, but the whole width from the Yemen to the Ethiopian escarpments), and then it spreads North. When it gets far enough North, it may rise, on this occasion because of the high-level jet over it. The dynamics of the jet-stream allows convection to deepen as the South-East winds approach its axis. It goes up into deep clouds and the tops spread away. Most of the water may well fall over the sea, but some of it spreads all the way to the Russia at middle levels in the atmosphere.

As to estimates of quantities I just do not know. I suppose one could make a guess based on the Aden radio sonde ascents. One could for example take long period averages as being representative of the flow into the southern Red Sea. From that one could at least work out the moisture flux and then try to make some calculations as to how much moisture is added from the Red Sea before it gets to the rain area. The difficulty is that the only radio sondes available on that occasion of rains in April 1968 were Jeddah (which was put out of action by the thunderstorms) and Port Sudan (which makes one ascent every two days).

It's just possible that if someone wanted to work with that particular occasion there would be marginally enough data. I have not done that but it would be an interesting project.

Dr. MORCOS : Are there any annual averages for rainfall over the Red Sea ?

Mr. PEDGLEY : Over the Red Sea itself I don't know of any figures except for the Daedalus Rock lighthouse but of course they are old records and at the very arid end. There is also a short period of records from Dhalak Island but it is so short it is really hardly worth taking. Of course ships in general don't record amounts of rainfall.

Dr. ROBINSON : What is the frequency of the cloud cover ?

Mr. PEDGLEY : If you look at the mean cloud amounts based on satellite data, which are published by Sadler and Atkinson, for example, you will see that in January the mean cloud amount in the central part of the Red Sea is only about 2/8 to 3/8, and it decreases on either side.

What that does not reflect is that there are a number of days when there is a complete cloud coverage from one side of the Red Sea to the other over a narrow range of latitudes. I would have thought that one would have such a complete coverage perhaps no more than five days per month in the cloudiest, mid-winter months. By April there are probably no days when you get a complete cloud coverage.

Dr. ROBINSON : Well no. Even so I did not realise that there was as much as your discussion pointed out.

Mr. PEDGLEY.: Yes. The difficulty with satellite averages is that quite often cirrus clouds are not at all well shown on the pictures. I don't know whether they are of significance from your radiation balance studies. Most of the clouds which show up are the layer clouds or large convective clouds. Large convective clouds out over the water are rather rare events confined to special synoptic occasions. They occur maybe five times a year. Of course they don't all occur in the same place in any season of any year. A given place may go several years before it has a heavy storm with a large amount of cloud for a period of a day or two.

Dr. ROBINSON : I was thinking of the pattern of clouds that you don't have in the Atlantic.

Mr. PEDGLEY : In the middle of winter, in December and in January, there are perhaps five days a year when you have a cover right over the Red Sea for several degrees of latitude and this shows up very nicely on individual satellite pictures.

Dr. MANN : Are there many clear days over the Red Sea ?

Mr. PEDGLEY : We have daily satellite pictures which are mosaics and these show that there are many days on which the Red Sea is essentially clear. But then of course the satellite does not pick up the small cumulus clouds. The resolution of the order of one or two kilometers cannot do this. However if there is a field of small cumulus clouds covering some few square degrees, for example, then this would produce a fuzziness which one can see. We can only make guesses as to what sorts of cloud are present. But I should have thought that there are quite a large number of days in the year when relatively the whole of the Red Sea is free of cloud. Particularly in May and June. June is about the driest month.

Dr. MANN : Another question which has nothing to do with oceanography. You said that it rained very heavily when the locusts were building up. What happened to the locusts ?

Mr. PEDGLEY : Well, that's another big story. In a few words-locusts need wet ground in which to lay their eggs. When the eggs are laid there is not enough moisture in them for complete incubation so they must absorb water from the soil. Therefore to produce a big upsurge in locust populations good rains are necessary in a succession of breeding areas. It so happened that the rains in April 1968 formed part of a sequence of rains which ran from November 1966 in Oman on to

July 1968 in the Sudan after which there were hundreds of square kilometers of swarms and that was the height of the new plague.

ATLAS OF MONTHLY MEAN SEA SURFACE AND SUBSURFACE TEMPERATURE AND DEPTH OF THE TOP OF THE THERMOCLINE

M.K. ROBINSON *

Résumé :

Atlas de temperature moyenne mensuelle de l'eau superficielle et sub-superficielle et profondeur du haut de la thermocline en Mer Rouge.

Les cartes mensuelles de répartition horizontale de température et les courbes de variation annuelles, contenues dans ce rapport, donnent pour la première fois une description spatiale et temporelle détaillée de la distribution de la température moyenne, de la surface à 150 m, dans la Mer Rouge. Les modèles de circulation générale, qui ont été décrits par d'autres scientifiques pour des ensembles particuliers de données, sont confirmés par ces distributions moyennes de température.

Abstract

The monthly horizontal temperature charts and annual cycle curves contained in this report provide for the first time a comprehensive space-time description of the mean temperature distribution, surface to 150 m, in the Red Sea. The main circulation patterns which have been described for individual sets of data by others are confirmed by these mean temperature distributions.

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INTRODUCTION

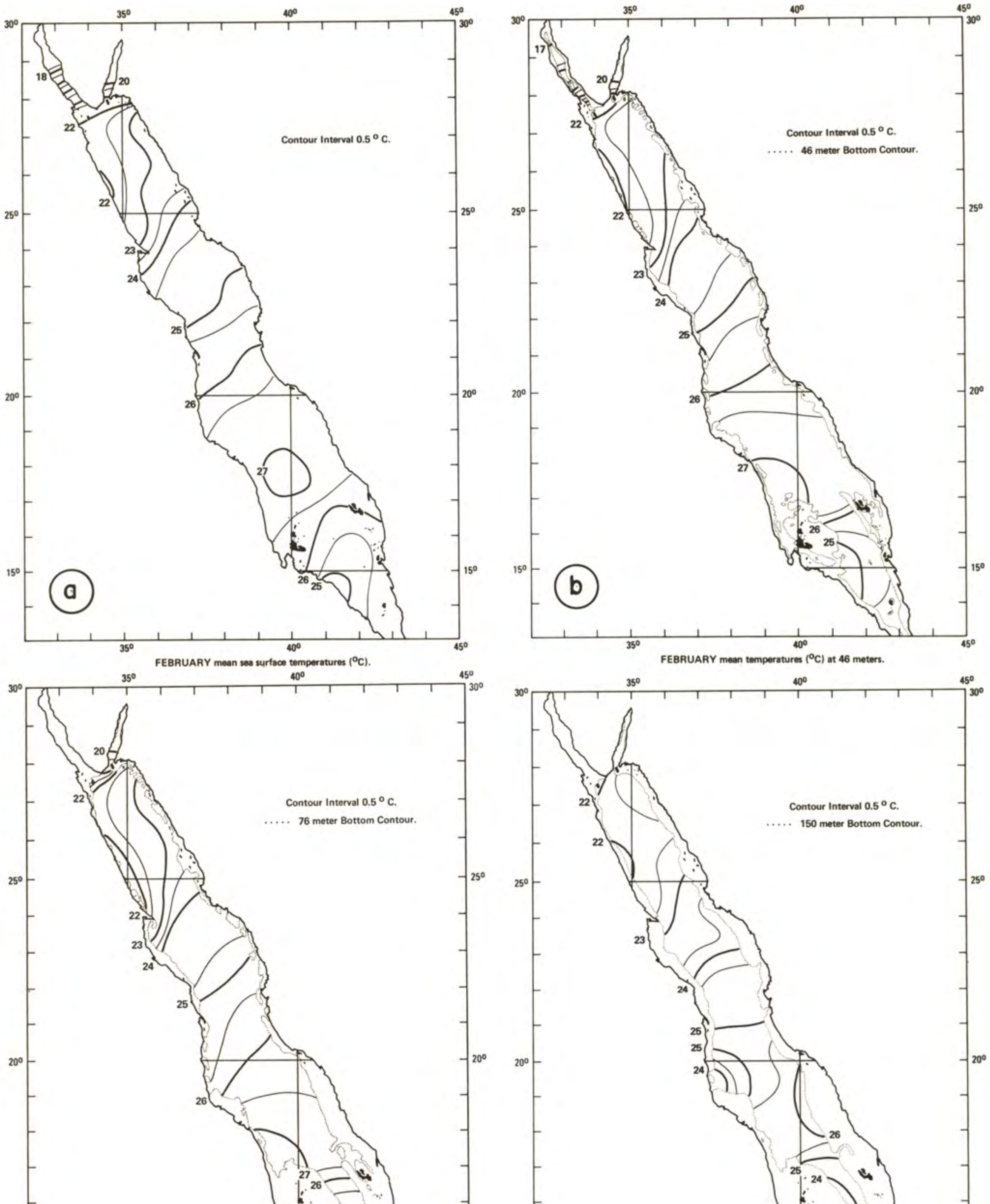
A selection of figures from the "Red Sea Atlas of Monthly Mean Sea Surface and Subsurface Temperature", Fleet Numerical Weather Central Technical Note 73-4, November 1973, is presented in this paper. The project was supported by the Office of Naval Research and the Fleet Numerical Weather Central, where all computer work was performed. The monthly temperatures will also be included in an atlas covering sea temperature distribution in the Atlantic Ocean and adjacent seas – Mediterranean Black, Red, North, Baltic, Caribbean and the Gulf of Mexico– a joint project of Margaret K. ROBINSON, Scripps Institution of Oceanography, La Jolla, California, and Elizabeth H. SCHROEDER, Woods Hole Oceanographic Institution; Woods Hole, Massachusetts.

Detailed monthly temperature charts for the Red Sea have heretofore been available only for the sea surface. MORCOS' (1970) excellent paper reviewed in detail both surface and subsurface data, and oceanographic studies of the Red Sea to that date. Most previous work dealing with subsurface conditions has been based on quasi-synoptic hydrographic cast data, with incomplete coverage in time and space. Using compilations of bathythermograph (BT) temperature data and hydrocast reversing thermometer and salinity data, PATZERT (1972, 1973) constructed mean monthly distributions of temperature and salinity in the upper 200 m along the central axis of the Red Sea, from which he developed a model of wind-driven circulation, ignoring cross sea gradients.

Using similar but more extensive BT and reversing thermometer data than used by PATZERT, the author has constructed complete space-time fields of temperature from the surface to 150 m, derived from monthly means of available data over 1° quadrangles for the six selected levels, surface, 30, 46, 76, 100 and 150 m. These mean temperatures are presented for four months–February, May, September and November–for four levels, and in annual cycle curves by 1° quadrangles for six levels. Individual BT traces have been reproduced to show the latitudinal and seasonal extent of subsurface temperature inversions. The charts, the data base, and the analysis procedures are described below. Circulation deduced from the mean temperature fields will be discussed.

CHARTS

The 4 horizontal mean temperature charts (figs. 1-4) are arranged in monthly groups for February, May, September and November–each containing 4 charts representing mean temperature at the surface, 46, 76 and 150 m. The charts were traced from computer plots made directly from the mean monthly temperatures for 1° quadrangles at the selected levels generated by the computer analysis programs. The contour interval is 0.5°C, based on means in tenths of degrees Celsius. Contours end where the depth level of the chart intersects the bottom.



FEBRUARY mean sea surface temperatures (°C).

FEBRUARY mean temperatures (°C) at 46 meters.

FEBRUARY mean temperatures (°C) at 76 meters.

FEBRUARY mean temperatures (°C) at 150 meters.

Fig. 1

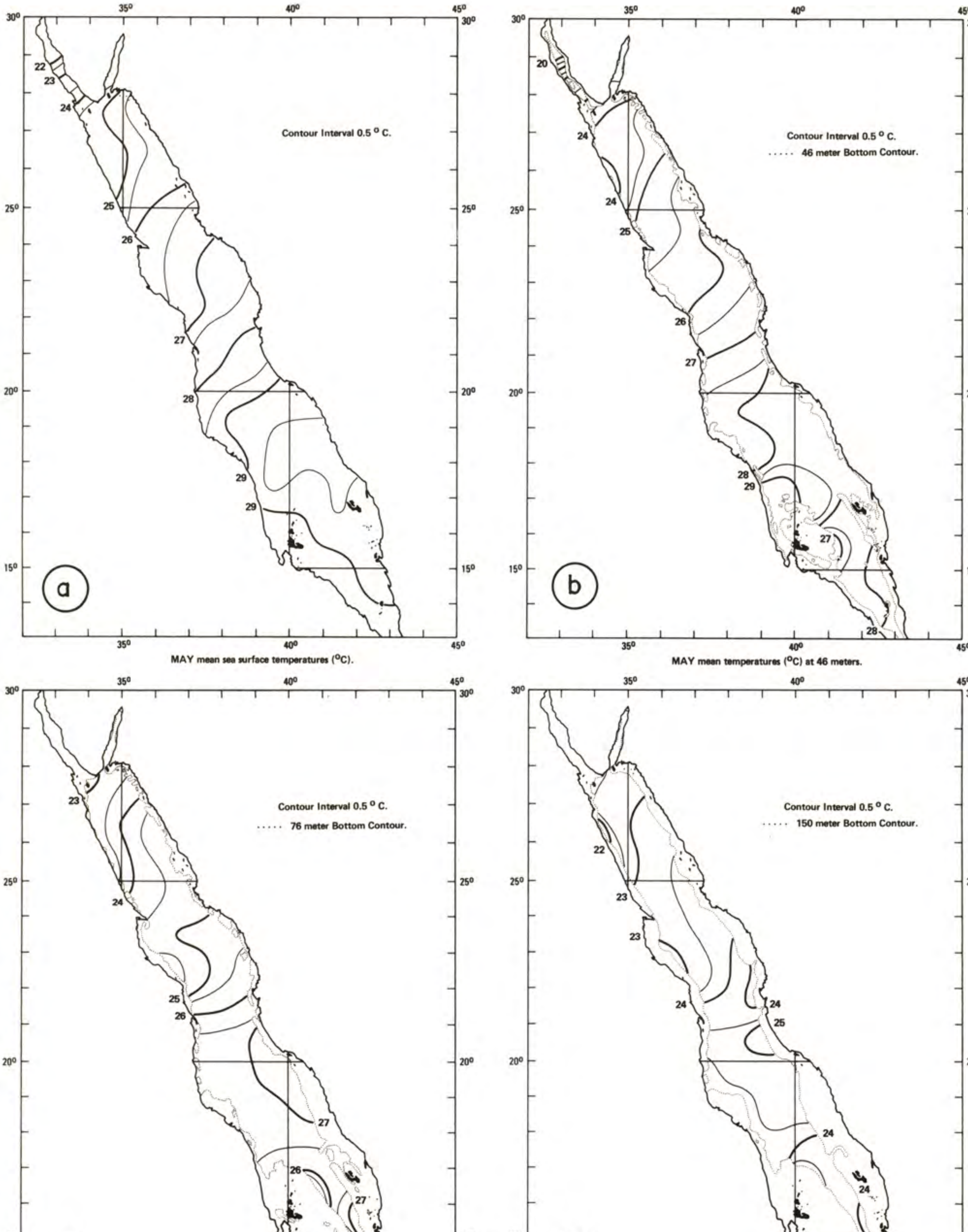
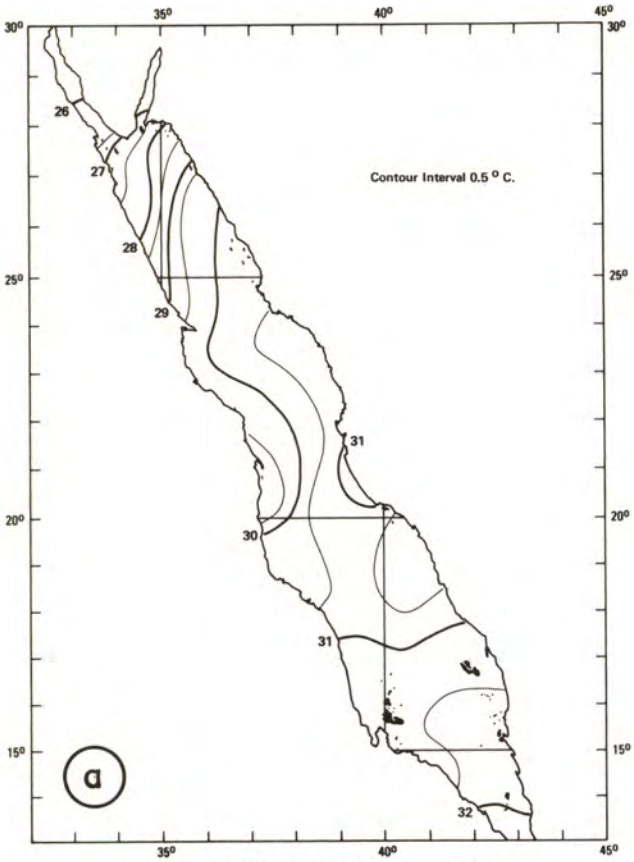
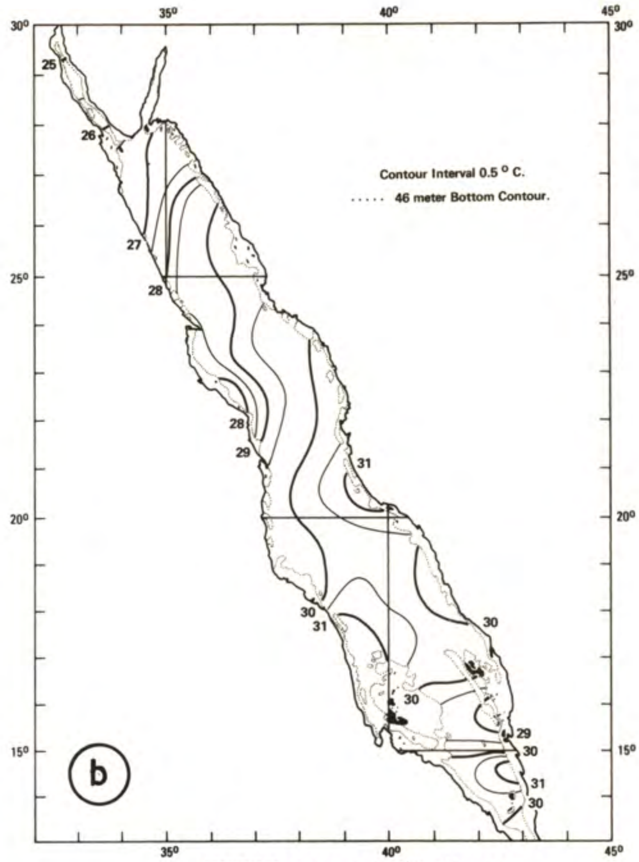

Contour Interval 0.5 °C.
MAY mean sea surface temperatures (°C).
Contour Interval 0.5 °C.
..... 46 meter Bottom Contour.
MAY mean temperatures (°C) at 46 meters.
Contour Interval 0.5 °C.
..... 76 meter Bottom Contour.
MAY mean temperatures (°C) at 76 meters.
Contour Interval 0.5 °C.
..... 150 meter Bottom Contour.
MAY mean temperatures (°C) at 150 meters.

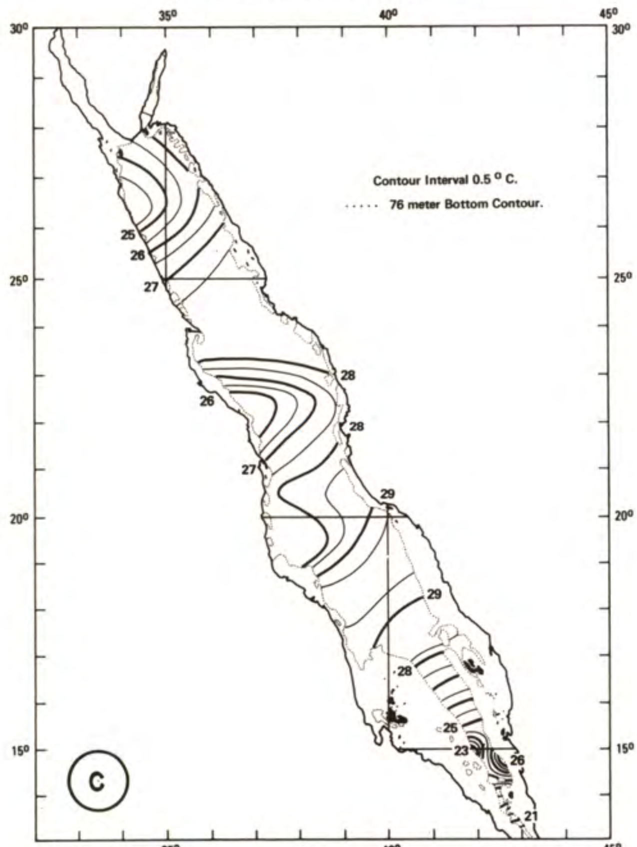
Fig. 2



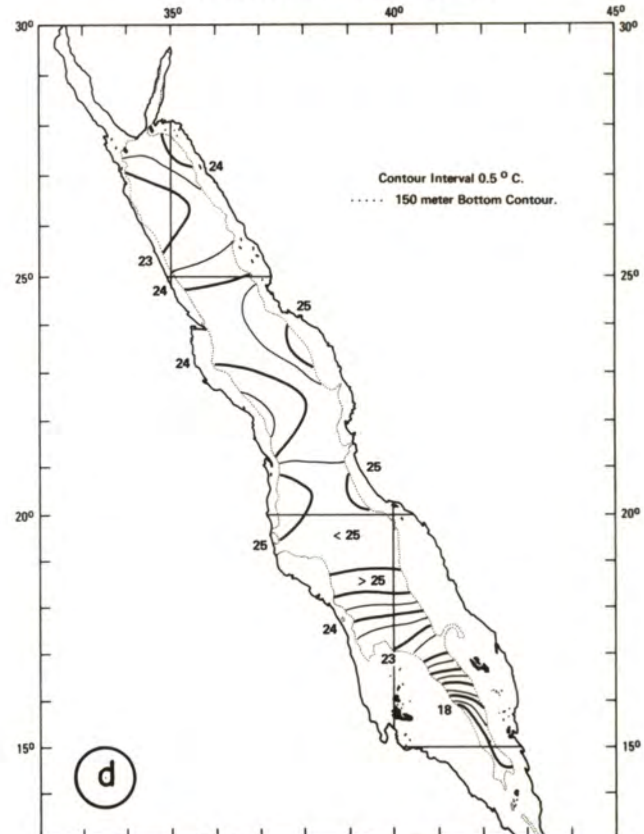
SEPTEMBER mean sea surface temperatures (°C).



SEPTEMBER mean temperatures (°C) at 46 meters.

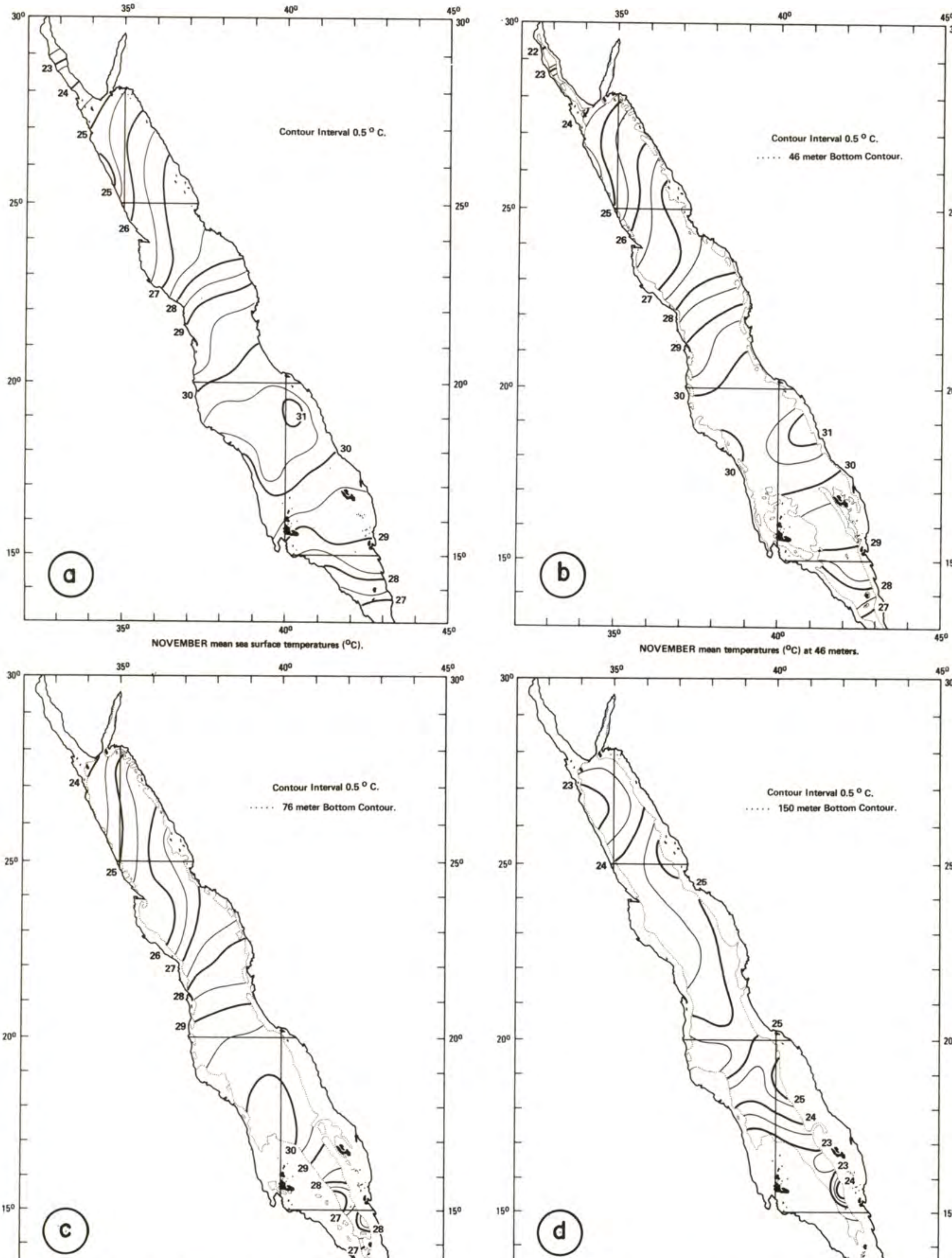


SEPTEMBER mean temperatures (°C) at 76 meters.



SEPTEMBER mean temperatures (°C) at 150 meters.

Fig. 3



NOVEMBER mean sea surface temperatures (°C).

NOVEMBER mean temperatures (°C) at 46 meters.

NOVEMBER mean temperatures (°C) at 76 meters.

NOVEMBER mean temperatures (°C) at 150 meters.

Fig. 4

Figures 5-8 contain mean annual cycle curves by 1° quadrangles for six levels, arranged in geographic order. These curves are computer plots, generated by 6 th harmonic coefficients derived from the monthly means. Weekly values are generated, and connected into continuous curves.

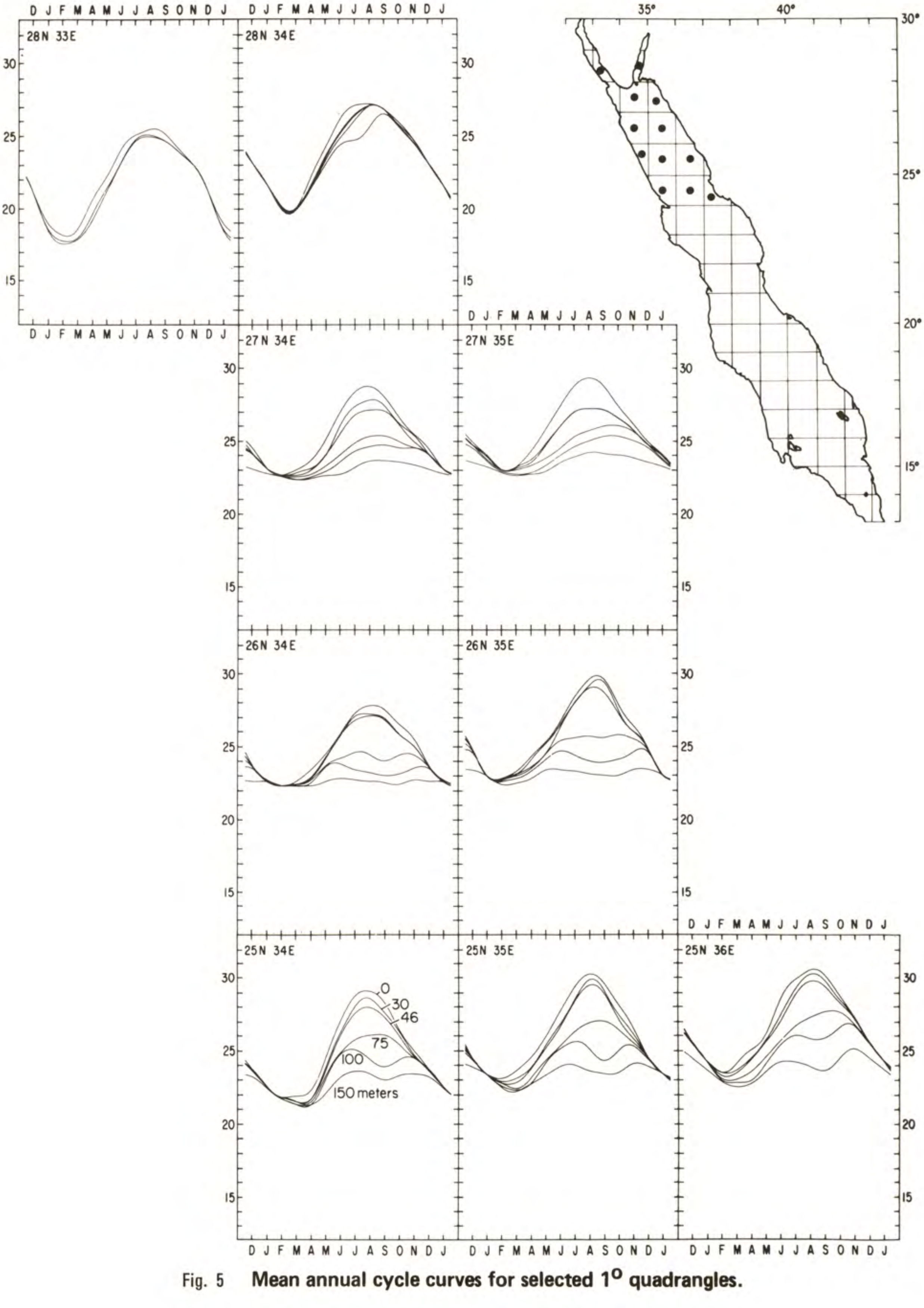


Fig. 5 **Mean annual cycle curves for selected 1° quadrangles.**

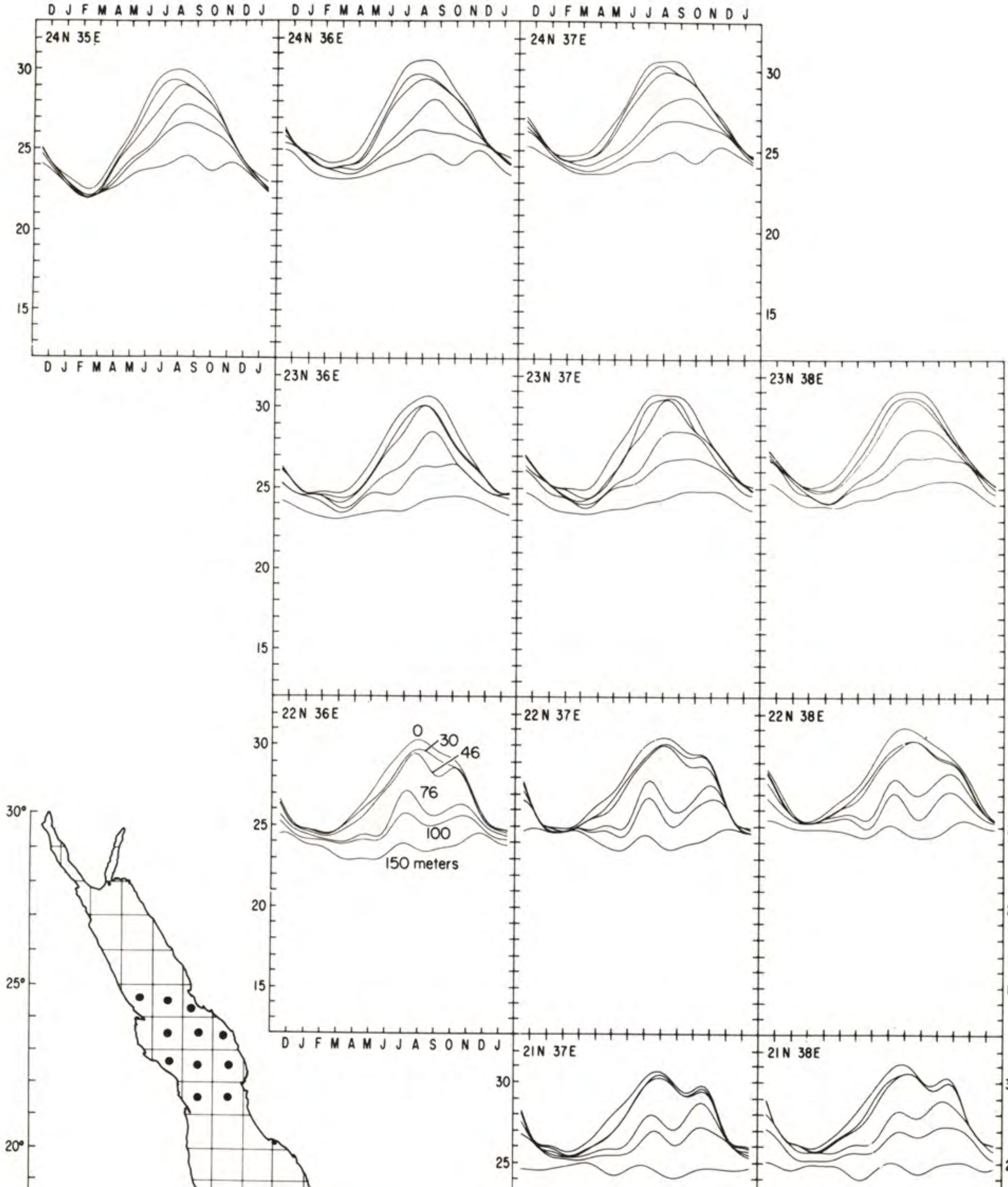


Fig. 6 **Mean annual cycle curves for selected 1° quadrangles.**

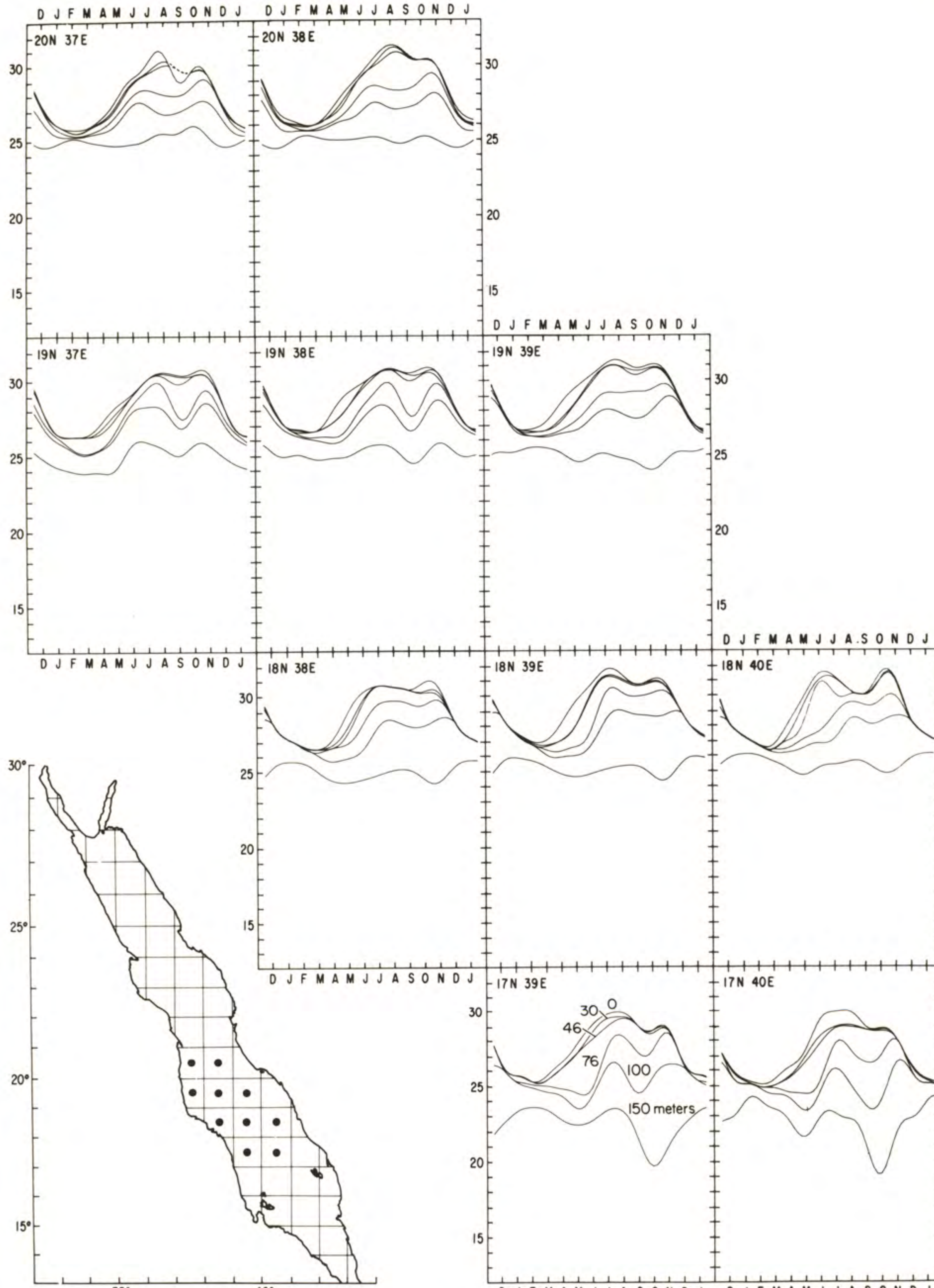


Fig. 7 **Mean annual cycle curves for selected 1^{o} quadrangles.**

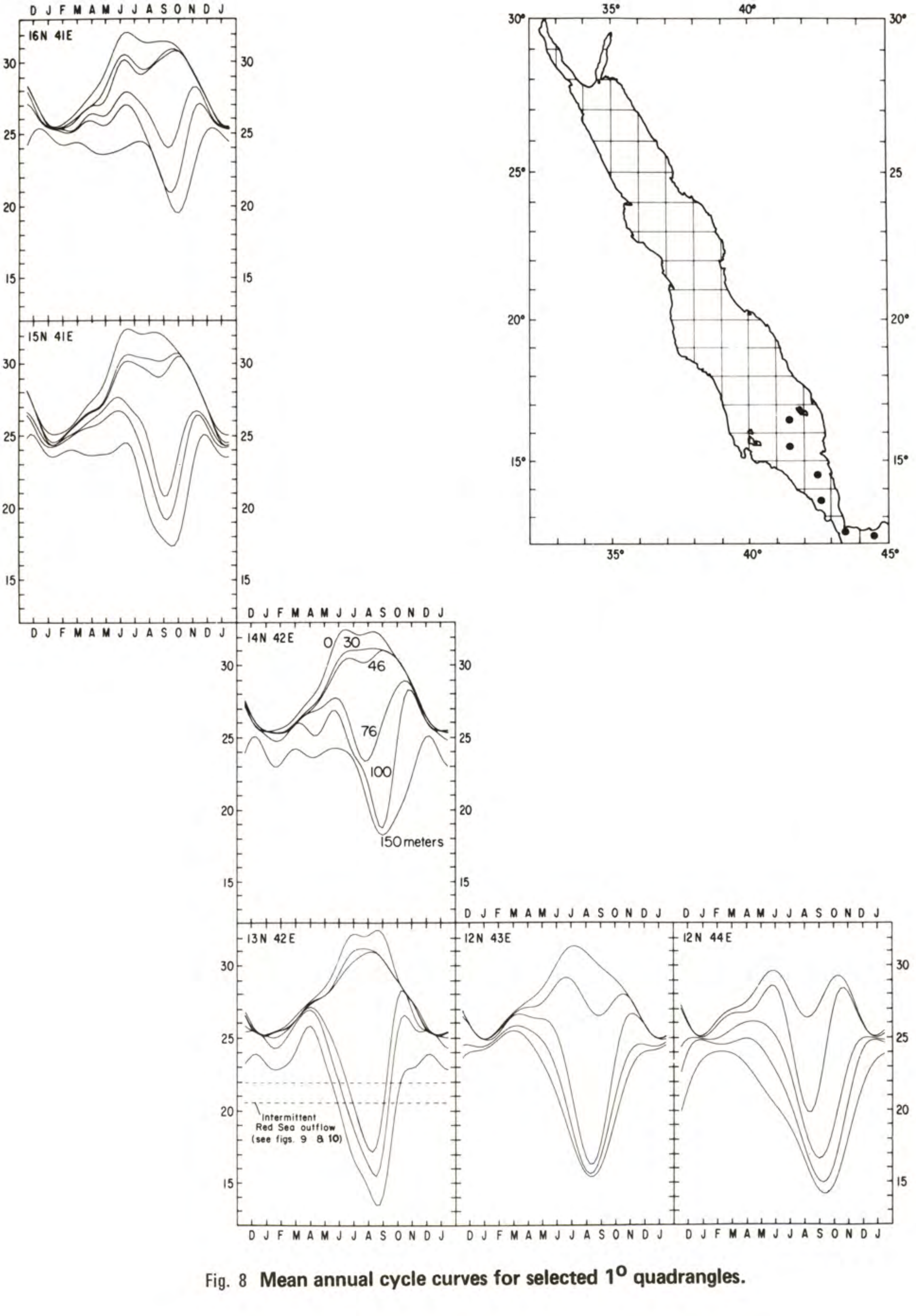


Fig. 8 **Mean annual cycle curves for selected 1° quadrangles.**

The mean fields suppress interesting features in the temperature-depth fields that can be seen on individual BT traces. Figures 9-10 present a selection of BT traces, plotted against latitude, taken during December, April, August and October, except as noted.

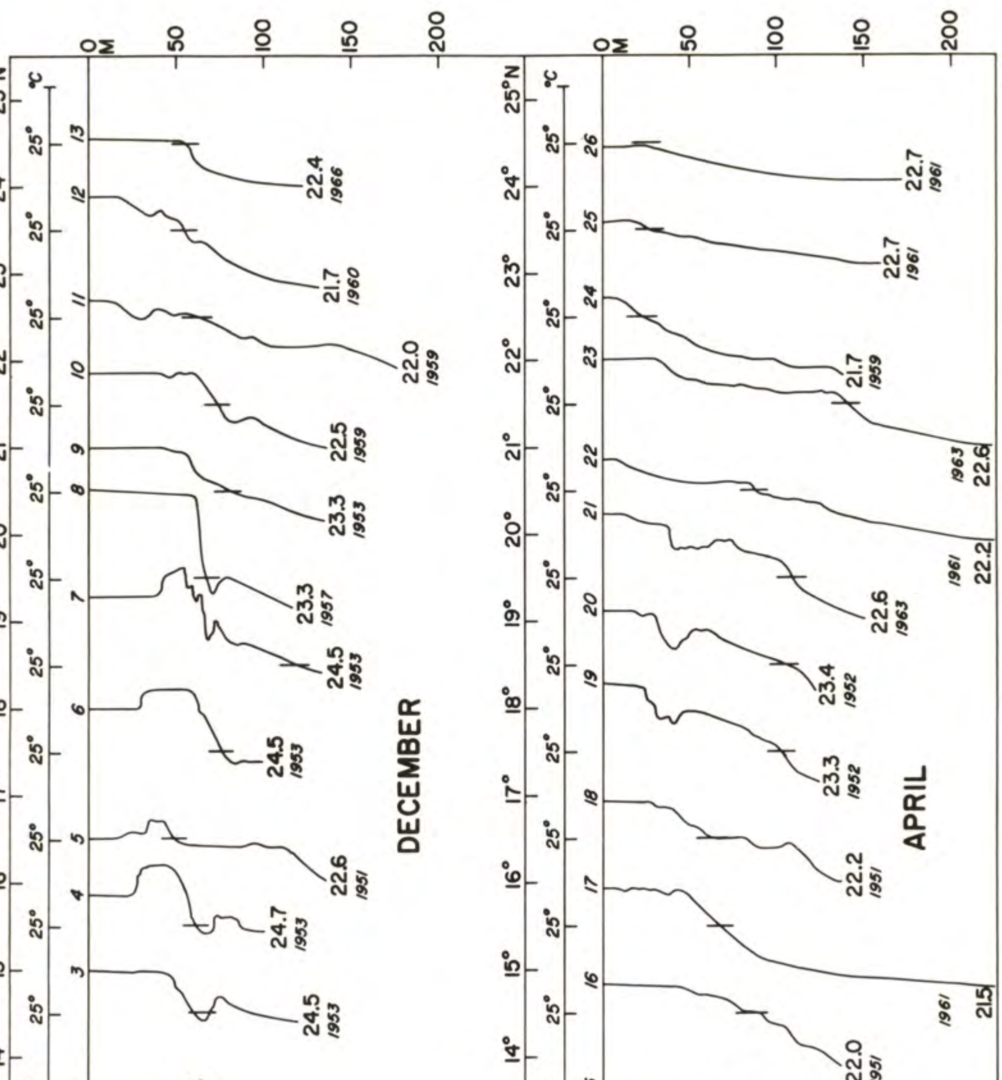


Fig.9 Selected bathythermograph traces, showing latitude limits of occurence of temperature inversions.

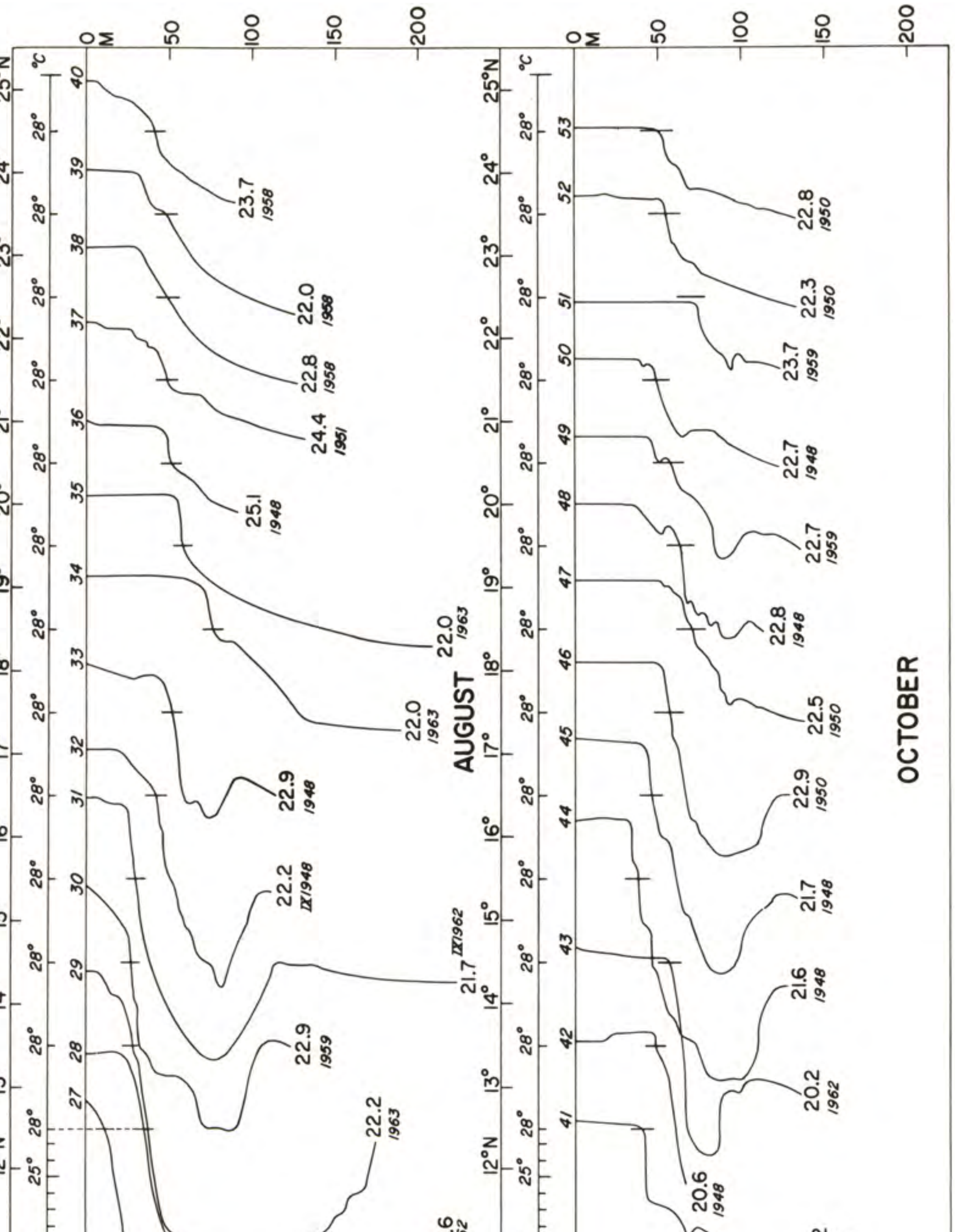


Fig.10 Selected bathythermograph traces, showing latitude limits of occurence of temperature inversions.

DATA

Temperature data used in the Red Sea analysis came from many sources. The primary source was 2,328 photographic prints of BT observations on file at Scripps Institution of Oceanography (SIO) and as prints and on magnetic tape at the National Oceanographic Data Center (NODC), and summaries of 525 reversing thermometer observations from hydrographic casts obtained from NODC.

The data base includes slightly more BT data and hydrocast data than used by PATZERT (1960). The NODC compilation included only half of the available hydrocast data listed by MORCOS (1,036) (1970).

ANALYSIS PROCEDURE

The basic premise of the analysis system is, given an adequate sample, there would exist a smooth mean seasonal cycle curve in the temperature fields of the oceans that would vary relatively systematically with latitude, longitude and depth, depending upon the net effects of advection and the local heat budget.

Computer programs have been developed to reduce the subjective hand analysis of data. The purpose of the programming effort was to produce a complete field of reasonable mean temperature values for each month and depth in the unit analysis grid, a 1° of latitude by 1° of longitude area. The analysis procedures were designed to permit subjective intervention and modification of the computer-produced numerical values whenever sparse data or lack of data produced unsatisfactory results.

Data Preparation

Temperatures were read, tabulated and keypunched at the selected levels -0, 30, 46, 76, 100 and 150 m- from individual BT prints. (Depth levels used for Atlantic temperature atlas). These data were combined with values at the same levels from standard level hydrocasts, interpolated when necessary. The data were ordered by 1° quadrangles by months, and monthly means and standard deviations were computed.

Main Analysis Programs

The main compunter analysis programs which have been developed and successfully used in open ocean areas consist of three steps based on input data of available 1° quadrangle means at selected analysis levels. The three computational steps consist of 1) space interpolation , 2) space smoothing, and 3) time smoothing. The first two steps do not produce satisfactory results in narrow seas, such as the Red and Adriatic, and the Gulf of California, or in cases where space coverage is inadequate in some months. In these areas, a combination of subjective methods and computer programs must be used.

Testing Vertical Consistency

The analysis programs operate on each level independently and may produce values that are not vertically consistent. The three processes that can cause vertical inconsistency are : 1) interpolation over different distances at various levels , 2) space smoothing to different degrees at separate levels, and 3) time smoothing at locations where the true subsurface annual cycle curve has a cusp or pointed peak shape that a 3rd harmonic curve cannot produce. Values in each 1° square are checked by computer graphic techniques and subjective editing to ensure that vertical inconsistencies are removed.

The Red Sea data were first run through the three analysis programs. When the vertical consistency test indicated unsatisfactory results, the following subjective techniques were substituted.

Special Handling of Red Sea Data

Available 1° square monthly means were computer-plotted by levels against time on transparent vellum. In a different symbol, the space interpolated values were plotted by hand on the same sheets, and smooth curves were drawn between the plotted points. If the interpolated values were obviously out of context in time, they were ignored. Means were altered if they appeared to be typical of early or late month, rather than mid-month time. Linear interpolation was used primarily during periods of rapid increase or decrease of temperature in spring or fall ; curvilinear interpolation in mid-winter and mid-summer, times of minimum and maximum temperatures. Subsurface time curves were constructed similarly, with particular attention paid to maintaining isothermal relationships with depth in months where they occur.

During the curve drawing, if data were missing in more than one month in a given quadrangle, comparisons were made with curves of adjacent quadrangles for shape guides. When all curves were drawn, mid-month temperature values were read from the curves and listed geographically by months and levels. These values were contoured. Whenever any value appeared to be out of space context with surrounding values, the original curves were re-examined for possible shape changes that might improve the space context. These requirements, simply stated, meant that a missing month's value had to fall between those of adjacent months, but at such a point that the north-south or east-west temperature gradients were maintained.

The data along both east and west coasts of the Red Sea are fewer than along the Central axis. In constructing curves in these coastal areas, attention was paid to see that the interpolations maintained the same horizontal gradients with adjacent 1° quadrangles that occurred in months where there were data. The thermocline intersects some depth levels between spring and fall. The raw data means near the thermocline may fluctuate widely from month to month. Rather than smoothing subjectively, in these cases, all sets of date were run through the 3rd harmonic time smoothing program, which modifies smooth curves only slightly but supresses shorter period oscillations. This program frequently produces vertical inconsistency in the fall months. A further program compares the vertical gradients of the input and output data of the 3rd harmonic program. If an increase of temperature with depth occurs in the output (the cusp problem) but not in the input, the output value is altered to maintain the original gradient. Only in cases where both sets of data show positive gradients are such allowed to remain in the final results.

From such corrected data, 6th harmonic annual cycle curves are produced (figures 5-8). The monthly values shown on these curves are the same as those contoured on the horizontal temperature charts.

DISCUSSION

MORCOS (1970) published G.A. TUNNELL'S compilation of annual variation of sea temperature (°C) and range (°F) recorded by British ships passing through the Red Sea. The data were taken 1855-1943, and agree within 0.2°C with a similar compilation contained in the Dutch Atlas (1949). The means were calculated for 2° latitude strips over the width of the Red Sea and Gulf of Suez. The data were far more numerous (64,751) than those used in this paper (2,853). The BT data were taken 1944-1969, and the hydrocast data 1923-1966.

A comparison of the annual range of temperature from the two reports shows good agreement for the Red Sea, but ROBINSON'S values are 2°C higher in the Gulf of Suez and at Bab el Mandeb :

	TUNNELL			ROBINSON		
	Max.	Min.	Range	Max.	Min.	Range
Gulf of Suez (28-29°N)	26.5	17.9	8.6	27.5	17.1	10.4
Gulf of Aquaba (28°N)				27.1	20.0	7.1
Entire Red Sea (14-27°N)	31.9	21.3	10.4	32.2	21.6	10.6
Bab el Mandeb (13-14°N)	30.4	24.9	5.5	32.2	24.7	7.5

All values in °C.

These results may not be indicative of a real climatic difference in the values at Suez and Bab el Mandeb, but rather that the 1° quadrangle averages are more sensitive to maxima than are 2° bands of latitude averages.

Tunnell's table lists ranges of temperature in °F for 90 % of his sample for each of his 2° latitude sub-areas. Standard deviation values were derived from the BT and hydrocast sample for 1° quadrangle areas in °C. A comparison has been made, equating means, ranges and standard deviations of the two sets of data.

Position	Mo.	TUNNELL $\overline{X}$	R	σ	N	ROBINSON $\overline{X}$	R	σ	N	RM	n	D
14-16°N	Dec.	25.8	2.8	.85	585	26.5	2.7	.82	38	2.7	5	- .7
18-20°N	Apr.	27.2	3.9	1.18	750	28.2	2.3	.70	49	1.7	5	-1.0
26-28°N	Feb.	21.3	5.0	1.52	704	22.7	2.2	.69	49	2.1	6	-1.4
26-28°N	Oct.	26.2	3.3	1.00	715	26.2	3.8	1.14	35	1.8	4	0

All values in °C.

$\overline{X}$ = Mean over 2° latitude area.
R = Range, of 90% of sample. (For Robinson data computed from σ).
σ = Standard deviation (For Tunnell data, computed from range).
N = Total sample size.
RM = Range of Robinson 1° quadrangle means.
n = Number of 1° quadrangles in 2° latitude bands.
D = Difference between Tunnell and Robinson means.

The interesting result of this comparison is that the range of Robinson's 1° quadrangle means across the 2° latitude band accounts for a large part of Tunnell's range. The difference in means computed for the entire band, however, does not exceed one standard deviation derived from Tunnell's range, but does exceed in two cases, one of Robinson's standard deviations computed from individual observations.

Tunnell's ranges include whatever year-to-year variation occured between 1855-1943, while Robinson's samples were restricted to the period 1948-1966. Thus, both contain year-to-year variation, but differences between means may be due to real differences in the time periods. In three cases, Robinson's are higher, in agreement with similar comparisons of mean temperature in Pacific and Atlantic Oceans, based on BT data taken from 1942-1970, with compilations of sea surface temperatures based on data taken between 1855-1943, published in H.O. 225 (1944).

There was good agreement with both Tunnell's and Patzert's values concerning the latitude of maximum temperature at the surface in different months, although Tunnell's positions range from 14-20°N, and Robinson's and Patzert's extend from 15-19°N, because of finer definition of values.

The standard deviations at the surface ranged from .05°C in June to 2.30°C in May. The maximum standard deviations, 3.65°C, occurred in the thermocline layer in October.

Horizontal Temperature Charts

The principal contribution of the horizontal charts is the detailed description of the east-west temperature gradients. LUKSCH (1898, 1901), VERCELLI (1927), MOHAMED (1938), DEACON (1952), and others have noted that temperatures on the east, Asian side, of the Red Sea were higher than on the west, African side, and temperatures in the Gulf of Aquaba are higher than in the Gulf of Suez. These statements are confirmed in the horizontal charts, but in the Red Sea proper the situation varies considerably with latitude and depth.

In general, at all depths, temperatures along the African Coast are lower than on the Arabian Coast except in the convergence region between 18-19°N, where the situation is reversed. North of 22°N, the isotherms run almost due north and south, then the slope is gradually changed until the isotherms run nearly east-west, as the convergent area is approached. To the south of the convergent area 14-17°N, again temperatures are lower on the west side. Beginning in December, but more pronounced January through April, and diminishing in May, there is evidence of divergence and upwelling at 19°N, 37°W, in the temperatures at 150 m.

Little Gulf of Aden water appears to intrude at the surface beyond 19°N, during the southeast monsoon season. In the surface layer above 75 m, the isotherms and thermocline topographies suggest a northern circulation cell between 20-28°N and south of the convergence a southern cell of Gulf of Aden water, in agreement with Patzert. The southern cell, unlike that in the north, does not appear to have any cross sea circulation. Such a circulation would be impeded by the narrowing of the trough south of 17°N at depths as shallow as 46 m.

July through September, beginning on the 76 m charts, the intrusion of cold subsurface Gulf of Aden water is clearly seen. In July, it reaches 15°N ; August 17°N, and in September, to 18°N.

In October and November, at 150 m, cold water is still present at 16°N, but at 13°N the mid-level intrusion of Gulf of Aden water has already subsided and has been replaced by water of higher temperatures.

The temperature fields suggest that north of 22°N there may be northward flow against the wind in all months long the Arabian Coast, with wind-driven southward flow along the African Coast in all months, and with cross-sea flow in large eddies during the winter, December to May, as postulated by LUSCK (1901). BIBIK (1966) and BOISVERT (1966) also indicate the existence of a large cyclonic eddy in the northern Red Sea in winter.

Between 76 and 150 m, December through June, temperatures are higher at 14°N ; approximately the same at both locations in July, and August to November, much lower at 14°N than at 28°N.

Annual Cycle Curves

The annual cycle curves (Figures 5-8) for six levels for each 1° quadrangle, are arranged in geographic order. These curves confirm the north-south and east-west differences pointed out previously, but add the additional dimension of time.

In the Gulfs of Suez and Aquaba, the summer crests are wider and flatter than the winter troughs, with temperature values in all months higher in the Gulf of Aquaba. Between 25-27°N, the summer crests, 0-46 m, become more peaked and the winter troughs broader. At 23-24°N, the summer crests are somewhat flatter, but beginning at 22°N and extending to 13°N, there are pronounced depressions in the curves in September and/or October, followed by a slight increase in temperature in late October and November. This temperature depression in September is so wide spread that the original data were re-examined to verify that the September depression was not an artifact of the analysis method. Fortunately, the original data confirm the existence of lower September temperatures, but it appears they may be due to sample bias. September observations were taken in only one year, 1948, at

13-15, 17 and 21°N, and in only two years, 1948 and 1962, at 16, 18, 20 and 22°N. August means in these latitudes were based on data in five years - 1948, 1951, 1958, 1959 and 1963, with data in three of the five years at four latitudes, and in four of the years at six latitudes.

October means were based on data in ten years, 1948, 1949, 1950, 1953, 1957, 1958, 1959, 1960, 1962 and 1966, with data in six years at four latitudes, five years at three latitudes, 4 years at two latitudes, and three years at one.

Thus, the September means, based on 1948 and 1962 data may not be representative of average conditions, which are better represented in the August and October means, based on data from several years, and it is not possible to say that the shape of the annual cycles in these areas is present every year. On the other hand, annual cycle surface curves based on Tunnell's data in these areas, show similar tendencies and variability, including month of maximum temperature. One may safely conclude, however, that surface temperatures will range between 30-32°C between July-October, at latitudes between 14-22°N, and that the maximum temperatures may occur in any of the four months. September is a time of weaker winds, as the northwest monsoon begins to wane, and what we see in these curves may be merely the reflection of the change in wind regime, before the rapid decrease of temperature in the surface layer with the onset of the southeast monsoons.

The shape of the subsurface curves in this region are dependent upon the strength of the mid-level intrusion of Gulf of Aden water, and on the mean level of the thermocline. These, too, will vary from year to year, but the general features of these annual cycle curves should be found in any given year.

The subsurface cycles, 76-150 m, north of 22°N, are quite different than those in the south. With annual ranges diminishing rather than increasing with depth. At 25°N, the deeper levels appear to receive some heat by mixing in the spring until the thermocline builds up in June, when these curves level off, and in some cases temperatures decrease during the summer as mixing is impeded by the summer thermocline. Then, as convective overturn begins with fall cooling, heat is mixed to greater depths and temperatures increase at the lower levels until isothermal conditions have been reached. At 25°N, this does not appear to be advective cooling, instead, summer cooling may be a result of divergence.

In the covergence region, temperatures at 150 m remain above 25°C throughout the year. Then to the south, the intrusion of cold Gulf of Aden water dramatically reduces the temperatures, 76-150 m. The average curves, however, do not reveal the upwelled 20.8-22°C, Red Sea water as it pours over the sill during the northwest monsoon.

Curves at 12°N, 43°E, in the Gulf of Aden, have been added to show that even at this location, the dense, saline Red Sea water sinks quickly below 150 m.

Individual BT Traces

The mean fields suppress interesting features in the temperature-depth field that can be seen on individual traces. Intermittent or transient features may be lost in the mean fields if their occurrence is rare, smaller than the contour interval, of it the vertical extent is less than the selected depth interval of the horizontal analysis. Temperature inversions are a means of tracing subsurface penetration of Gulf of Aden water into the Red Sea. Figures 9-10 show selected BT temperature-depth traces plotted against latitude during December, April, August and October, except where data were not available in the given month, as noted in Table I, which gives in detail the position, date and name of collecting ship for each trace. The traces were selected to show the existence and variability of subsurface temperature inversions. When there was a choice, the BT with largest inversion was selected. None were found in the data north of 25°N, nor in all months south of 25°N.

In August and October, there are beautiful examples of mid-depth intrusions of Gulf of Aden water and the 3-layer current system that exists at this time, but which was not evident on the horizontal charts or annual cycle curves. In October curves, a small, cold intrusion is still present in the BT at 21°N.

December curves between 16-19°N show lower temperatures at the surface, overlying subsurface water of higher temperatures at depths ranging from 25-60 m, indicating that the Gulf of Aden surface water intrusion in December has both lower temperature and lower salinity than the water beneath. In December, April and August, at 18-20°N, the multiple inversions seen on the BT traces are typical of convergence regions.

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TABLE I - Detailed positions, dates and collecting ships of BT observations shown in Figures 9-10.

a - December

OBS. No.	POSITION		DATE	SHIP
1	12°27'N,	043°34'E	XII-17-67	USS HAROLD J ELLISON
2	13°51'N,	042°55'E	II-23-51	HMS DALRYMPLE
3	14°50.9'N,	042°10.2'E	XII-17-53	USS C K BRONSON
4	15°56.4'N,	041°25'E	XII-17-53	USS C K BRONSON
5	16°17'N,	041°19'E	II-25-51	HMS DALRYMPLE
6	17°13.5'N,	040°33.9'E	XII-17-53	USS C K BRONSON
7	18°50'N,	039°32.5'E	XII-17-53	USS SMALLEY
8	19°40'N,	038°52'E	XI-19-57	HMS CEYLON
9	20°53'N,	038°10'E	XII-18-53	USS COTTEN
10	21°24'N,	037°23'E	XII- 6-59	USS TANNER
11	22°02'N,	037°06'E	XII- 6-59	USS TANNER
12	23°52'N,	037°08'E	XII- 5-60	HMS SALISBURY
13	24°50'N,	036°10'E	XII-17-66	USS CONE

b - April

OBS. No.	POSITION		DATE	SHIP
14	12°43'N,	043°18'E	IV-11-61	USS STRONG
15	13°36'N,	042°18'E	III- 5-62	USS HARLAN R DICKSON
16	14°48'N,	042°12'E	IV-21-51	HMS OWEN
17	15°53'N,	041°35'E	IV-28-61	USCGC EASTWIND
18	16°17'N,	041°10.4'E	IV-21-51	HMS OWEN
19	17°49'N,	040°26'E	IV-22-52	USS MAURY
20	18°19'N,	040°08'E	IV-22-52	USS MAURY
21	19°01'N,	039°45'E	IV-17-63	USS DECATUR
22	20°24'N,	038°42'E	IV-21-61	USS TANNER
23	21°25'N,	037°55'E	IV-16-63	USS DECATUR
24	22°28'N,	037°02'E	IV-26-59	HMS OWEN
25	23°59'N,	036°48'E	IV-24-61	USS TANNER
26	24°47'N,	036°00'E	IV-25-61	USS TANNER

TABLE I (cont.)

a - August

OBS. No.	POSITION		DATE	SHIP
27	12°04'30"N,	044°23'12"	IX-18-62	R/V HORIZON
28	12°53'30"N,	043°12'E	IX-18-62	R/V HORIZON
29	13°14'N,	043°02'E	VIII- 3-63	R/V ATLANTIS II
30	14°28'N,	042°23'E	VIII- 7-59	HMS LOCH FADA
31	15°18'30"N,	041°53'54"E	IX-17-62	R/V HORIZON
32	16°40'N,	041°02'E	IX- 3-48	USS ZELLARS
33	17°49'N,	040°06'E	VIII-10-48	USS ZELLARS
34	18°05.5' N,	039°48.5'E	VIII- 2-63	R/V ATLANTIS II
35	19°03.5'N,	038°56'E	VIII- 2-63	R/V ATLANTIS II
36	20°55'N,	038°23'E	VIII- 9-48	USS CARPELLOTTI
37	21°29'N,	037°33'E	VIII-14-51	HMS ARMADA
38	22°30'N,	037°25'E	VIII-19-58	HMS LOCH ALVIE
39	23°18'N,	036°55'E	VIII-19-58	HMS LOCH ALVIE
40	24°32'N,	036°20'E	VIII-10-58	USS NOA

b - October

OBS. No.	POSITION		DATE	SHIP
41	12°36'N,	043°21'E	X-29-50	HMS DALRYMPLE
42	13°54'24"N,	042°52'06"E	X-17-48	USS MAURY
43	14°47'N,	042°16'E	X- 7-62	HMS LOCH ALVIE
44	15°32'12"N,	041°47'36"E	X-16-48	USS MAURY
45	16°22'00"N,	041°13'24"E	X-16-48	USS MAURY
46	17°47'N,	040°09'E	X-27-50	HMS DALRYMPLE
47	18°28'N,	039°23'30"E	X-26-50	HMS DALRYMPLE
48	19°07'48"N,	039°22'00"E	X-15-48	USS MAURY
49	20°59'N,	038°17'E	X-28-59	USS BENHAM
50	21°39'48"N,	037°53'30"E	X-15-48	USS MAURY
51	22°00'N,	037°39'E	X-28-59	USS BENHAM
52	23°12'N,	037°16'E	X-24-50	HMS DALRYMPLE
53	24°46'N,	036°07'E	X-23-50	HMS DALRYMPLE

DISCUSSION AND COMMENTS

Dr. MORCOS : I should like to show you the ressemblance between Mrs. ROBINSON's charts and the LUKSCH (1901) Chart for surface temperature in the Red Sea in winter as well as the Mohamed Chart for the Northern Red Sea in winter (MORCOS, 1970, fig. 7). The "POLA" and 'MABAHISS" charts are based on single observations while the ROBINSON charts are based on averages. Also it is astonishing that the less accurate thermometers of "POLA" had revealed the warmer water on the eastern side of the sea.

The observations used by TUNNEL extend over a period of 90 years (1855-1943). During the preparation of the table,I was sceptical on the reliability of the older data and thought of asking TUNNEL to limit the table to the last 50 years or so. Now I am glad to see a good agreement between this table and Mrs. ROBINSON's data. It may, however, be possible to divide the data into two intervals, of say 45 years and compare it with Mrs. ROBINSON's data (43 years, 1923-1966) in order to find out any change with time.

I can say that I was not influenced at all, but, when I saw that, I was absolutely delighted. I do not think the observations lie. When we deal with averages I have come to the conclusion that even if our BT. data are, say, plus or minus 1/2 degree Fahrenheit, nevertheless the real features of the oceans are still there and our vertical gradients are good enough. Taking into consideration the internal waves and all of the other things that go on subsurface we are still getting a better seasonal picture than we have ever had before, which we could never have done without a BT.

Dr. MANN : Why is there a double peak in the summertime ? All these graphs of temperature versus time of the year showed a double peak in summertime, almost invariably I thought, for the sea surface temperatures or near sea-surface.

Mrs. ROBINSON : Well, in MORCOS's text there is some indication that he also had a dip in September. I have looked back at my data to try to see if this is just a fiction of the data.

If you go there every year will you find that September is lower than August and October ? This is something that I wish someone would verify. It is there in these data and since it existed in those observations, I certainly was not going to take it out in any way. It looks to me like it may possibly be in September that there is a change in the wind regime ?

Pr. WYRTKI : No. This is a fact of the stronger winds during the summer months causing evaporative cooling. This effect is quite obvious. You have again a certain increase in the wind during July and August.

Dr. PATZERT : Another explanation for that might be that during the summer the circulation of the surface reverses and it is from the North towards the South and this is colder water being advected South in the surface layer at all latitudes in the Red Sea. So I think what you see is surface advection.

Mrs. ROBINSON : That is right. But you cannot see it in the North of the Red Sea.

Dr. GORMAN : What appear to be the reasons for the dip in sea surface temperature, most noticeable in August in the Gulf of Aden ?

Mrs. ROBINSON : You really do have a different wind regime in the Gulf of Aden. Over the Gulf of Aden and around into the Somali coast you can see upwelling and all of the other changes that have occurred there. Over the whole of the Arabian Sea you have this dip in sea-surface temperature.

Dr. PATZERT : In the Gulf of Aden itself the dip in the surface temperature is due to a very strong upwelling that occurs along the Arabian coast.

Dr. PEDGLEY : That is because there is quite a considerable component across the Gulf in the Gulf of Aden whereas the winds in the Red Sea are mostly of course along the sea.

Dr. GORMAN : Is that component off the Somali coast in the summer ?

Dr. PATZERT : It's similar case but the two areas are entirely different and not connected.

Dr.PEDGLEY : There is a very strong diurnal variation in this component off the land and on the Somali coast. Take for example the wind from the South West during say July and August at Berba, a classic site on the Somali coast. The wind is strongest at about dawn or soon after and you can have winds of 10 to 15 metres per second blowing off shore. Then, by the time you come to midday or soon after, this wind has decreased and you get a weak sea-breeze developing and so there is a component onshore. This lasts until the early evening and then the reversal takes place and gradually accelerates during the night. This is a well-known phenomenon and it is important to note.

Dr. GORMAN : Is this offshore component a strong part of that phenomenon during the land-breeze ?

Dr. PEDGLEY : It os probably a combination of land-breeze and a kind of cascading of the flow from South of the Somali. It is part of the southerly monsoon.

In July and August the flow across this region is between South and Southwest and there is an inversion at about 3 kilometers so that one has a relatively dense layer between the escarpment which is at an altitude of about 1,5 to 3 kilometers. During the night one would expect such a layer to cascade with acceleration down the slope reaching a maximum speed when it approaches the coast.

During the daytime of course there is convection meeting this layer and the density difference between that air and the air above decreases, so that the cascading motion should decrease, and at the same time there is a sea-breeze tending to form. In my view, it is the combination of these two processes which produces the very strong diurnal variation of wind speed along the coast. There is also a weaker diurnal variation out over the Gulf of Aden which has been looked at in Great Britain at Reading University.

Dr. MANN : I would like to remark that I do not think you should take that dip out of your data, it's very convincing. Is it due to evaporation or due to the advection of cold water from the North ?

Pr. WYRTKI : The lower surface temperature in the Red Sea in August and September may be due to the combined action of advection from the North and evaporative cooling by the stronger winds.

Mrs. ROBINSON: There is one other question I would like to raise on this subject.

In the ocean as a whole it seems to be extremely difficult to get temperatures above 32°C. It is almost as if we have a ceiling on them just as we have a bottom on freezing. Maybe this is essentially a ceiling effect and therefore you are going to have oscillations. We have got up to 32°C and the temperature is not just going to stay there all the time. There are things happening at the surface (e.g. eveporation, cooling, winds, etc..), but it is not until we get the difference in the wind system, and we begin to get cooling near the end of the summer when the unput of heat is decreasing that then we get the convective overturn and the temperature comes down. So that maybe it gets up to a certain maximum in July and then it doesn't just stay constant but has oscillations of some period.

This phenomenon may vary from year to year and that is why I included it in the text so that in time we may look at the data again and perhaps see, for example, that in this lower region September always has a dip. But from PATZERT's wind charts it looked to me as though the wind change in the winter was a little later than this. I wish I knew.

I did at least want to document the differences in periods of time of the observations so that in the future we may have some documentation on what existed when these data were analysed.

SEASONAL REVERSAL IN RED SEA CIRCULATION

William C. PATZERT *

Abstract

The monsoon reversal in the Red Sea circulation is analyzed by presenting a monthly mean description of variations that occur in the oceanic structure and circulation in the upper 250 m of the Sea and how they are related to the winds acting at the sea surface. During winter (October to May), the surface waters flow north, sink in the northern Red Sea, and return to the south as a warm, high-salinity subsurface current that flows out over the shallow sill into the Gulf of Aden. During summer (June to September), the winter cellular flow pattern reverses : i.e., the surface waters of the Sea flow south, causing an upwelling of the structure in the northern Red Sea, while in the southern Red Sea a subsurface inflow over the shallow sill of cool, low-salinity Gulf of Aden water occurs. This reversal in circulation is closely associated with reversals in the monsoon winds acting at the sea surface in the southern Red Sea and Gulf of Aden.

Résumé

Renversement saisonnier de la circulation en Mer Rouge

En Mer Rouge, le renversement de circulation lié à la mousson est analysé en présentant une description des variations qui apparaissent sur les moyennes mensuelles de la structure hydrologique et de la circulation des 250 premiers mètres et leur relation avec les vents qui agissent à la surface de la mer. Pendant l'hiver (octobre à mai), les eaux de surface s'écoulent vers le Nord, s'enfoncent au Nord de la Mer Rouge et retournent vers le Sud, formant un courant sub-superficiel chaud et fortement salé qui s'écoule au-dessus du seuil peu profond vers le Golfe d'Aden. Pendant l'été (juin à septembre), la circulation s'inverse par rapport au modèle d'hiver en cellule : ainsi, les eaux de surface s'écoulent vers le Sud, entraînant l'apparition d'un upwelling au Nord de la Mer Rouge, tandis qu'au Sud, un courant d'entrée, sub-superficiel, d'eau du Golfe d'Aden froide et peu salée se forme au-dessus du seuil peu profond. Ce renversement dans la circulation est étroitement lié aux renversements des vents de mousson agissant à la surface de la mer au Sud de la Mer Rouge et dans le Golfe d'Aden.

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The objective of this investigation is to present a description of the circulation reversals that occur in the Red Sea through analysis of available oceanographic and meteorologic data, and to use this description to provide some insights into how the monthly mean circulation is generated.

Because of the high salinities observed within the Sea (surface salinities vary from 37.0°/₀₀ at the southern entrance near the Strait of Bab-el-Mandeb to 40.0°/₀₀ in the north) and the arid climate of the area, many investigators concluded that evaporative processes alone control the circulation (MAURY, 1855; NEUMANN and McGILL, 1962; PHILLIPS, 1966). Other investigators have proposed that the winds exert a strong influence on the circulation (THOMPSON, 1939a, b; SIEDLER, 1969). For more than a century, oceanographers heve theorized that the formation of dense water due to the large excess of evaporation over precipitation and the shifting wind field over the Red Sea interact to generate the circulation, but there is confusion and disagreement over which of these forces is dominant at different latitudes and at different times.

Much of this confusion results from the fact that not since THOMPSON'S (1939a, b) discussion of the seasonal variations of the structure and circulation of the Red Sea has this subject been studied. This is surprising, since his analysis was based on evaluation of only eight hydrographic stations in May and six in September. Perhaps the major reason that Red Sea circulation has not received much attention is that, as MORCOS (1970) states, "The Red Sea is one of the least explored areas in the world". He discusses the need for a systematic measurement program and notes that fewer than half as many hydrographic observations are made during the hot, sultry summer months as are made during the winter.

Although a systematic study of the Sea was not considered during the planning stages of the International Indian Ocean Expedition (IIOE) (MORCOS, 1970), the understanding of this region's hydrography was somewhat improved during the IIOE years (1954 to 1959). Discovery of hot brine pools and evidence of sea-floor spreading in the Red Sea (DEGENS and ROSS, 1969) have been an impetus to more investigations, mostly by geophysicists and geochemists. Although the various geophysical studies have increased the hydrographic data describing the structure of the Sea, lack of a systematic program to study its physical oceanography has probably discouraged most investigators from discussing the seasonal variations in its structure and circulation.

In the following analysis, data describing wind conditions at the surface of the Red Sea and the oceanographic structure within the Sea, including currents, mean sea level, and hydrographic structure, will be analyzed and described to show the close relationship between the surface winds and circulation.

THE MEAN ATMOSPHERIC AND OCEANOGRAPHIC CONDITIONS OF THE RED SEA

WYRTKI (1971), in compiling "The Oceanographic Atlas of the International Indian Ocean Expedition", obtained all available hydrographic data on the Indian Ocean, including the Red Sea. These data, combined with data from other sources |discussed by MORCOS (1970)|, provided enough information to describe the monthly mean variations in structure and circulation along the central axis in the Sea. Data describing the hydrographic structure are not yet available for all areas in the Sea, and data that are available are almost wholly derived from the central channel of the Sea. This holds true for data gathered by scientific vessels as well as by merchant and military ships. Consequently the figures which accompany the following analysis show the distribution of various properties by months and 1° of latitude (with the data concentrated along the central channel) in the Gulf of Suez and the Red Sea. Since the existing discussions of the hydrographic structure (NEUMANN and Mc GILL, 1962; MAILLARD, 1971) and surface meteorological data (Koninklijk Nederlands Meteorologisch Instituut (KNMI), 1949) perpendicular to the NNW-SSE axis of the Red Sea suggest that lateral variations are small or transient, a longitudinal description can be considered as an accurate first-order description of the hydrographic structure of the Sea. Also included are the areas located at the entrance to the Red Sea (12° to 13°N, 43° to 44°E) and South of Aden in the Gulf of Aden (11° to 13°N, 44° to 45°E). (In the following analysis, this last area is referred to as 11° to 12°N.) The Gulf of Aqaba is not included in this analysis, since few data are available because it is off the main shipping routes.

WYRTKI'S (1972) findings indicate that circulation in the Red Sea below 250 m depth is thermohaline-driven and that the strength of this deep circulation is almost an order of magnitude less than the circulation in the upper 250 m of the Sea. Consequently, the following investigation considers only the variations occurring above 250 m depth.

1 - Physiography

The Red Sea is a flooded rift valley that can be described as a young ocean, being created by the pulling apart of Arabia and Africa. From the Strait of Bab-el-Mandeb in the south to the Sinai Peninsula in the north (Fig. 1), it is about 1,900 km long, and average width is 220 km, but at the Strait of Bab-el-Mandeb it is only 27 km wide (at Perim Island). Surface area of the Red Sea is 4.4×10^{15} km^2 and mean depth is 524 meters. The maximum recorded depth is 2,920 m, while sill depth at the southern end is only 100 meters. This shallow sill, separating the Gulf of Aden and the Red Sea water masses below 100 m, is located near the Hanish Islands, 125 km NNW of Perim Island. Coastal waters of the southern Red Sea are characterized by a wide shelf containing shallow reefs and many small islands. In the north, the coastal shelves are narrower, and mean cross-sectional depths are much greater than in the south. Near 28°N, the Red Sea branches into the Gulf of Suez and the Gulf of Aqaba. Although similar in shape and size, the Gulf of Suez has a mean depth of only 40 m, whereas the Gulf of Aqaba, a deep rift bassin, has depths exceeding 1,800 m and a sill depth at the entrance of approximately 175 m (NEUMANN and McGILL, 1962).

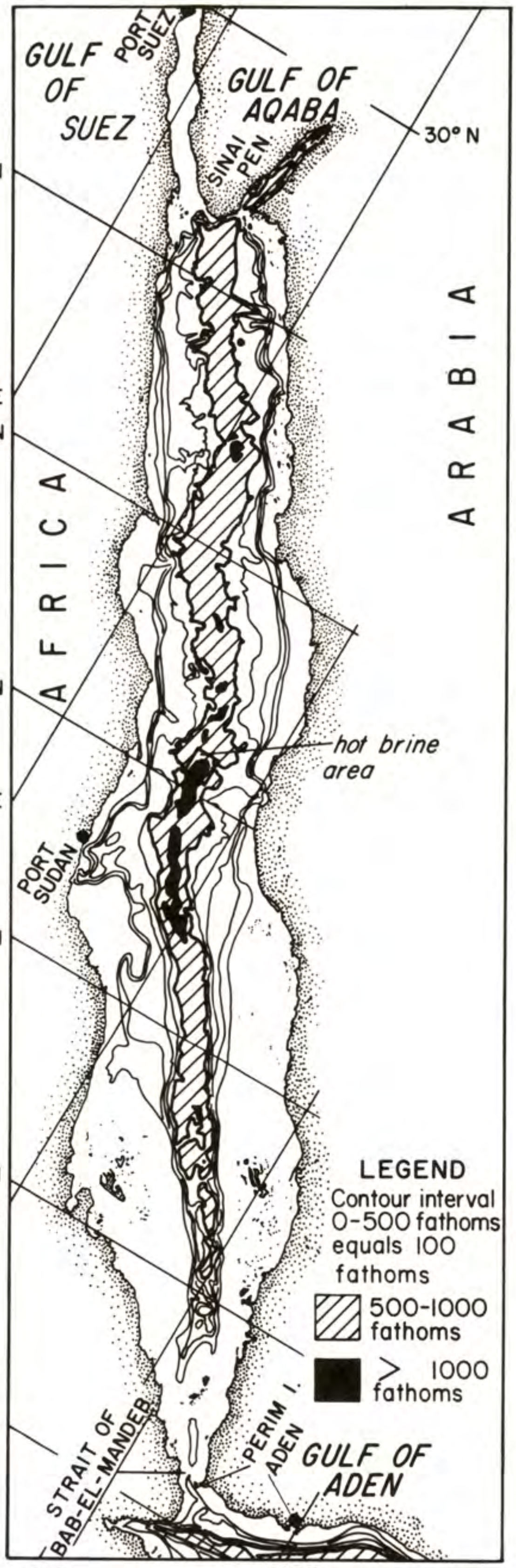

Fig.1.
Bathymetric chart of the Red Sea (after ALLAN, 1966).

2 - Surface Winds

The high mountains and high plateaus on both sides of the Red Sea constrain the monthly mean atmospheric circulation in the lower troposphere to flow parallel to the Sea axis (FLOHN, 1965). The KNMI Atlas (1949) presents the monthly mean surface vector wind calculated from over 1,000,000 wind observations for 1° squares in the Red Sea and the Gulf of Aden. These data show that the vector winds are directed primarily either north or south along the central axis of the Sea and that, laterally, direction and speed vary only slightly. Consequently, the wind component parallel to the axis of the Sea is an accurate representation of the vector wind. Figure 2 shows that throughout the year the monthly mean vector winds in the Red Sea north of 19°N latitude are from the NNW. South of 19°N, the winds, controlled by the monsoon system of the Arabian Sea, reverse direction twice annually : during the northeast monsoon (October to May), the winds are from the SE-SSE, and, during the southwest monsoon (June to September), they are from the NW-NNW. From October to December, the weak NNW winds (~2.4-4.4 m/s) in the north and the strong SSE winds (~6.7-9.3 m/s) in the south converge near 19°N. This convergence zone gradually moves southward until by June the winds are from the NNW for the entire length of the Red Sea.

To illustrate the unequal distribution of wind stress acting on the Red Sea surface, the monthly mean wind stress along the central axis of the sea (τ) has been calculated from:

$$\tau = \rho_a \, c_D W^2$$

where ρ_a = density of air (1.2×10^{-3} g/cm^3)

c_D = drag coefficient (2.5×10^{-3})

W = monthly mean wind speed (see Fig. 2).

Calculated wind stress at the sea surface is given in dynes/cm^2 in Figure 2.

During the winter, SSE wind stresses in the south are stronger than the NNW wind stresses in the north, especially during November and December when the mean wind stress between 13° and 10°N is 1.2 dynes/cm^2, while the opposing mean wind stress in the north, between 20° and 25°N, is only 0.2 dynes/cm^2. During the summer, the strongest mean wind stresses are from the NNW in the north, while in the south the wind reverses (Fig.2), and due to the low wind speeds, yields weak wind stresses.

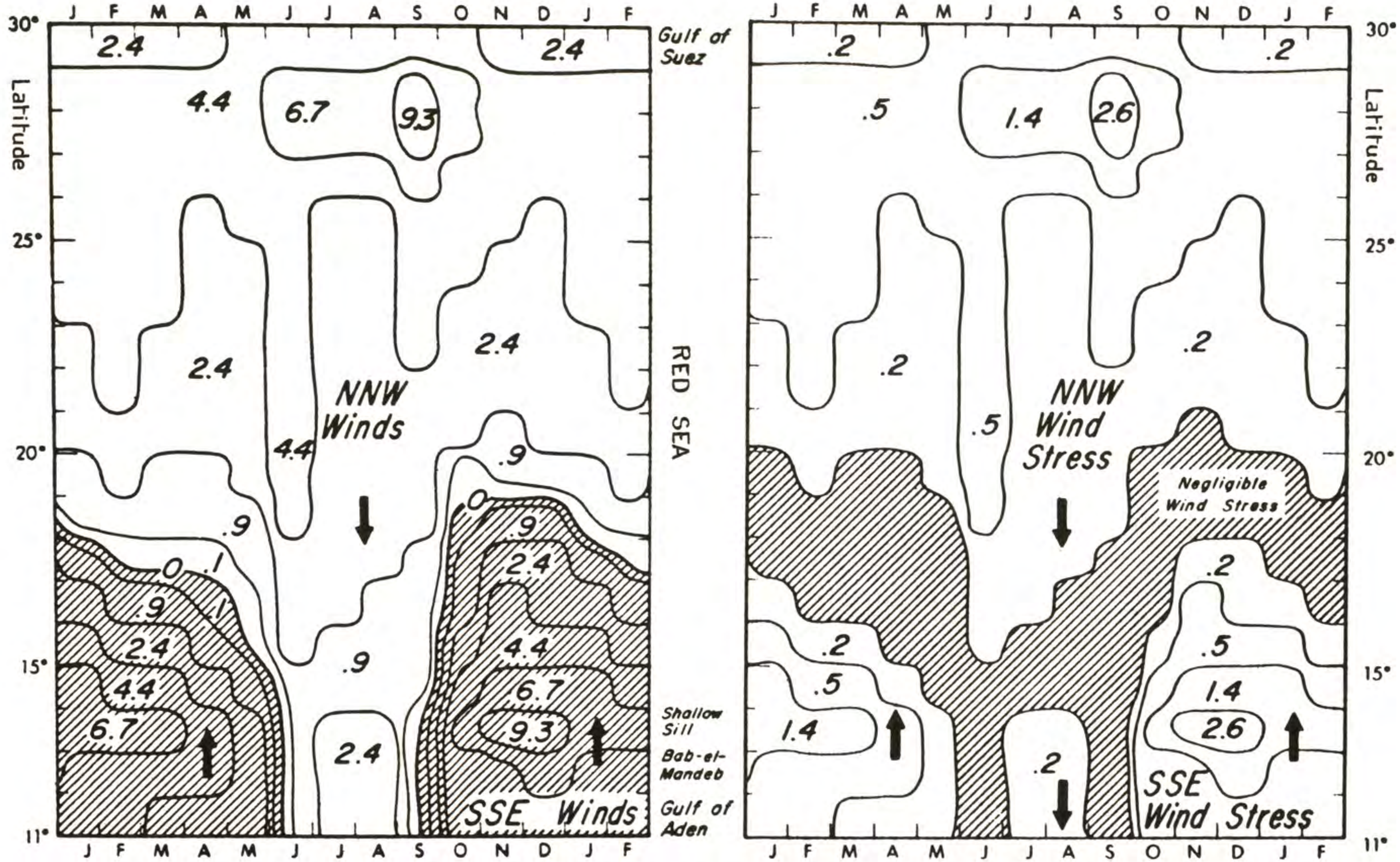

Fig. 2. Magnitude (m/sec) and direction (unshaded : from NNW ; shaded : from SSE) of monthly mean vector surface winds over the Red Sea along the central axis (left) and monthly mean wind strees (dynes/cm^2) at the sea surface calculated from these winds (right). Negligible wind stresses (<.03 dynes/cm^2) are shaded (right). Because the mean winds are taken as the middle or average value of a Beaufort range, the values of wind speeds and stresses appear as steps. January and February are repeated.

3 - Observed Circulation in the Red Sea

The only published current observations available for the Red Sea are those of 15 days of continuous measurements during the March 1924 cruise of the ARIMONDI (VERCELLI, 1925) and moored, recording current-meter observations taken during the November 1964 METEOR cruise (SIEDLER, 1968). Both sets of data were taken in the Strait of Bab-el-Mandeb near Perim Island (see Fig. 1). VERCELLI'S (1925) measurements show a (March) maximum mean surface inflow of 66 cm/s at the surface and a maximum mean subsurface outflow of 68 cm/s at 150 m. SIEDLER'S (1968) analysis shows a similar distribution, with a (November) maximum mean surface inflow of almost 80 cm/s and a maximum mean subsurface outflow of 50 cm/s at 120 m. These two sets of observations are probably typical of conditions during March and November in the central channel of the Strait of Bab-el-Mandeb. Calculated displacements between astronomical positions and "dead reckoning" positions (ship's drift), recorded by ships passing through the Red Sea, are the only other available information on the circulation during other months of the year between Suez and Aden. Published ship's drift observations and analyses by BARLOW (1934), Koninklijk Nederlands Meteorologisch Instituut (1949), and BOISVERT (1966) agree in the description of the main features of the mean surface circulation ; i.e., all three sources indicate that the monthly mean flow runs parallel to the central axis of the Red Sea and not across it.

The monthly mean current vectors presented in the KNMI Atlas have been summarized for 1° latitude strips and are shown in Figure 3. These vectors were calculated from 103,284 ship's drift observations ; thus, each data point represents, on the average, the vector mean of approximately 450 observations.

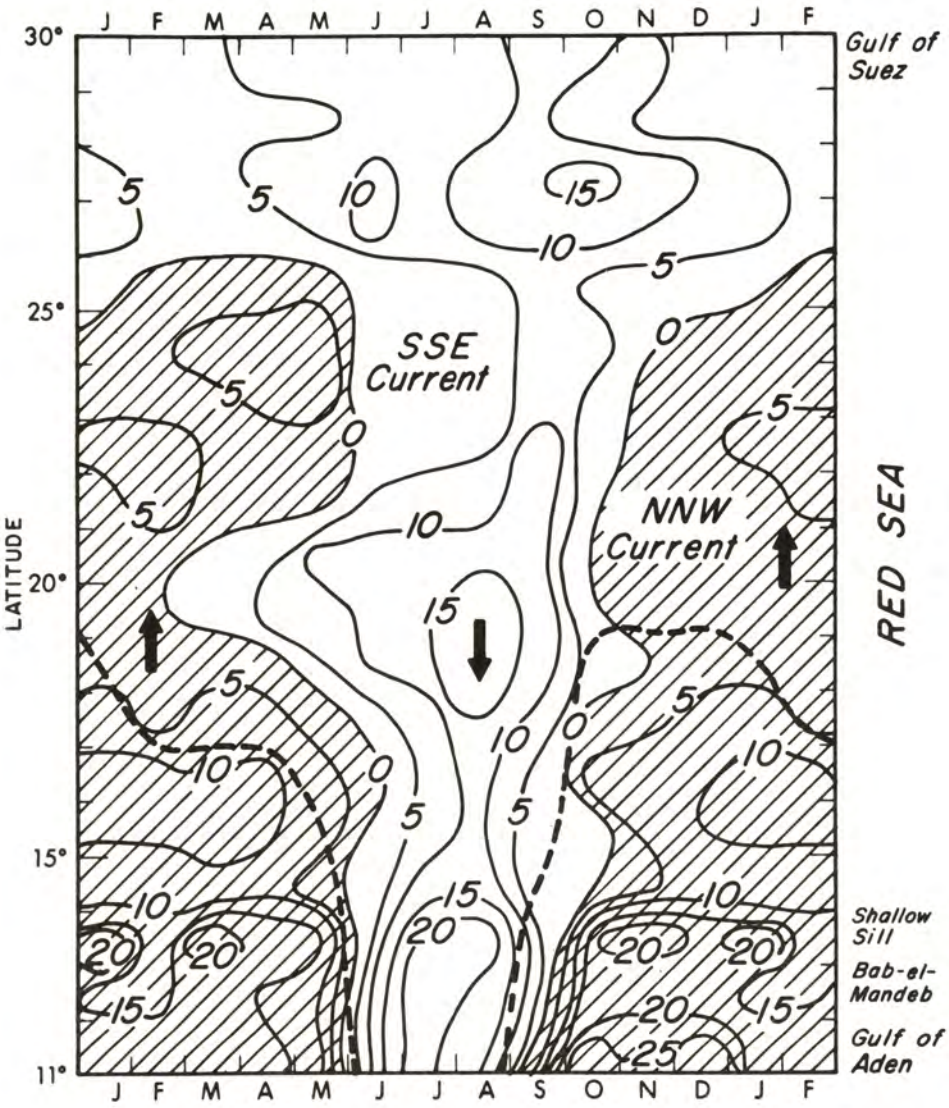

Fig. 3. Magnitude and direction of monthly mean surface currents in cm/sec in the Red Sea as calculated from ship's drift data. Dashed line represents the zero wind vector shown in Fig. 2. January and February are repeated.

3a - Currents During Winter

During the northeast monsoon season (October to May) in the Indian Ocean, the easterly winds of the Gulf of Aden become south-southeasterly and increase in strength as they enter the Strait of Bab-el-Mandeb, and the surface water of the Gulf of Aden is driven into the Red Sea and flows northward. A strong mean surface flow of 15 to 20 cm/s occurs when mean vector winds of 6.7 to 9.3 m/s are present in the Strait. Between 19° and 25°N, the mean surface flow is NNW against the wind. This phenomenon appears in the BARLOW (1934), Koninklijk Nederlands Meteorologisch Instituut (1949), and BOISVERT (1966) analyses. North of 25° to 26°N, the flow is weakly to the south with the NNW winds.

3b - Currents During Summer

During the southwest monsoon (June to September), winds over the Red Sea and mean surface currents are directed toward the Gulf of Aden. These NNW winds and SSE currents flow through the Strait of Bab-el-Mandeb to join the strong atmospheric and oceanic flow directed from the Gulf of Aden into the Arabian Sea. During late summer, speeds of the SSE-flowing current north of 26°N in the northern Red Sea increase, apparently due to the strong NNW winds present at this time. Although the winds are weak over the southern Red Sea during July and August, strong southerly surface currents are present in the central Sea between 18° and 20°N. The strongest flow occurs during July in the Strait of Bab-el-Mandeb when speeds of over 20 cm/s are calculated for the surface outflow. Since the Red Sea has no significant entrance to the north and the surface flow is everywhere toward the Gulf of Aden, the surface layer of the Sea must be divergent during the summer.

3c - Currents During Transition Periods

During periods when monsoon winds of the southern Red Sea change direction (May through June and September through October), monthly mean currents are weakest and most variable. In the southern Red Sea during early June, the currents change direction approximately in phase with the shift in wind direction from the SSE to the NNW. In the central Red Sea, as these SSE winds decrease in strength, the current reverses and begins to flow southward. In the southern Sea, with the onset in early September of the northeast monsoon or SSE winds, the change in current direction lags behind the change in wind direction by approximately one month.

4 - Mean Sea Level

Although observations of sea level of one year's duration or more in the Red Sea region are few, the existing information shows a seasonal variation that is remarkably well correlated with the seasonal reversal in circulation. VERCELLI (1931) listed the monthly mean sea levels calculated from data recorded at stations at Perim and Port Suez for the years 1923 through 1926, as well as the sea-level variations at a station at Port Sudan from 1925 to 1928 (Fig. 4). PATTULLO, MUNK, REVELLE and STRONG (1955) listed the monthly mean sea levels calculated from data recorded at two stations : at Aden for the years 1879 through 1893 and 1937 through 1946, and at Port Suez for the years 1923 through 1929 and 1931 through 1946.

Both the VERCELLI (1931) and the PATTULO, MUNK, REVELLE and STRONG (1955) curves for Suez are included in Figure 4 and are labeled h(b) and h(a), respectively.

All four locations (which are shown in Fig. 1) exhibit a maximum in mean sea level in winter and a sharp decrease in mean sea level from May to late summer. With the advent of the Arabian Sea northeast monsoon (in September), the mean sea level again rises (33 and 35 cm at Port Suez and Port Sudan, and 24 cm at Perim and Aden). Although the times of occurrence of maximum and minimum mean sea level in the Red Sea are similar to those in the Gulf of Aden and the western Indian Ocean (PATTULLO, MUNK, REVELLE and STRONG, 1955), the amplitudes are greater in the Red Sea and Gulf of Suez.

The parameters that control the seasonal oscillations of mean sea level are astronomical effects, effects of evaporation, precipitation, and river discharge, atmospheric pressure, and steric sea-level effects. The effects of purely astronomical conditions (long-period tides) are not significant ; they do not exceed 12 mm at these latitudes (PATTULLO, MUNK, REVELLE and STRONG, 1955). Because rainfall is slight and no large rivers discharge into the Red Sea, these two factors can be ignored. Calculations by YEGOROV (1950) and PRIVETT (1959) show that maximum evaporation over the Sea occurs during winter when sea level is highest. Since the sea-level variations are completely incongruous with the variations in evaporation, evaporation is apparently not the controlling factor in the oscillation of mean sea level. Nevertheless, evaporation must be important both in forming the high-salinity Red Sea water and as a component in the heat budget.

The isostatic adjustment of the ocean surface to changing atmospheric pressure requires that the sea surface rise or fall 1 cm for every 1-mb decrease or increase in pressure. The mean monthly atmospheric pressure at all four locations is highest during January and lowest during July, with a range of approximately 10 mb. Corrections to the monthly mean sea-level curves for the monthly mean variations in atmospheric pressure at the latitude of each of the four locations (see Fig. 4) would result in increases in the range of the mean sea level at all four locations. thus, the observed variations in mean sea level are not a consequence of atmospheric pressure changes ; quite the opposite-they are diminished by the atmospheric pressure changes. Indirectly, pressure changes do affect the sea level because changes in the pressure field are accompanied by changes in the wind field.

Seasonal variations of the density within a water column, from which steric sea level can be calculated, are dependent on the month-to-month thermal and haline variations within the column. Thus, the steric sea level is high when water is warm and/or less saline and low when it is cold and/or more saline. In the discussion that follows, seasonal variations of the monthly mean geopotential anomaly, relative to a level where there are no seasonal variations, are taken as the seasonal variations of steric sea level. Figure 4 shows the monthly mean variations in steric sea level of the water columns within the 1° areas adjacent to the mean sea-level stations. Monthly variations of steric sea level in the upper 300 m of the column near Aden and Perim have the same phase and similar range as the monthly mean variations at the shore stations, although the range of the steric variations is larger by approximately 8 cm. The variation in steric sea level is due to the increase in density of the upper 300 m of the water column brought on by the upwelling of cool, low-salinity water that occurs in the northwestern Gulf of Aden during the southwest monsoon.

In summer the sea level is raised, and in winter, lowered, as a net result of the seasonal variation in density in the upper 200 m of the water column near Port Sudan and in the upper 50 m in the Gulf of Suez (Fig. 4). Consequently, by correcting the monthly mean sea level for steric sea level at these two stations, the range in monthly mean sea level would be increased. Thus, changes in steric sea level are not responsible for high monthly mean sea levels that occur in winter and low monthly mean sea levels in summer in the northern and the central Red Sea.

Figure 4 shows the four monthly mean sea-level curves corrected for both atmospheric pressure and steric variations. Combining these two effects at Aden and Perim accounts for almost all of the variation in mean sea level. The corrected sea levels at Aden and Perim show unexplained drops in mean sea level during June (Aden) and April (Perim). These anomalous drops in the corrected monthly mean sea level curves are probably within the range of data variability. This variability can be judged by comparing the two records of monthly mean sea level for Port Suez (Fig.4) [h(a) was calculated for 18 years of data, h(b) represents only 3 years of data]. The departures of these mean data sets from each other are approximately the same as the unexplained drops at Aden and Perim, indicating that the conditions that control mean sea level vary from one set of data to another.

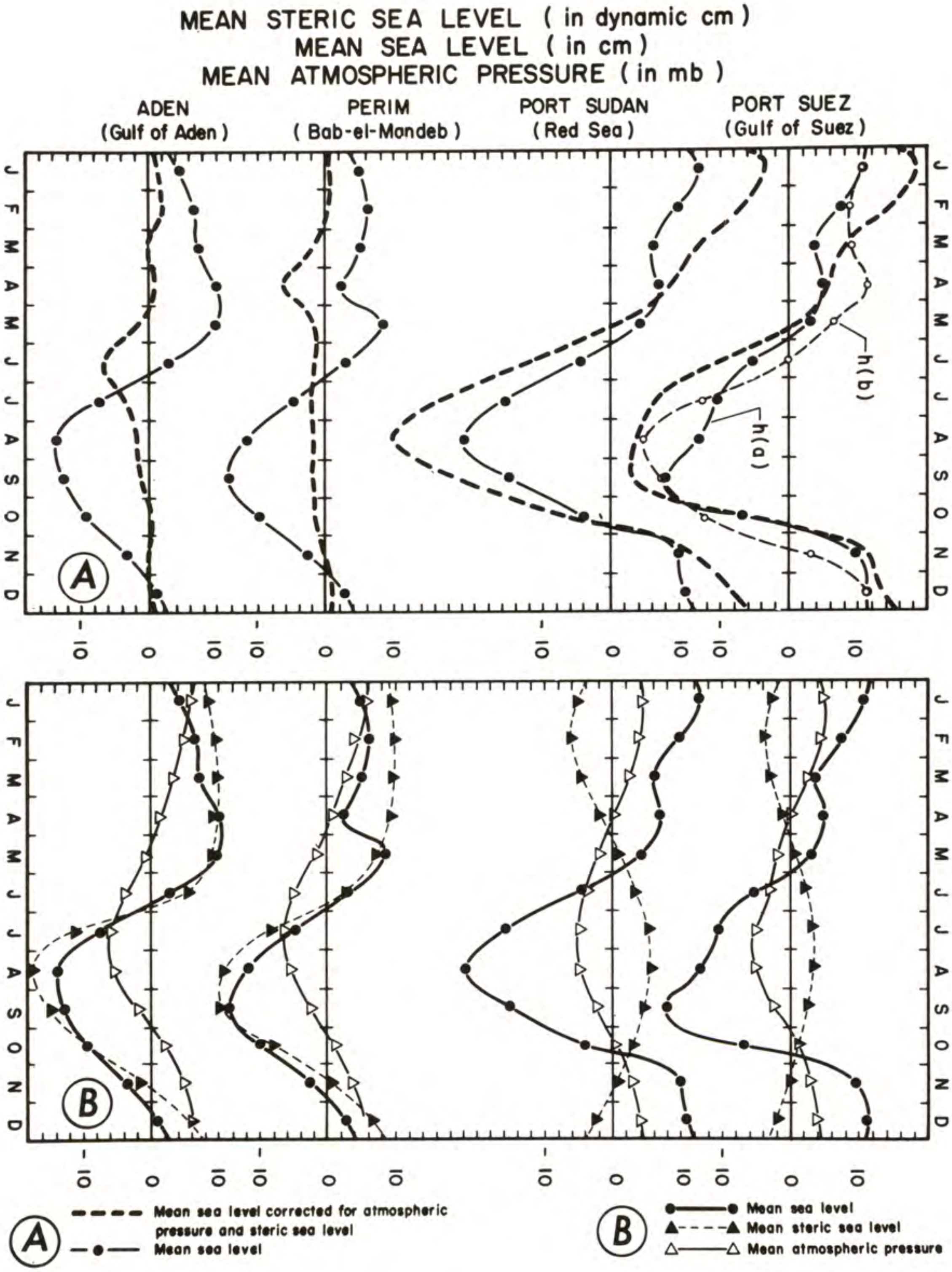

Fig. 4. Monthly variations in mean sea level at Aden (1879-93 and 1937-46), Perim Island (1923-26), Port Sudan (1925-28), and Port Suez [h(a) represents 1923-29 and 1931-46 and h(b) represents 1923-26] and monthly mean sea level after correcting for both atmospheric pressure and steric effects (left). Monthly variations in mean sea level at Aden, Perim, Port Sudan, and Port Suez ; monthly mean variations in atmospheric pressure over the sea near these stations ; and monthly mean steric variations in the sea near these stations (right).

After corrections for atmospheric pressure and steric variations were made to the Port Sudan and Port Suez mean sea level curves, the phases remain the same and the range of the Port Sudan mean sea level increases by 20 cm, while that of Port Suez increases by only 13 cm (Fig. 4). Thus, in the northern and central Red Sea the net effect of atmospheric pressure and steric variations is to diminish the rise and fall in monthly mean sea level. The sea-level variations here must be a regional response to the change in mean sea level at the southern entrance to the Red Sea and the observed increase in the NNW winds that occur in the northern Red Sea during summer.

5 - Hydrographic Structure

Although hydrographic data prior to the IIOE were inadequate to describe the monthly mean vertical structure at different latitudes, data gathered during the IIOE greatly improved the spatial and temporal coverage of the hydrographic structure. While data are still not available to describe all areas during all months, the IIOE data together with earlier measurements are sufficient to describe the monthly mean hydrographic structure along the north-south axis of the Sea.

5a - Temperature Structure and Circulation

All 1628 of the pertinent bathythermograph (BT) data on file with the National Oceanographic Data Center (NODC) in Washington, D.C., were used to construct monthly mean temperature sections from Suez to Aden (Figs. 5 to 7). (For a full explanation of the preparation of these sections, see PATZERT, 1972a). Data describing monthly mean vector surface winds, mixed-layer depths (defined as the depth where temperature varies from the surface temperature by 1.0°C), and schematics of the circulation are also presented in these figures. The circulation in the surface or mixed layer was taken from Figure 3. Below the mixed layer, circulation was inferred from the hydrographic structure. In the preparation of the schematics, convergences and divergences in the surface flow and in the probable corresponding subsurface flows are represented to maintain continuity of mass.

The temperature sections are not discussed in the sequence of the monsoon seasons (as are preceding discussions), but rather from January through December so that the sequence of the major variations in structure will be uninterrupted.

JANUARY (Fig. 5) : Surface temperature varies from < 20°C in the Gulf of Suez to a maximum of more than 26°C near 18°N in the region of converging winds. The mass of relatively warm surface water between 16° and 20°N is a consequence of convergence in the surface flow and lower evaporation due to decreased wind speeds. The mixed layer in the north is much deeper than in the south, and the thermocline has almost disappeared. This lack of stratification due to cooling and the convergence of the surface flow near 26°N suggest a mechanism for the formation of intermediate waters (50-200 m). If the surface waters are further cooled and/or mixed with Gulf of Suez water, deep water will form. The exchange over the sill consists of a surface inflow of ~25.0°C with the winds and a subsurface outflow of ~23.0°C into the Gulf of Aden.

FEBRUARY (Fig. 5) : Surface waters are coolest and the mixed layer in the north is deepest. This is the end of the cooling season and, since the gradient of the thermocline is minimized everywhere, the vertical exchange between the surface layer and deeper waters must be greatest at this time. The surface inflow of warm water (~25.0°C) and subsurface outflow of Red Sea water (~23.0°C) over the sill are intensified by the narrow Strait of Bab-el-Mandeb (Fig. 3). The circulation during January and February is the fully developed winter cellular pattern of warm surface inflow and slightly cooler subsurface outflow, with maximum vertical exchange between the two flows.

MARCH (Fig. 5) : The surface water begins to warm and the mixed layer becomes shallower. As the SSE winds weaken in the south, flow in the north against the winds weakens, and southward flow develops between 18° and 20°N.

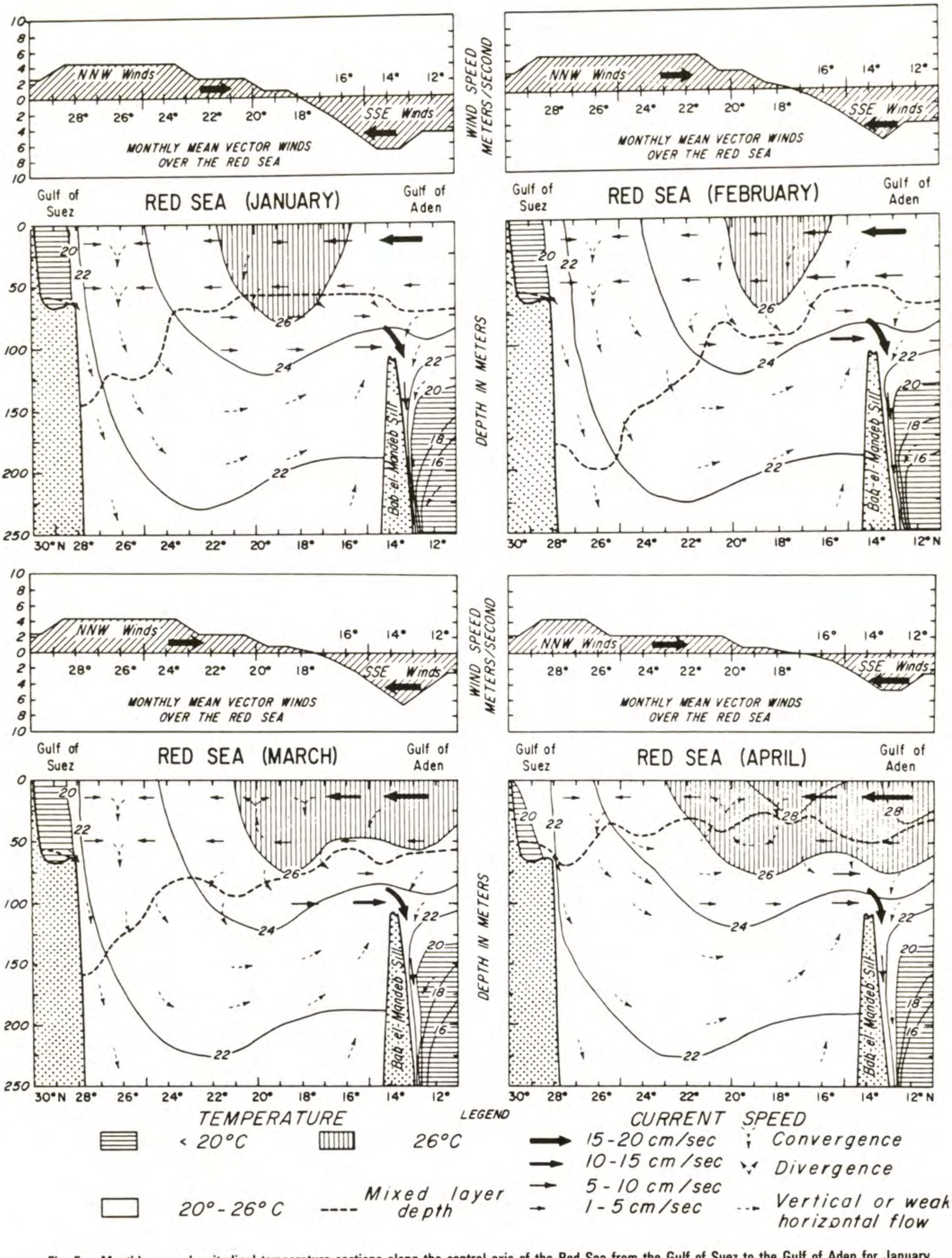

Fig. 5. Monthly mean longitudinal temperature sections along the central axis of the Red Sea from the Gulf of Suez to the Gulf of Aden for January, February, March, and April ; monthly mean vector winds over the Sea ; mixed layer depths ; and a schematic representation of the circulations.

APRIL and MAY (Figs. 5 and 6) : The surface layer warms rapidly. Surface temperatures south of 19°N are now >30°C. During this period the mixed-layer depth becomes shallower and the thermocline is well developed, decreasing the vertical exchange and, along with further weakening of SSE winds in the south, causes the winter circulation pattern to break down. By May, surface flow between 17° and 23°N is to the south, and inflow through Bab-el-Mandeb has slowed.

JUNE (Fig. 6) : Surface flow along the entire length of the Red Sea is now directed toward the Gulf of Aden, as indicated by the change in location of the temperature maximum in the southern Red Sea. As the circulation begins to reverse in March, the temperature maximum is advected to the south, and during June it shifts 250 km to the south. Assuming this shift is due to advection, the current velocity needed to cause it is approximately 10 cm/s to the south. This is, in fact, the velocity indicated by the ship's drift observations (Fig. 3). This surface outflow must be a response to the reversal in wind direction over the southern Red Sea and Gulf of Aden, which now is everywhere from the NNW. No direct observations of subsurface flow are available, but continuity of mass over the sill demands that subsurface outflow into the Gulf of Aden must decrease or reverse during this time.

JULY (Fig. 6) : At the entrance to the Red Sea and in the northwestern Gulf of Aden, winds of the southwest monsoon initiate an intense coastal upwelling which can be seen in the temperature structure. Horizontal divergence in the surface layer caused by the winds and the resulting ascending motion of subsurface waters from June to July is shown by the rise of the 20° and 18°C isotherms from 60 m below the sill depth to 25 m above it. This cool Gulf of Aden water must reverse the pressure gradient between 30 and 80 m, since Gulf of Aden water begins to flow into the Red Sea.

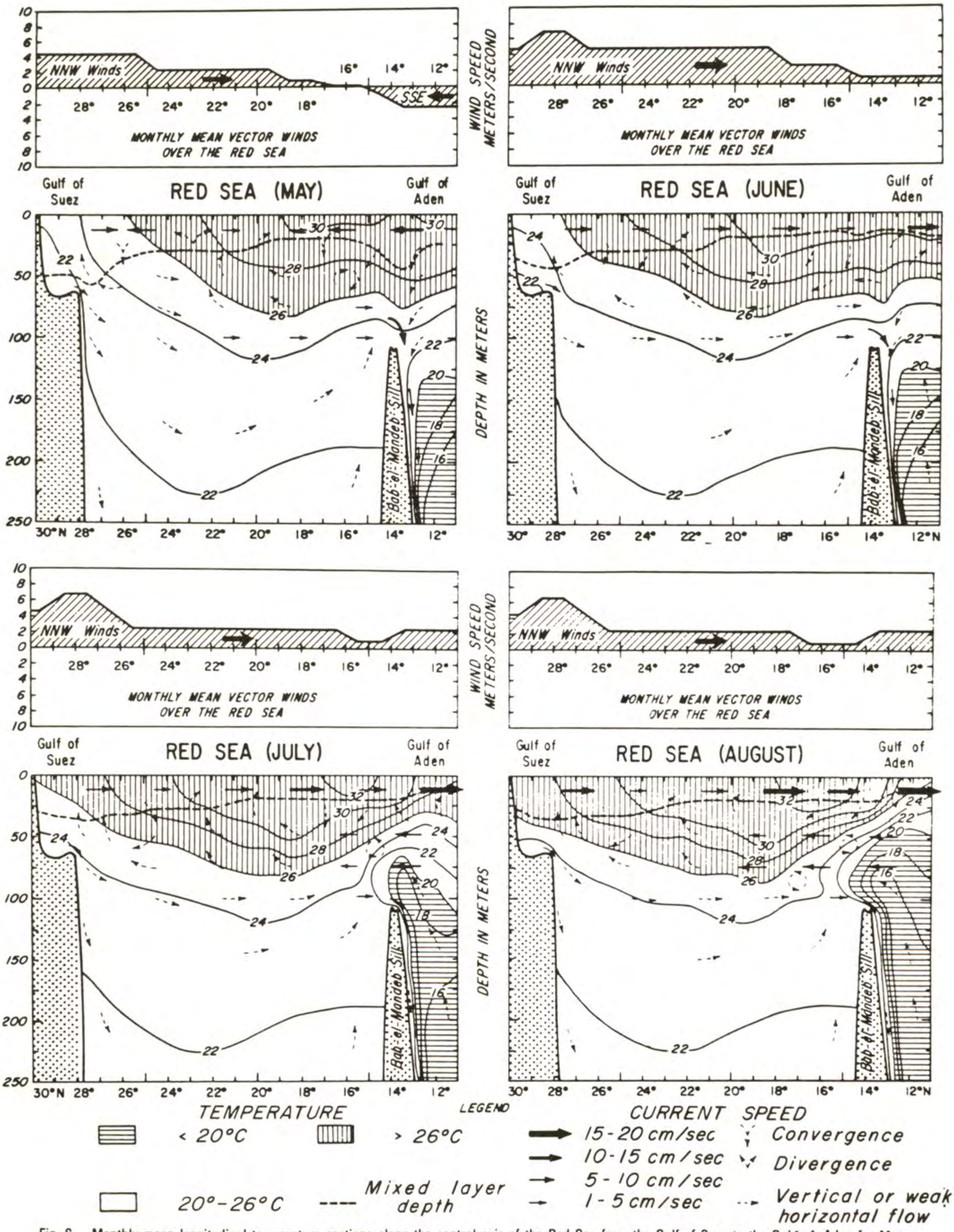

Fig. 6. Monthly mean longitudinal temperature sections along the central axis of the Red Sea from the Gulf of Suez to the Gulf of Aden for May June, July, and August; monthly mean vector winds over the Sea ; mixed-layer depths ; and a schematic representation of the circulations

AUGUST (Fig. 6) : This is the end of the heating season when the highest sea-surface temperatures are expected. Yet, at the entrance to the Red Sea, relatively cool temperatures are observed in the upper 200 m of the water column. From July to August, the 16°C isotherm rises from 175 m to 75 m at the entrance to the Red Sea in the Gulf of Aden, and the cool tongue penetrates farther into the Red Sea. At the surface, the flow is out of the Red Sea (~29.0°C), and, beneath, the subsurface flow is into the Red Sea (~18.0°C) (Figs. 6 and 9).

SEPTEMBER (Fig. 7) : As the winds begin to shift to the winter monsoon pattern of SSE winds into the Red Sea, the upwelling is less evident at the surface, and the surface outflow through Bab-el-Mandeb decreases. In three months, the cool subsurface tongue has moved to 18°N, approximately 750 km north of Bab-el-Mandeb. (This implies an average velocity of 10 cm/s from June to September for this subsurface inflow). In the north, the southerly surface flow increases as the winds increase, making the surface layer divergent, and continuity of mass demands that ascending motions or upwelling occur to compensate for this surface divergence. From July to September, flow in the surface layer is out of the Red Sea, while the cool subsurface layer flows northward. Thus, the cellular pattern of winter completely reverses.

THOMPSON (1939b) suggested that from July to September a third layer of highly saline Red Sea water continues to flow out over the sill. The mean temperature data also suggest this outflow, although the volume of this water must be much less during summer than during winter. KHIMITSA (1968) has shown that there is a seasonal variation in the amount of Red Sea water present at intermediate depths in the Gulf of Aden. His studies indicate that during the late summer, salinities and temperatures are lower than during the winter, suggesting a large decrease in the flow of Red Sea water over the sill and into the Gulf of Aden.

Recent salinity-temperature-depth casts and current measurements taken during late September 1971 indicated that the exchange between the Gulf and Sea was not a three-layer pattern, but showed that the cool, low-salinity Gulf of Aden water was flowing southward, back into the Gulf, while the surface layer had returned to the winter pattern of surface inflow (GORMAN, BROWNING and JONES, 1972). At this time, no warm, high-salinity Red Sea water was detected flowing out over the sill into the Gulf. These observations indicate that the summer circulation pattern breaks down by late September and that the discharge of Red Sea water over the sill is small or nonexistent during late summer.

OCTOBER (Fig. 7) : Winds over the southern Red Sea and Gulf of Aden quickly reverse to the winter pattern of the northeast monsoon. Surface circulation of the southern Red Sea reverses and the cool upwelling south of Bab-el-Mandeb disappears. From September to October, the cool subsurface tongue continues to move north (from 18° to 19°N) but becomes discontinuous near the sill as the Gulf of Aden water that ascended due to the summer upwelling begins to sink to its June level (beneath the shallow sill depth). JONES and BROWNING (1971) also traced the cool tongue as far north as 19°N in October 1969 and found it to be discontinuous at various places in the southern Sea. During October, the longitudinal circulation of the sea can be described as a pair of counterrotating cells in the vertical plane that converge at the surface between 18° and 20°N.

NOVEMBER (Fig. 7) : Surface convergence in the flow as indicated by the surface temperature maximum has moved farther north (~22°-24°N), due to decreasing NNW winds in the north and increasing SSE winds in the south. Although it has dissipated considerably, the cool Gulf of Aden tongue has not completely disappeared, since the temperature structure of the southern Sea still exhibits some temperature inversions. The major process responsible for the dissipation is vertical mixing. The cooling of the surface layer which begins in October-November and the deepening of the mixed layer (Fig. 7) increase the vertical exchange, and cool Gulf of Aden water trapped in the south must be mixed with surface waters of the southern Red Sea.

DECEMBER (Fig. 7) : The mixed layer deepens, especially in the north, and stratification weakens further. This permits more vertical exchange, and the cellular pattern that persists through February becomes fully developed. Strong winds present between 12° and 15°N intensify the relatively warm surface inflow, and ship's drift observations indicate that flow in the north is now against the winds. Hydrographic station data (SIEDLER, 1968) taken during December 1964 still showed a few small temperature inversions near the sill, but the cold tongue had almost disappeared. The accumulation of warm surface water between 18° and 20°N (~28.0°C) is now located in the zone of converging winds.

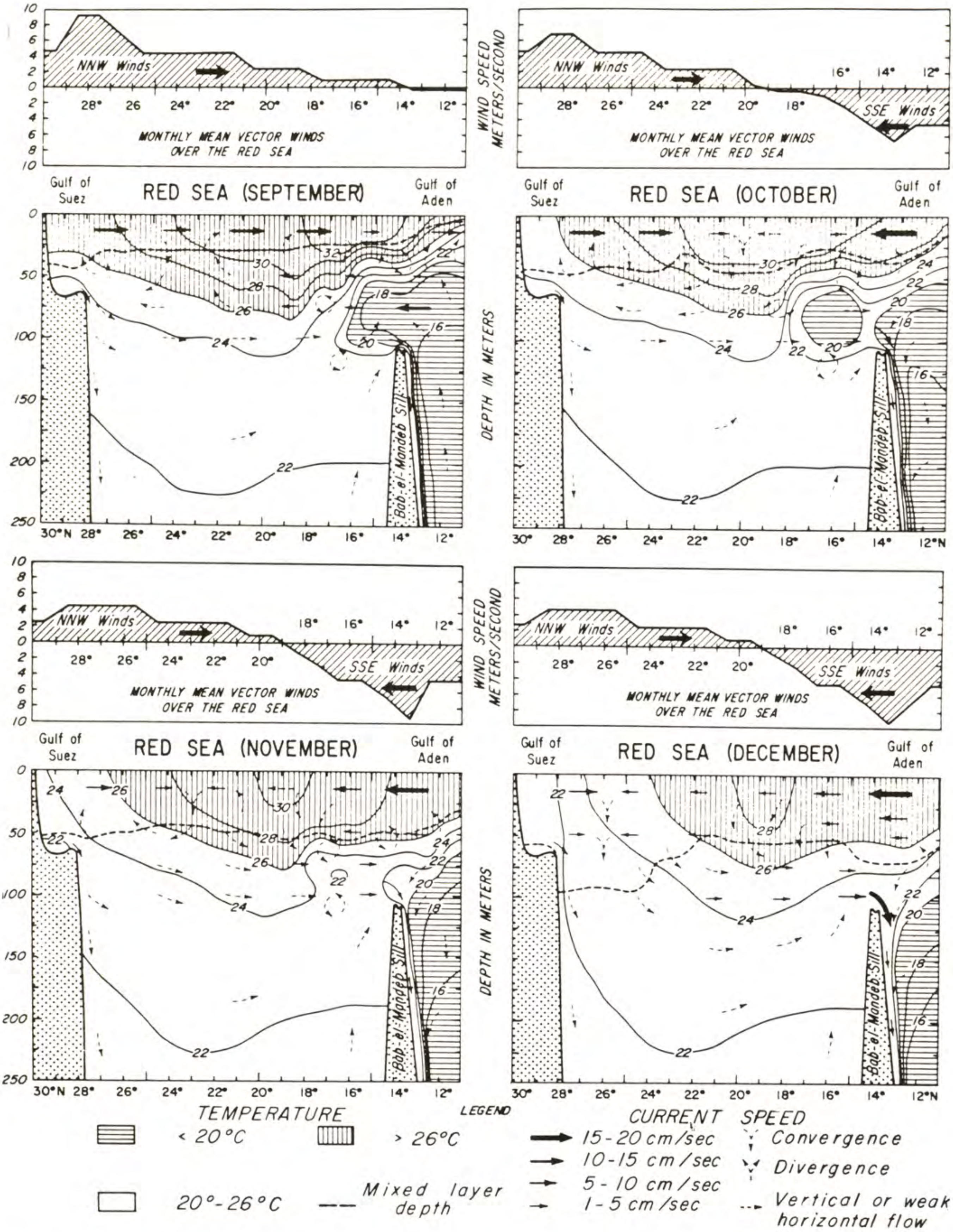

Fig. 7. Monthly mean longitudinal temperature sections along the central axis of the Red Sea from the Gulf of Suez to the Gulf of Aden for September, October, November, and December ; monthly mean vector winds over the Sea ; mixed-layer depths ; and a schematic representation of the circulations.

5b - Differences in Structure of the Red Sea and Gulf of Aden during the Winter and Summer of 1963

To compare the structure and the exchange of the Red Sea water masses with those of the Gulf of Aden, two sets of vertical sections were constructed of potential temperature, salinity, and potential density distributions during the winter and summer seasons of 1963. The summer sections were compiled from data collected aboard the R/V ATLANTIS from July 29 to August 4, 1963 (Fig. 9). To produce a comparable section for the winter season (Fig. 8), the data from the COM. R. GIRAUD (January 1 - February 7, 1963) were used. (For a full explanation of the preparation of these sections, see WYRTKI, 1972.) Cruise tracks for both sections are through the Red Sea to the Gulf of Aden and then ENE toward the Arabian Sea.

Readily seen in all the figures is the isolation of Red Sea water from Gulf of Aden water below sill depth (~100 m). Below 250 m, the warm, highly saline (θ ~21.5°C, S ~40.6°/oo) Red Sea water is weakly stratified and has a potential density of approximately 28.6 σ_θ (WYRTKI, 1971). Nowhere in the Gulf of Aden or in the Arabian Sea is water of such high density to be found. Within the Red Sea, water of 27.0 to 28.0 σ_θ is located near sill depth ; it flows out over the sill, mixes with Gulf of Aden water, and forms high-salinity "Red Sea water" in the Gulf of Aden. This mixture has a salinity maximum of approximately 36.6 to 35.6 °/oo, between 600 m and 800 m depth in the Gulf of Aden and the Arabian Sea (WYRTKI, 1971).

The summer and winter patterns of exchange over the sill are illustrated in Figures 8 and 9. During the winter of 1963, the 25, 26, and 27 σ_θ isopycnals sloped sharply downward toward the Gulf of Aden. (The winter pattern of outflow over the sill is controlled by the pressure gradients that result from this density distribution.) By July-August 1963, the downward slope of the 25 and 26 σ_θ isopycnals was reversed toward the Red Sea. This density gradient reversal was due to the summer upwelling of dense water at the entrance to the Red Sea and the warming of the surface waters to the north. These two effects combined to reverse the pressure gradient and caused the cool, low-salinity Gulf of Aden water between 30 and 80 m (Fig. 9) to flow into the Red Sea. During the winter (Fig. 8), the 27 σ_θ isopycnal dropped sharply over the sill into the Gulf of Aden, but during the summer (Fig. 9) the presence of water with a density of 27.0 σ_θ south of the sill was the only indication that, beneath the cool subsurface inflow, Red Sea water continued to flow out into the Gulf of Aden. This implies that the summer transport of Red Sea water over the sill and into the Gulf of Aden was much less than the winter transport.

A comparison of the winter sections of salinity and potential temperature below 250 m with the summer sections (WYRTKI, 1971) shows that during 1963 the "Red Sea water" in the Gulf of Aden was warmer and more saline during the winter than during the summer (PATZERT, 1972a). This is in agreement with KHIMITSA'S (1968) observation that discharge of this warm, highly saline water during the winter is greater than during the summer.

In the previous discussion of the circulation pattern in the north, the winter pattern of NNW flow indicated that the surface layer must be convergent, while the SSE flow of summer would make it divergent. The change in depth of the

28 σ_θ isopycnal in the north from ~ 200 m during winter to ~ 100 m during summer of 1963 indicates the response of the subsurface structure to the change from convergence to divergence. During winter, the 28 σ_θ isopycnal sloped downward from the ~ 100 m sill depth in the south to the ~ 200 m depth in the north (Fig.9). By July-August 1963, it had reversed. In the south, the 28 σ_θ water was found at 140 m near the sill and at 100 m depth in the north (Fig. 8). Thus, in the north the water between 100 m and 200 m depth was more dense during summer than during winter.

A comparison of salinity during these two seasons in 1963 shows that salinity in the north during the summer was greater than during the winter (Figs. 8 and 9). The strong southerly flow in the surface layer of the northern Red Sea during summer must make the surface layer divergent and cause the water between 100 and 200 m to upwell and to become more saline. As the circulation reverses to the winter pattern of northerly flow, the northern Red Sea is again a region of convergence and the water between 100 and 200 m sinks and, consequently, becomes less saline.

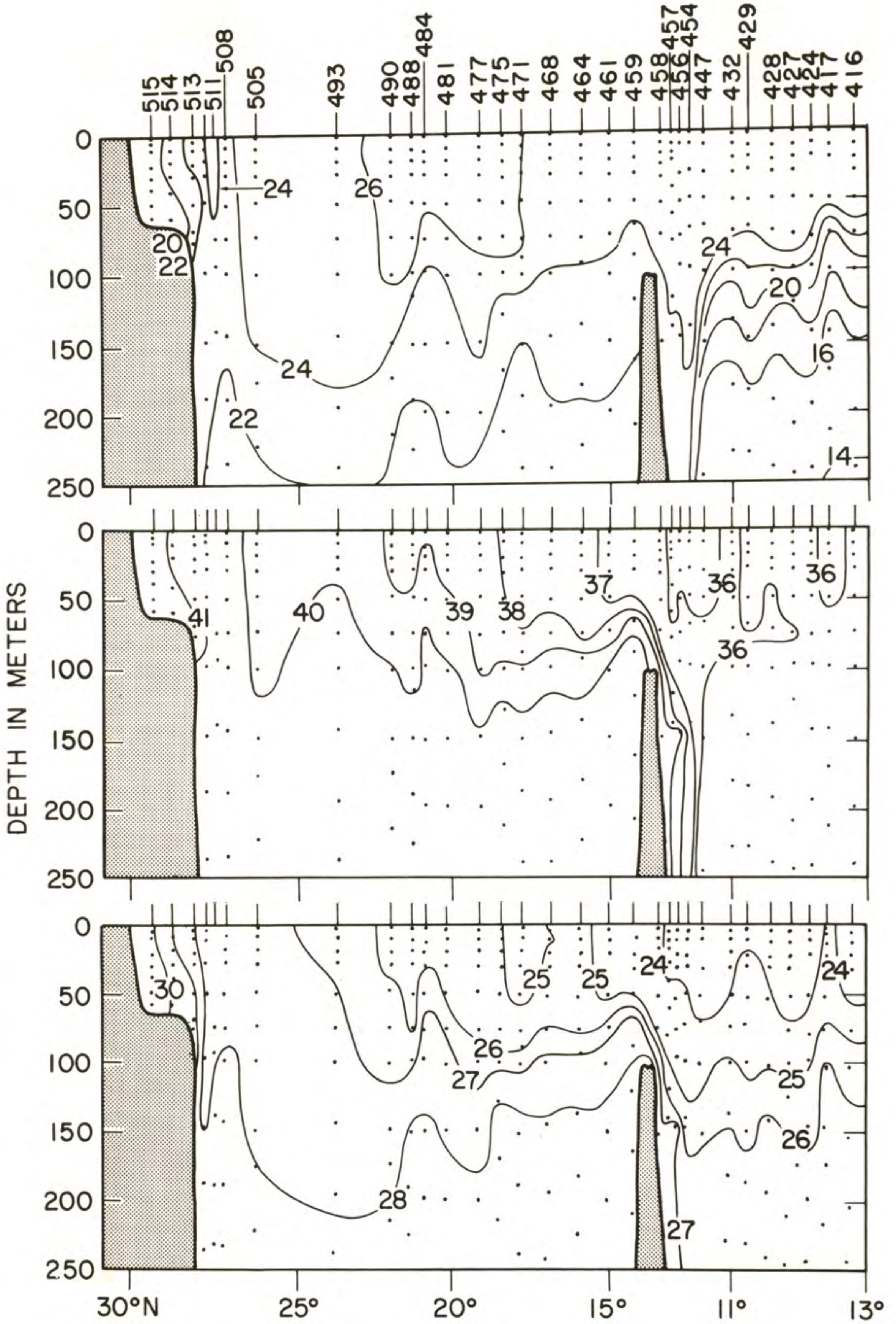

Fig. 8. Sections of potential temperature (°C) (upper), salinity (%) (middle), and potential density (σ_θ) (lower) from the Gulf of Suez to the Gulf of Aden and the ENE toward the Arabian Sea during winter 1963. Data from the COM. R. GIRAUD (Stations 416-515 from January 1 to February 7, 1963) were used.

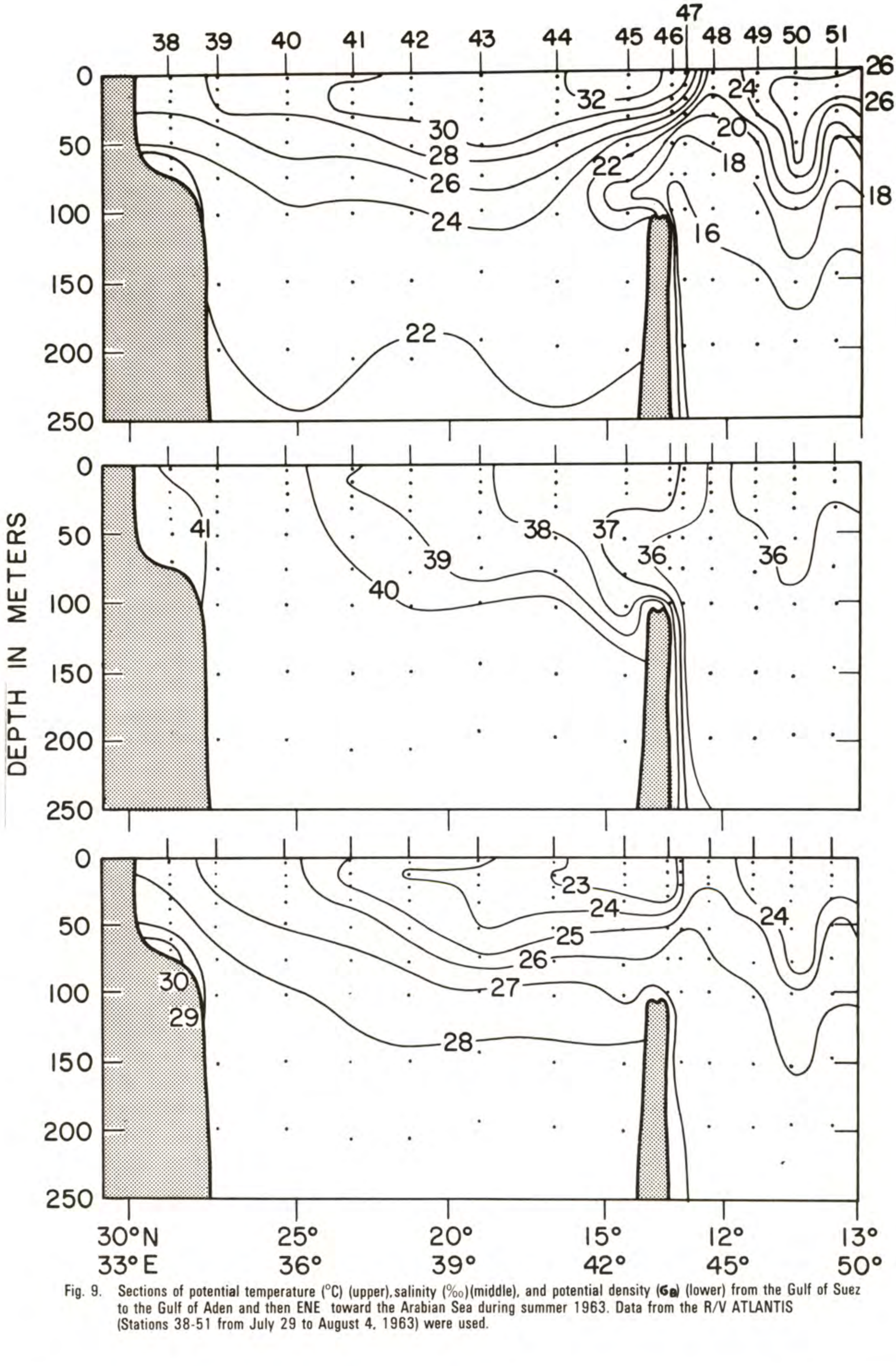

Fig. 9. Sections of potential temperature (°C) (upper), salinity (‰) (middle), and potential density (σ_θ) (lower) from the Gulf of Suez to the Gulf of Aden and then ENE toward the Arabian Sea during summer 1963. Data from the R/V ATLANTIS (Stations 38-51 from July 29 to August 4, 1963) were used.

6 - Volume Transports between the Red Sea and Gulf of Aden

PATZERT (1972b) calculated estimates of the monthly mean volume transports over the shallow sill separating the Red Sea and Gulf of Aden (Table I). These volume transports were confirmed by volume transports calculated from direct current observations (SIEDLER, 1968 ; VERCELLI, 1925) and by agreement of the calculated annual net heat transports between the Sea and Gulf with the annual net heat exchange between the Sea and atmosphere (YEGOROV, 1950), which are both close to zero (PATZERT, 1972b). That the net annual exchange of heat by advection between the Sea and Gulf should be small is indicated by the seasonal pattern of circulation over the sill. During the winter, surface inflow is warmer than subsurface outflow, while during summer the reverse is true. Thus, during winter there is a net gain of heat by advection and during summer a loss of heat by advection.

Table I : Approximate monthly mean transports in the surface layer, which are approximately equal to the oppositely directed subsurface transports, between the Red Sea and Gulf of Aden. Positive transports indicate surface flow into the Sea and negative transports indicate surface flow into the Gulf (from PATZERT, 1972b) :

Month	10^{12} cm^3/s	Month	10^{12} cm^3/s	Month	10^{12} cm^3/s
Jan.	.57	May	.38	Sept.	-.09
Feb.	.40	Jun.	-.06	Oct.	.52
Mar.	.57	Jul.	-.20	Nov.	.57
Apr.	.42	Aug.	-.21	Dec.	.51

During the winter monsoon season (October to May), the mean surface transport into the Sea and subsurface transport into the Gulf is approximately 0.44×10^{12} cm^3/s, while during the summer monsoon period (June to September) the mean exchange reverses and a surface outflow of Red Sea water and subsurface inflow of Gulf of Aden water of 0.14×10^{12} cm^3/s occurs.

Summary and Discussion

Although the circulation of any sea is caused by the interaction between the wind on the sea surface and the water masses of varying thermohaline characteristics which are formed in different climatic regions, the action of the wind is generally considered to be the more important in determining circulation in the upper strata. PHILLIPS (1966) theorized that the Red Sea is an exception where circulation above sill depth is caused primarily by convective or thermohaline forces. He noted that Red Sea circulation during winter and spring consists of "a surface inflow of warm water which, as it moves north, cools largely by evaporation and becomes more saline. It gradually becomes denser and sinks, returning south as a cooler, highly saline, subsurface current". Although this description of the winter-spring circulation is accurate, the circulation is not necessarily of convective origin. The preceding discussions of monthly mean variations in surface currents, sea level, and hydrographic structure indicate that the winter-spring circulation described by PHILLIPS (1966) must be influenced by the wind system acting over the Sea. The strong influence of the shifting wind field is dramatically revealed when the cellular winter circulation described by PHILLIPS (1966) reverses to the oppositely flowing cellular summer circulation of surface outflow and subsurface inflow with upwelling of the structure in the northern Red Sea. The results of this study and what these results imply about the causes of the Red Sea circulation may be summarized as follows :

1 - Through the Strait of Bab-el-Mandeb from October to May, the water exchange between the Red Sea and the Gulf of Aden over the shallow sill (~ 100 m depth) 140 km NNW of the narrowest portion of the Strait of Bab-el-Mandeb is controlled by the winds over the southern Sea and the Gulf. Direction of surface winds and flow is toward the Red Sea. When monthly mean vector SSE winds of 6.7 to 9.3 m/s present near the Strait (October to March), a warm, low-salinity (T ~25.0°C, S ~36.5 °/₀₀) surface transport of approximately 0.49×10^{12} cm^3/s is observed. Beneath this inflow, there occurs a subsurface outflow of cool, high-salinity Red Sea water (T ~23.0°C, S ~40.0°/₀₀). Since the transport needed to compensate for the loss of water due to evaporation is only 0.3×10^{12} cm^3/s, the inflow and outflow must be approximately equal (PATZERT, 1972b).

2 - Within the Red Sea from October to May, the strong SSE winds present in the southern Red Sea extend northward only to between 17° and 19°N, while in the north, weaker NNW winds (2.4 m/s) are oppositely directed. The strong SSE winds in the south cause a large surface inflow and "pile-up" of surface water in the zone of converging winds (16°-21°N). This convergence is indicated by a maximum of surface temperature (~ 26,0°C) at these latitudes. In the north, the surface transport is to the NNW against the wind, causing the surface flow of the northern Red Sea to be convergent. The monthly mean sea levels in the northern and central Red Sea, which are highest at this time, also indicate this convergence. To maintain continuity of mass, the pressure gradient and, consequently, the flow beneath the surface layer must be directed toward the Gulf of Aden. Because the stratification is weakest at this time, there is maximum vertical exchange between the two flows. This is the fully developed winter cellular pattern of surface inflow and subsurface outflow.

3 - As the monsoon winds begin to change from March to May, the SSE winds in the south weaken, and the winter cellular pattern starts to break down. By May, because of these weaker winds in the south, direction of surface flow between 17°-23°N reverses and is to the SSE, with the winds. The wind-driven surface inflow through Bab-el-Mandeb has decreased and is now ~0.38×10^{12} cm^3/s.

4 - From June to September, the direction of winds over the southern Red Sea and the Gulf of Aden is reversed, and the winds blow out of the Sea into the Gulf and toward the Arabian Sea. Although the monthly mean magnitude of these winds in the south is only 2.4 m/s, the direction of surface flow of water reverses with the winds and is out of the Sea during summer. In July and August, this warm, high-salinity (T ~29.0 °C, S ~37.3 °/₀₀) surface outflow is confined to a shallow

(~20 m depth) surface layer and its transport is approximately 0.21×10^{12} cm^3/s. Beneath this shallow outflow, a cool, low-salinity (T ~18.0°C, S ~36.0°/oo) inflow (between 30 and 80 m depth) of Gulf of Aden water is observed, but only from July through September. And beneath this layer, a third layer of highly saline Red Sea water can continue to flow out of the Red Sea into the Gulf of Aden, as it does during winter, but, if it does, its transport is much smaller during the summer than during the winter.

5 - Starting in July, a cool tongue of Gulf of Aden water moves north into the Red Sea and has been traced as far north as 19°N in October, almost 900 km north of Bab-el-Mandeb. This 900 km displacement over a three-month period yields a mean velocity of 10 cm/s. This inflow of cool, low-salinity Gulf of Aden water must be due to the reversal in the pressure gradient over the sill between 30 and 80 m depth. Two effects combine to reverse the pressure gradient : the wind-induced coastal upwelling of cool, low-salinity water in the northwestern Gulf of Aden increases the density of the waters in the upper 300 m south of Bab-el-Mandeb, while the summer heating of the Red Sea decreases the density of the waters north of Bab-el-Mandeb. Without the strong surface divergence or upwelling and the resulting drop in steric sea level in the northwestern Gulf of Aden during the summer, the surface outflow would be less or even nonexistent ; the pressure gradient force over the sill could not reverse, and the cool, low-salinity subsurface inflow would not occur. In this way, the monsoon winds in the Gulf of Aden exert a strong influence on the circulation of the Red Sea. During November and December, deepening of the mixed layer due to cooling of the surface waters and the strong SSE winds now present in the southern Red Sea increase the vertical exchange, and the tongue of cool, low-salinity water that originated in the Gulf of Aden becomes mixed with the surface waters of the southern Red Sea.

upwelling
côte d'Arabie

6 - During summer, the surface flow between the Gulfs of Suez and Aden is to the south, causing the surface layer of the northern Red Sea to be divergent ; to compensate for this divergence, the water between 100 and 200 m depth in the north is upwelled. Since surface flow is out of the Red Sea, while subsurface flow in the south moves northward and the structure in the north is upwelled, the winter cellular pattern is completely reversed.

7 - By September, at the end of summer, the winds begin to shift to the winter monsoon pattern of SSE winds into the Red Sea. The upwelling in the Gulf of Aden is less evident at the sea surface, and the surface outflow through Bab-el-Mandeb has decreased to $\sim0.9\times10^{12}$ cm^3/s. The winds in the south are weak, but winds in the north increase in strength. This is accompanied by a drop in mean sea level in the north and in increase in southward flow, and, consequently, the lowest monthly mean sea level at Port Suez is in September.

8 - In the preceding discussion, the Red Sea is considered to be a channel with flow occurring only northerly or southerly parallel to its central axis. Maintaining this simple description, the observed conditions in the Red Sea indicate how the thermohaline characteristics of the water masses and the wind acting on the sea surface interact at different times and places to generate the circulation. Only in the northern Red Sea during winter is the surface flow against the winds. Two

explanations are presented. During winter, the large evaporation and cooling could create a sea-surface slope that cannot be maintained by the weak winds in the north. Also, northerly flow is necessary to compensate for the water that sinks to form intermediate and deep waters at this time. Another possibility is that the pile-up of warm water near 20°N by the strong winds in the south causes the slope in the north to increase and the surface flow to be against the weak winds in the north. This explanation is consistent with the high monthly mean sea levels observed during winter. Regardless of which of these effects is dominant, it is important to recognize that these thermohaline and wind effects reinforce each other and create the conditions which cause the surface flow to be against the NNW winds. In the southern Red Sea during the summer, the winds and the drop in steric sea level at the entrance to the Sea induce a surface flow in the same direction : i.e., southward. Since the winds in the south are weak at this time, the surface outflow and subsurface inflow must be due to the drop in sea-surface slope through the Strait of Bab-el-Mandeb and the reversal in the pressure gradient over the sill caused by the strong, wind-induced upwelling in the northwestern Gulf of Aden. This drop in steric sea level at the entrance to the Sea ultimately affects the circulation of the entire Sea. The explanation for the observed summer drop in monthly mean sea level at Port Sudan and Port Suez is that these drops are a regional response to dropping sea level in the south and the resulting reversal in the circulation between Port Suez and Aden. This study illustrates the close relationship that exists between the thermohaline and wind forces in generating the Red Sea circulation.

This study has presented the first comprehensive description of the monsoon reversal in the circulation of the Red Sea. It is hoped that further investigations, both theoretical and observational, will attempt to supply more complete answers than have been presented in this paper. To these future investigators the author presents one interesting question that remains as yet unanswered in the literature : The cool, low-salinity tongue of Gulf of Aden water that enters the Red Sea between 30 and 80 m depth during the summer is low in oxygen (~1.0 ml/l) and high in phosphate (~2.0 µg-at/l). Are there any important biological consequences of periodically introducing this high-nutrient water into the euphotic zone ?

Acknowledgements - This study of the Red Sea is an extension of a larger undertaking, the preparation of the Oceanographic Atlas of the International Indian Ocean Expedition (WYRTKI, 1971). The foundations for both the Atlas and the Red Sea study are based on the efforts of all those scientists and technicians who collected data at sea and of the crews of their respective research ships. To these many men and women, I acknowledge my debt. The major portion of this work is contained in my Ph. D. dissertation (University of Hawaii, July 1972) and was supported by the National Science Foundation under NSF Grants GA-10277 and GA-21171. Scripps Institution of Oceanography, under an Office of Naval Research Contract, provided support for the final preparation and publication of this paper.

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DISCUSSION AND COMMENTS

Dr. ROBINSON : Do you not think, with reference to the minimums of my surface temperature charts, that your models which show northern flow in the North in winter against the wind must take into consideration the cross sea gradients which suggest inflow along the Arabian coast and outflow on the African coast ?

Dr PATZERT : In this analysis, I have ignored these differences. In the South, you had the little dip in the surface temperatures at the end of the summer. What I think you see there is the mixing of the cool, low-salinity waters with the surface waters.

Dr. MILLER : Cross-component circulation is very strong at about the neighbourhood of Jedda. This was evident during the discovery of the hot brines when the ship's position was very difficult to maintain because of the current.

Dr. GORMAN : What do you credit as being the source of the warming of the intermediate layer sloping down from the Gulf of Aden toward the Strait of Bab-el-Mandeb ?

Dr. PATZERT : Well, I think that as the strong winds are initiated there is strong mixing between the cool, low-salinity water and the relatively warm surface surrent. Also, there is the deepening of the mixed layer (i.e.; causing the mixing of the cool, low-salinity water with water from the surface layer).

Dr. ROBINSON : When that current disappears relatively quickly, it must mix from both directions instead of just one. This must be mixing both from above and below. If we can believe double-diffusion !

Dr. ZORE-ARMANDA : The Adriatic has a very similar annual variation in the flow pattern to that of the Red Sea. Some studies showed that it could be due to the thermohaline processes as well as to the wind system and to the variation of the air pressure gradients. So most probably in the Red Sea also it would not be possible to ascribe all such variations to the changes in wind system.

Dr. GERGES : I'm particularly interested in the process of water exchange between the Red Sea and the Gulf of Aden. It was mentioned in the talk that we could have a 3-layer regime through the strait of Bab-el-Mandeb. I would like to know how and when we could have such a 3-layer system of water exchange and what would be the extent of each of these 3 layers ?

Dr. PATZERT : The three layers are : the surface outflow, the subsurface inflow, and the existence of warm, highly saline water. Now the interesting thing about this intermediate inflow is that it is dependent upon the intensity of the upwelling that occurs at the entrance. In an extremely intense upwelling situation the pressure gradient in the upper 100 m over the sill can be reversed.

Dr. MORCOS : What is your definition of mixed-layer ? Has this layer any dynamic significance ?

Dr. PATZERT : It is taken as the depth where the surface temperature varies by one degree Celsius. This is also a layer of constant salinity. There is no dynamic reference in this definition.

Dr. MORCOS : When you presented the currents in the Gulf of Suez, you were trying to explain the difference between winter and summer by the reversal of the wind. But the wind in the Gulf of Suez doesn't change appreciably in direction.

Dr. PATZERT : The Gulf of Suez was only presented very schematically. It wasn't meant to figure in the large picture. The only thing I wanted to indicate in that schematic was that the Gulf of Suez water clearly mixes with water in the Northern Red Sea : that there is an exchange.

Dr. MORCOS : What are the bases of the choice of the 4 grades of velocities in your schematic representation ?

Dr. PATZERT : Well, the ship drifts are taken as the surface currents and the subsurface currents are taken as the best guess. Also we consider water masses ; what's inflowing, what's being lifted, what structure is sinking. But they are not based on current observations.

Pr. LACOMBE : It is interesting to note, not only the connection between the surface current and the wind, but also the fact that the wind affects the distribution of properties to fairly deep levels.

On the other hand, it is obvious that the mean distribution of the density shows that the thermohaline effects have a great influence and that the Red Sea is clearly a basin of concentration.

To reconcile these two points of view, one must allow that there is a mean effect of the thermohaline process upon which is superimposed an annual system governed by the wind.

Dr. PATZERT : The deep waters are driven by thermohaline effects and the surface variations are influenced by drift effects.

Pr. LACOMBE : There is in fact a rather deep effect of this reversal of wind on the surface which can go up to 2 or 3 hundred meters.

Pr. WYRTKI : I think that one will never be able to separate the results of wind drift and thermohaline circulation completely because the whole system is very strongly non-linear.

You would have a clear wind-driven circulation if the density were constant throughout. Or, you would have a thermohaline circulation if there were never any wind. But, since both are working, I think separation is impossible. Also there is always a stratification present. We don't have a case in the ocean where there is no stratification.

Dr. MILLER: Is it not possible that the wind circulation, rather than causal, might be a partial by-product of thermohaline circulation ?

Dr. PATZERT: There is clearly an interaction between the two. Nobody asked me the right question : for instance, why is the circulation against the winds in the Northern Red Sea during winter ?

Pr. LACOMBE : We may have very great differences between the eastern part of the Red Sea and the western part of the Red Sea. I think Miss MAILLARD will show that tomorrow. I think there are very important cross currents in the Red Sea at times.

Dr. ROBINSON : There is one other question that I would like to raise for discussion and that is the period of time it takes for the ocean to settle down to a reversal of wind. If you look at the case in the Arabian Sea, there is this total change in direction with the monsoon. It still takes a certain period of time for these things to come about. They are not as quick a change as the wind is. We are trying to integrate the effects, the fact that we have changes in the conditions which take time. They don't happen as fast as ordinary response times, e.g. the change in the wind fields.

Pr. TCHERNIA : It was one of the most pertinent questions when we were preparing the Indian Ocean Expedition - the time lapse. I think that something very important and relevant to this has been investigated in the laboratory of Pr. WYRTKI by DÜING. It seems that the ocean has a period of time to adjust itself. Pr. WYRTKI can speak about this better than I.

Pr. WYRTKI : I will speak about what the situation is with regard to the response of the ocean.

Now, first of all, let us say, 20 years ago and earlier people believed that the ocean was reacting in reasonable time. Then about 10 years ago there was a nice theory by Pr. H. STOMMEL who said the ocean reacts according to time scales of 10 to 200 years and this is what they believed. And then they come to the Indian Ocean.

The Indian Ocean definitely reacted in something shorter than one month, so then they modified their theory and said, "Our theory is only good for the higher latitudes". This hasn't been refuted so far. So up to about 20° North and South it reacts very fast.

Pr. LACOMBE : Perhaps I can say that in Gibraltar, in summer, when there is a high easterly wind blowing in the Straits, the surface current, perhaps down to 10 or 15 meters, can be reversed. That is to say, at these times, the mean current in Gibraltar is outflowing down to these depths. Below, the normal inflow takes place while, much lower, the classical outflow occurs ; thus there is a reversal in the surface layers due to the high wind.

Dr. PATZERT : How long does this last ?

Pr. LACOMBE : It depends on the wind. One day you have 30 knots of wind, the next day you have zero wind and the normal regime is restored.

CIRCULATION AND DEEP WATER FORMATION IN THE NORTHERN RED SEA IN WINTER
(BASED ON R/V MABAHISS SECTIONS, JANUARY-FEBRUARY, 1935)

S. MORCOS * et G.F. SOLIMAN **

Résumé : Circulation et formation d'eau profonde en Mer Rouge septentrionale en hiver.

En hiver 1935, le R/V "MABAHISS" exécuta cinq sections transversales au Nord du 25°N où la formation d'eau profonde est la plus probable. Les profils de vitesse de MOHAMED (1938, non publiés et MORCOS, 1970) étaient basés sur l'hypothèse que le gradient de courant est négligeable au niveau commun le plus profond entre deux stations voisines. Dans ce travail, les profils de vitesse ont été reconstruits en prenant le coeur de la couche intermédiaire d'oxygène minimun comme niveau de référence. Les vitesses calculées montrent le schéma général d'un flux Nord-Ouest au-dessus du niveau de référence et Sud-Est au-dessous. Ceci correspond mieux avec le schéma généralement donné de la circulation en Mer Rouge.

Des cartes de topographie dynamique en surface, à 100 m, 300 m et 700 m, relatives à ce niveau de référence de profondeur variable, ont été construites et comparées à celles de BIBIK (1968) et MAILLARD (1971).

La représentation schématique du volume d'eau transporté à travers ces sections indiquait qu'un flux vers le Sud et vers le bas est dominant dans la partie la plus septentrionale de la Mer Rouge et qu'une partie de ce flux est compensé par un mouvement d'upwelling dans la partie centrale de la mer et par un flux vers le Nord dans les couches supérieures.

Abstract

In winter 1935, R/V MAHAHISS carried out five cross sections north of 25°N where the formation of deep water is mostly expected. The velocity profiles of MOHAMED (unpublished 1938, and MORCOS, 1970) were based on the assumption that the gradient current is negligible at the lowest level common to two neighbouring stations. In the present work, the velocity profiles were reconstructed taking the core layer of the intermediate minimum oxygen as a reference level. The calculated

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velocities show the general pattern of a northwest flow above the reference level and a southeast flow below. This is more compatible with the generally accepted scheme of circulation in the Red Sea.

Charts of dynamic topography at surface, 100, 300 and 700 m relative to this reference level of variable depth were constructed and compared with those of BIBIK (1968) and MAILLARD (1971).

The schematic representation of the volume of water transported through these sections indicated that a southward and downward flow is dominant in the most northern part of the Red Sea and that part of this flow is compensated by upwelling in the central part of the sea and northward flow in the upper layers.

The Northern Red Sea is the natural place for the formation of deep and bottom waters during winter. The Egyptian R/V "Mabahiss" carried out five cross sections between 25°N and 28°N from 3.1.1935 to 13.2.1935 when the formation of deep water by winter convection would be mostly expected. MOHAMED (unpublished, 1938) constructed velocity profiles representing the distribution of the velocity of the component of the horizontal currents perpendicular to the plane of four of these cross sections (G, H, I and J). These sections and a summary of MOHAMED's conclusions were published by MORCOS (1970). Only few research vessels made transverse sections in the Red Sea ; the majority made their observations along the main axis of the sea. The investigations of "Mabahiss" were the most thourough and detailed in the Northern Red Sea in winter. They were followed by two sections (R and G) made in this region by R/V "Commandant Robert Giraud" in winter 1963 (MAILLARD, 1971) and a number of stations by R/V "Ichtyolog' in winter 1964-65 (BIBIK, 1968).

The velocity sections of MOHAMED (1938) were based on the assumption that the gradient is negligeable at the lowest level common to two neighbouring stations. In the Red Sea the surface transport along the main axis must be compensated by an opposite flow in the deeper layer. MORCOS (1970) pointed out the importance of applying other reference levels at intermediate depths, and suggested the use of the layer of oxygen intermediate minimum for this purpose. Although the choice of this layer as a reference level was criticised by a number of authors, it is assumed that the peculiar character of this layer in the Red Sea, makes it one of the exceptional cases referred to by Sverdrup (1938) where the oxygen minimum may be found close to, or even in,a layer of no motion.

Figure 1 shows the horizontal distribution of the depth of the core layer of intermediate minimum oxygen which is taken as a reference level of variable depth in the Northern Red Sea. The velocity sections of the five cross sections of "Mabahiss" : F, G, H, I and J are represented by figures 2, 3, 4, 5 and 6 respectively. For the sake of comparison section H constructed by MOHAMED (1938) is reproduced in fig. 7. An immediate result of the choice of a reference level at an intermediate depth, is that the calculated velocities show the general pattern of positive values indicating a northwest flow above the reference level and negative values indicating a southeast flow below the reference level. Moreover, the positive values of velocity at the surface becomes less than in Mohamed sections ($>$25 cm/sec compared with 70 cm/sec respectively in section H), while the deeper waters show reasonable negative values compared with very weak positive northward current in Mohamed's sections respectively (-10 to -15 cm/sec compared with +10 to 0 cm/sec respectively in section H). The present calculations are more compatible with a general scheme of circulation based on continuity of flow in which the waters transported at the surface are balanced by a water transport in the opposite direction.

However, the circulation inferred from the present sections as well as

Mohamed's sections is not so simple. Alternation in the direction of flow in the same stratum across one section appears with various degrees in almost all the sections. Mohamed suggested that such opposite movements would tend to produce vertical motion on a large scale, both cyclonic and anticyclonic. He noted waters with lower temperature at surface in certain stations, and warmer water at 100-200 m at another position. These abnormal temperature phenomena would find their explanation in the cyclonic and anticyclonic vortices, the former causing less warm water to well up from below and the latter resulting in the warm surface water sinking down. This vertical movement is supported by the complicated topography of the bottom, the irregularities of the coast line, the presence of islands and by the fact that at the time of observation the main flow is opposite to the prevailling wind.

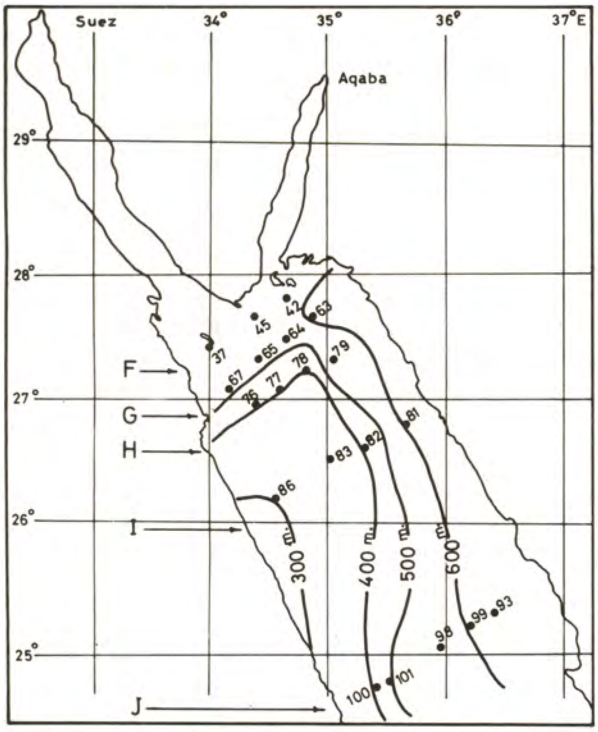


Figure 1 : Horizontal distribution of the depth of the core layer of intermediate minimum oxygen in the Northern Red Sea. Dots indicate the positions of stations comprising the five cross sections (F to J).

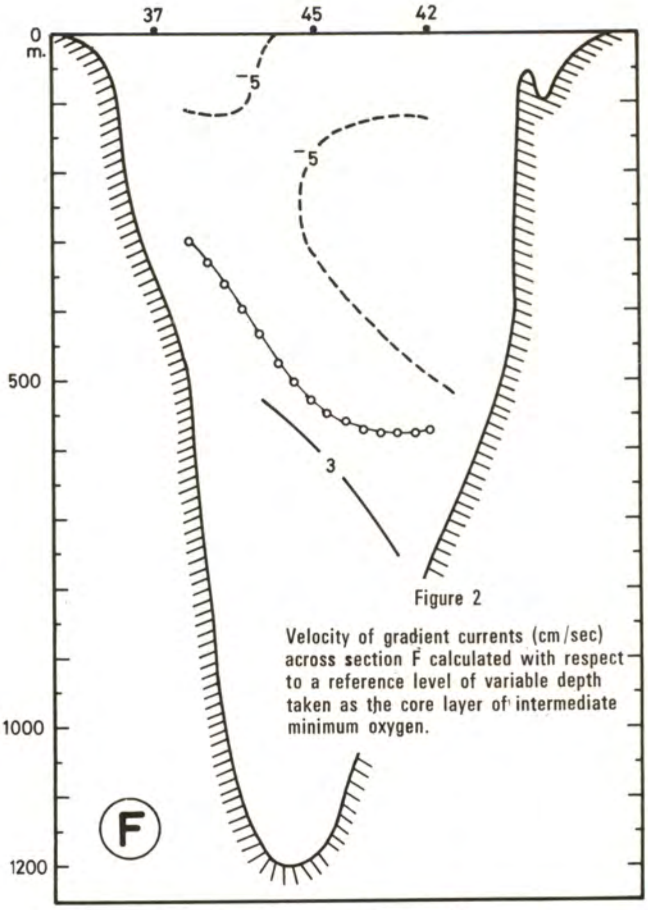


Figure 2

Velocity of gradient currents (cm/sec) across section F calculated with respect to a reference level of variable depth taken as the core layer of intermediate minimum oxygen.

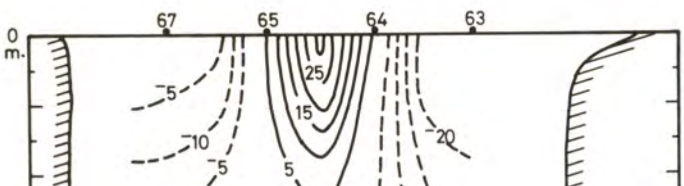


Figure 3 : Velocity of gradient currents (cm/sec) across section G.

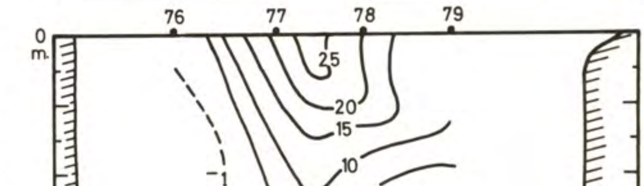


Figure 4 : Velocity of gradient currents (cm/sec) across section H.

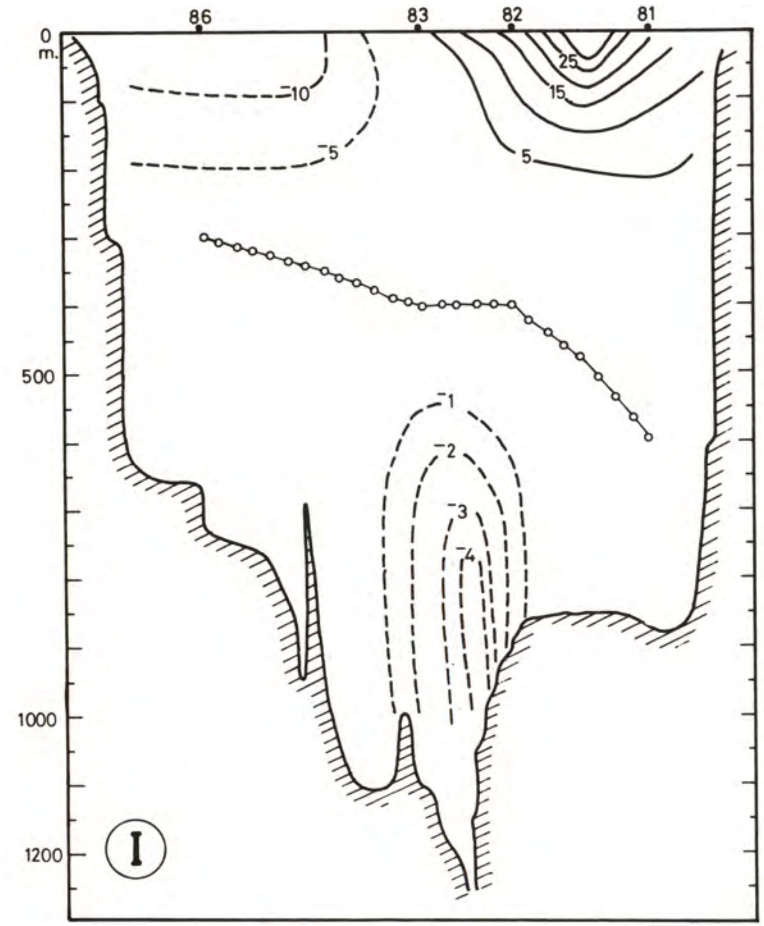


Figure 5 : Velocity of gradient currents (cm/sec) across section I.

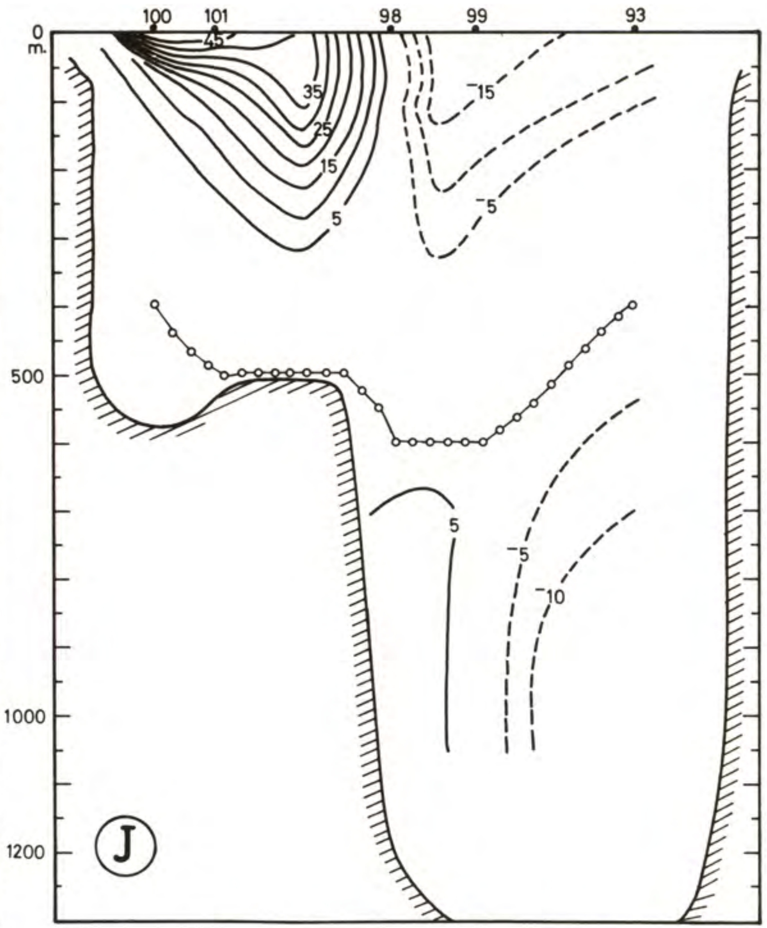


Figure 6 : Velocity of gradient currents (cm/sec) across section J.

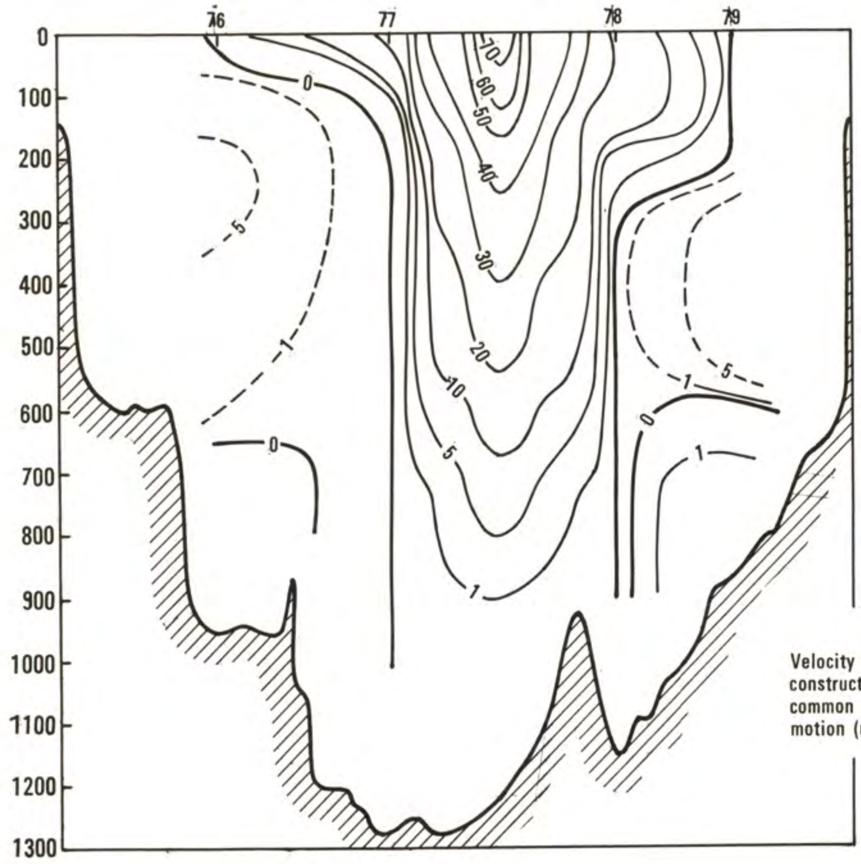


Figure 7

Velocity of gradient currents (cm/sec) across section H, constructed by Mohamed (1938) by taking the lowest level common to two neighbouring stations as the level of no motion (reference level).

Figures 8a, b, c and d represent the dynamic topography at the 0-decibar surface (sea level) as well as at 100, 300 and 700 m levels respectively relative to our intermediate reference level.

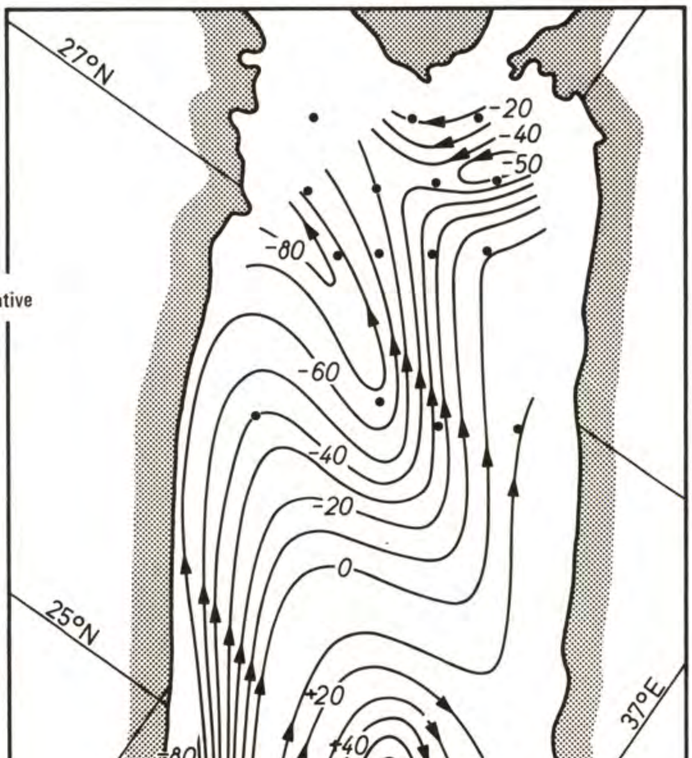
The geostrophic currents at the surface generally set toward N.N.W. i.e. along the main axis of the sea. They are relatively strong on the western side of the sea at about 25°N (section J), and less strong on the eastern side of the sea at about 26°-27°N. However many irregularities occur in the geostrophic flow, and the current shows a meandering character. Cyclonic and anticyclonic circulations occur, with currents flowing in opposite direction to the main flow. Also cross curents which set across the central channel of Red Sea in an easterly or westerly direction find their explanation in the meandering character of the main flow and the cyclonic and anticyclonic circulations. Such cross currents are observed between 25° and 26°N where weak currents flow from west to east between sections J and I (figure 8a).

BIBIK (1968) and MAILLARD (1971) constructed charts for dynamical topography of the surface referred to 500 db and 300 db respectively. Both charts agree with respect to the presence of a large cyclonic vortex in the northern Red Sea and a small anticyclonic vortex at the extreme north of the sea. While the cyclonic vortex represented a more constant character in winter, the small anticyclonic vortex changed in position and according to Bibik charts appeared in December-January and disappeared in April. The detailed chart of dynamical topography according to Mabahiss observations show a different picture in which the northern part of a large anticyclonic circulation appear at about 25°N, and the southern part of a small cyclonic circulation at 27°N. This disagreement between the present chart and the published charts of Bibik and Maillard is only an apparent disagreement if displacement in position is taken in consideration. In fact the geostrophic circulation between 25°N and 28°N in "Mabahiss' chart shows the same pattern of circulation between 23°N and 26°N in "Robert Giraud" chart, which may be interpreted by a displacement of 2° latitude towards the south when comparing the observations of winter 1935 with those of winter 1963. It seems that such displacement in position is a property of geostrophic circulation in the Red Sea. Bibik (1968) observed that the center of the main cyclonic vortex in the Northern Red Sea has been displaced about 1° 30' towards the north from December 1964 to April 1965.

Figure 8

The dynamic topography of the Northern Red Sea in winter relative to the core layer of intermediate minimum oxygen.

a. at 0-decibar surface (sea level)
b. at 100 m.
c. at 300 m.
d. at 700 m.



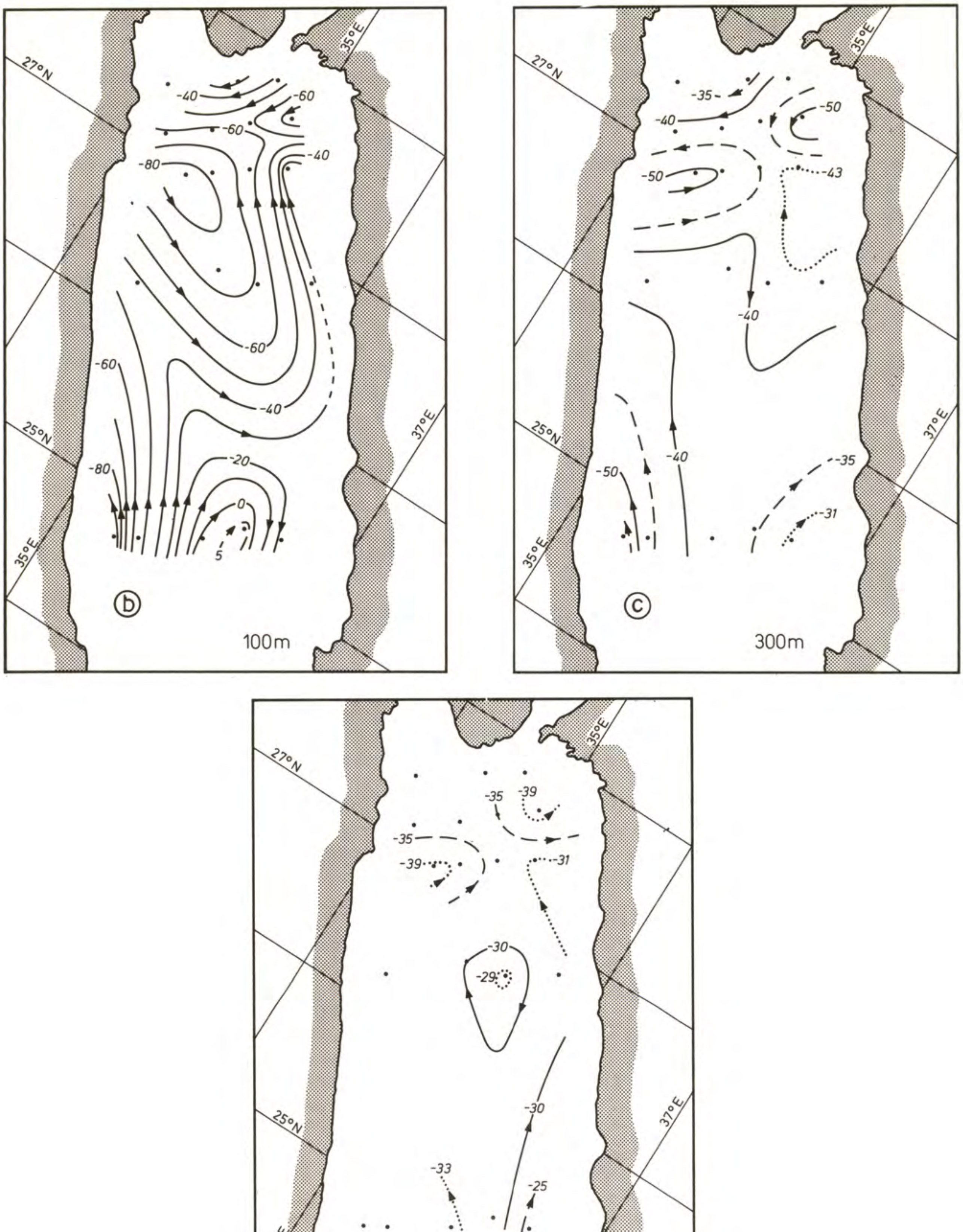

27°N
25°N
35°E
37°E
-40
-60
-60
-40
-80
-60
-60
-40
-20
-80
0
5
b
100m
-35
-50
-40
-50
-43
-40
-40
-50
-35
-31
c
300m
-35
-39
-35
-39
-31
-30
-29
-30
-33
-25
d
700m

Fig. 8

The volume of water transported in 10^6 m^3/sec was calculated between every two neighbouring stations in each section at successive layers from surface to the lowest level common to every two stations. Figure 9 is a simplified schematic representation of water transport through the three sections G (27,5°N), I (26,5°N) and J (25°N). Water is transported through section G southward from surface to bottom. A northward transport occurs only in the upper 100 m in section I and in the upper 500 m in section J, while the deeper layers of both sections show a southward transport. The northward transport diminishes in a northwards direction, having a small value in the surface layer of section I and disappearing completely in the section G. Considering the segment of the Red Sea enclosed between sections G and I which represents the extreme north of the Sea, and calculating the amount of water inflowing from north (section G) and south (at the upper 100 m of section I) and the amount of water outflowing to the south (from 100 m to 1 200 m in section I), will show a net inflow of $0,86.10^6$ m^3/sec in this segment. In winter the surface currents in the Red Sea flow northwesterly opposite to the direction of the wind which blows from north and northwest. However, this generalization does not extend to the extreme north of the Red Sea. Sections F and G show a southward transport in the same direction of wind. Water accumulates in the extreme north as a result of the encounter between southward transported and northward transported waters. Part of this water is consumed by evaporation and increase of mean sea level which is higher in winter than in summer. However, the contribution of the two factors is in the order of $0,002.10^6$ m^3/sec compared with $0,86.10^6$ m^3/sec excess inflow in the segment between sections G and I. The most obvious explanation is that this region in winter is the natural place for formation of deep water enhanced by winter convection and high density of water due to relatively high salinity and low temperature at the extreme north of the sea. The $0,86.10^6$ m^3/sec excess inflow will find their way to the south through sinking and flowing in deep channels (below 1 200 m). A similar consideration for water transport inflowing and outflowing in the segment of the Red Sea enclosed between sections I and J shows a slightly less amount of 0,72 m^3/sec as an excess inflow which should leave this segment. The total volume of water leaving the two segments is $1,58.10^6$ m^3/sec, from which only $0,46.10^6$ m^3/sec leaves section J in order to maintain balance between inflowing and outflowing water across this section. The residual amount of $1,12.10^6$ m^3/sec which is actually the same amount of water inflowing through section G from the north, must well up at various positions and return to the north in the water circulation outside the main channel i.e. on the continental shelf and slope which is not included in the present calculation.

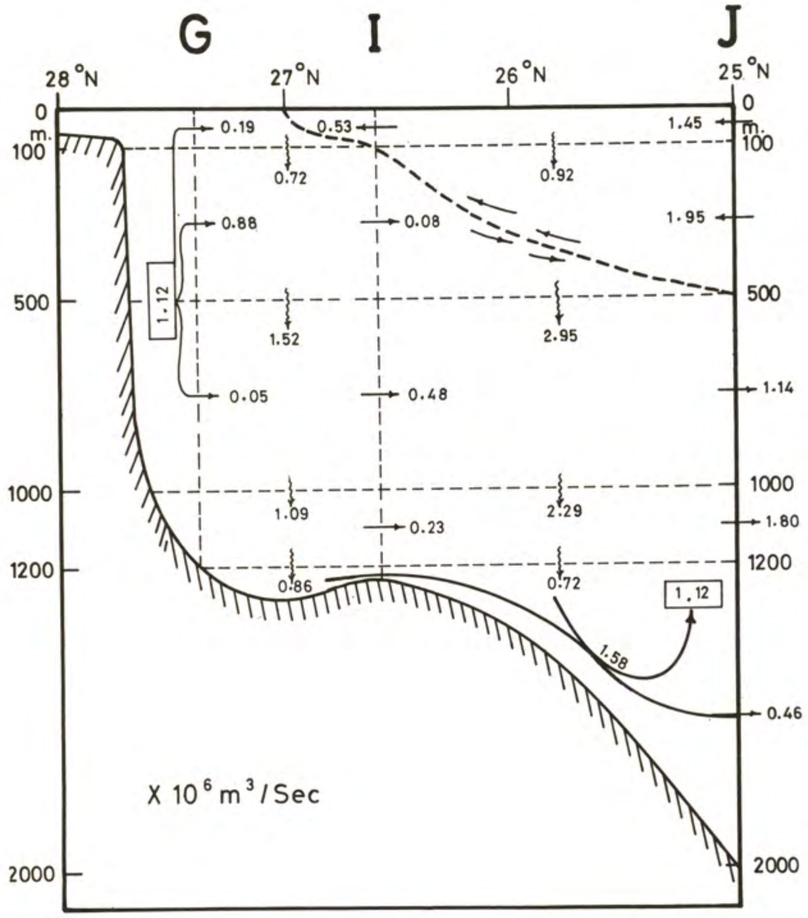


Figure 9 : Simplified schematic representation of water transport in the Northern Red Sea through the three sections : G (27.5° N), I (26.5° N) and J (25° N).

Comparing the scheme of circulation constructed by MAILLARD (1971, Fig. 65) for the whole Red Sea, with the present detailed scheme for the northern Red Sea shows good agreement. The amount of water transported northward over 300 m is $2{,}17.10^6$ m^3/sec at 24°N ("ROBERT GIRAUD", section P) compared with $2{,}77.10^6$ m^3/sec at 25°N ("Mabahiss", section J). However, MAILLARD (1971) restricted her calculations to the upper 300 m, and considered the difference between successive sections as water transport by vertical motion either downward in the north or upward in the south. The downward motion in the Northern Red Sea is a dominant feature in the present scheme of circulation as well as in Maillard's schematic representation.

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EAUX INTERMEDIAIRES ET FORMATION D'EAU PROFONDE EN MER ROUGE

C. MAILLARD *

Résumé

L'analyse des données du "Cdt ROBERT GIRAUD" (14 Janvier - 11 Février 1963) met en évidence une stratification plus complexe que la simple réduction à deux couches d'eau généralement admise en hiver. Entre l'eau superficielle venue de l'océan Indien et l'eau profonde formée par plongée des eaux superficielles au Nord de la mer, s'intercalent des masses "d'eaux intermédiaires" dont la présence se traduit par des modifications de la forme des diagrammes θS. Leur formation implique l'existence de mouvements convectifs à toutes les latitudes de la Mer Rouge. A cet égard, il est très probable que les larges plateaux côtiers qui la bordent, jouent un rôle prépondérant.

Au Nord de la Mer Rouge, c'est un processus identique qui est à la source de la formation de l'eau profonde : sur les hauts fonds du Golfe de Suez, l'eau qui entre en surface, déjà passablement transformée au cours de son trajet en Mer Rouge, voit sa densité s'accroître très brusquement jusqu'à atteindre des valeurs très supérieures (σ_t = 30,16 en surface) à celle de l'eau profonde (σ_θ = 28,60). Les mesures hydrologiques et courantométriques auxquelles nous avons pu avoir accès, ont permis de suivre d'une manière assez détaillée l'évolution de cette eau dense, et d'identifier dans le mélange eau du Golfe de Suez - eau superficielle de la Mer Rouge, la principale source de formation d'eau profonde.

Abstract : Intermediate waters and deep water formation in the Red Sea

Analysis of the "Cdt. ROBERT GIRAUD" data, collected in the Red Sea from January 14 th to February 11 th 1963, showes a more complex stratification than the simple two-layer system that is considered to exist in the Red Sea in winter. Between the surface water coming from the Indian Ocean and the deep water formed by sinking of the surface-water in the North of the Red Sea, are inserted some "intermediate waters", whose presence shows up as modifications in the shape of the diagrams. Their formation implies the existence of convection at all latitudes

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in the Red Sea. This, it is probable that the large continental shelves around the sea play an important part in the formation of the intermediate waters.

In the North of the sea, a similar process is responsable for the deep water formation. In the shallow Gulf of Suez, the entering surface water, already transformed during its passage across the Red Sea has a vary abrupt increase of density. The density of the surface water reaches a value (σ_t = 30,16) much greater than that of the deep water (σ_θ = 28,60). The hydrological and currentmeter data to which we have had access, have permitted us to follow the evolution of this dense water and to identify the mixing of Gulf Suez water and Red Sea subsurface water as the main source of deep water formation.

INTRODUCTION

Le régime hivernal en Mer Rouge est généralement décrit par le schéma suivant :

1° - en surface une eau venant de l'Océan Indien qui forme un courant vers le NNW selon l'axe de la mer et dont la densité croît sous l'effet de l'évaporation et du mélange avec l'eau sous-jacente ;

2° - au nord de la mer, une plongée des eaux de surface ;

3° - en profondeur, un courant de retour vers le SSE d'une eau dense et très homogène ;

4° - au Sud de la mer, une remontée de l'eau profonde et un déversement partiel dans l'Océan Indien à travers le détroit de Bab-el-Mandeb.

En réalité la stratification est beaucoup plus complexe et les mouvements convectifs qui renouvellent les couches inférieures se produisent à toutes les latitudes. Cependant, dans la plus grande partie de la mer, les densités atteintes en surface ne sont pas assez élevées pour permettre un écoulement en profondeur ; il apparaît alors des "eaux intermédiaires" entre l'eau de surface et l'eau profonde. Dans leur formation, le rôle des larges plateaux côtiers semble prépondérant.

Au Nord de la mer, dans le Golfe de Suez, les densités atteintes permettent des plongées d'eau jusqu'aux plus grandes profondeurs, donc un renouvellement de l'eau profonde. Ce mécanisme de renouvellement, qui a pu être étudié de manière assez détaillée, semble être identique à ceux qui interviennent dans la formation des eaux intermédiaires.

Ces résultats exposés ici, ont pu être déduits des observations du "Cdt. ROBERT GIRAUD" du 14 janvier au 7 février 1963, car elles forment un réseau plus dense que la plupart de celles des campagnes précédentes : 60 stations hydrologiques réparties en une coupe longitudinale et 10 coupes transversales (coupes I à R). De plus, nous avons pu avoir accès à des mesures directes de courant effectuées par la compagnie COCEAN dans le Golfe de Suez.

1 - EAUX INTERMEDIAIRES EN MER ROUGE

L'étude des diagrammes θS a permis de déceler la présence d'eaux intermédiaires en Mer Rouge. Lorsqu'il n'y a que deux couches d'eaux dans une stratification, le diagramme θS vertical est un segment de droite : à chaque extrémité se groupent les points représentatifs de chaque masse d'eau, et, sur le segment qui les joint, ceux de la couche de transition qui n'est formée que du mélange de ces deux eaux.

Ce n'est pas le cas des diagrammes θS des stations effectuées par le "Cdt ROBERT GIRAUD" : entre 50 et 150 m ils présentent généralement de forts renflements avec, dans certains cas, apparition d'un extremum de temperature. De telles formes indiquent la présence d'une masse d'eau intermédiaire distincte aux stations considérées. L'intersection des tangentes aux origines des diagrammes θS détermine les caractéristiques initiales de cette eau (LACOMBE, 1965). Cependant, du fait du nombre restreint de prélèvements hydrologiques (généralement limités aux dimensions standards), les valeurs ainsi trouvées comportent une assez large marge d'incertitude.

Dans une même région, les formes des diagrammes sont parfois semblables et traduisent alors l'influence d'une même masse d'eau intermédiaire. Sept de ces eaux ont été suivies sur plusieurs stations voisines. On peut voir, sur les figures 1, 2, 3, 4 et 6 les diagrammes correspondants avec les caracteristiques initiales et, sur la figure 6 les domaines géographiques intéressés.

La plus importante de ces masses d'E.I. *) est la 5° qui couvre presque toute la partie centrale de la Mer Rouge. Vers 21°N, une eau supplémentaire (la 6° E.I.) s'intercale entre l'eau de surface et la 5° E.I.. Contrairement aux autres, cette 6° E.I. se caractérise par un minimum de température ; sur les bathythermographes de la figure 5, la stratification complexe apparaît très nettement.

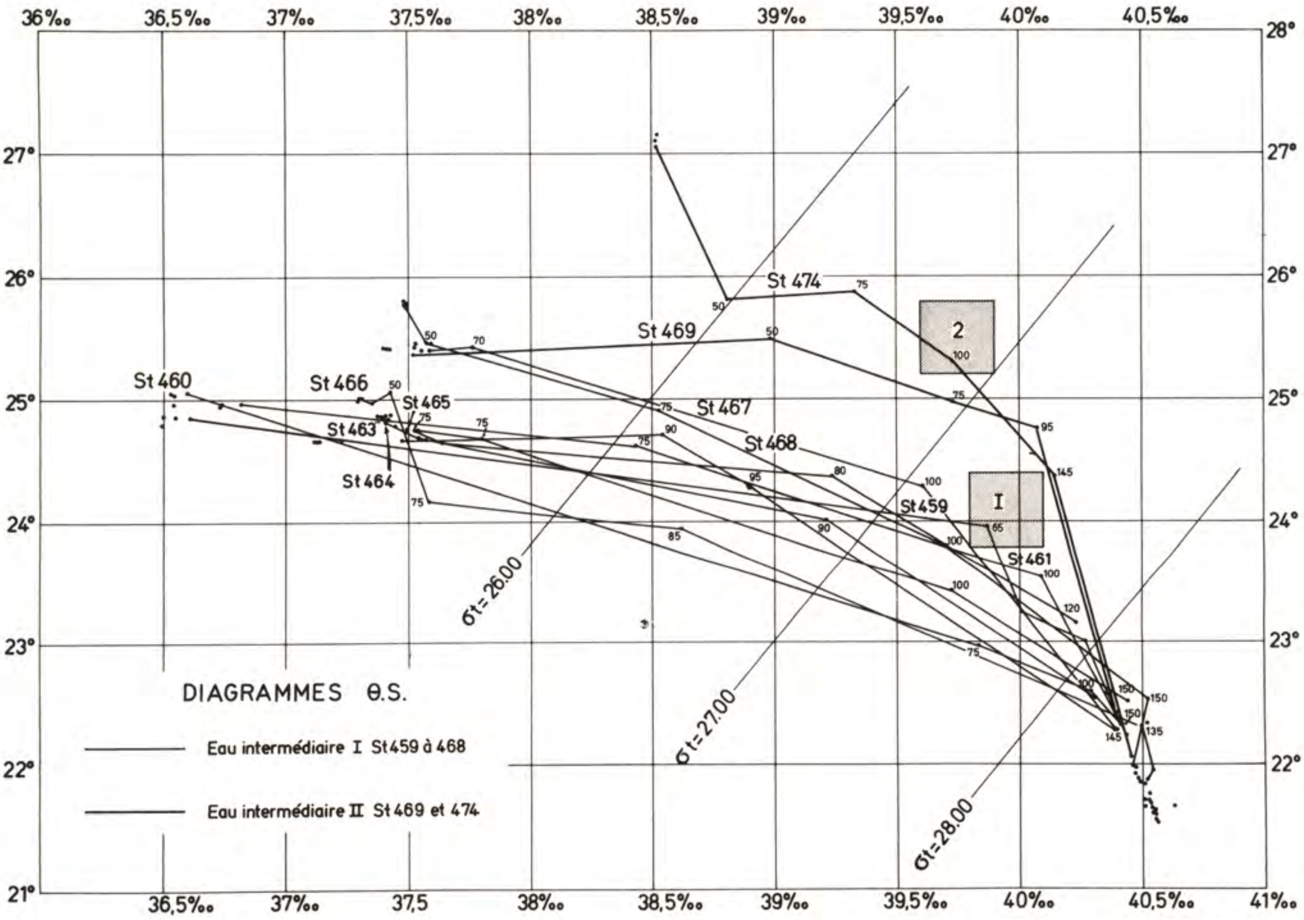
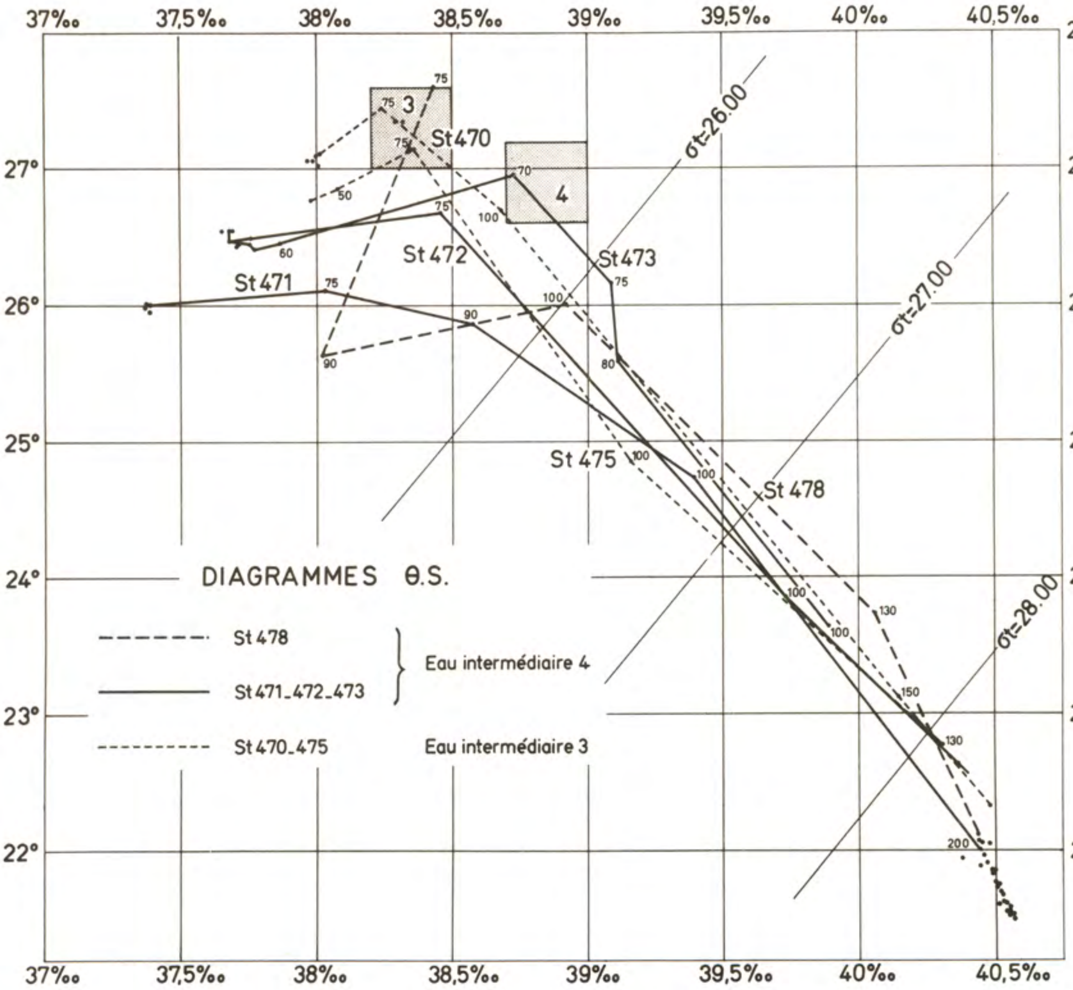


Fig. 1

*) Nous abrègeons désormais "eau intermédiaire" en E.I..


37‰
37,5‰
38‰
38,5‰
39‰
39,5‰
40‰
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28°
27°
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24°
23°
22°
σt=26.00
σt=27.00
σt=28.00
3
4
St 470
St 471
St 472
St 473
St 475
St 478
DIAGRAMMES θ.S.
St 478
St 471_472_473
Eau intermédiaire 4
St 470_475
Eau intermédiaire 3

Fig. 2

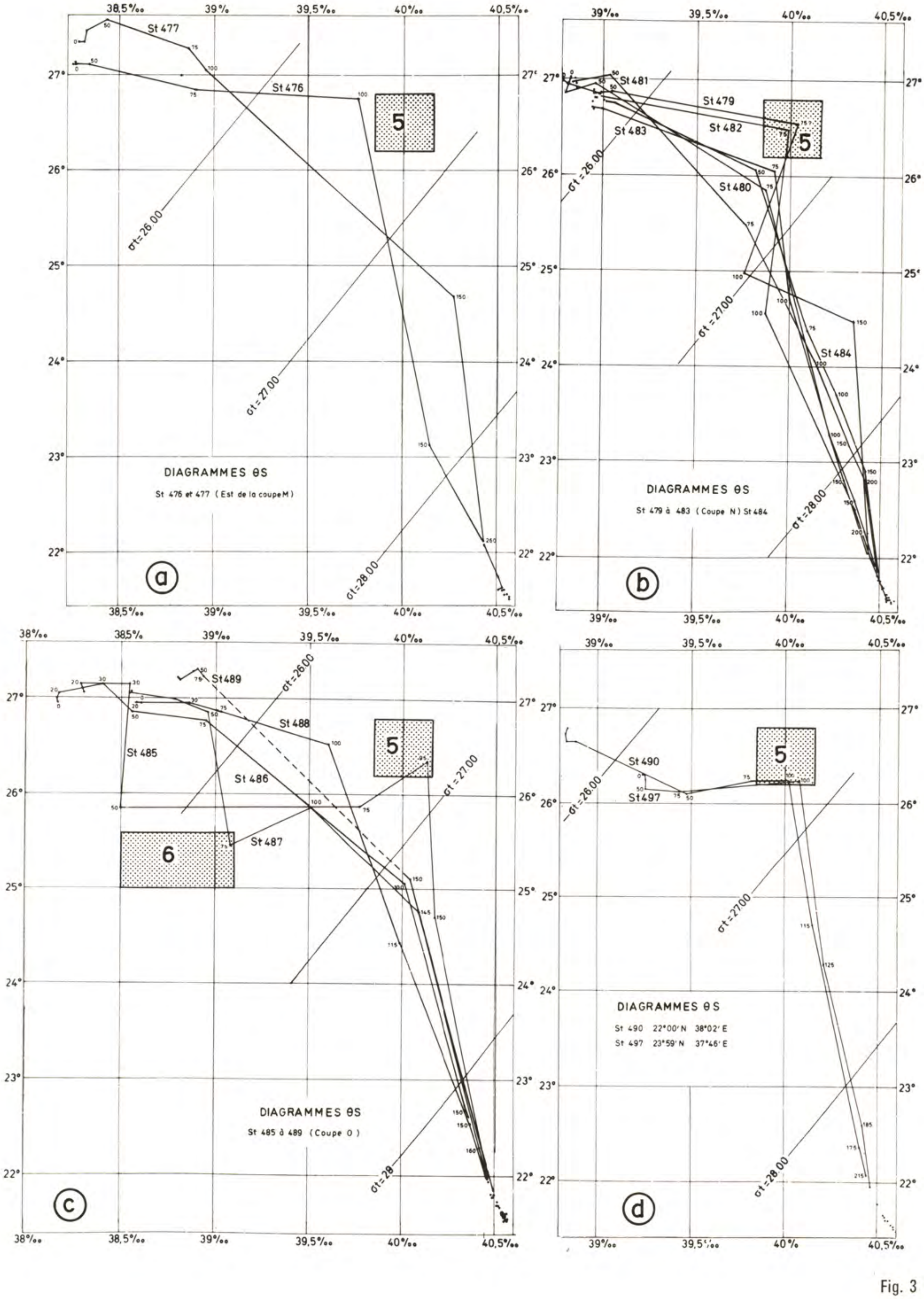

DIAGRAMMES θS
St 476 et 477 (Est de la coupe M)
St 477
St 476
σt=26.00
σt=27.00
σt=28.00
DIAGRAMMES θS
St 479 à 483 (Coupe N) St 484
St 481
St 479
St 482
St 483
St 480
St 484
DIAGRAMMES θS
St 485 à 489 (Coupe O)
St 489
St 488
St 485
St 486
St 487
DIAGRAMMES θS
St 490 22°00'N 38°02'E
St 497 23°59'N 37°46'E
St 490
St 497
a
b
c
d
5
6

Fig. 3

BATHYTHERMOGRAMMES

Coupe O

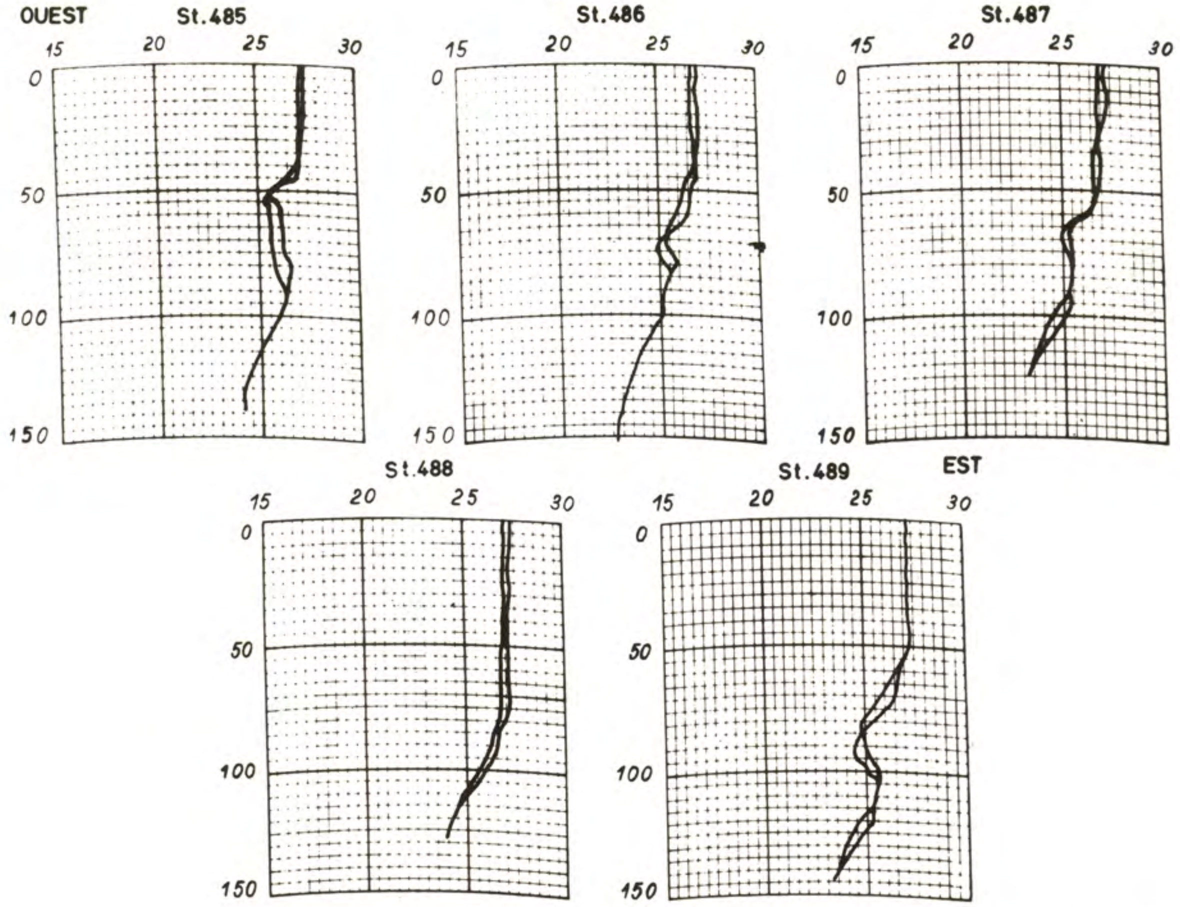


Fig. 4

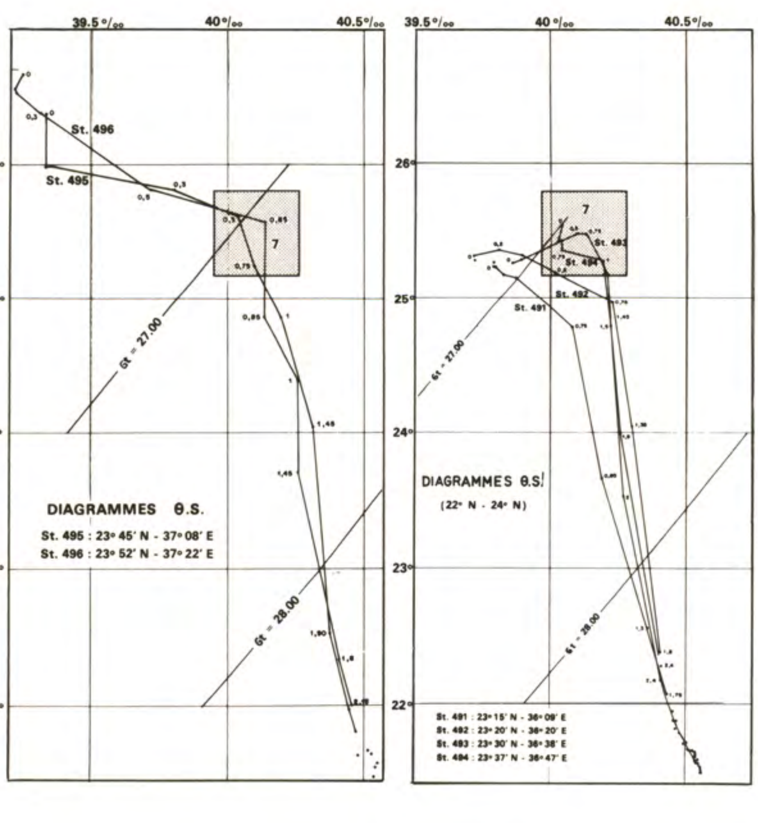


Fig. 5

A une station donnée, si les caractéristiques de l'E.I. sont proches de celles de l'eau d'origine (déterminée par l'intersection des tangentes), la proportion de cette eau est relativement forte dans le mélange et l'on se trouve vraisemblablement assez près de la zone de formation.

Il est remarquable que pour les E.I. 1, 2, 4 et 6, ce sont les stations les plus proches de la côte occidentale qui comportent la plus forte proportion d'E.I. (les diagrammes θS présentent les courbures les plus marquées). Pour l'I.E. 5, ce sont aussi les stations voisines des côtes qui contiennent le plus d'E.I., mais on en trouve aussi bien à l'Est qu'à l'Ouest. Il est vraisemblable que les larges plateaux côtiers qui bordent la Mer Rouge, principalement vers les archipels Dhalak et Souakin (voir figure 6), jouent un rôle important dans la formation de ces E.I. : au voisinage des côtes désertiques, l'évaporation est intensifiée et, sur les hauts fonds, les modifications hydrologiques qui en résultent ne se répartissent que sur une faible épaisseur d'eau, d'où un plus fort accroissement de densité sur les plateaux qu'au large. De plus, sous l'effet de la force de Coriolis, le courant de surface vers le NNW est, en moyenne, plus fort à l'Est qu'à l'Ouest de la mer ; à l'Ouest, les eaux superficielles subissent donc plus longtemps l'effet de l'évaporation ce qui expliquerait qu'il semble se former plus d'eau dense à l'ouest qu'à l'Est.

Pour la 7° E.I., ce sont les stations de la partie médiane qui comportent le plus fort pourcentage d'E.I., et, de plus, on trouve les valeurs initiales de cette eau, en surface, à la station 494 qui se trouve au milieu de la coupe P (voir figure 6). On doit donc rechercher la source de cette eau dans un mouvement convectif au large, probablement d'origine tourbillonnaire, ce que confirme d'ailleurs une analyse dynamique des données (MAILLARD, 1971).

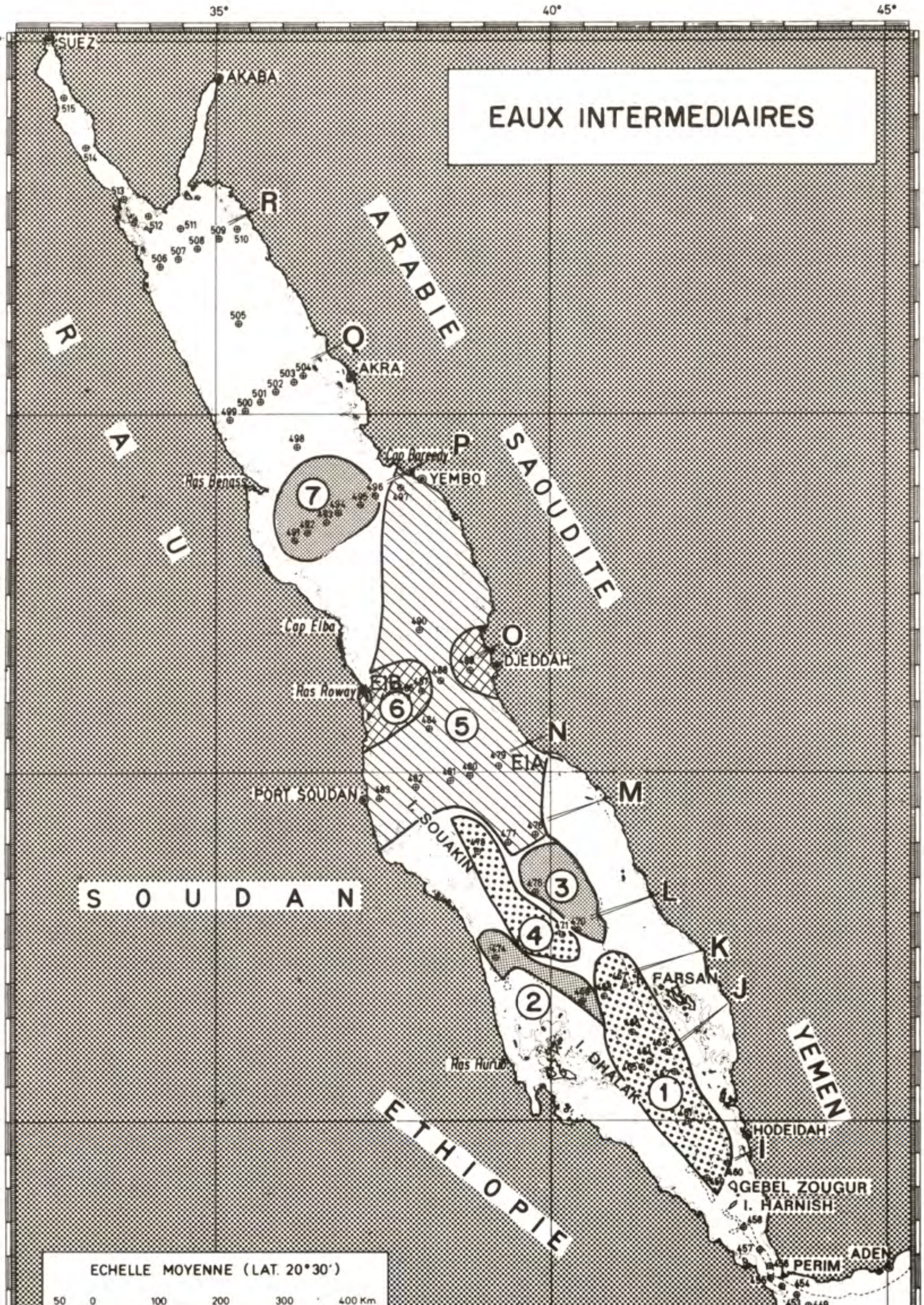

EAUX INTERMEDIAIRES
ARABIE
SAOUDITE
RAU
SOUDAN
ETHIOPIE
YEMEN
SUEZ
AKABA
AKRA
YEMBO
Cap Bareedy
Ras Benass
Cap Elba
Ras Roway
DJEDDAH
PORT SOUDAN
I. SOUAKIN
FARSAN
I. DHALAK
Ras Hurub
HODEIDAH
GEBEL ZOUGUR
I. HARNISH
PERIM
ADEN
DJIBOUTI
ECHELLE MOYENNE (LAT. 20°30')
50 0 100 200 300 400 Km
Latitude NORD
Longitude EST de Greenwich

Fig. 6

Quant à la 3° E.I., il est difficile de rattacher sa formation à l'un ou l'autre des processus car en fait, bien qu'on la trouve dans la partie orientale de la Mer Rouge, les stations correspondantes ont été effectuées assez loin du plateau continental. Un processus de plongée d'eau au large n'est pas à exclure, d'autant plus que l'on se trouve dans une zone de convergence des vents.

Les eaux intermédiaires ont toutes été trouvées au Sud de 24°N. Plus au Nord, leur présence n'est cependant pas exclue, mais alors, les gradients verticaux sont trop faibles pour que l'on puisse la mettre en évidence par de seules mesures aux immersions standards.

Finalement, les données du "Cdt ROBERT GIRAUD" ont permis de déceler la présence de sept masses d'eau intermédiaires en Mer Rouge au-dessous de l'eau superficielle, entre 50 et 150 m d'immersion. Leurs caractéristiques initiales et leur origine sont :

	θ	S	σ_θ	Origine probable
1	24,0	40,0	27,5	Sud de l'archipel Dhalak
2	25,5	39,7	26,8	Nord de l'archipel Dhalak
3	27,5	38,3	25,1	Côte Est vers 18°N ?
4	27,0	38,8	25,6	Sud de l'archipel Souakin
5	26,5	40,0	26,7	Côtes E et W entre 19°N et 24°N
6	25,2	38,8	26,2	Côte Ouest vers 21°N
7	25,5	40,1	27,1	Large vers 23°40'N

Bien que le volume de chacune des E.I. prise séparément soit faible vis à vis de celui des couches superficielles ou profondes, leur nombre est suffisant pour qu'elles aient une grande influence dans la transformation des eaux de surface venues de l'Océan Indien.

Par ailleurs, la formation d'eau dense sur les plateaux continentaux et l'existence de mouvements convectifs à toutes les latitudes (ce qui implique la présence des E.I.), sont des éléments importants qu'il ne faudra donc pas négliger lors d'une étude plus théorique de la circulation. Malheureusement, les données dont nous disposons sont encore insuffisantes pour donner la moindre évaluation quantitative de processus aussi complexes et il faut espérer pouvoir disposer de données nouvelles plus complètes : profils continus de températures et de salinité, mesures de courant au voisinage des côtes.

II - FORMATION DE L'EAU PROFONDE

L'eau profonde de la Mer Rouge, très homogène, remplit une fosse de plus de 2 000 m de profondeur dans sa partie médiane et séparée de l'Océan Indien par un seuil élevé (110 m environ au niveau des îles Harnish).

Avant d'aborder le problème de sa formation, nous allons donner rapidement les principales caractéristiques de cette masse d'eau.

1° - L'eau profonde de la Mer Rouge

Des mesures du "Cdt ROBERT GIRAUD", il ressort qu'au-delà de 400 m :

- la température, la salinité et la densité à une immersion donnée ne varie pratiquement pas d'un point à l'autre ;
- les variations de ces caractéristiques avec l'immersion sont très faibles et ne jouent que sur quelques centièmes de degré ou de g de sel /1 000 g d'eau. Pour chaque tranche d'eau, les valeurs les plus fréquemment rencontrées sont :

Profondeur	400-500 m	500-600 m	600-800 m	800-1 000 m	au-dessous de 1 000 m
θ	21,61	21,57	21,56	21,55	21,54
S	40,54	40,55	40,56	40,56	40,57
σ_θ	28,56	28,58	28,59	28,59	28,60

On admet généralement que cette eau se forme au Nord de la Mer Rouge par plongée d'eau superficielle ayant atteint la densité de l'eau profonde sous l'effet de l'évaporation. Elle s'écoule ensuite lentement vers le Sud de la mer, où elle remonte et, après avoir franchi le seuil, se déverse en partie dans l'Océan Indien. Bien que la formation d'eaux très denses, dans le Golfe de Suez, contribuant à la formation de l'eau profonde ait été observée dès 1934 par le "MABAHISS" (MORCOS, 1970), le mécanisme de formation de l'eau profonde dans le Nord de la Mer Rouge n'avait pas encore été étudié jusqu'ici de manière détaillée.

2° - Formation d'eau dense dans le Golfe de Suez

L'eau profonde doit se former dans une région où l'on trouve, en surface, des densités au moins égales à $\sigma_t = 28,60$. Or, la seule région où l'on a rencontré de telles valeurs superficielles est le Golfe de Suez (voir Fig. 7). Avant d'aborder le processus proprement dit de formation de l'eau profonde, nous allons donc étudier l'hydrologie de cette région.

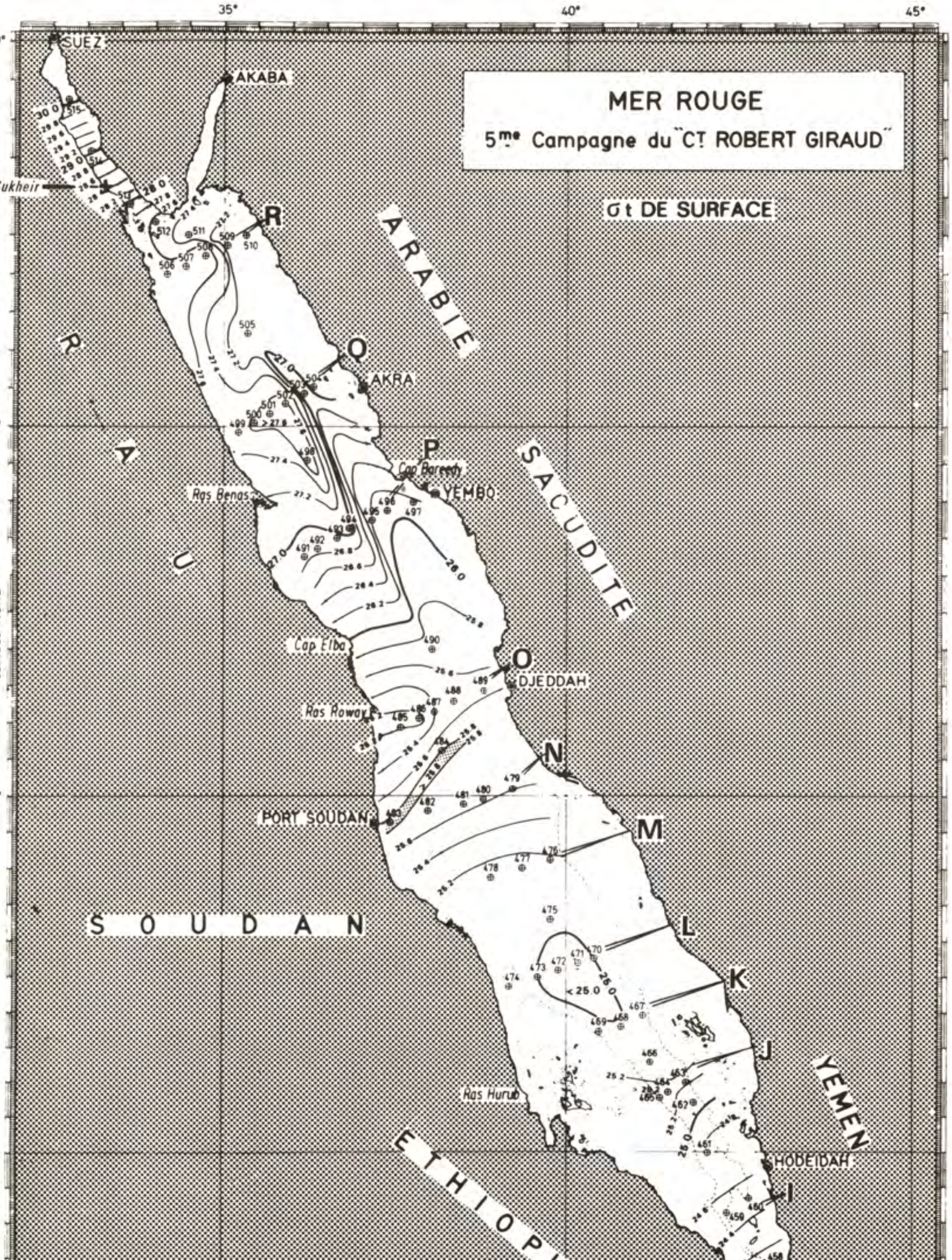

MER ROUGE
5me Campagne du "Ct ROBERT GIRAUD"
σt DE SURFACE
ARABIE
SAOUDITE
EGYPTE
SOUDAN
ETHIOPIE
YEMEN
SUEZ
AKABA
Ras Sukheir
AKRA
Cap Baredy
YEMBO
Ras Benas
Cap Elba
DJEDDAH
Ras Roway
PORT SOUDAN
Ras Hurub
HODEIDAH
ADEN
DJIBOUTI
ECHELLE MOYENNE (LAT. 20°30')
50 0 100 200 300 400 Km
Latitude NORD
35° Longitude EST de Greenwich
40°
45°
30°
25°
20°
15°
12°

Fig. 7

a) Eaux denses du Golfe de Suez

Sur la coupe longitudinale effectuée dans le Golfe de Suez (Fig. 8), il apparaît nettement une structure en deux couches. L'eau superficielle subit de fortes modifications pendant son séjour dans le Golfe ; ainsi, entre la station 512 effectuée sur le talus continental à l'entrée du Golfe et la station 515, la plus septentrionale, on observe une baisse de température de 5° environ, une augmentation de salinité de 1,5 g °/oo et une augmentation de densité d'environ 2,6 en σ_t. La densité maximale enregistrée est : σ_t = 30,16 au Nord, ce qui est très nettement supérieur à la densité de l'eau profonde.

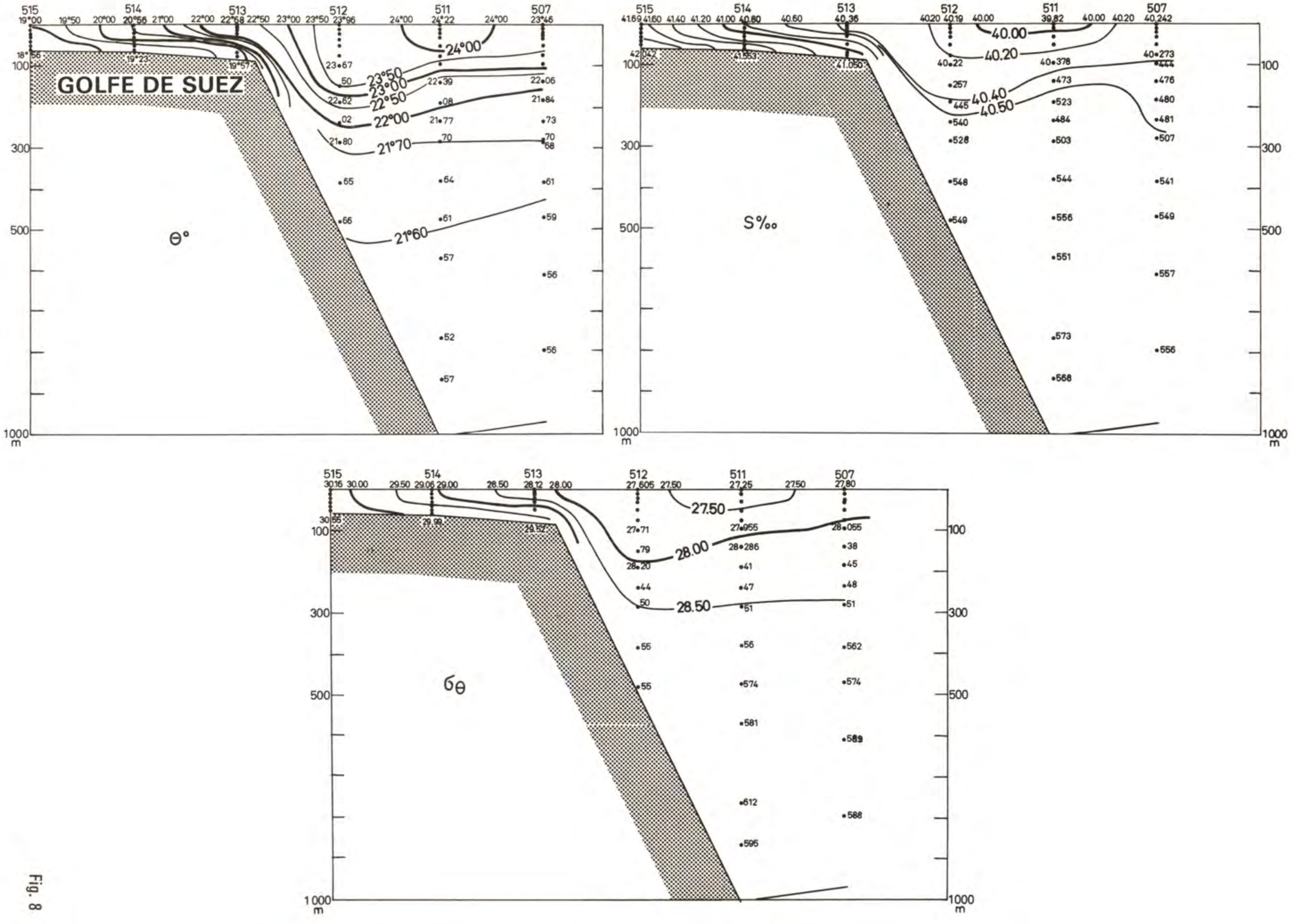

GOLFE DE SUEZ
515
514
513
512
511
507
Θ°
24°00
23°50
23°00
22°50
22°00
21°70
21°60
S‰
40.00
40.20
40.40
40.50
σθ
27.50
28.00
28.50
100
300
500
1000 m

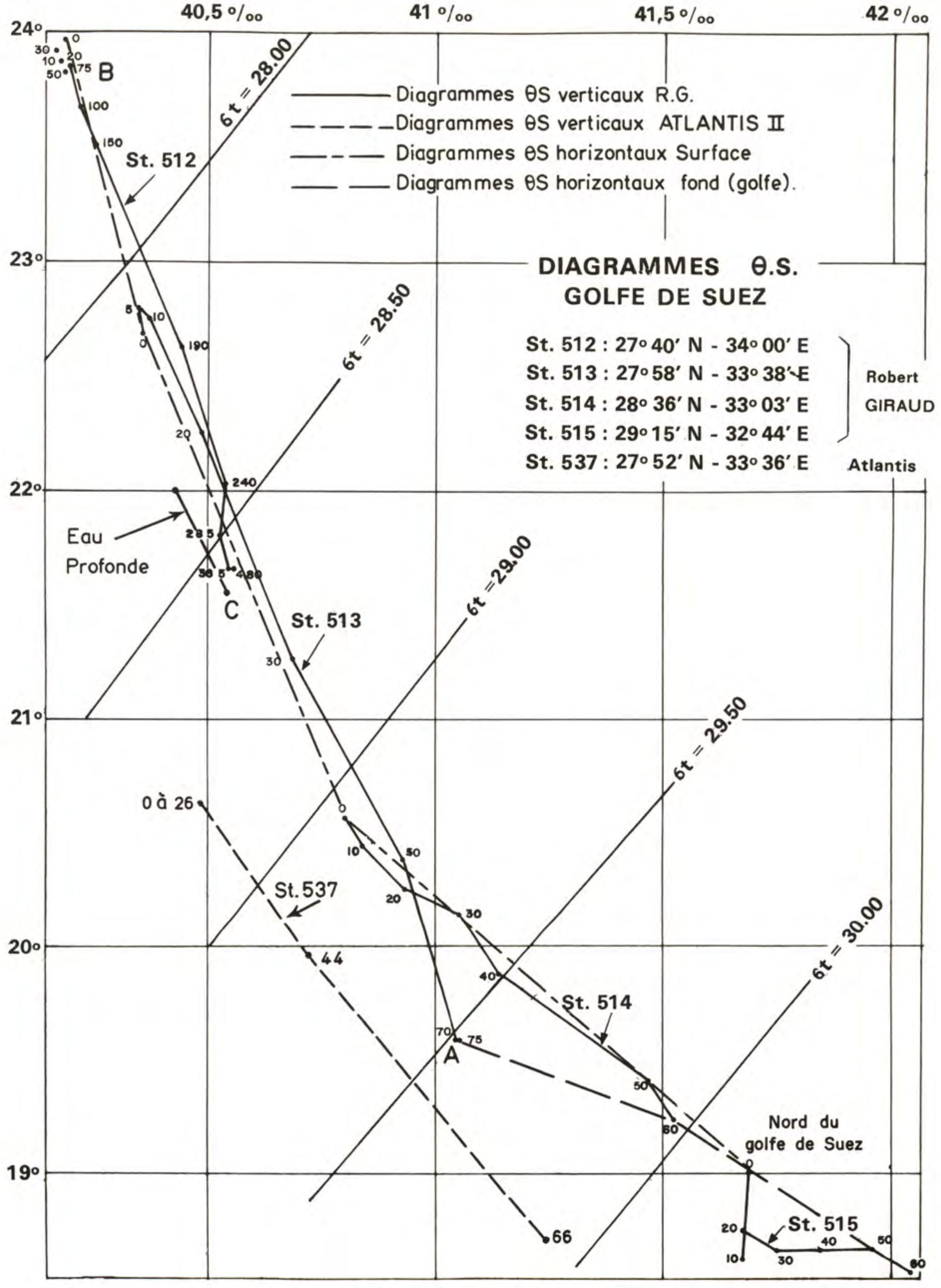
Fig. 8

Ces variations rapides sont dues à l'effet d'une intense évaporation, elle-même créée par des vents forts et secs canalisés entre deux côtes montagneuses et désertiques. L'influence de l'évaporation est d'autant plus forte que l'épaisseur d'eau concernée est faible (une trentaine de mètres environ pour la couche supérieure).

En conséquence, on constate du Sud au Nord du Golfe une diminution de la différence de densité entre la surface et le fond, un accroissement de l'homogénéité de l'eau sur une même verticale et une intensification des mouvements verticaux. Sur les diagrammes θS verticaux de chaque station (Fig. 9), le groupement des points θS de chaque station s'accentue vers le Nord, reflétant l'homogénéité croissante de la masse liquide. A la station 515, la température est pratiquement homogène sur toute la colonne d'eau ; la salinité ne l'est pas entièrement mais il se peut que l'influence d'échanges ayant lieu plus au Nord (la position de la station ne coïncide pas exactement avec l'extrémité Nord du Golfe) ou même d'un courant de fond issu des lacs amers puisse expliquer l'accroissement de salinité au voisinage du fond.

Ces eaux très denses, après avoir plongé au voisinage de l'extrémité Nord du Golfe, s'écoulent sur le fond en se mélangeant en partie avec les eaux sus-jacentes. Comme, pratiquement, l'ensemble des diagrammes θS verticaux coïncide avec le diagramme θS horizontal de surface (voir Fig. 9), on peut dire que toutes les eaux du Golfe sont formées de mélange d'eaux superficielles.

A la station la plus méridionale du Golfe (St. 513), les caractéristiques de l'eau de fond qui va aller s'écouler dans la Mer Rouge proprement dite sont :
θ = 19,57°C ; S = 40,05 °/₀₀ ;σ_θ = 29,52.



40,5 ‰
41 ‰
41,5 ‰
42 ‰
24°
23°
22°
21°
20°
19°
Diagrammes θS verticaux R.G.
Diagrammes θS verticaux ATLANTIS II
Diagrammes θS horizontaux Surface
Diagrammes θS horizontaux fond (golfe).
DIAGRAMMES θ.S.
GOLFE DE SUEZ
St. 512 : 27° 40′ N - 34° 00′ E
St. 513 : 27° 58′ N - 33° 38′ E
St. 514 : 28° 36′ N - 33° 03′ E
St. 515 : 29° 15′ N - 32° 44′ E
St. 537 : 27° 52′ N - 33° 36′ E
Robert GIRAUD
Atlantis
σt = 28.00
σt = 28.50
σt = 29.00
σt = 29.50
σt = 30.00
St. 512
St. 513
St. 514
St. 515
St.537
B
C
A
Eau Profonde
0 à 26
44
66
Nord du golfe de Suez

Fig. 9

b) Mélange des eaux de fond du Golfe de Suez avec les eaux de la Mer Rouge

Les eaux de fond du Golfe de Suez (A) rencontrent les eaux de la Mer Rouge sur le talus continental au Sud du Golfe ; à la station 512, qui y a été effectuée, on distingue (voir Fig. 9) :

- une eau superficielle très homogène jusqu'à 75 m (B) ;
- de 100 à 240 m, un mélange d'eau de surface 512 et d'eau de fond 513 ;
- au-dessous, l'eau profonde de la Mer Rouge (C).

Le point C est très voisin du milieu du segment AB, ce qui montre que l'eau profonde peut être formée du mélange par moitié environ de l'eau superficielle du Nord de la Mer Rouge avec les eaux denses du fond du Golfe de Suez.

Une telle situation hydrologique permet donc une formation d'eau profonde si les eaux qui s'écoulent sur le fond du Golfe de Suez se mélangent avec un égal volume d'eaux superficielles, qui se trouvent aux mêmes immersions (30 à 75 m) dans le Nord de la Mer Rouge.

Dans une situation hydrologique différente, telle celle qu'a trouvé l'"ATLANTIS II" en février 1965, la densité de l'eau de fond du Golfe, immédiatement au Nord du talus, peut être encore plus élevée (voir Fig. 9). Il suffit d'une quantité moindre d'eau dense, dans le mélange avec les eaux du Nord de la Mer Rouge, pour alimenter l'eau profonde.

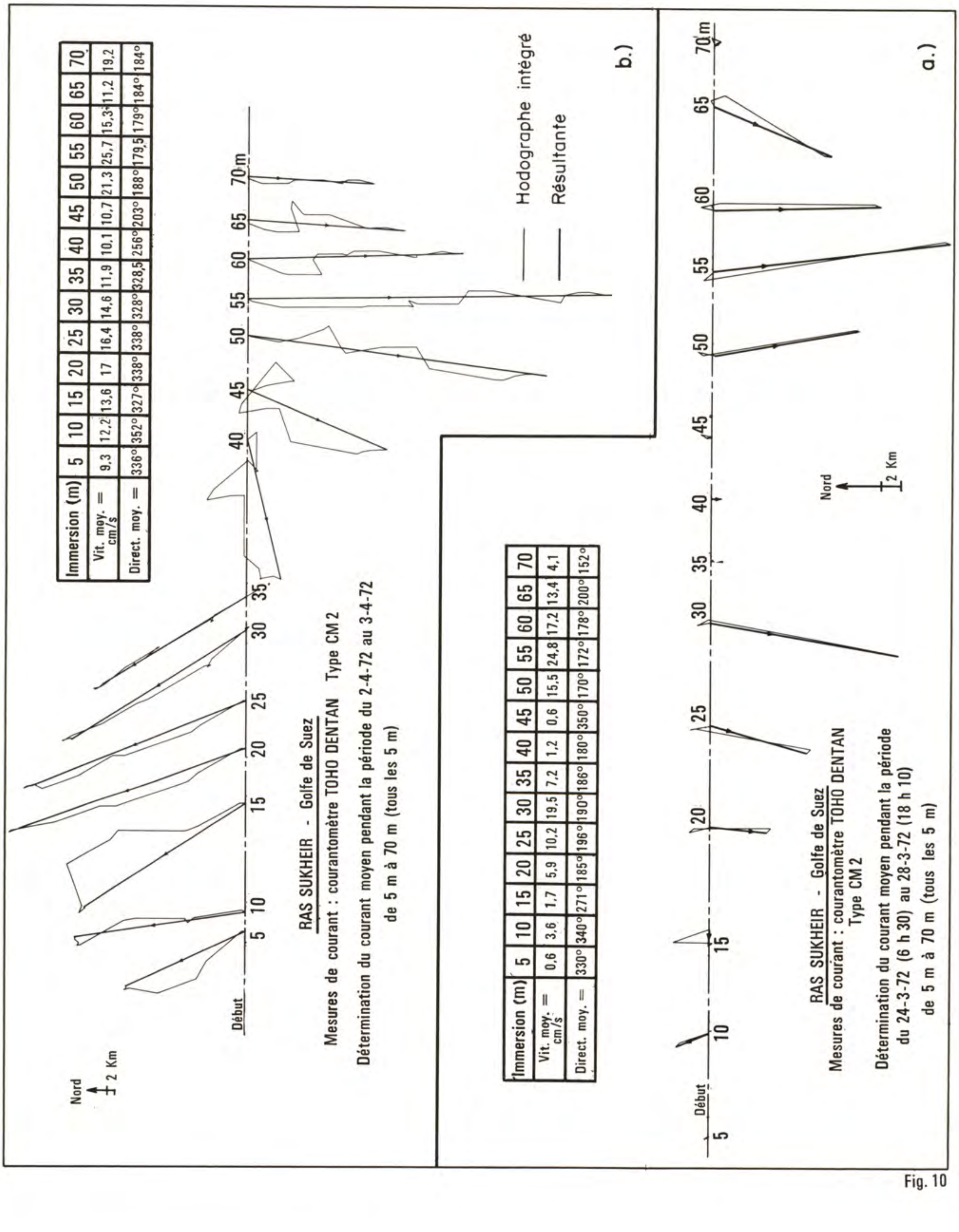
Il semble donc que le Golfe de Suez soit une importante source de formation d'eau profonde de la Mer Rouge. Cependant, la question des flux d'eau intéressés restait encore à résoudre ; en fait, en raison des dimensions restreintes du Golfe bien des scientifiques pensent que les quantités d'eau profonde formées ainsi sont d'un ordre de grandeur tout-à-fait négligeable vis-à-vis des quantités nécessaires pour renouveller cette masse d'eau. Aussi les mesures directes de courant opérées par la Compagnie COCEAN au large de Ras Sukheir apportent-elles des renseignements particulièrement intéressants pour l'étude de ce problème.

3° - Quantité d'eau profonde formée dans le Golfe

Les mesures de courant ont été faites, au large de Ras Sukheir, dans la partie la plus profonde du Golfe, du 24 mars au 14 avril 1972, donc tout-à-fait en fin de période hivernale. Au total 48 enregistrements de vitesse ont été effectués à tous les niveaux, de 5 m en 5 m, entre 5 et 70 m. Pour calculer la vitesse moyenne à chaque immersion, nous avons déterminé le déplacement qu'aurait eu une particule d'eau entraînée par la vitesse mesurée pendant l'intervalle de temps qui la sépare de la mesure suivante et ainsi de suite. Comme il y a eu des interruptions de plus de 24 heures dans les observations, nous avons en fait considéré cinq périodes distinctes :

Date	24-28 mars	30 mars	2-3 avril	5-11 avril	13 avril
Durée	107 h 40 '	25'	26 h 10'	138 h 55'	10 h 25'
Nombre de mesures	21	1	4	16	6

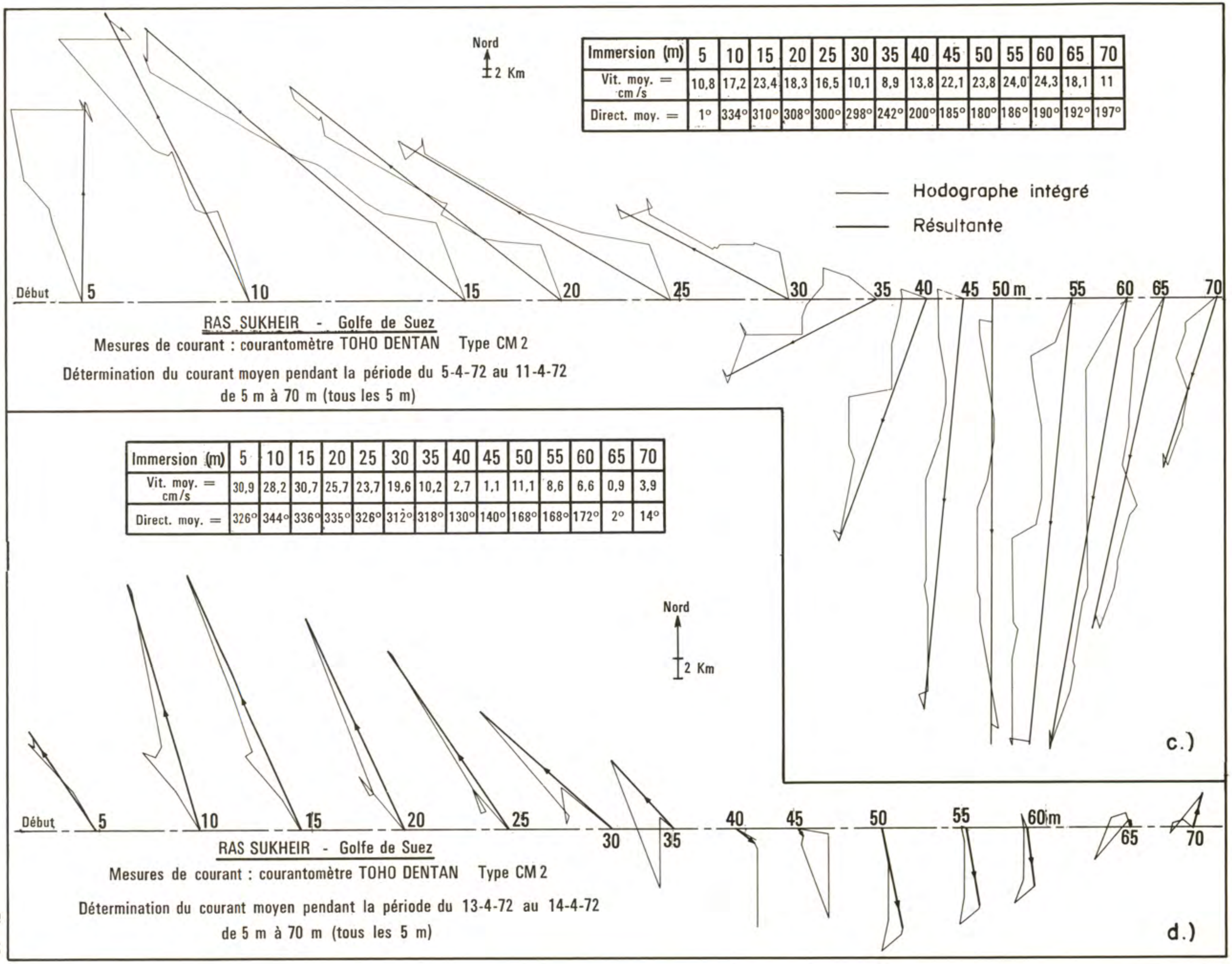
Des périodes qui comportent un nombre assez élevé de mesures donnent une assez bonne représentation du courant moyen puisque le courant de marée tend à s'annuler dans la composition vectorielle. Les résultats trouvés pour chacune de ces périodes sont portés sur les figures 10a à 10d.



Immersion (m)	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Vit. moy. = cm/s	9,3	12,2	13,6	17	16,4	14,6	11,9	10,1	10,7	21,3	25,7	15,3	11,2	19,2
Direct. moy. =	336°	352°	327°	338°	338°	328°	328,5	256°	203°	188°	179,5	179°	184°	184°

Immersion (m)	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Vit. moy. = cm/s	0,6	3,6	1,7	5,9	10,2	19,5	7,2	1,2	0,6	15,5	24,8	17,2	13,4	4,1
Direct. moy. =	330°	340°	271°	185°	196°	190°	186°	180°	350°	170°	172°	178°	200°	152°

Fig. 10



Immersion (m)	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Vit. moy. = cm/s	10,8	17,2	23,4	18,3	16,5	10,1	8,9	13,8	22,1	23,8	24,0	24,3	18,1	11
Direct. moy. =	1°	334°	310°	308°	300°	298°	242°	200°	185°	180°	186°	190°	192°	197°

RAS SUKHEIR - Golfe de Suez

Mesures de courant : courantomètre TOHO DENTAN Type CM 2

Détermination du courant moyen pendant la période du 5-4-72 au 11-4-72 de 5 m à 70 m (tous les 5 m)

Immersion (m)	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Vit. moy. = cm/s	30,9	28,2	30,7	25,7	23,7	19,6	10,2	2,7	1,1	11,1	8,6	6,6	0,9	3,9
Direct. moy. =	326°	344°	336°	335°	326°	312°	318°	130°	140°	168°	168°	172°	2°	14°

RAS SUKHEIR - Golfe de Suez

Mesures de courant : courantomètre TOHO DENTAN Type CM 2

Détermination du courant moyen pendant la période du 13-4-72 au 14-4-72 de 5 m à 70 m (tous les 5 m)

Fig. 10.

Ces mesures sont en bon accord les unes avec les autres : sur les 35 premiers mètres on trouve un flux vers le NW puis une giration vers l'Ouest et, de 45 à 70 m, un courant vers le Sud.

Afin d'avoir un résultat global, nous avons calculé, à chaque immersion, la vitesse résultante, en additionnant géométriquement les vitesses résultantes de chaque série préalablament multipliées par le nombre de mesures de la série. Les vitesses moyennes ainsi trouvées (voir Fig. 11) sont pour chaque immersion :

Immersion	5	10	15	20	25	30	35	40	45	50	55	60	65	70
Direction	340	341	320	325	320	306	302	220	189	182	180	184	189	187
Vitesse	11,4	14,4	15,8	15,4	13,6	10,0	6,9	7,9	12,4	20,2	22,6	17,3	11,9	7,6

<u>**GOLFE DE SUEZ**</u>

Vitesse moyenne du courant au large de Ras Sukheir du 24-3 au 13-4-72

de 5 m à 70 m (tous les 5 m)

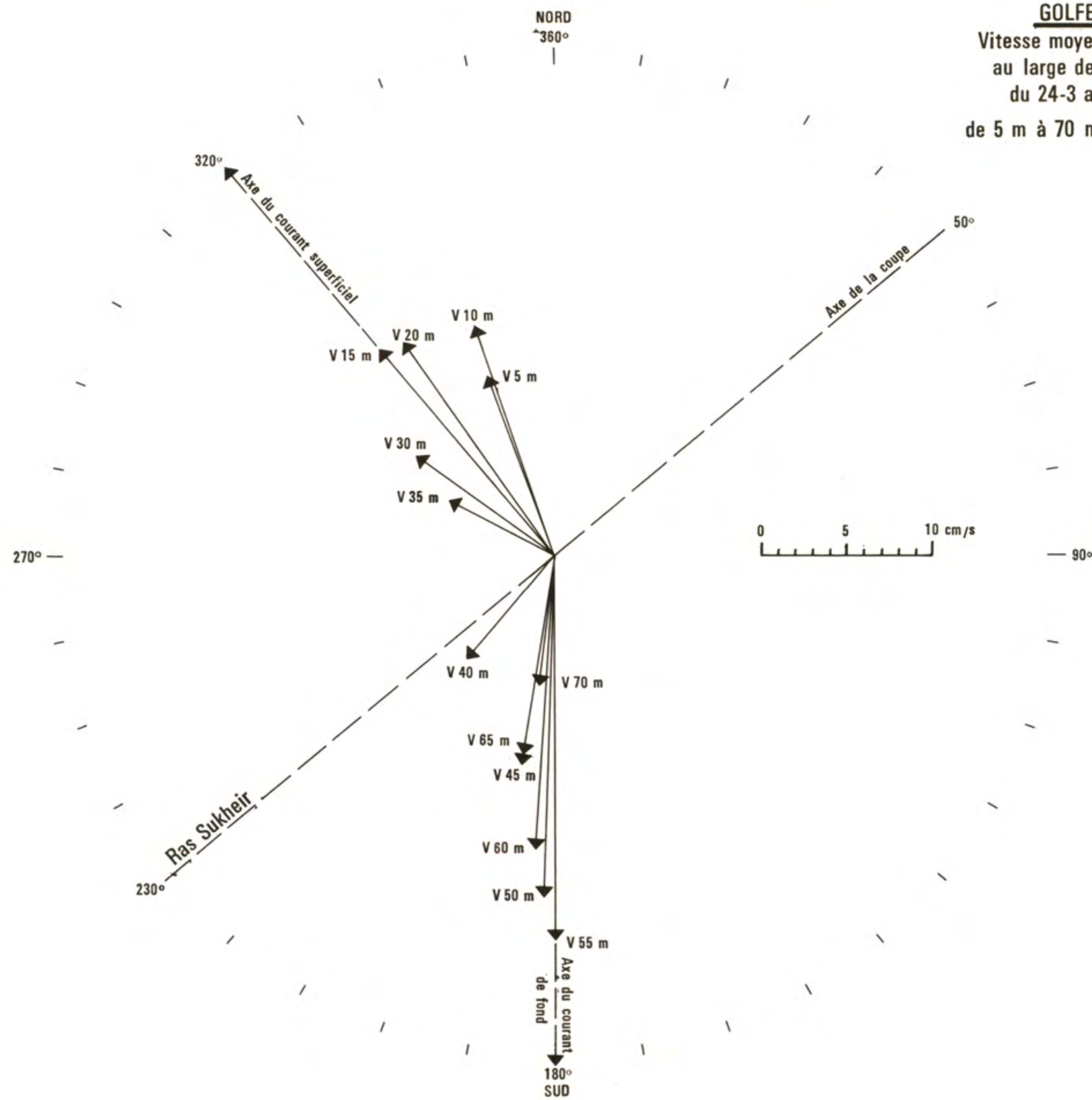


Fig. 11

Le flux superficiel se dirige donc vers le 320° environ, parallèlement à l'axe du golfe. Le flux profond est orienté vers le Sud ; cette direction qui n'est pas l'inverse du flux superficiel doit être imposée par le relief du fond mais la bathymétrie de la région n'est pas connue avec assez de précision pour le déterminer.

En supposant la vitesse constante sur toute la largeur de la coupe à une immersion donnée, on a pu calculer les flux transportés dans les deux directions principales, c'est-à-dire vers 320° pour la couche 0-35 m et 180° pour la couche 40-75 m. Les flux partiels pour chaque tranche d'eau sont portés sur la figure 12 ; les flux globaux sont :ù

$\Phi_S = 0{,}114.10^6\ m^3/s$ en surface vers le 320° ;
$\Phi_F = 0{,}050.10^6\ m^3/s$ en profondeur vers le 180°.

La différence entre le flux portant au NW et le flux de retour vers le Sud ne peut s'expliquer par une évaporation intense. En effet, même en adoptant la valeur élevée de 4 m/an, qui correspond à un maximum hivernal pour l'évaporation, le volume d'eau qui s'évapore entre Ras Sukheir et l'extrémité septentrionale du Golfe (sur une superficie de $6\ 640.10^6\ m^2$, la superficie totale du Golfe étant de $8\ 990.10^6\ m^2$) est :

$$\Phi_E = 0{,}0008.10^6\ m^3/s,$$

ce qui est d'un ordre de grandeur nettement inférieur aux flux précédents. L'écart tient donc à l'imprécision de la méthode : il est très peu probable que le courant soit uniforme sur toute la largeur de la section, principalement dans la couche superficielle où il peut exister des tourbillons et, en ce qui concerne le courant de fond, les sondes ne sont pas assez nombreuses pour donner avec précision la surface de la section.

Pour qu'il y ait conservation de la masse, on doit avoir l'égalité :

$$\Phi_S = \Phi_F + \Phi_E \# \Phi_F .$$

On doit adopter pour Φ_S et Φ_F, la valeur moyenne :

$$\Phi_F = 0{,}082.10^6\ m^3/s$$

avec une erreur possible :

$$\Delta\Phi = 0{,}032.10^6\ m^3/s, \quad \text{soit 39 \% d'incertitude.}$$

Bien qu'élevée, cette incertitude sur le flux ne dépasse pas celles que l'on trouve habituellement dans de telles déterminations.

L'eau profonde étant formée d'un mélange par moitié environ de l'eau de fond du Golfe et d'eau superficielle de la Mer Rouge, le flux précédent correspond à un flux de renouvellement de l'eau profonde de :

$$\Phi = 2\Phi_F$$

$$\boxed{\Phi = 0{,}16.10^6\ m^3/s}$$

Cette valeur est à comparer à la valeur du flux qui sort de la Mer Rouge par le Détroit de Bab-el-Mandeb : en surface, VERCELLI (1927) puis SIEDLER (1968) donnent un flux de $0{,}58.10^6$ m^3/s. Avec la valeur de l'évaporation de 4 m/an, le flux de retour en profondeur doit être de $0{,}54.10^6$ m^3/s.

L'eau qui s'écoule hors de la Mer Rouge par le détroit de Bab-el-Manded n'est pas de l'eau profonde mais un mélange d'eau superficielle et d'eau profonde, comme on peut le constater sur la figure 13. En fait, considérant les caractéristiques moyennes de l'eau entre 100 m et le fond, on peut dire que l'eau profonde n'en constitue que la moitié environ. C'est donc, en plein hiver, une perte :

$$\boxed{\Phi' = 0{,}27.10^6 \ m^3/s}$$

d'eau profonde qui s'écoule hors de la Mer Rouge et qui doit être compensée par une formation équivalente.

Avant de considérer les deux valeurs : flux de renouvellement de l'eau profonde (Φ) et perte de cette eau à travers le détroit (Φ'), il faut faire une remarque importante. Les mesures de courant à Bab-el-Mandeb ont été faites en pleine période hivernale, en février, lorsque les échanges sont les plus intenses. Les mesures du Golfe de Suez, au contraire ont été faites plus tard, en mars-avril, alors que le réchauffement atmosphérique tend à diminuer la formation d'eau dense. Compte tenu de cette remarque et de l'imprécision de la méthode de calcul, il semble cependant tout-à-fait légitime de dire que Φ et Φ' sont du même ordre de grandeur et que le Golfe de Suez intervient, au moins pour une très grande partie, dans la formation de l'eau profonde.

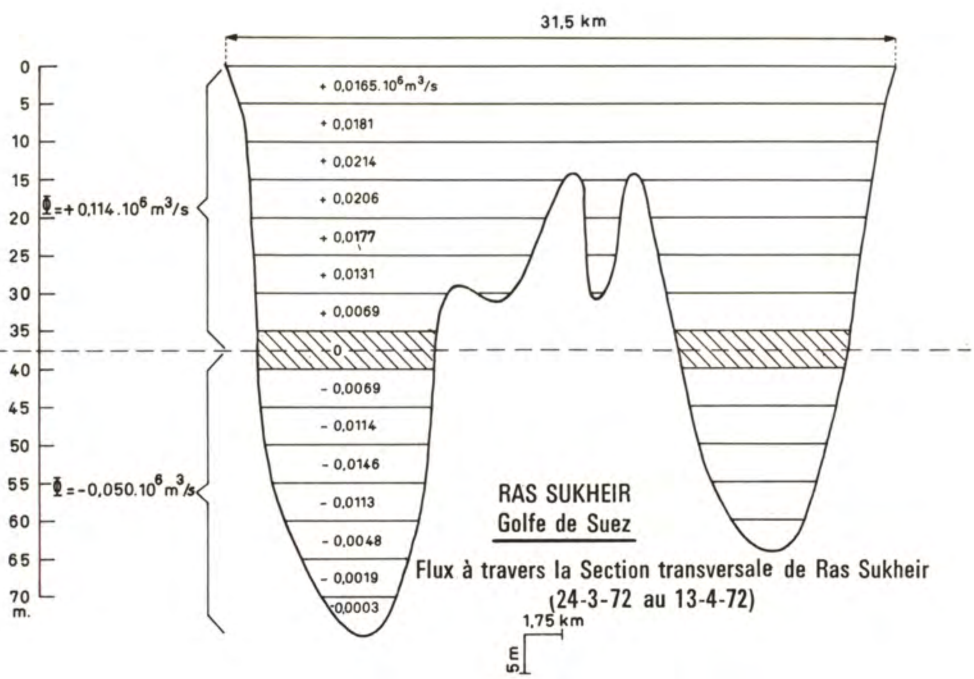

31,5 km
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
m.
Φ = + 0,114 . 10⁶ m³/s
Φ = - 0,050 . 10⁶ m³/s
+ 0,0165 . 10⁶ m³/s
+ 0,0181
+ 0,0214
+ 0,0206
+ 0,0177
+ 0,0131
+ 0,0069
0
- 0,0069
- 0,0114
- 0,0146
- 0,0113
- 0,0048
- 0,0019
- 0,0003
RAS SUKHEIR
Golfe de Suez
Flux à travers la Section transversale de Ras Sukheir
(24-3-72 au 13-4-72)
1,75 km
5m

Fig. 12

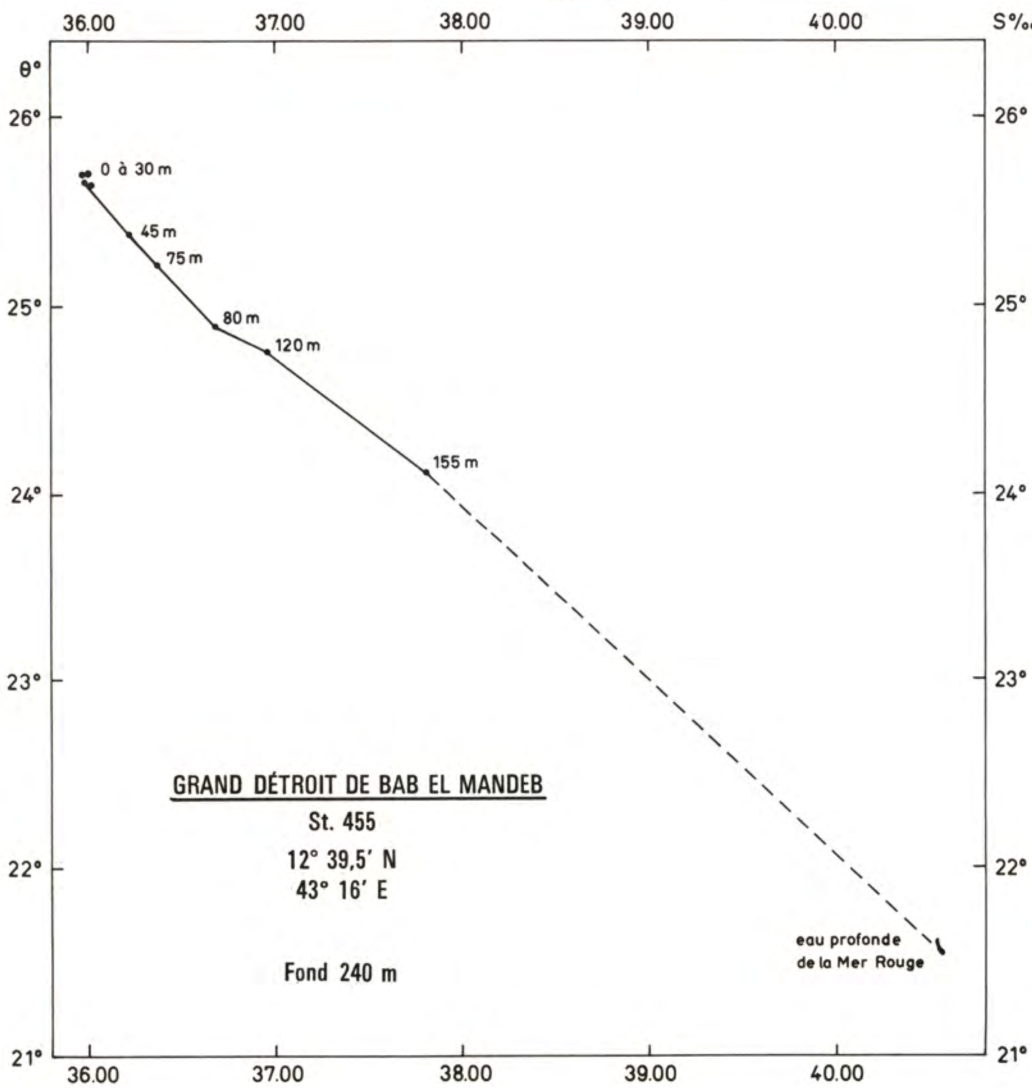

36.00
37.00
38.00
39.00
40.00
S‰
θ°
26°
25°
24°
23°
22°
21°
0 à 30 m
45 m
75 m
80 m
120 m
155 m
GRAND DÉTROIT DE BAB EL MANDEB
St. 455
12° 39,5' N
43° 16' E
Fond 240 m
eau profonde
de la Mer Rouge

Fig. 13

CONCLUSION

Il n'est pas possible de réduire le régime hydrologique de la Mer Rouge à un simple système à deux couches. En effet, la plongée des eaux superficielles, après accroissement local de densité, est à l'origine de l'apparition d'"eaux intermédiaires". Les mouvements convectifs qui interviennent peuvent se produire dans toutes les parties de la Mer Rouge, mais ils semblent particulièrement intenses sur les larges plateaux continentaux qui la bordent et sur lesquels des observations complémentaires seraient particulièrement souhaitables.

Cependant, ce n'est qu'à l'extrémité septentrionale de la Mer Rouge, que les mouvements convectifs atteignent les couches les plus profondes et c'est le Golfe de Suez qui semble être la principale source de formation d'eau profonde.

L'importance du périmètre côtier dans cette région désertique où règnent des vents forts, favorise l'évaporation et l'accroissement rapide de densité. Les eaux très denses ainsi formées se mélangent avec les eaux superficielles de la Mer Rouge qu'elles rencontrent vers 80 m sur le talus continental au Sud du Golfe et forment cette eau profonde. Les volumes d'eau intéressés sont susceptibles d'équilibrer en grande partie la part de l'eau profonde qui s'écoule dans l'Océan Indien par le détroit de Bab-el-Mandeb.

REMERCIEMENTS

Je tiens à remercier ici bien vivement tous ceux qui ont participé à ce travail, en particulier M. le Professeur LACOMBE et M. le Professeur TCHERNIA, qui ont déterminé cette étude ; M. MENACHE, l'équipe scientifique et l'équipage du "Cdt ROBERT GIRAUD", embarqués sur ce navire pendant la Vème campagne en Océan Indien et qui ont effectué les mesures hydrologiques ; M. BELLIARD et la Compagnie COCEAN, qui ont réalisé les mesures de courant dans le Golfe de Suez et ont bien voulu nous les communiquer ; et Madame CAHEN-HERZ, qui a opéré la plus grande partie du travail de dépouillement de ces mesures et les calculs nécessaires.

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DISCUSSION AND COMMENTS

Dr. SHARAF EL DIN : Five cruises were taken in the Gulf of Suez from April 1966 to April 1967. The information resulting from these cruises was compiled in an M. Sc. thesis by Mr A. MASHALL at the Institute of Fishery and Oceanography at Alexandria. This thesis was submitted in 1968 to Caire University, Department of Physics, Faculty of Science.

Pr. SAINT-GUILY : Can you specify what are the special characteristics of the deepest sample taken at the first station on the shelf of the Gulf of Suez. What was the depth and the density of the water ?

Dr. MAILLARD : The deepest measurement was on the sea bed at about 500 meters, σ_θ is then 28,55. At that point one can no longer distinguish the Gulf of Suez water from the sea water.

Pr. LACOMBE : I think it would be helpful if any of you could afford some information on these particular sorts of waters which insert themselves between the surface layer and the deeper layer and which have special characteristics. It is clear that those waters are of great importance and it is time perhaps somebody deal with the temperature and salinity of the waters down to perhaps 150 meters. By that I mean measurements from these very shallow places on both sides of the Red Sea because it appears that these play a very important part in the general hydrology of the sea.

Pr. TCHERNIA : The source is from the side. You'd have to work there with a launch.

Pr. WYRTKI : I agree because I think I read that very high salinities are observed on some of the coastal areas along the Red Sea.

Pr. TCHERNIA : There was a time when some people thought that the deep water of the holes was coming from the side before they had new data about them.

Pr. WYRTKY : You see such areas of formation of very high salinity waters are nothing new in the ocean really. I know of two that are near Australia. The whole of the Gulf of Carpentaria for instance is of much higher density and much higher salinity than the adjoining Timor Sea, but is has very little effect on it. The same is true for the two gulfs in the South of Australia, not far from Melbourne and Adelaïde. Water is found there that has salinities of 37 to 38°/₀₀ and outside the ocean has only 35°/₀₀ at the most.

Local formation of extremely high salinity water along the coasts of the Red Sea in shallow water seems to have limited effect on the surrounding deeper areas.

Dr. MORCOS : You exclude the Gulf of Suez actually from this. Would you say that the Gulf of Suez is a rare place for the formation of these high salinity layers ?

Pr. WYRTKI : At a distance you can trace it as an identifiable water. It is probably not formed in very great quantities.

Dr. MORCOS : Actually is it not possible to trace this intermediate water by tangent method ?

Pr. LACOMBE : Yes. This is only estimation.

Pr. TCHERNIA : A lot of work has yet to be done in the Red Sea and we have some people who are interested in this. The difficulty is that it is so far from here.

Dr. MORCOS : There is also the difficult problem of navigation owing to the coral reefs.

Pr. TCHERNIA : You need launches to go there and people, working on the shore specialists. If all these people who are interested were not divided but united some good work could be done. Similarly in the Adriatic which is another sea with canal features.

Pr. LACOMBE : Well, then some papers of Miss MAILLARD show that the intermediate waters occur all through the length of the Red Sea with a range of latitudes of 3-4 degrees.

Dr. MAILLARD : They are observed throughout the middle and the south of the Red Sea. They are probably found in the North also, but the temperature and salinity gradients there are weak and the only standard hydrological measurements are insufficient to show their existence.

Dr. ROBINSON : I think what is so interesting also is that it has a relation to the bottom topography.

Pr. LACOMBE : I wonder if some of the layers that you found in the mean of your B.T.'s don't show the same thing in fact.

Dr. ROBINSON : I do think that if we sit down and look for this that we can find evidence of this. I hope that we can do so.

Dr. PEDGLEY : There has been some exploration for oil off the Ethiopian coast. I wonder whether the oil companies have any records which may be of interest here ? Certainly in 1964 Mobil Oil, I think, was operating in a number of sites North of Dhalack Island. They certainly kept some meteorological records for me. I do not know whether they have any water temperature records (probably not salinity), at various depths which may be of interest.

Pr. LACOMBE : That is interesting because some of those waters come from North of the Dhalack archipelago, I think.

Pr. TCHERNIA : It is very difficult to obtain such information. It is very difficult to get information in the Red Sea from a scientific point of view when the land belong to petroleum companies. They are not willing to offer information.

Pr. LACOMBE : I find the same thing with the companies operating in the Gulf of Suez. But we have been fortunate to have got some results.

I wonder if something could be discovered about the sea-surface temperature measurements by means of satellite (it's possible perhaps to obtain charts which indicate surface temperature).

Dr. ROBINSON : They did make some special measurements in the Gulf of California with satellites because there they have a good chance of predicting whether it will be clear and show on the satellite pictures. That is why I was asking you about the cloud cover : whether it is open enough in the pictures you have seen. There are new satellites which are going to be equipped with infra-red or other sensors in fact, it is possible they already exist. The only problem is whether or not the definition is good enough to make the differentiations.

Dr. MILLER : I would like to suggest that such a shallow place like the Bitter Lake area may contribute salt to this edge portion of the Red Sea.

Dr. SHARAF EL DIN : I understand there was a study by LUKSCH about the increase of salinity in the Suez Canal. It was descending from the Bitter Lake and flowing out in both directions. However, I don't recall the amounts.

ON THE DEEP CIRCULATION OF THE RED SEA

Klaus WYRTKI *

Résumé : Sur la circulation profonde en Mer Rouge

En contraste avec la circulation superficielle en Mer Rouge, qui est principalement commandée par le vent, la circulation profonde suit le modèle classique d'une circulation thermohaline puisque l'étroite vallée de la partie profonde de la Mer Rouge diminue l'effet de l'accélération de Coriolis. La seule question réelle sur la circulation profonde est son intensité. En mer Rouge il n'y a pas de mesures directes de la vitesse de formation de l'eau de fond et, par conséquent, on doit utiliser les méthodes indirectes.

Les mouvements ascendants en Mer Rouge peuvent être calculés d'après le bilan de l'advection et de la diffusion verticale de chaleur et de sel. En considérant dans la région de la Mer Rouge la décroissance avec la profondeur, les distributions verticales du coefficient de diffusion et du mouvement ascendant peuvent être calculées mais l'intensité de la circulation n'est pas déterminée entièrement. Une circulation profonde de 6×10^{10} cm^3s^{-1} donne des vitesses ascendantes de 2.10^{-5} cm s^{-1} et une diffusion turbulente verticale de 0,14 cm^2 s^{-1} pour la couche comprise entre 100 et 200 mètres de profondeur. Cette valeur du coefficient de diffusion est en accord avec des valeurs provenant d'autres régions de l'océan soumises à des conditions analogues.

La consommation d'oxygène en Mer Rouge profonde est aussi estimée d'après des considérations de bilan. La consommation totale est proportionnelle à la vitesse de la circulation profonde. Puisque la production primaire en Mer Rouge a la même valeur que dans l'océan subtropical ouvert, la consommation totale d'oxygène doit aussi avoir la même valeur, qui est proche de 25×10^{-8} ml cm^{-2} s^{-1}. Cette consommation exige une circulation profonde de 6×10^{10} cm^3 s^{-1} et un temps de résidence de 72 ans. Il est intéressant, à ce propos,de noter qu'une circulation profonde réduite à 40 % conduirait à un épuisement total de l'oxygène dans le bassin de la Mer Rouge.

Un modèle d'advection et de diffusion verticale pour l'oxygène est utilisé pour étudier les effets d'une variation des différentes constantes impliquées dans

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la distribution de l'oxygène. Des changements dans la consommation de l'oxygène total changent la valeur du minimum d'oxygène mais pas sa profondeur. Des variations dans l'intensité de la circulation profonde changent la profondeur et la valeur du minimum, qui sont toutes deux très sensibles aux variations de son intensité et limitent assez fortement son ordre de grandeur. Les distributions des teneurs en oxygène observées sont compatibles avec une circulation profonde de 6.10^{10} $cm^3\ s^{-1}$, qui représente environ 1/5 de l'intensité du courant dans la couche de surface.

D'après la considération des flux d'eau et de sel dans la couche de surface de la Mer Rouge, il est clair que la plupart de l'eau dont la salinité a augmenté par évaporation doit plonger dans la partie Nord de la Mer Rouge, de la couche de surface jusqu'à la couche de subsurface puis s'écouler sur le seuil dont la profondeur n'est que de 100 mètres. Ces équations de bilan ne déterminent pas cependant entièrement la quantité d'eau de forte salinité qui circule à travers le bassin profond.

Il y a trois sources possibles de formation d'eau profonde en surface en Mer Rouge septentrionale, qui sont le Golfe d'Aquaba, le large de la Péninsule du Sinaī et le Golfe de Suez. La plus prononcée est probablement le Golfe de Suez, mais pour produire assez d'eau profonde pour la circulation définie plus haut, le Golfe devrait être drainé entièrement trois fois chaque hiver. Les forts courants assocciés devraient être aisément mesurables mais ne sont indiqués dans aucune des observations existantes. L'amplitude possible de cet échange d'eau impose une limite supérieure stricte à l'intensité de la circulation profonde.

D'après la considération des changements saisonniers de la circulation de la Mer Rouge, il est vraisemblable qu'en hiver, quand l'eau de surface entre et que l'eau de subsurface sort sur le seuil de 100 mètres de profondeur du détroit de Bab-el-Mandeb, toute l'eau profonde de la Mer Rouge se forme et le niveau supérieur de l'eau profonde s'élève d'environ dix mètres. Pendant l'été, quand l'eau de surface sort sous l'action des vents et que l'eau de subsurface, remontant dans le Golfe d'Aden, entre en Mer Rouge sur le seuil, les eaux profondes en Mer Rouge sont essentiellement stagnantes.

Une étude de tous les aspects variés de la circulation de la Mer Rouge, à savoir les flux verticaux de sel et de chaleur, la consommation d'oxygène, la formation d'eau profonde en surface et les fluctuations saisonnières de la circulation indiquent qu'ils limitent assez fortement l'intensité de la circulation et la vitesse de formation de son eau profonde, qui est très vraisemblablement proche de 6.10^{10} cm^3/s et peut être sujette à de fortes fluctuations d'un hiver à l'autre suivant les changements de conditions climatiques.

Abstract

In contrast to the surface circulation of the Red Sea, which is chiefly wind driven, the deep circulation follows the classical model of a thermohaline circulation, since the narrow valley of the deep Red Sea minimizes the effect of the Coriolis acceleration. The only real question about the deep circulation is its strength. In the Red Sea there are no direct measurements of the rate of formation of bottom water, and consequently indirect methods have to be used.

Ascending movements in the Red Sea can be computed from a balance of vertical advection and diffusion of heat and salt. Considering the decrease in area of the Red Sea with depth, the vertical distributions of the diffusion coefficient and of ascending motion can be computed, but the strength of the circulation is not uniquely determined. A deep circulation of 6×10^{10} cm/s gives ascending velocities of 2×10^{-5} cm s^{-1} and a vertical eddy diffusion of 0.14 cm^2/s for the layer between 200 and 100 meter depth. This value of the diffusion coefficient is in agreement with values derived for other parts of the ocean under corresponding conditions.

The oxygen consumption in the deep Red Sea is also estimated from budget considerations. The total consumption is proportional to the rate of deep circulation. Since primary production in the Red Sea has the same value as in the open subtropical ocean, total consumption of oxygen must also have the same value, which is near 25×10^{-8} ml cm^{-2} s^{-1}. This consumption requires a deep circulation of 6×10^{10} $cm^3 s^{-1}$ and a residence time of 72 years. It is interesting in this connection to note that a deep circulation only 40 % as strong would lead to a total depletion of oxygen in the Red Sea basin.

A vertical advection-diffusion model for oxygen is used to investigate the effects of a variation of the different constants involved on the oxygen distribution. Changes of total oxygen consumption change the intensity of the oxygen minimum, but not its depth. Changes in the strength of the deep circulation change depth and intensity of the oxygen minimum, both of which are very sensitive to changes in its strength and place rather strong constraints on its magnitude. The observed distributions of oxygen content are compatible with a strength of the deep circulation of 6×10^{10} $cm^3 s^{-1}$, which is about 1/5 of the strength of the circulation in the surface layer.

A consideration of water and salt fluxes in the surface layer of the Red Sea makes it clear that most of the water increased in salinity by evaporation must sink in the northern part of the Red Sea from the surface layer to the subsurface layer and then flow out over the only 100 meters deep sill. These budget equations do, however, not uniquely determine the amount of high-salinity water circulated through the deep basin.

There are three possible sources of deep water formation at the surface in the northern Red Sea, namely the Gulf of Aqaba, the open northern Red Sea South of Sinaī Peninsula, and the Gulf of Suez. The most pronounced is probably the Gulf of Suez, but in order to produce enough deep water for the circulation specified above, the Gulf has to be drained completely three times during each winter. The associated strong currents should be easily measurable, but are not indicated in any existing observations. The possible magnitude of this water exchange also

puts a strong upper limit on the strength of the deep circulation.

A consideration of the seasonal changes of the Red Sea circulation makes it likely that during winter, when surface water flows in and subsurface water flows out over the 100 meters deep sill of the Strait of Bab-el-Mandeb, all the deep water of the Red Sea is formed and the water inside the deep basin rises by about 10 meters. During summer, when surface water flows out due to the action of the winds, and subsurface water upwelling in the Gulf of Aden enters the Red Sea over the sill, the deep waters in the Red Sea are essentially stagnant.

A consideration of all the various aspects of the Red Sea deep circulation, namely vertical fluxes of heat and salt, oxygen consumption, formation of deep water at the sea surface and seasonal fluctuations of the circulation, place rather strong constraints on the strength of the deep circulation and the formation rate of its deep water, which is most likely near 6×10^{10} cm^3/s, and may be subject to strong fluctuations from winter to winter according to changing climatic conditions.

INTRODUCTION

This study will attempt a reassessment of the deep circulation of the Red Sea and especially a determination of its magnitude. Because of its shape and climatic conditions, the Red Sea is an ideal place for the development of a thermohaline circulation. High-salinity water is formed by evaporation and is cooled in the northern part during winter where it then can sink and fill all of the 2000 m deep basin up to its shallow sill of but 100 meters. The excess of the annually formed deep water or a mixture of deep and subsurface water will escape over the sill into the Gulf of Aden. The question is primarily one of at what rate is deep water formed in the Red Sea.

So far no attemps have been made in the Red Sea to observe directly the formation of its deep water, to measure the sinking, and to estimate the rate of formation, as was done in the western Mediterranean by the MEDOC Group (1970). Consequently, the present investigation will be restricted to an evaluation of indirect evidence, with the aim to determine the rate of deep water formation from budgets of properties and from their distribution.

Little information can be gained from the application of Knudsen's formula, using the salt balance. It determines only the difference between inflow and outflow as 3×10^{10} cm^3/s, which results from an evaporation rate of 200 cm/year. The out flow resulting from this salt budget is about 33×10^{10} cm^3/s and its magnitude has been confirmed by direct measurements over the sill (SIEDLER, 1968). A number of similar estimates have been summarized and discussed by MORCOS (1970, p. 159). The outflow determined from the salt balance is, however, not the same as the amount of deep water rising upward or its formation, but must be larger due to the effect of admixture of subsurface water to the outflow which can be seen in the reduced salinity of the outflowing water, relative to that of the bottom water.

Neither does the heat budget offer any important clues to the rate of deep water formation. Despite a large heat loss due to evaporation, the Red Sea has a slightly positive or essentially zero heat balance. This is sowewhat surprising since during most of the year warm surface water enters the Red Sea, while cooler subsurface water flows out. However, during summer the situation is reversed by the winds, as shown by PATZERT (1972) ; warm surface water flows out, and much cooler subsurface water enters the Red Sea from the Gulf of Aden. Thus, because of strong seasonal and random variability, there is apparently no simple way in which to relate the heat and water exchange over the sill to the rate of deep water formation.

In the northern Red Sea and especially in the Gulf of Suez where salinities are usually higher than those of the deep water, winter cooling to temperatures less than 20°C produces water of a higher density than that of the deep water in the Red Sea. This dense water is unobstructed from leaving the shallow gulf and subsequently sinking into the deep layers of the Red Sea. The existence of this process has been clearly shown by MORCOS (1970, Fig. 10) based on winter data from the MABAHISS. It is, however, very difficult to estimate the rate of this outflow from the Gulf of Suez using the amount of winter cooling, but an attempt will be made later in this study. There is little doubt that the amount of cooling, and consequently the amount of deep water formed, will vary considerably from winter to winter. Also comparatively unknown is the contribution of deep water formed in the Gulf of Aqaba, where deep water of a higher density than that of the Red Sea flows over an approximately 300 m deep sill into the Red Sea proper.

The Red Sea is certainly the best existing example to test the classical picture of a pure thermohaline circulation as developed by Sandström (1908). The narrow, deep trench reduces the problem to two dimensions, depth and distance. The source for the sinking of deep water is at its northern, closed end. Deep spreading is possible only along the axis of the narrow trench. The interior of the Red Sea must be subject to slow ascending movements, which oppose the downward flux of heat. The shallow sill at its southern end allows only a limited exchange of surface and subsurface waters with the Gulf of Aden and the open Indian Ocean, where the fresh water source is located. Consequently, the hydrographic conditions within the deep Red Sea must be governed by the same processes that govern the conditions in the deep sea basins of the Indonesian Waters (WYRTKI, 1961). The distributions of temperature and salinity in the ascending region will yield information on the relative importance of vertical advection and diffusion, while the distributions of non-conservative properties such as oxygen will result in information on the time scales involved, and consequently on the rate of deep water formation. In the following paragraphs I will attempt to analyze these distributions carefully and derive a value for the rate of deep water formation, which will eventually be compared with estimates of this rate from climatological factors in the Gulf of Suez.

1 - THE ASCENDING OF DEEP WATER

The classical model of a thermohaline circulation requires that within the interior region of ascending, the vertical fluxes of heat and salt are free of divergence, if stationary conditions are to be maintained. In the absence of horizontal gradients, vertical upward advection must be balanced by a downward diffusion of heat

$$\frac{\partial}{\partial z}\left(wT - A\,\frac{\partial T}{\partial z}\right) = 0 \qquad (1)$$

where T is the potential temperature, w the vertical velocity, A the vertical eddy conductivity, and z the depth. This equation is strictly valid only for a basin with vertical walls and must be modified if the area of the basin decreases rapidly with increasing depth, as in the Red Sea. At the sill depth of about 100 m, its area is only 65 % of the surface area and decreases from there about linearly to 14 % of the surface area at 1000 meters. To allow for this change in area, equation (1) is modified. If F(z) is the area at depth z, and $V = F(z).w(z)$ is the total upward flow of water, then equation (1) reads

$$\frac{\partial}{\partial z}\left|VT - F(z)\,A\,\frac{\partial T}{\partial z}\right| = 0 \qquad (2)$$

and can be integrated

$$V(T-T_B) = F(z)\, A\, \frac{\partial T}{\partial z} \qquad (3)$$

where T_B is the temperature near the bottom. The value of V/FA can be determined from the vertical distribution of potential temperature according to

$$\frac{V}{F(z)\, A(z)} = \frac{\partial}{\partial z} \ln\, (T-T_B) \qquad (4)$$

An identical relationship exists for salinity, in spite of the fact that both the advective and the turbulent flux of salt are upward. In figure 2 the natural logarithms of $T-T_B$ and $S-S_B$ are plotted against depth. Before discussing these curves, it might be worthwhile to assess briefly the accuracy of the data.

Potential temperature in the deep Red Sea is 21.54 $\pm$ 0.03°C, according to the Indian Ocean Atlas (WYRTKI, 1971), p. 186) and is found by all expeditions to be essentially the same. Salinity, by contrast, varies considerably from expedition to expedition, as shown in table 1.

Table 1 - Salinity values below 700 meters depth in the central Red Sea observed by four expeditions.

Ship	Date	salinity °/oo	Remarks
HORIZON	Sept. 1962	40.59 - 40.60	
COM. R. GIRAUD	Jan. 1963	40.56	
ATLANTIS	July 1963	40.62 - 40.69	Some values in the north and south as high as 40.82
METEOR	Nov. 1964	40.61 - 40.62	

The standard deviation of salinities shown in the Atlas is 0.08°/oo and is more likely caused by measurement errors than by changes in the properties of the water formed or in the rate of deep water formation. Titration errors are very likely, because a salinity of 40°/oo exceeds the capacity of the normal burettes which have to be refilled to complete the titration. In spite of this large standard deviation in the salinity values, averaging of the data from all expeditions gives rather smooth curves which exhibit some differences between the southern part (15°N to 20°N) and the northern part (20°N to 25°N) of the Red Sea.

In the ascending layer of the upper deep water between 200 and 600 m depth, the T-S relationship is essentially linear (Fig. 1). Comparing T-S values in the northern and southern halves of the Red Sea, it is apparent that salinities are systematically higher in the south at corresponding levels, which is due to a stronger ascending motion in the southern part. Below the 700 m depth, potential temperature in the deep water is essentially constant, while salinity increases with depth in the northern part, where newly formed deep water enters first.

In figure 2 the vertical distributions of the natural logarithm of $T-T_B$ and $S-S_B$ are given : For T_B and S_B the values in the layer 800 to 1200 m are taken.

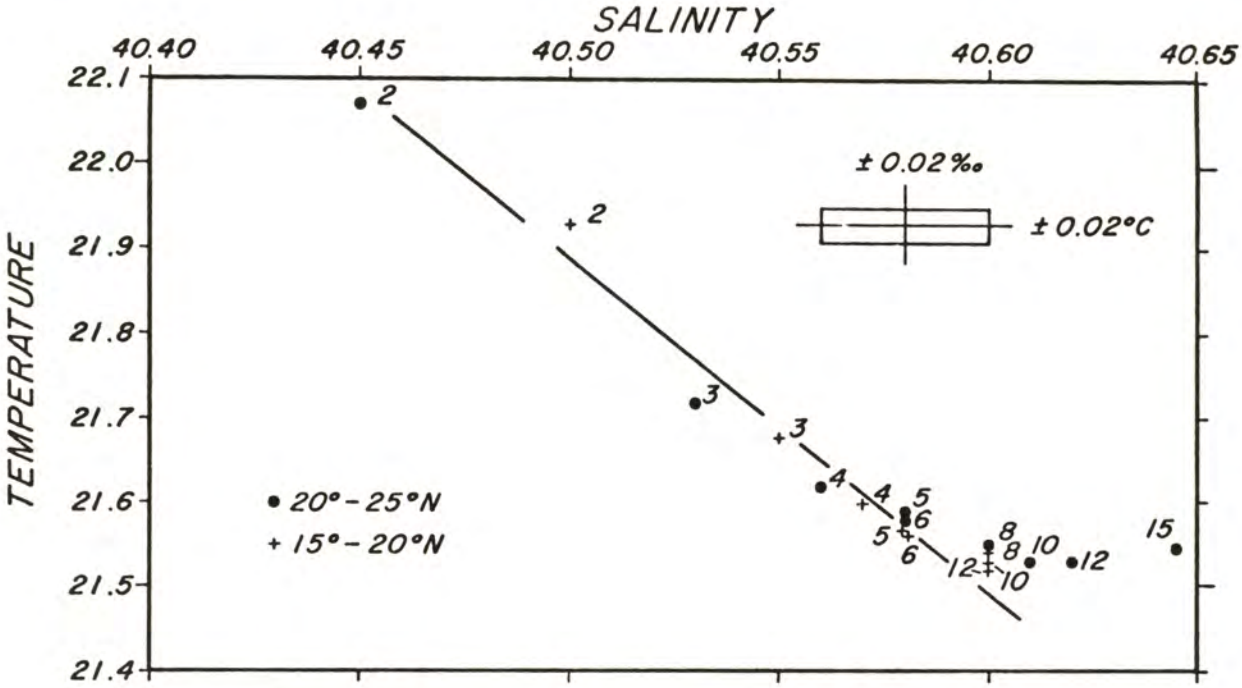

Fig. 1. Potential temperature-salinity relationship for the deep water of the Red Sea. The numbers give the depth in hundreds of meters.

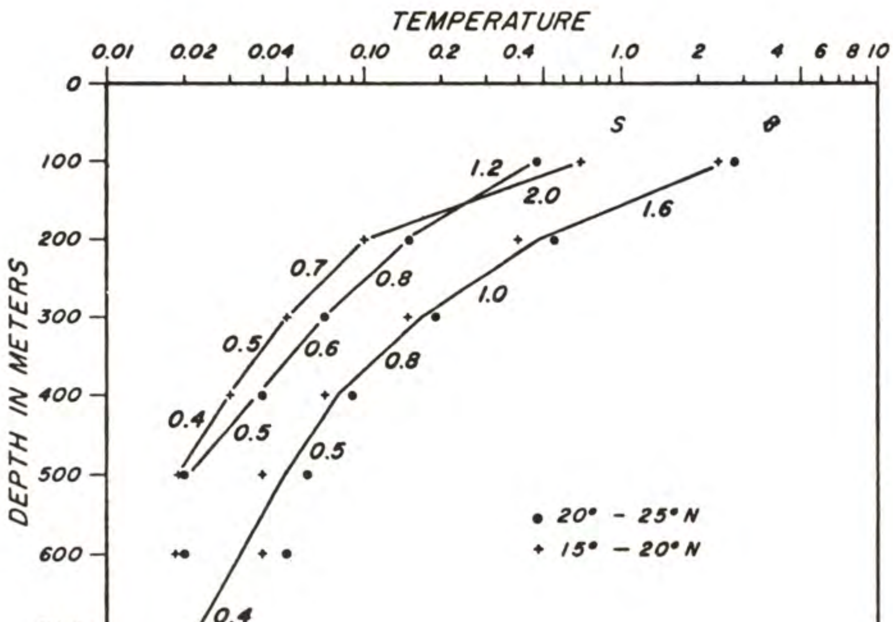

Fig. 2. Vertical distribution of the logarithm of potential temperature and of salinity. Values give the slope according to equation (4) in $10^{-4} cm^{-1}$.

The shape of these curves represents, according to equation (4), the value of V/A F, which has the same meaning as w/A. This value increases upward from about 0.4×10^{-4} to 1.6×10^{-4}. The differences between values derived from temperature and from salinity in the northern and southern parts of the Red Sea are more likely caused by uncertainties of the data rather than the result of real differences. For the following computations, values have been averaged within each depth interval and are given in table 2 and figure 3. Knowing the area of the Red Sea as a function of depth F(z), and the strength of the deep circulation V, the vertical exchange coefficient A(z) can be calculated from V/A F and the vertical ascending velocity w(z) from V/F. Both values are directly proportional to V. Taking the strength of the deep circulation as $V = 6\times10^{10}$ cm^3/s, the values of A(z) and w(z) are also given in table 2. A is as small as 0.14 between 100 and 200 m in the lower portions of the discontinuity layer, and may be even smaller near its center. It increases with depth to more than 1.0 in the deep water. The ascending velocity w decreases upwards as the Red Sea becomes wider from 4×10^{-5} to 2×10^{-5} cm/s.

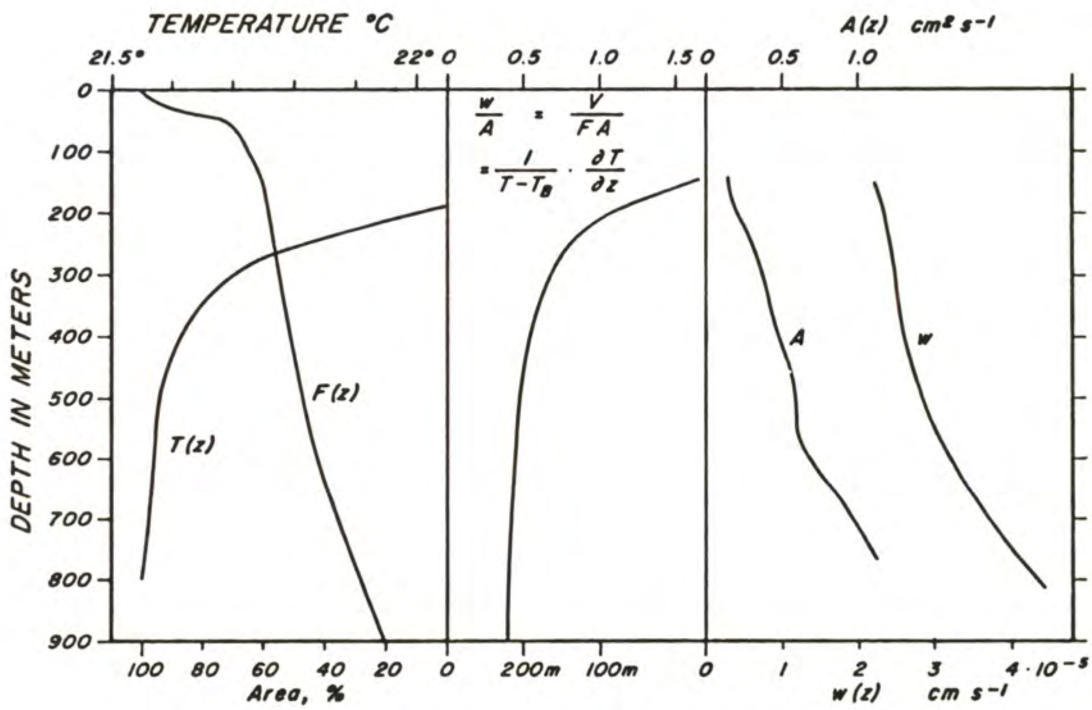

Fig. 3. Vertical distribution of the area of the Red Sea F(z), the potential temperature T, the ratio w/A, the vertical eddy diffusivity A, and the vertical ascending velocity w.

Table 2 - Values of w(z) and A(z) as calculated from Equation (4) for a strength of the deep circulation $V = 6\times10^{10}$ cm^3/s.

m	$\frac{1}{T-T_B}\frac{\partial T}{\partial z}$ 10^{-4} cm^{-1}	Area F(z) 10^{13} cm^2	Vertical Velocity w(z) 10^{-5} cm/s.	Exchange Coefficient A(z) cm^2 s^{-1}
100				
	1.6	270	2.2	0.14
200				
	0.8	250	2.4	0.30
300				
	0.6	240	2.5	0.42
400				
	0.5	220	2.7	0.56
500				
	0.5	200	3.0	0.60
600				
	0.4	180	3.3	0.80
700				
	0.4	140	4.2	1.08
800				

Values as low as 0.14 for the vertical exchange coefficient in strongly stratified water are not unusual. SPENCER and BREWER (1971) derive a value of 0.14 cm^{2}s^{-1} for the layer between 100 and 300 m depth in the Black Sea, where conditions are very similar. Their value in based on a known water input from the Bosporus. The strength of the deep circulation in the Black Sea is, however, only about 1/10 of that of the Red Sea, namely $V = 0.6\times10^{10}$ cm^3/s and $w = 0.17\times10^{-5}$ cm/s. Similar low values for the vertical exchange coefficient are quoted by KULLENBERG (1971); who finds values ranging from 0.04 to 0.7 in stratified water exposed to wind stirring.

It is also possible to estimate the vertical diffusion coefficient A from the disappearance of an intermediate layer of low temperature, which enters the Red Sea seasonally during summer from the Gulf of Aden (PATZERT, 1972). A remnant of this layer characterized by a temperature minimum has been observed as late as December by the METEOR (GRASSHOFF, 1969, Fig. 17). This layer is about 30 m thick and the temperature minimum about 1.5°C strong. It was originally advected into the Red Sea in August and September, when it was 50 m thick and had a temperature contrast of about 4°C. One can estimate the diffusion coefficient A from the diffusion equation for temperature T

$$\frac{\partial T}{\partial t} = A\,\frac{\partial^2 T}{\partial z^2} \qquad (5)$$

which has a solution of the form

$$T \approx e^{-kt} \cos \frac{\pi z}{h} \qquad \text{with } A = \frac{kh^2}{\pi^2} \qquad (6)$$

The time constant k is determined by the fact that over the four-month period the temperature in the minimum has been reduced to 1/e, yielding $k = 10^{-7}\ s^{-1}$. Taking $h = 40$ m for the average thickness of the minimum, a value $A = 0.16\ cm^2/s$ results, which is in agreement with the value for A determined from the vertical diffusion-advection model.

2 - OXYGEN CONSUMPTION IN THE DEEP RED SEA

The vertical distribution of oxygen content X in the absence of strong horizontal gradients is given as a balance between vertical advection, vertical diffusion, and consumption R by the equation

$$\frac{\partial}{\partial z}\left(wX - A\frac{\partial X}{\partial z}\right) = R(z) \qquad (7)$$

A simple estimate of the rate of consumption R can be made if the equation can be integrated over a well-defined water body. The deep Red Sea is especially suitable, if one assumes that a deep circulation of the strength V introduces water with an oxygen content X_D by sinking at the northern end of the Red Sea into the deep basin. Elsewhere water rises, and oxygen is subject to consumption. This water must somewhere ascend through the oxygen minimum. In the minimum the vertical oxygen gradient is zero, and therefore the total oxygen flux is given by $V\ X_{min}$, where X_{min} is the oxygen content in the oxygen minimum. Equation (7) integrates to

$$V(X_D - X_{min}) = \int R\ dv = \bar{R}\ Q \qquad (8)$$

where $\bar{R}$ is the average oxygen consumption and Q the volume of the Red Sea below the oxygen minimum layer. Using numberical values like $X_D = 2.8$ ml/l, $X_{min} = 1.0$ ml/l, $V = 6\times10^{10}\ cm^3/s$, and $Q = 130\times10^{18}\ cm^3$ for the volume of the Red Sea below 350 m depth, the consumption rate is $R = 8.3\times10^{-10}\ cm^3/s$. From these values a residence time $\tau = Q/V$ of 72 years and a vertical velocity $w = V/F_{350} = 2.5\times10^{-5}$ cm/s results.

This consumption rate of 8×10^{-10} ml/l s^{-1} might be compared with other estimates. WYRTKI (1962) based on data by RILEY (1951) gives the following formula for the subtropical regions of the oceans.

$$R = 100\times10^{-10} \exp(-3.5\times10^{-5}\ z)$$

GRASSHOFF (1969) adjusts this formula for the higher temperature in the Red Sea and introduces another (mysterious) correction, which results in

$$R = 100\times10^{-10} \exp(-0.6\times10^{-5}\ z)$$

From this formula he calculated $R_{1500} = 37\times10^{-10}$, for 1 500 m depth, a value which is extremely high. RILEY (1951) gives a value of 0.5×10^{-10} at 1 500 m, and WYRTKI (1962) uses a value of 1.25×10^{-10} for the Coral sea between 800 and 3 000 m depth to explain the oxygen distribution. The high value of consumption used by GRASSHOFF (1969) requires an extremely intense deep circulation according to equation (8), which for reasons given in this investigation is not found in the Red Sea.

More light can be shed on the question of oxygen consumption by considering the total consumption C between the surface and the bottom, which is given by

$$C = \int_o^\infty R\,dz = \int_o^\infty R_o\,e^{-\alpha z}\,dz = R_o/\alpha \qquad (9)$$

From Riley's data it follows that $C = 30\times10^{-8}$ ml cm^{-2} s^{-1} for the open ocean ; from Grasshoff's data, 167×10^{-8} ml cm^{-2}s^{-1} for the Red Sea ; and there is no obvious reason that the productivity of the Red Sea should be several times that of the open ocean.

Based on computations in Section 3, we have derived for the Red Sea the formula.

$$R = 50\times10^{-10}\ \exp\ (-2\times10^{-5}\ z) \qquad (10)$$

for the consumption of oxygen. This formula gives a slower decrease of consumption with depth, but has a total comsumption $C = 25\times10^{-8}$ ml cm^{-2}s^{-1}, about the same as the open ocean. Half of the total consumption takes place above and half of it below the oxygen minimum ; a value of $R = 8\times10^{-10}$ as calculated earlier for the deep Red Sea below the oxygen minimum is found at 900 m depth.

3 - DEEP CIRCULATION AND THE VERTICAL DISTRIBUTION OF OXYGEN

Inside the Red Sea basin below sill depth the distribution of oxygen is characterized by a sharp decline of oxygen content to the oxygen minimum at 300 to 400 m depth. The oxygen content within the oxygen minimum is lower in the south, about 0.5 ml/l, and higher in the north, about 1.5 ml/l. Below the oxygen minimum, the oxygen content increases slowly to more than 2.0 ml/l in the water below a depth of 1000 m , but there is still a noticeable horizontal oxygen gradient in the deep water. This stratification is interrupted only near the northern end of the Red Sea during winter, when sinking occurs, and when water with an oxygen content of more than 3.5 ml/l can reach to a depth of more than 1000 m off the Gulf of Suez. Although the general features of the oxygen distribution are found at every oxygen section, the absolute values and the details of the distribution change noticeably.

The vertical distribution of oxygen can be modeled in essentially the same way as that of temperature and salinity in Section 1, if the rate of oxygen consumption is included. In the case that vertical advection, vertical eddy diffusion, and consumption balance each other, the equation is given by

$$w\,\frac{\partial X}{\partial z} - A\,\frac{\partial^2 X}{\partial z^2} = R(z) = R_o\,e^{-\alpha z} \qquad (11)$$

where the symbols are the same as those used in equation (2), and R(z) is the rate of oxygen consumption. This equation has the solution

$$X = C_1 + C_2\,e^{-\frac{w}{A}z} + C_3\,e^{-\alpha z} \qquad (12)$$

with $$C_3 = \frac{R_o}{\alpha A(\alpha - w/A)}$$

Since the dependence of the solution on the parameters w/A, R_o/A, and α will be investigated in the following, we are using the equation in a form appropriate to a basin with vertical walls, because it is simpler. The boundary conditions determining the constants C_1 and C_2 are given by the observed oxygen content at 100 and 1200 m depths, representing the essentially saturated surface layer and the oxygen content in the lower parts of the deep water. Figure 4 shows the dependence of the oxygen distribution on R_o/A, representing the total consumption $C = R_o/\alpha$, in this case, where α is kept constant. The three curves show that an increase of the total consumption reduces the oxygen content in the oxygen minimum, as one would expect, but does not change the depth of the oxygen minimum appreciably. In fact, the value of the oxygen content in the oxygen minimum places rather strong constraints on the value of oxygen consumption, and allows its choice only within narrow limits.

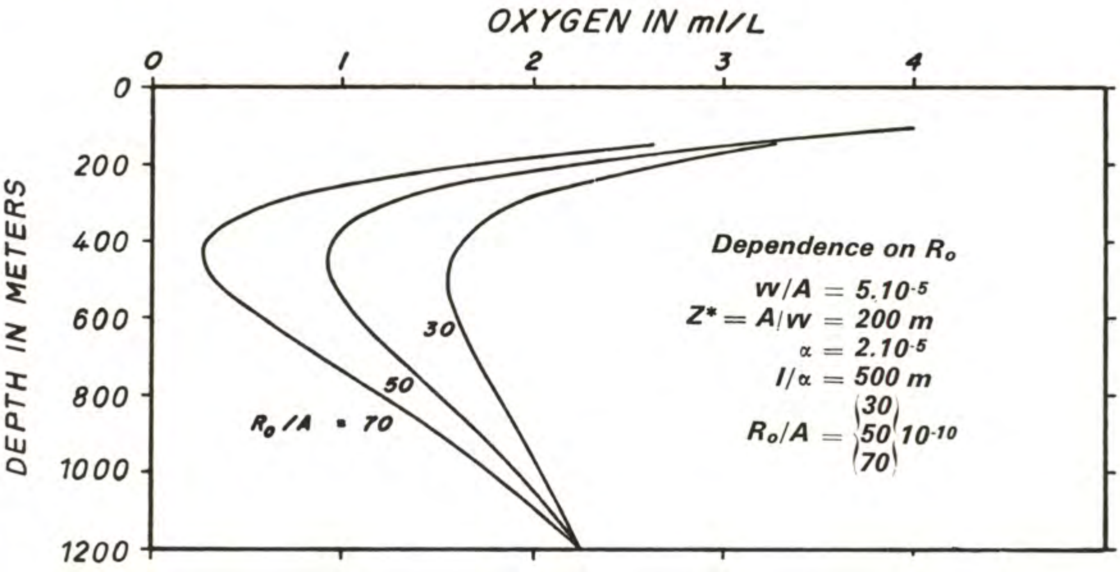

Fig. 4. Vertical distribution of oxygen according to equation (11) for three values of R_o/A, representing different rates of total consumption.

A variation of the rate of vertical decrease of oxygen consumption as expressed by the parameter α has a very similar effect on the oxygen distribution, as shown in figure 5. A stronger decrease of oxygen consumption with depth raises the oxygen content in the oxygen minimum, because it decreases the total consumption. Also in this case, the choice of α has to be within narrow limits, if the observed curve should be closely approximated.

The most pronounced changes occur when the ratio of vertical advection to diffusion w/A is changed. An increase of w/A shifts the oxygen minimum upwards and simultaneously increases the oxygen content in it (Fig.6). This means that increasing upward flow will advect deep water of relatively high oxygen content higher upward, and will simultaneously reduce the effect of downward diffusion from the surface layer. At the same time, the shorter residence time of the water in the basin implies a shorter exposure of the water to consumption, and the oxygen content in the minimum will be higher. Consequently, it can be concluded that the observed depth of the oxygen minimum and the oxygen content in it are very sensitive to the strength of the deep circulation expressed by w, and place rather strong constraints on the range of its magnitude.

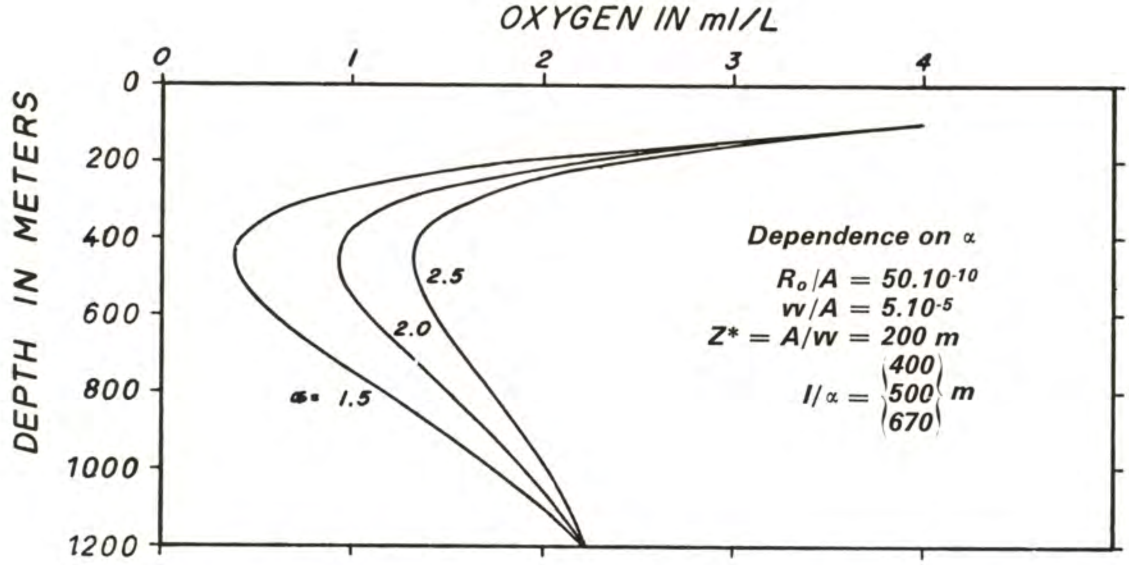

Fig. 5. Vertical distribution of oxygen according to equation (11) for three different values of α, representing the rate of vertical decrease of oxygen consumption.

Since the vertical distribution of oxygen content differs in the northern and southern parts of the Red Sea, although the same features occur, the solution (12) has been fitted to both distributions, namely the average oxygen curves for the area between 15° and 20°N (Fig. 7) and for the area 20° to 25°N (Fig. 8). The parameters used show a slightly stronger ascending velocity in the southern part, where the oxygen minimum is shallower, and also a slightly higher total consumption to account for the lower oxygen content. The calculated curves fit the observations rather well, but it should be pointed out that such an agreement can be expected only with average vertical curves representing a stationary situation, and not with data from individual stations, where transient events may have distorted the distributions.

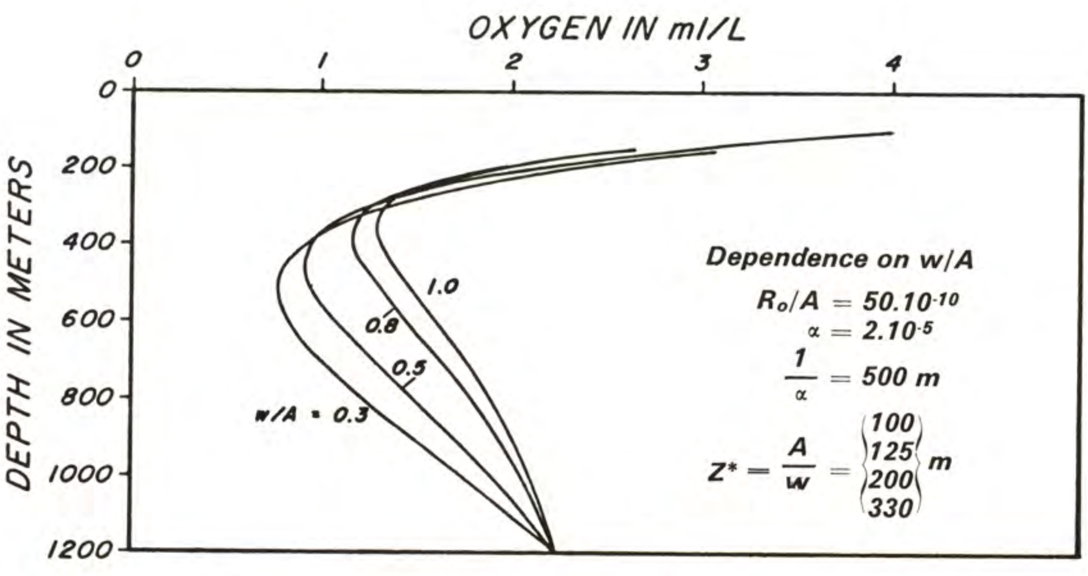

Fig. 6. Vertical distribution of oxygen according to equation (11) for three different values of w/A representing the strength of the deep circulation.

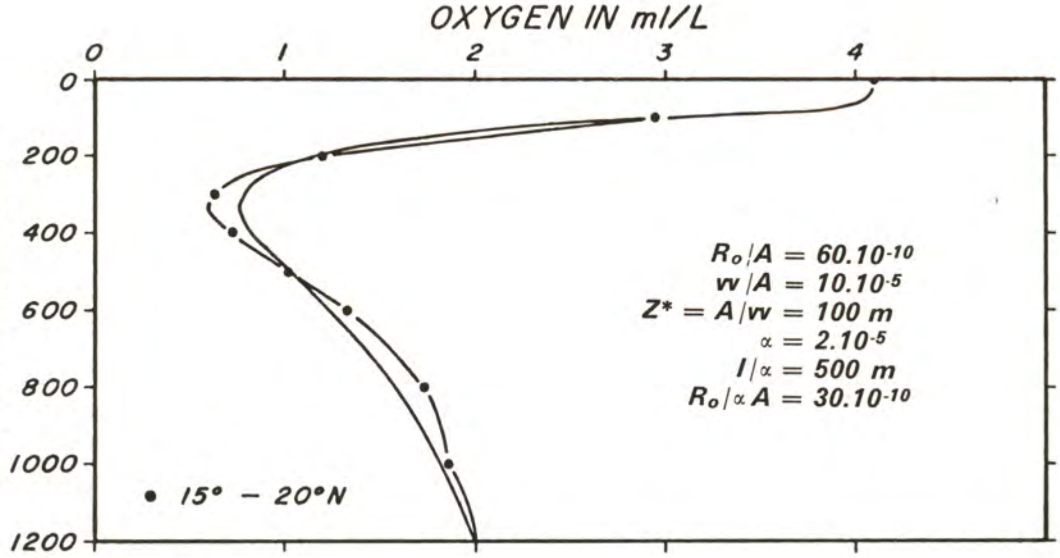

Fig. 7. Comparison of the observed and computed vertical distribution of oxygen for the southern half of the Red Sea, and parameters used.

The values of R_o and α are of some interest in themselves, because they show that the total consumption in the Red Sea $C = R_o/\alpha = 25\times10^{-8}$ ml $cm^{-2}s^{-1}$ is about the same as that in the subtropical oceans, a fact which is also supported by a mean value of primary production of 0.21 g Carbon m^{-2} day^{-1} (YENTSCH and WOOD, 1961) in the Red Sea, which corresponds to that of other subtropical regions. This agreement indicates clearly that the values of oxygen consumption used by GRASSHOFF (1969) are much too high, and could be matched only with an excessively strong deep circulation. The value found for α is smaller than that in the open ocean, indicating that consumption decreases less rapidly in the Red Sea, an effect which may be due to the higher temperatures, as argued by GRASSHOFF (1969).

The numerical value of $w/A = 8$ to 10×10^{-5} cm^{-1} determined from the oxygen distribution in a basin with vertical walls agrees with a value of to 16×10^{-5} cm^{-1} determined from the temperature and salinity distribution in the layer between 100 and 400 m, (table 2) and shows that both distributions can be explained by a deep circulation of about 6×10^{10} cm^3/s. A deep circulation of this strength leads to values of oxygen consumption which agree with values of primary production and to values of vertical eddy diffusion, which also agree with other investigations. If the area of the basin would have been a function of depth, as in the temperature model, the value of $w/A = V/FA$ would also have decreased with depth, but the dependence of the oxygen distribution on the value of w/A could not have been demonstrated as clearly. The agreement between the numerical values derived from the temperature and the oxygen distribution indicates clearly that the deep circulation of the Red Sea must be close to 6×10^{10} cm^3/s, about twice as large as the water loss due to evaporation, and about 1/5 of the strength of the surface circulation.

Salt Fluxes in the Red Sea and Deep Circulation

The salinity of the water entering the Red Sea in the surface layer is increased by evaporation to more than 40°/oo in its northern part and to more than 41°/oo in the Gulf of Suez. Conceivably it would be possible that all this water flows in a subsurface layer above sill depth back to the south and leaves the Red Sea. The salinity of the subsurface return flow would then be only slightly reduced due to some diffusive losses to the upper layer. Very little or no formation of bottom water would take place, but in such a case the bottom water should be essentially depleted of oxygen, as in the Black Sea. Such a condition would exist if the residence time of the deep water were in excess of 200 years and the deep circulation less than 2.5×10^{10} cm^3/s. This results from applying equation (8) and taking an oxygen content X_B = 4.5 ml/l for the high-salinity water entering the deep basin and X_{min} = 0 for the water ascending out of the basin. It is interesting to note that the deep circulation determined from the observed oxygen distribution in section 4 is only 2.5 times as strong.

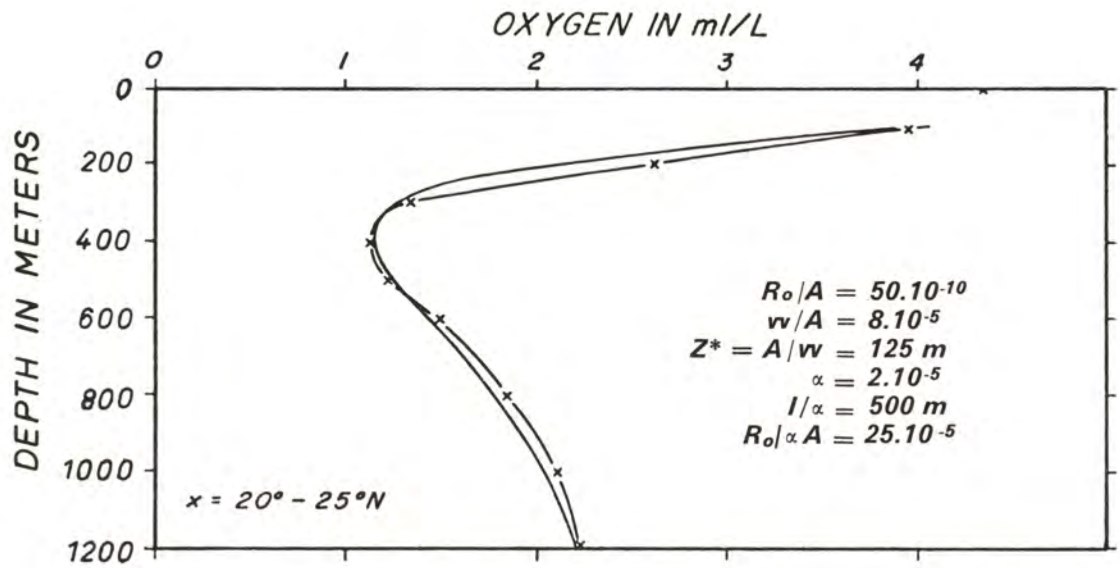

Fig. 8. Comparison of the observed and computed vertical distribution for the northern half of the Red Sea, and parameters used.

A second possibility for the return flow of the high-salinity water formed in the northern Red Sea is that all high-salinity water descends into the deep basin and ascends near the sill to form the outflow. In this case the basin should be extremely well ventilated, or the oxygen consumption should be very high, which in turn would require a very high biological production of the Red Sea, which is not observed. GRASSHOFF (1969) goes even further and introduces an additional vertical circulation within the deep basin, which about doubles the ascending and descending movements within the basin and leads to a deep circulation of 56×10^{10} cm^3/s, approximately twice as strong as the outflow. Such a circulation would lead to a residence time of only 8 years for the water in the layer below the oxygen minimum. There is no evidence for the formation of such amounts of deep water in the northern Red Sea.

In the following we will discuss some aspects of the salt balance of the upper portions of the Red Sea. If the evaporation of the Red Sea is taken as 3×10^{10} cm^3/s, the inflow as 36×10^{10} cm^3/s, and the outflow as 33×10^{10} cm^3/s, the salinity of the inflow is 36.4°/₀₀ and that of the outflow is 39.7°/₀₀, according to the Knudsen formula. These are the same values as used by MORCOS (1970) and imply a salt flux of 1310×10^7 g/s. They are the boundary conditions at the entrance of the Red Sea in the following six diagrams, figures 9 and 10. Dividing the Red Sea into an upper and a lower layer and into three regions of equal evaporative water loss of 10^{10} cm^3/s each, a variety of circulations have been imposed and the corresponding salt fluxes and salinities were determined from salt balance. In the six diagrams the salinities are given by the large italic numbers with a decimal point, the water fluxes in units of 10^{10} cm^3/s by large-size numbers of 36 or less, and the advective salt fluxes in 10^7 g/s by the smaller size numbers, usually exceeding 100.

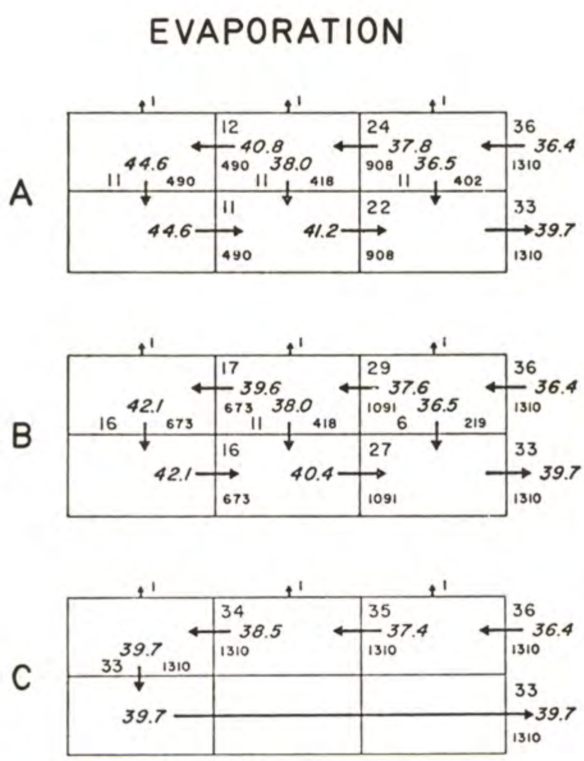

Fig. 9. Salinities, water, and salt fluxes for different circulation schemes in the Red Sea as computed from budget equations. Large italic numbers with decimals are salinities; large-size numbers without decimals are water transports in 10^{10} cm^3/sec, and small-size numbers are salt fluxes in 10^7 g/sec.

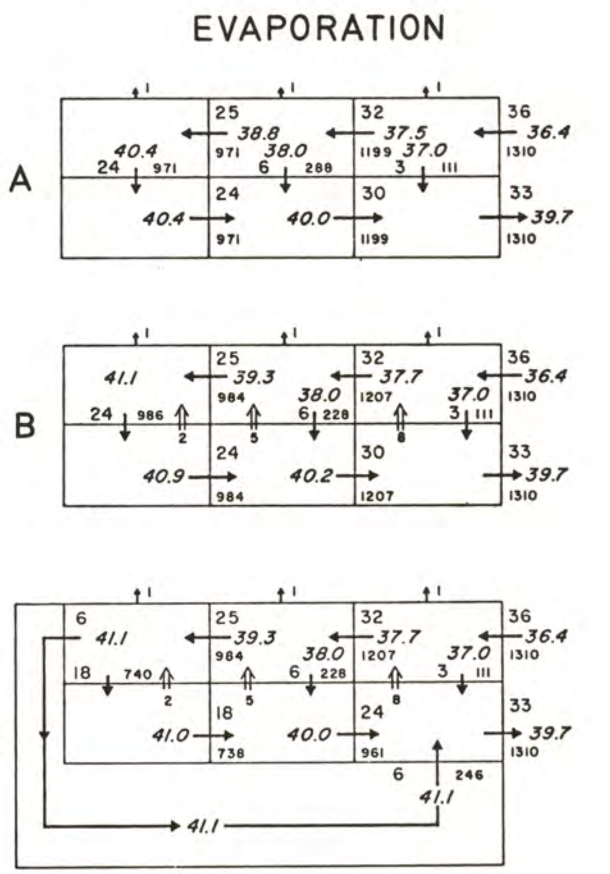

Fig. 10. Salinities, water, and salt fluxes for different circulation schemes in the Red Sea as computed from budget equations. Large italic numbers with decimals are salinities; large-size numbers without decimals are water transports in 10^{10} cm^3/sec, and small-size numbers are salt fluxes in 10^7 g/sec. The open arrows represent diffusive fluxes.

If equal transfer of water from the upper to the lower layer takes place in all three regions (Fig. 9a) the salinity in the northern region will be more than 44°/₀₀, much higher than that observed. If the downward flux of water from the upper to the lower layer is asymmetric and concentrated in the northern region, the salinity becomes lower, about 42°/₀₀ (Fig. 9b). If all water sinks from the upper layer into the lower layer in the northern region (Fig. 9c), the salinity there does not reach 40°/₀₀, which indicates that this situation is too extreme. A more reasonable distribution of salinity results when about 2/3 of the downward flow takes place in the northern region (Fig. 10a).

Besides the advective fluxes there will be diffusive salt fluxes from the lower to the upper layer through the halocline, which increase the salinity of the nortwardmoving surface water. An estimate of this vertical salt flux for the entire Red Sea can be easily made. With an area of $F = 35\times10^{14}$ cm^2 at 50 m depth, a vertical exchange coefficient $A = 0.14$ cm^2 s^{-1}, and an average salinity difference of 1.5°/₀₀ between the upper and the lower layer over a distance $\Delta h = 50$ m, the salt flux is $A\ F\ \Delta S/\Delta h = 15\times10^7$ g/s. This salt flux is rather small compared with the salt fluxes by advection, but has a pronounced effect on the salinity distribution as seen in figure 10b. The total salt flux has been distributed between the three regions in a somewhat arbitrary way, but in fair agreement with the salinity difference between the layers in each region. In comparing figure 10a with figure 10b it is apparent that salinity has increased in the central and northern regions, in both the surface and the subsurface layers. In the last of the diagrams, figure 10c, a part of the water in the northernmost region is supposed to sink into the Red Sea basin and to ascend north of the sill into the lower layer to join the outflow. It is obvious that such a deep circulation does not change the salinity appreciably. Consequently, the distribution of salinity will not tell us whether most of the high-salinity water formed in the north returns within the subsurface layer, without ever sinking below sill depth, or whether most of this water sinks into the Red Sea basin and then ascends into the subsurface layer. Although it is quite clear from these simple computations that the water from the inflowing layer must descend into the outflowing subsurface layer, and that most of this descending occurs in the northern part of the Red Sea, it cannot be concluded how much water participates in the deep circulation.

Knudsen's famous relationship linking the volumes of inflow and outflow from a basin with the salinities associated with these flows has apparently been misinterpreted with regard to the driving mechanism of the circulation involved, insofar as water exchange is calculated from the observed salinities and the evaporation-precipitation difference and it is tacitly implied that this difference actually drives the circulation. Knudsen's equations for the Red Sea, where evaporation E is the only important factor, gives the water balance between inflow V_{in} and outflow V_{out} as

$$V_{out} = V_{in} - E$$

and the salt balance as

$$S_{in}\ V_{in} = S_{out}\ V_{out}$$

Usually V_{in} and V_{out} are calculated from the observed values of S_{in} and S_{out} and E, implying that the latter values are those determining the system. In fact, the evaporation is given by the climatic factors over the basin, the inflow may be determined by the wind conditions and the inflowing salinity by the surface water outside the entrance. The outflow and especially the salinity of the outflow have to be treated as the unknown parameters, although the salinity of the outflowing water is more readily determined by observations than the inflow. Rewriting the equations in terms of the unknown outflowing salinity, one obtains

$$S_{out} = S_{in} \frac{1}{1 - E/V_{in}} \simeq S_{in}(1+E/V_{in})$$

The factor E/V_{in} is small compared wi th 1, and it can be easily seen that a larger inflow will cause a lower salinity of the outflow. In contrast, a smaller inflow will result in an increase of the salinity of the outflow. Under extreme conditions, when the inflow is accounting only for the evaporation, the salinity in the basin will rise to infinity and the outflow will stop. Summarizing, one may state that when the climate controls the amount of evaporation and the winds the amount of inflow into the basin, the outflow and its salinity are a result of these conditions. Knudsen's relation does not imply that evaporation is the exclusive agent that drives the circulation ; in fact most of the inflow is caused by the wind. Therefore, we may conclude that the intensity of the water exchange of the Red Sea through the Strait of Bab-el-Mandeb, which is largely wind-driven, determines the value of salinity - which evaporation produces in the northern part - and consequently also the salinity of the outflow.

4 - FORMATION OF DEEP WATER AT THE SURFACE

Water of sufficiently high density to sink into the Red Sea basin can be formed at three locations : in the Gulf of Aqaba, in the Gulf of Suez, and in the northern parts of the open Red Sea southeast of the Sinaï peninsula. In these areas the highest surface salinities are found, and winter cooling can lower the temperature of the surface water below that of the deep water. In the deep Gulf of Aqaba below 300 m the temperature is lower and the salinity higher than in the deep Red Sea, and consequently this water can escape over the approximately 300 m deep sill near Tiran Island into the Red Sea basin. This water is probably formed during each winter, although in different quantities, but estimates of the quantities involved are difficul to make. One could conclude that the contribution of the Gulf of Aqaba to the deep-water formation of the Red Sea is small because of its small surface area, but the salinity at its surface is high during most of the year and only very little cooling is required to produce deep water in winter. The fact that oxygen content at depth in the Gulf is more than 3.5 ml/l indicates a rather intense formation of deep water.

Even more difficult is an appraisal of the deep-water formation in the open Red Sea southeast of the Sinaï peninsula. Surface salinities in this region can be as high as those of the deep water, and it has been observed that the mixed layer during winter reaches as deep as 200 m, but no observations of a complete breakdown of the structure and of isothermal and isohaline conditions are available. The processes associated with deep-water formation in this location should be about the same as those observed off Marseilles in the western Mediterranean, and their measurement would require a very sophisticated observational effort. One might speculate that formation of deep water in the open northern Red Sea is probably a process that occurs during certain years of abnormal climatological conditions.

The most likely place for deep-water formation is the Gulf of Suez. Salinities in the Gulf are above 41°/oo during the entire year, and above 42°/oo during winter in the northernmost part of the gulf. Temperatures are less than 20°C during at least the three winter months from January to March. Consequently, density of the water in the Gulf is higher than that of the deep water in the Red Sea during most of the year. The Gulf of Suez is shallow, only about 60 m deep, but water flow into the Red Sea basin is not restricted by topography. These conditions make the Gulf the ideal place for deep-water formation, but again it is difficult to estimate the quantities involved.

The volume of the Gulf of Suez is about 30×10^{16} cm^3, and in order to supply a deep-water formation of 6×10^{10} cm^3/s continously, the entire volume of the Gulf would have to be drained six times during the year. If the outflowing layer above the bottom were 20 m thick and 20 km wide, this flow would require a speed of 15 cm/s. It is known that strong tidal currents of about 1 knot are present, and MORCOS (1970, p. 117) remarks that with persistent southeast winds the non-tidal currents attain velocities of more than 30 cm/sec to the northwest. Both phenomena would allow a deep outflow of water into the Red Sea Basin. Another estimate can be derived from consideration of the salt budget. The surface area of the Gulf is about 5×10^{13} cm^2 and evaporation about 200 cm/year, yielding a water loss of 10^{16} cm^3/year. If the salinity of the inflowing water is 40.5°/oo and that of the outflowing water is 41.0°/oo, the outflow must be 80 times the rate of evaporation, namely 2.7×10^{10} cm^3/s, a value which is about half of the strength of deep circulation estimated from the oxygen distribution.

It is, however, likely that most of the deep water is formed during winter, when temperatures are sufficiently low, and density accordingly high. Assuming that half of the deep water is formed in the Gulf of Suez, this would require a complete draining of the entire Gulf three times during winter. Assuming also that this draining happens during 20 days, the speed of the outflow of a 20 m thick layer would be 50 cm/s, a value which appears to be rather high and should be easily measureable. Such an outflow would also require that a corresponding inflow into the Gulf take place, which is not indicated in the ship's drift observations. Consequently, one must conclude that the strength of the deep circulation is limited by the ability of the Gulf of Suez to form the bulk of the deep water, and cannot be much higher than the value proposed earlier. It is also worthwhile to mention that during winter the northern Red Sea loses heat at a rate of about 500 cal cm^{-2} day^{-1}, equivalent to a temperature decrease of 0.1°C per day for a 50 m thick layer or 2.0°C during 20 days. This means that cooling is sufficient to produce enough cool water to feed the deep circulation. In summer, heat gain creates a warm upper layer of lower density, but it is disconcerting that even during summer on the bottom of the Gulf a layer is found with a salinity above 41.5°/oo, a temperature below 22°C, and a density of more than 30 sigma-t, much denser than the Red Sea deep water. This situation indicates that the heavy water on the bottom of the Gulf does not readily sink into the Red Sea basin, and must be a remnant from last winter since it cannot have been formed there during summer.

The water flowing out of the Gulf of Suez will mix rather rapidly with surrounding waters, and the resulting mixture may very well have properties which do not allow a sinking to the bottom of the Red Sea basin. If this situation occurs, water at different deep layers may be renewed at different times. The fact that oxygen content in the deep Red Sea is more than 2 ml/l, and is slightly higher at 2 000 m than at 1 500 m depth, does, however, indicate that this is usually not the case.

5 - SEASONAL VARIATIONS OF THE DEEP CIRCULATION

From a study by PATZERT (1972) we know that the circulation of the Red Sea and especially the water exchange through the Strait of Bab-el-Mandeb is subject to strong seasonal changes indiced by the winds. A typical winter and a typical summer situation can be differentiated. While circulation in winter follows the classical pattern of surface inflow and subsurface outflow, the summer circulation is completely reversed.

During summer, when strong werterly winds blow over the Gulf of Aden and lower the sea level, surface water flows out of the Red Sea. Simultaneously deeper water is upwelling in the Gulf of Aden, which is of greater density than the water just inside the Red Sea and flows between 30 and 80 m depth inti the Red Sea as a tongue of low-temperature water. During this time there is very little or no outflow of Red Sea deep water over the sill. During summer, temperatures in the northern Red Sea, as elsewhere, are highest, evaporation is comparatively low, and a surface layer of low density is formed. These conditions prevent formation of deep water during summer, and one must assume that during summer the deep layers of the Red Sea are essentially stagnant. This situation lasts from June through September. During the remainder of the year, and especially during the winter months, surface water flows into the Red Sea, and subsurface water flows out. From January to March conditions are suitable for the formation of deep water in the northern portions of the Red Sea, and during this time probably most of the deep water is actually formed. The sinking of this water into the Red Sea basin causes the water inside the basin to ascend. The amount of this ascending is about 10 m per year, all of which probably occurs during the winter months. This ascending elevates the density surfaces and contributes some high-salinity water to the outflow over the sill, which is, however, chiefly supplied from subsurface water flowing southward between 50 and 100 m depth below the surface layer and above sill depth.

This analysis and description of the seasonal changes of the circulation show clearly that all the activity in the deep basin is limited to the winter months, when new deep water is supplied and older deep water ascends. The deep circulation is rather independent of the circulation in the surface and subsurface layers, in which a seasonal reversal takes place. The strength of this seasonally reversing circulation above sill depth is determined by the winds and the sea level in the Gulf of Aden and is independent of the strength of the deep circulation.

SUMMARY AND CONCLUSIONS

In contrast to the surface circulation of the Red Sea, which is chiefly wind-driven, the deep circulation follows the classical model of a thermohaline circulation, since the narrow valley of the deep Red Sea minimizes the effect of the Coriolis acceleration. The only real question about the deep circulation is its strength. In the Red Sea there are no direct measurements of the rate of formation of bottom water, and consequently indirect methods heve to be used.

Ascending movements in the Red Sea can be computed from a balance of vertical advection and diffusion of heat and salt. Considering the decrease in area of the Red Sea with depth, the vertical distributions of the diffusion coefficient and of ascending motion can be computed, but the strength of the circulation is not uniquely determined. A deep circulation of 6×10^{10} cm^3/s gives ascending velocities of 2×10^{-5} cm s^{-1} and a vertical eddy diffusion of 0.14 cm^2/s for the layer between 200 and 100 m depth. This value of the diffusion coefficient is in agreement with values derived for other parts of the ocean under corresponding conditions.

The oxygen consumption in the deep Red Sea is also estimated from budget considerations. The total consumption is proportional to the rate of deep circulation. Since primary production in the Red Sea has the same value as in the open subtropical ocean, total consumption of oxygen must also heve the same value, which is near 25×10^{-8} ml cm^{-2} s^{-1}. This consumption requires a deep circulation of 6×10^{10} $cm^3 s^{-1}$ and a residence time of 72 years. It is interesting in this connection to note that a deep circulation only 40 % as strong would lead to an almost total depletion of oxygen in the Red Sea basin.

A vertical advection-diffusion model for oxygen is used to investigate the effects of a variation of the different constants involved in the oxygen distribution. Changes of total oxygen consumption change the intensity of the oxygen minimum, but not its depth. The depth and intensity of the oxygen minimum are dependent upon the strength of the deep circulation and are very sensitive to changes in its strength ; therefore, they place rather strong constraints on its magnitude. The observed distributions of oxygen content are compatible with a strength of the deep circulation of 6×10^{10} $cm^3 s^{-1}$, which is about 1/5 of the strength of the circulation in the surface layer.

A consideration of water and salt fluxes in the surface layer of the Red Sea makes it clear that most of the water which increased in salinity by evaporation must sink in the northern part of the Red Sea from the surface layer to the subsurface layer and then flow out over the shallow sill at Bab-el-Mandeb. These budget equations do, however, not uniquely determine the amount of high-salinity water circulated through the deep basin.

There are three possible sources of deep-water formation at the surface in the northern Red Sea, namely the Gulf of Aquaba, the open northern Red Sea south of the Sinaï Peninsula, and the Gulf of Suez. The most pronounced is probably the Gulf of Suez, but in order to produce enough deep water for the circulation specified above, the Gulf has to be drained completely three times during each winter. The associated strong currents should be easily measureable, and such measurements have been reported during this symposium. The possible magnitude of this water exchange also puts a strong upper limit on the strength of the deep circulation.

A consideration of the seasonal changes of the Red Sea circulation makes it likely that during winter, when surface water flows in and subsurface water flows out over the shallow sill at Bab-el-Mandeb, all the deep water of the Red Sea is formed and the inside the deep basin rises by about 10 meters. During summer, when surface water flows out due to the action of the winds, and subsurface water upwelling in the Gulf of Aden enters the Red Sea over the sill, the deep waters in the Red Sea are essentially stagnant.

A consideration of all the various aspects of the Red Sea deep circulation, namely, vertical fluxes of heat and salt, oxygen consumption, formation of deep water at the sea surface, and seasonal fluctuations of the circulation, place rather strong constraints on the strength of the deep circulation and the formation rate of its deep water, which is most likely near 6×10^{10} cm^3/s, and may be subject to strong fluctuations from winter to winter according to changing climatic conditions.

ACKNOWLEDGMENTS

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DISCUSSION AND COMMENTS

Dr. MORCOS : In 1970, there was no literature handling the problem of the formation of high salinity deep water and so I wrote about the Gulf of Suez as a source of salt. In that study, I noted that the salinity gradient in the Gulf of Suez is at least 5 times as great as in the Red Sea proper or the Gulf of Aqaba. With an evaporation of 200 cm/year you will get an increase of only 0.5°/₀₀ salinity from the mouth of the gulf to the head of the gulf.

At that time I said there were 2 possible sources. Either, water coming from the Suez Canal, but this is too small in magnitude ; or, increased evaporation in the Gulf. But the problem here is that if you assume high velocities in order to flush the Gulf frequently, the water will not have time to evaporate and get SALTIER.

Pr. WYRTKI : We are almost tempted to compare a situation like the Gulf of Suez with a channel but it is by no means right to do that. One should rather compare it with an estuary, with a bay, and in estuaries (even when there is very strong mixing, very strong tidal currents) the stratification is very persistent. One needs only to think about the Norwegian Fjords or the Gulf of Saint Lawrence and the entrance to the Baltic and so on.

The movements in the Gulf are so much more restricted by bottom friction and lateral restraints. Such stratifications of water are rather permanent and rather strongly resistant to the influence of the wind while similar stratifications in the open oceans are not restricted to that extent.

I would say a final answer could only come from actual measurement and I think with present technology it should not be at all difficult to put in chains of current meters and take readings for many months and we should find a very clear picture of what is going on (that is : if somebody really spent the money and the effort to do it).

Pr. LACOMBE : From measurements made on the bottom near the southern end of the Suez Gulf for 2 months or so, an outward flow of 15-20 cm/s was found near the bottom. This was from February to March.

How long do you think that conditions with great evaporation (i.e., conditions similar to those which are found in January and February) can last within the year ? Would you say from November to April ?

Pr. WYRTKI : Probably somewhat shorter ; two to three months.

Pr. LACOMBE : Two to three months, you would say. Because there is something I have just noticed in the work by Mrs. ROBINSON that astonishes me.

In the open ocean you normally have 7 or 8 degrees variation in temperature between winter and summer, sometimes even more. For example in the Atlantic the difference is 7 or 8 degrees ; in the Mediterranean it is 12 degrees. What is curious is that in the Suez Canal you have much less swing in temperature during the year, not more than 3 or 4 degrees.

Pr. WYRTKI : I think that if you look at the annual charts the annual variations will show this quite clearly.

Dr. ROBINSON : Yes. It's from 18 to 25. It's 7 degrees.

Pr. WYRTKI : So it is actually bigger than the variation in the South. The extreme difference I find in the Gulf of Suez between winter and summer is from 15 to 30 degrees.

Pr. LACOMBE : Also what seems interesting to me is that the temperature is almost the same at 36 meters as it is at the surface. That is to say the thermocline is approximately the depth of the bottom. There is no vertical gradient.

Dr. ROBINSON : It is essentially mixed in temperature.

Pr. LACOMBE : What is the reason for that mixing ?

Pr. WYRTKI : The strong stratification of salinity ; you can have haline convection at any time. Usually, in the ocean, we are concerned with thermal convection because the salinity is preconditioned in such a way that the salinity gradients that are left are really small and we have to break down the thermal structure. But in this case we have essentially no thermal structure so we have the possibility of haline convection all the time.

Pr. LACOMBE : Haline convection is very important. Do you think that the evaporation is possibly of the same order of magnitude in summer and winter ?

Pr. WYRTKI : It's probably greater in winter.

Pr. LACOMBE : But is it so much different in winter ?

Pr. WYRTKI : In winter you will have a bigger sea-air vapour pressure difference.

Pr. LACOMBE : Here, I suppose, we have a very special condition because dry air is arriving on the water and the mean annual evaporation is 200 centimeters. That makes it 16 centimeters per month (you may have 30 centimeters in winter and 10 centimeters in summer). Is this value not sufficient to maintain a constantly high salinity at the bottom ?

Dr. ROBINSON : Doesn't a lot of the salinity at the bottom of Suez still come from the Bitter Lake regime ? Isn't there anything coming in from that ?

Dr. PATZERT : The evaporation is probably 300, not 200 centimeters.

Pr. LACOMBE : So I think we have a source of salt in any season of the year in the northern Gulf of Suez and this possibly maintains layers of high salinity near the bottom.

Pr. WYRTKI : We could compute the flux of salt that was necessary. During one month you increase the salt by 1/80. That would give a salt flux of about 2.7×10^8 grammes per second. Any deposit of salt that is diluted at that rate is finished after a few years.

Pr. LACOMBE : So there is no possibility of getting salt from the bottom.

Dr. ROBINSON : The reason I raise this question is that in Edinburgh someone gave a talk stating that when the canal was first opened they were very much concerned about this situation. I am purely quoting from memory and my figures may not be exactly right but something like 4 meters of salt must have been dissolved in the opening years because the depth increased. Then some kind of stable condition seemed to settle down. But I was not sure whether there was still any more input through the Bitter Lake or not.

Pr. WYRTKI : I don't know if anything like that is present.

Dr. ROBINSON : Another question about this circulation. The only other place that you've got water really cold enough is the water that comes in, say in mid-depth, from the Gulf of Aden. As it comes in it starts out at 16, 18, 20, 21°C pretty soon at the values of temperature that are present at the bottom. If it gains salinity all the time, couldn't the salinity be increased enough so that this water could just turn round and go back out again without really going to the bottom. Then you do not need to have water coming from the bottom in the quantity that we are saying. What you're saying is that all of it has to be bottom water that comes up out of the sill.

Pr. WYRTKI : Yes, part of the water is doing just that, but this is not the whole story. We have already observed one season when the Red Sea behaves as its classical model, with surface inflow, and outflow over the sill and during that time we have the formation of bottom water. But let us look at the other season when we have the surface outflow and deep inflow. During that time it is most likely that nothing will happen to the bottom water except for changes immediately over the sill caused by tides. Tides can always cause a pumping effect. In this period no water is added to the deep Red Sea because no bottom water is formed. Then, you have the switch to the normal situation where you have inflow and some bottom water formation and during that season that layer may rise about 10 meters. That is not very much.

Dr. PATZERT : I'd also like to mention that during the summer in the Gulf of Suez salinity seemed to be higher than during the winter although it's warmer. However, there are very few observations.

Pr. WYRTKI : So this would lend support to the idea that high salinity water is continuously formed in the Gulf of Suez throughout the year and therefore this lens can be present.

temperature gradient is nil at any time of the year (Mrs. ROBINSON) and that there is a high density stratification due to a high salinity gradient. As the evaporation, even in summer, is high it could be supposed that the surface is a source of salt which keeps the salt lens on the bottom.

Pr. WYRTKI : We were wondering why the lens system is present during the whole year and does not flow out or vanish during the summer. It is a continuous supply of salts, a continuous formation.

Dr. MORCOS : Concerning the salinity increase just at the head of the Gulf, in summer we have a southward current in the Suez Canal bringing salt over from the Bitter Lakes to the Gulf of Suez, which is very clear. There is a very regular seasonal rise in summer in this area of Suez due to waters coming from the Suez Canal.

WATER TRANSPORTS IN THE GULF OF AQABA

David A. ANATI *

Résumé : Transports d'eau dans le Golfe d'Aqaba

Les volumes transportés sous l'effet de l'évaporation, des marées et des vents dans le Golfe d'Aqaba ont été évalués à partir de cinq campagnes et d'études climatologiques existantes. Une section de temperature et une section de salinité selon l'axe principal du golfe sont présentées pour la fin de l'été. On a pu mettre en évidence une similitude entre la répartition saisonnière des courants dans le Golfe d'Aqaba et celle de la Mer Rouge proprement dite.

Abstract

The volume transports resulting from evaporation, tides and winds in the Gulf of Aqaba are estimated from five past cruises and existing climatological studies. A salinity and a temperature section along the main axis of this gulf in late summer are presented. A similarity between the seasonal current structure of the Gulf of Aqaba and that of the Red Sea proper is indicated.

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FOREWORD

This note was prepared mainly for the benefit of the biologist with immediate interest in the currents, the temperature and salinity ranges, and the residence time of the water in the Gulf of Aqaba. In the calculation of the wind-driven transports, the simplest Ekman's model was used. Very little field work has ever been done in this basin, and I was in no position to reject any available data. VEMA station 69, for instance, is not close enough to the straits of Tiran and MANIHINE station 30 has only one temperature and three salinity samples ; nevertheless both stations are used in the analysis for want of better ones.I hope that this work will soon be replaced by a thorough analysis of a systematic survey, and that in the mean time it will be of some value to those interested in this region.

SOURCES AND PREVIOUS WORKS

The bottom topography of the Gulf of Aqaba is given by ALLAN and MORELLI (1971, Fig. 24). POR and LERNER-SEGEV (1966) compare the typical bottom steepness of this basin with that of four other long and narrow gulfs. SCHICK (1958) discusses the geologic structure of the straits of Tiran. The latest information on the sill depth indicates 243 meters at the saddle-point of the main passage (private communication).

MORCOS includes the gulf of Aqaba in his work on the Red Sea ; it appears that even in winter (January 1935) a clear thermocline existed in the central part at about sill depth (MORCOS 1970, p. 120, section D). In September 1967, the thermocline was thicker and, as expected, stronger (Fig. 2).

DEACON (1952) discusses the diurnal variation of surface temperature in the Gulf in early February. NEUMANN and Mc GILL (1962) note that the most saline water is that enclosed in the gulf of Aqaba below sill depth and that this water, 0,6°C colder than that outside the straits of Tiran, has high oxigen concentrations throughout the water column and no minimum layer, a fact mentioned also by MOHAMED (1940).

Although Luksch's equipment was very rudimentary by today standards, his description of the physical oceanography of the Gulf (1901) is by far the most complete. His work includes temperature and salinity charts for various depths, as well as a comparison of the general hydrographic features among the Gulf of Aqaba, the Gulf of Suez, and the Red Sea proper.

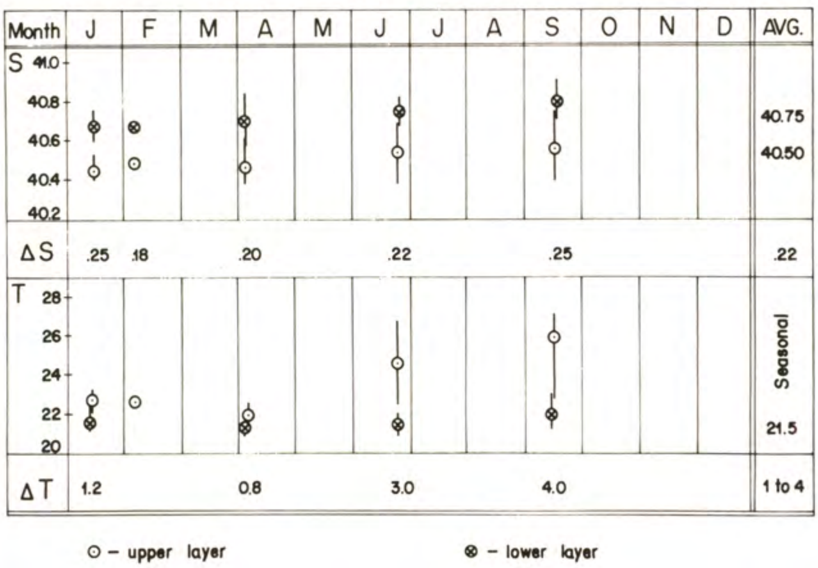

FIG. 1 : Temperature and Salinity at the straits of Tiran from five different cruises. S indicates salinity. Δ S indicates difference in salinity between lower and upper layers. T indicates temperature. Δ T indicates difference in temperature between upper and lower layers. At the top, the month during which the measurements were taken is indicated. (Temperature in degrees centigrade, salinity in parts per thousand)

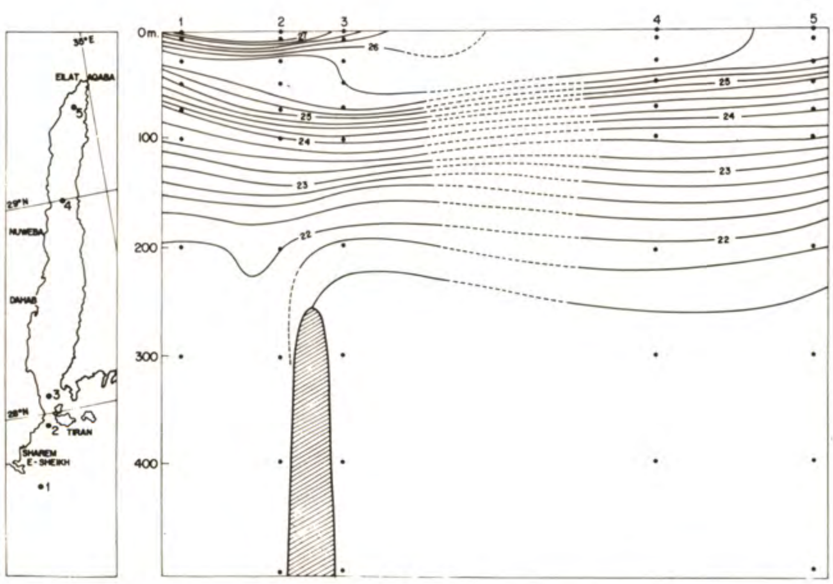

FIG. 2 : A temperature section along the main axis of the gulf of Aqaba in September. Temperature in degrees centigrades, depth in meters. INS SNAPIR stations 1 - 5 .

Evaporation rate in the Red Sea area is estimated by NEUMANN (1952) and by PRIVETT (1959).

The following five cruises include hydrographic stations in the gulf of Aqaba :

1 - S.M. POLA, April 1895.
2 - R/V MOBAHISS, January 1935.
3 - R/V MANIHINE, February 1949.
4 - R/V VEMA, June 1958.
5 - INS SNAPIR, September 1967.

From these sources, the typical temperature and salinity at the upper and lower layers could be estimated in the neighborhood of the straits of Tiran. The results are summarized in Fig. 1. Since hydrographic information from the INS SNAPIR cruise (1967) was never published, its temperature and salinity sections are here included (Figs. 2 and 3). I am grateful to H.O. Oren for letting me use his raw data.

Concerning the tides, MORCOS (1970) reports that in the Gulf of Aqaba high water is nearly simultaneous over the whole gulf. Tides observations at Eilat are reported yearly by the Israel Port Authority. Table 1 summarizes some averages and extremes for the year 1970.

Table 1 - Summary of tides observations at Eilat for the calendar year 1970.

MHW - Mean High Water. MLW - Mean Low Water.- MTR - Mean Tidal Range. MaxSR/day - Maximal Springtide Range / day of month. minNR/day - Minimal Neaptide Range/day of month. Numbers are in cm, reference is the zero Israel land survey datum.

Month	J	F	M	A	M	J	J	A	S	O	N	D
MHW	59.2	51.4	43.4	46.3	42.2	24.5	29.0	26.8	21.0	25.9	38.3	33.8
MLW	-5.5	-12.9	-12.2	-10.2	-21.5	-29.8	-26.5	-34.2	-40.0	-32.4	-16.8	-22.3
MTR	64.7	64.3	55.6	56.5	63.7	54.3	55.5	61.0	61.0	58.3	55.1	56.1
MaxSR/day	82/9	103/8	94/8	92/6	82/5	66/22	87/23	105/19	106/16	92/15	85/11	75/30
minNR/day	42/30	33/16	28/15	23/15	34/11	31/11	31/13	32/10	38/23	34/19	29/19	24/22

VOLUME TRANSPORTS

There is pratically no precipitation in this area. Evaporation is about 2 m/year (NEUMANN 1952 : PRIVETT 1959, Fig. 3) ; a net influx of water from the Red Sea proper must therefore result.

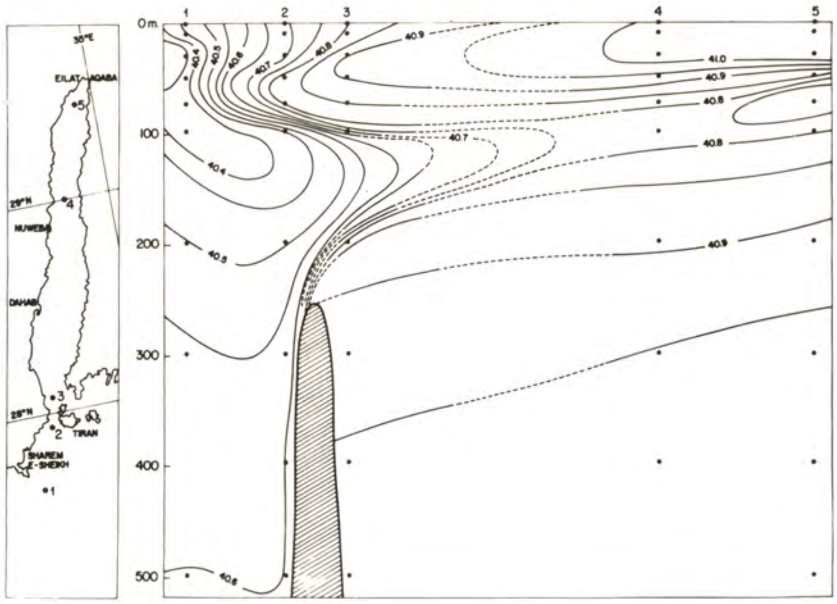

FIG. 3 : A salinity section along the main axis of the gulf of Aqaba in September. Salinity in parts per thousand, depht in meters. INS SNAPIR stations 1 - 5.

Assuming the evaporation estimate correct to within 20 % and since the surface area A is about $2,4.10^9$ m^2, we have for this influx :

$$V_E = 150 \pm 30 \quad m^3/sec \tag{1}$$

The thermohaline circulation typical to basins in arid zones is an inflow at the upper layers and an outflow at the deeper layers. The magnitude of the transports, V_{TH}, can be computed by conservation of mass and salt content (Knudsen's method) :

$$\left.\begin{aligned} V_{TH1} &= V_{TH2} - V_E \\ V_{TH1} \cdot S_1 &= V_{TH2} \cdot S_2 \end{aligned}\right\} \tag{2}$$

where the subscripts 1 and 2 indicate inflow and outflow respectively. Taking ΔS and its uncertainty from figure 1 we have :

$$V_{TH1} \sim V_{TH2} \equiv V_{TH}$$

$$V_{TH} = 3.10^4 \ m^3/sec \tag{3}$$

within a factor of 2.

The tidal transport, from table 1, is :

$$V_T = 3.10^4 \ m^3/sec \tag{4}$$

within a factor of 3,

in the vicinity of the straits, and of course diminishing toward the north.

Surface winds in the Gulf of Aqaba are in the direction of the main axis of the gulf, predominantly from the north. Their intensity along the coasts varies from 0 to 30 Kts, rarely exceeding 40 Kts, with an average around 10 Kts. (KESSLER 1972). Under strong winds of about 25 Kts, we have an Ekman transport $V_{Ek} = \tau/\rho f$, perpendicular to τ, of the order of 10 cubic meters per second per meter, most of it concentrated above the depth $D = \pi\sqrt{2K/f}$. This transport is expected to cause sinking on the Sinai coast, upwelling on the Arabian coast, and vice-versa on the rare occasions of southerly winds. More relevant, in our case, are the longitudinal Ekman transports (in the direction of τ) : a simple integration of the pure Ekman current from $z = - D/4$ to $z = 0$ shows that a net transport of magnitude

$$V_W = V_{Ek} \cdot \sqrt{2}/2 . e^{-\frac{\pi}{4}} \sim 1/3 \; V_{Ek} \qquad (5)$$

occurs in this shallow layer in the direction of τ. A return transport of the same magnitude but in the opposite sense occurs below $z = -D/4$ (see dotted line in Fig. 4). These two transports cancel each other when integrated from $z = - \infty$ to $z = 0$, a well known result. In our case, since the vertical distribution of currents is important, these two wind-driven transports in the direction of τ will be considered separately. Their magnitude, under the same conditions,

$$V_W = 3.10^4 \; m^3/sec \qquad (6)$$

and the variation depends upon τ.

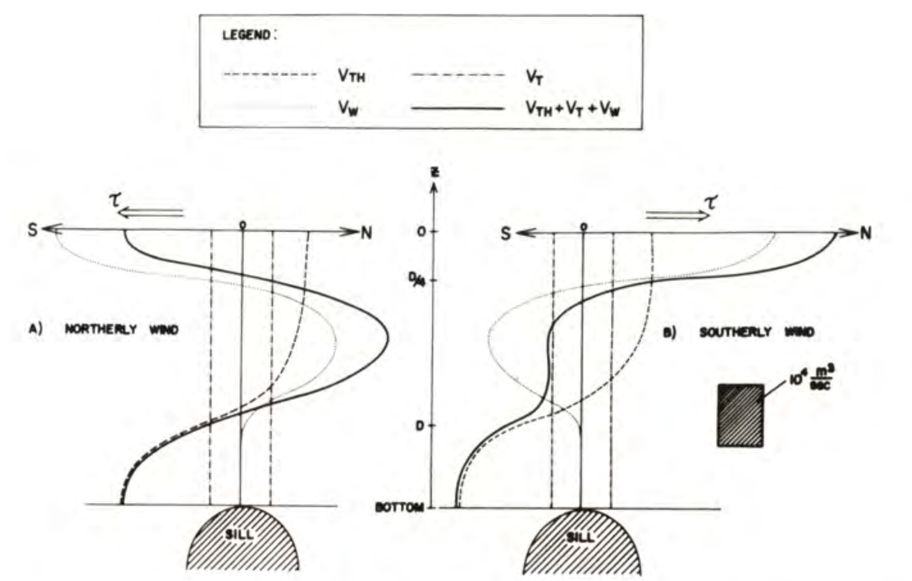

FIG. 4 : Schematic representation of the currents versus depth at the straits of Tiran, for southerly winds and northerly winds

COMMENTS

It is seen that V_E is about 200 times smaller than the other three transports considered. V_{TH}, V_T, and V_W are of the same magnitude, however they differ considerably from each other in their z-derivative, i.e. in the vertical structure of current. Superimposing the three types of current we arrive at two typical regimes, one for northerly winds and another for southerly winds (Fig.4). A prevailing three-layer structure is expected at the straits of Tiran (Fig. 4A), and occasionally, with southerly winds, a structure similar to the one depicted by figure 4B. The intrusion of Red Sea water into the gulf of Aqaba at intermediate depth may therefore be interpreted as being largely due to the Ekman return transport given by equations (5) and (6). This intrusion was prominent in September 1967 (Fig. 3) and it apparently was absent in January 1935 (MORCOS 1970, p. 120, section D). A general similarity between these two current regimes and those observed at Bab-el-Mandeb is indicated, although there are differences in sill depth and in duration of southerly winds.

Conservation of heat,

$$C_p \cdot V_{TH} \cdot \Delta T = H \cdot A \qquad (7)$$

enables to estimate the heat flux H through the surface A. Taking ΔT and its variation from figure 1 we arrive at :

$$H = (1,2 \text{ to } 5).10^{-3} \text{ cal/cm}^2 \text{ sec} \qquad (8)$$

By using an average depth of 800 meters, and assuming that the residence time t_r = volume/V_{TH} is meaningful for this basin, we have :

$$t_r \sim 2 \text{ years} \qquad (9)$$

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DISCUSSION AND COMMENTS

Dr. PEDGLEY : Spells of southerly winds at Eilat, lasting up to a few days and replacing the dominant northerlies, occur ahead of vigorous atmospheric disturbances moving eastwards across North Africa and the Mediterranean. These southerly winds can cover the whole length of the Red Sea, in which case the Red Sea Convergence Zone is temporaly destroyed, or they may cover only the northern part, in which case the convergence zone is not destroyed and northerly winds persist over the central Red Sea.

Pr. WYRTKI : Residence time is strongly dependent on the boundaries of the volume concelved. My calculation was for deep water only below the O_2 minimum.

Pr. LACOMBE : Volume of the Gulf ?

Dr. ANATI : $1,9.10^{12}$ m^3.

CIRCULATION HIVERNALE EN MER ROUGE

C. MAILLARD *

Résumé :

Une étude dynamique de la Mer Rouge a été effectuée sur les données du "Cdt ROBERT GIRAUD" (14 janvier - 7 février 1963) qui comprenaient 60 stations d'hydrologie classique et 2 parcours longitudinaux GEK. Nous avons calculé le courant geostrophique à partir de la surface de référence 300 dbars et, en surface nous avons comparé ces valeurs avec celles du GEK.

Un des principaux résultats est la mise en évidence de l'existence de courants traversiers ; le flux superficiel progresse vers le NNW par une série de méandres.

Par ailleurs, le calcul des flux à travers les différentes sections transversales, montre que le flux longitudinal croît du Sud au Nord, et que la solution de continuité n'est vérifiée que s'il y a des plongées d'eau dans la moitié Nord de la mer, et des remontées d'eau au Sud, conclusions qui sont en bon accord avec celles des études hydrologiques dans cette région.

Abstract : Winter circulation in the Red Sea

A dynamical study of the Red Sea has been made with the data of the "Cdt ROBERT GIRAUD" (January 14 th to February 11 th 1963) which includes 60 classical hydrology stations and 2 longitudinal GEK set of observations along the Sea. We have calculated the geostrophic current from the 300 dbars surface as reference, and, at 0 dbar, we have compared these values with those of the GEK.

One of the main results was to show the existence of cross-currents : the surface flux moves to the NNW with a succession of meanders.

Also, the calculation of the water transport across the different transvers sections shows that the longitudinal flux increases from South to North, and the continuity condition implies that there is a sinking of water in the North of the Sea and upwelling in the South. This agrees with the hydrological study of this region.

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INTRODUCTION

La circulation générale en Mer Rouge est encore mal connue : les mesures directes de courants sont rares, sauf dans quelques régions particulières comme le détroit de Bab-el-Mandeb et le Golfe de Suez (VERCELLI, 1927 et SIEDLER, 1968). En ce qui concerne la Mer Rouge proprement dite, la plupart des renseignements consignés dans les divers atlas de courants ou instructions nautiques proviennent du calcul de la dérive des navires et sont très imprécis. Le seul résultat qui ressorte vraiment nettement de ces observations comme des études hydrologiques est, en hiver, un flux superficiel d'ensemble vers le NNW selon l'axe de la mer et un flux profond de retour vers le SSW. En surface, des courants traversiers ont été observés par les navigateurs mais, compte-tenu de l'incertitude sur la position des navires (due à une réfraction atmosphérique anormale), leur existence et leur localisation sont très controversées.

Une première étude plus précise de la répartition des vitesses a été faite par BIBIK en 1968 pour le Nord de la Mer Rouge, en calculant le courant geostrophique à partir de la surface de référence 500 dbars sur les données du navire russe "ICHTYOLOGUE", pendant l'hiver 1964-1965. BIBIK montrait que le courant géostrophique forme, dans cette région, un tourbillon cyclonique, dont le centre oscille autour de 26°N au cours d'une même saison et auquel s'ajoute, par périodes, un tourbillon anticyclonique de moindre importance le long de la côte orientale.

Sur les données du "Cdt. ROBERT GIRAUD" (14 janvier - 9 fevrier 1963), comprenant 60 stations hydrologiques réparties en une coupe longitudinale et 10 coupes transversales (coupes I à R) ainsi que deux parcours longitudinaux GEK, nous avons pu faire une étude dynamique basée essentiellement sur le calcul du courant géostrophique à partir de la surface 300 décibars.

A ce niveau, les courants sont très faibles (c'est d'ailleurs l'immersion du sommet de la couche de minimum d'oxygène) et, en fait, au-delà de 200 m, un changement de surface de référence ne modifie pratiquement pas la répartition des vitesses calculées en surface. Pour les flux ce n'est pas vrai et la marge d'incertitude est assez élevée ; dans certains cas, en particulier dans le Nord de la Mer Rouge, les valeurs du flux longitudinal n'ont pu être prises en considération.

Malgré ses limites, il semble que le courant géostrophique donne, au premier ordre, une bonne idée de la circulation générale en Mer Rouge car, en surface, les observations du GEK sont en bon accord.

1° - Répartition des vitesses

Le courant géostrophique a, en surface (Fig. 1) et jusqu'à 75-100 dbars (voir Fig. 2 pour la surface 100 dbars), une composante générale selon l'axe de la mer mais sa distribution est irrégulière et présente des méandres, d'où une composante transversale importante. Il semble donc bien que les courants traversiers ont une existence réelle. Dans les observations du "Cdt. ROBERT GIRAUD", ils apparaissent principalement :

- entre les coupes K, L et M le courant a une composante transversale vers l'Ouest ;

les plus fortes valeurs, trouvées entre les coupes K et L, sont de 16 cm/s ;

- entre les coupes M et N, le courant porte à l'ENE, sa vitesse transversale vers l'est, maximale entre les stations 477 et 480, atteint 31 cm/s en surface ;
- entre la station 484 et la coupe 0 le courant porte à l'WNW ; la vitesse transversale, maximale entre les stations 484 et 487, est de 42 cm/s en surface ;
- entre les coupes P et Q, le courant porte à l'ENE, avec 24 cm/s de vitesse transversale en surface entre les stations 494 et 498 ;
- entre la coupe R et l'extrémité septentrionale de la mer, un courant vers l'Ouest de 20 cm/s en surface.

Ces courants sont associés à des tourbillons, dont trois ont une assez grande extension. Un premier, anticyclonique, est centré approximativement sur la station 477 dans la région où le"Cdt ROBERT GIRAUD" a trouvé la convergence des vents ; un autre, cyclonique, centré sur la station 484 et, enfin, un grand tourbillon cyclonique dans le Nord de la mer.

Cette répatition des vitesses est en bon accord avec le courant fourni par les deux parcours longitudinaux GEK (voir Fig. 1), qui montrent que :

- il existe bien des courants traversiers, dans des zones qui coïncident à peu près avec celles indiquées par le calcul géostrophique ;
- les vitesses transversales croissent du Sud au Nord ;
- outre les courants traversiers décelés par la méthode dynamique, il existe entre les coupes 0 et P un méandre cyclonique que le trop grand espacement des stations hydrologiques dans cette région n'avait pas permis de déceler.

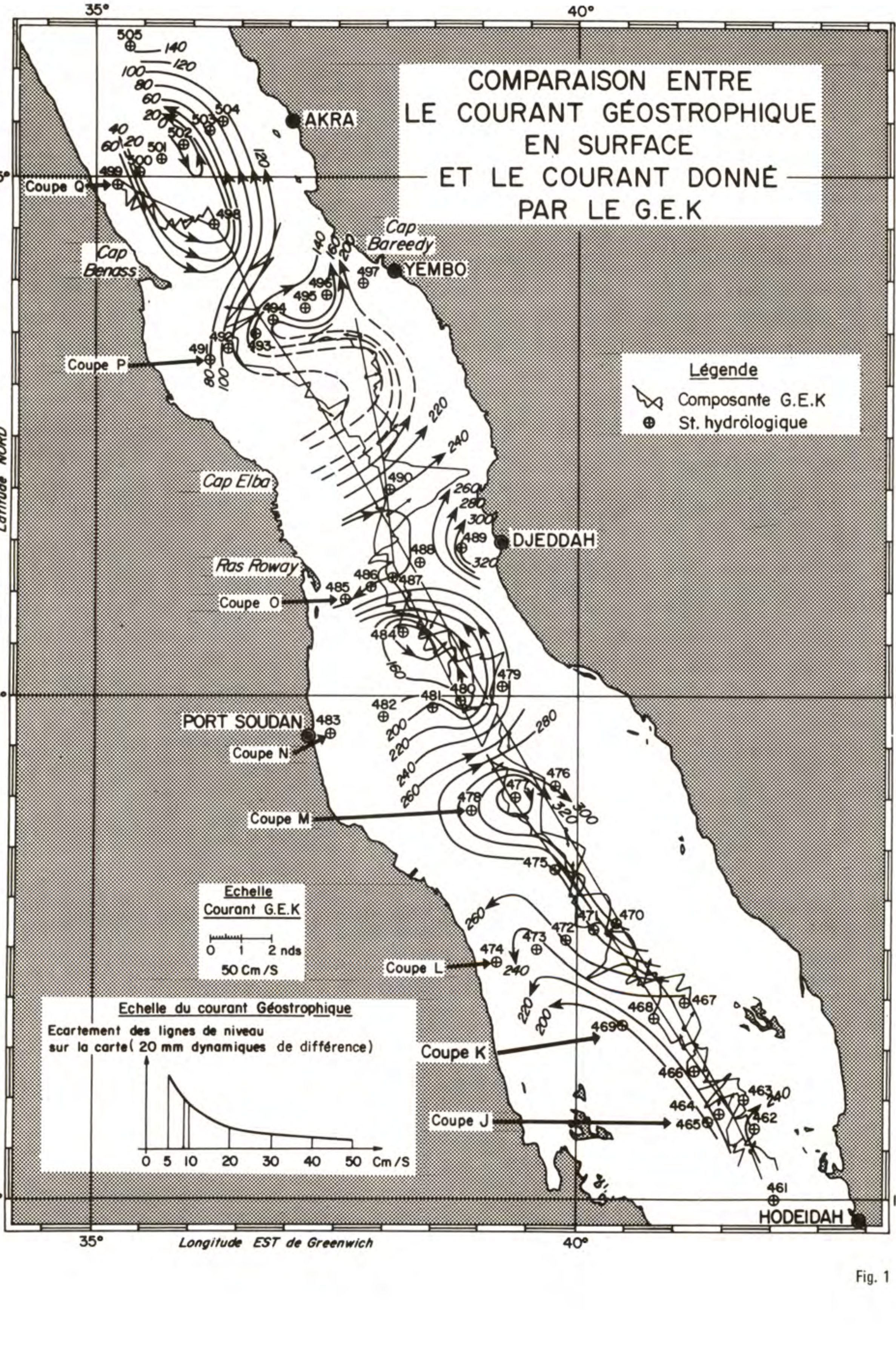

COMPARAISON ENTRE
LE COURANT GÉOSTROPHIQUE
EN SURFACE
ET LE COURANT DONNÉ
PAR LE G.E.K
Légende
Composante G.E.K
St. hydrólogique
Echelle
Courant G.E.K
0 1 2 nds
50 Cm/S
Echelle du courant Géostrophique
Ecartement des lignes de niveau
sur la carte(20 mm dynamiques de différence)
0 5 10 20 30 40 50 Cm/S
AKRA
YEMBO
DJEDDAH
PORT SOUDAN
HODEIDAH
Cap Benass
Cap Bareedy
Cap Elba
Ras Roway
Coupe Q
Coupe P
Coupe O
Coupe N
Coupe M
Coupe L
Coupe K
Coupe J
35°
40°
25°
20°
15°
Latitude NORD
Longitude EST de Greenwich

Fig. 1

En ce qui concerne la répartition verticale de la vitesse, un fait caractéris- -ristique apparaît. Au Sud de la Mer Rouge, le courant devient négligeable au-dessous de 100 m d'immersion (voir coupe K, Fig.3 a), tandis qu'au Nord, on a des vitesses de plus de 5 cm/s sur les 200 premiers mètres d'eau (voir coupe O, Fig. 3b). Ce fait traduit l'intensification de la circulation thermohaline du Sud au Nord et va être précisé d'une manière plus quantitative avec le calcul des flux.

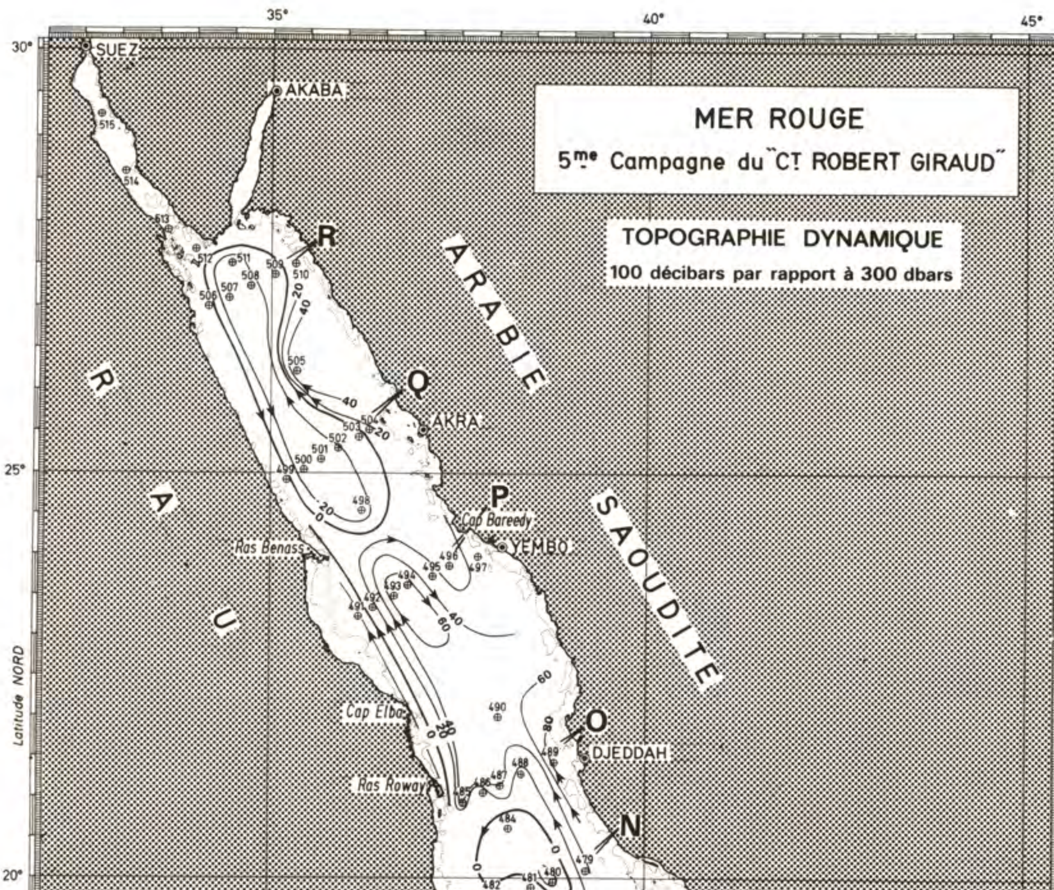

MER ROUGE
5me Campagne du "Ct ROBERT GIRAUD"
TOPOGRAPHIE DYNAMIQUE
100 décibars par rapport à 300 dbars
SUEZ
AKABA
AKRA
Cap Bareedy
YEMBO
Ras Benass
Cap Elba
DJEDDAH
Ras Rowaya
PORT SOUDAN
Ras Hurub
HODEIDAH
ADEN
DJIBOUTI
ARABIE
SAOUDITE
R A U
SOUDAN
ETHIOPIE
YEMEN
Ecartement des lignes de niveau sur la carte (20mm dynamiques de différence)
cm/s
ECHELLE MOYENNE (LAT. 20°30')
50 0 100 200 300 400 Km
Latitude NORD
Longitude EST de Greenwich

Fig. 2

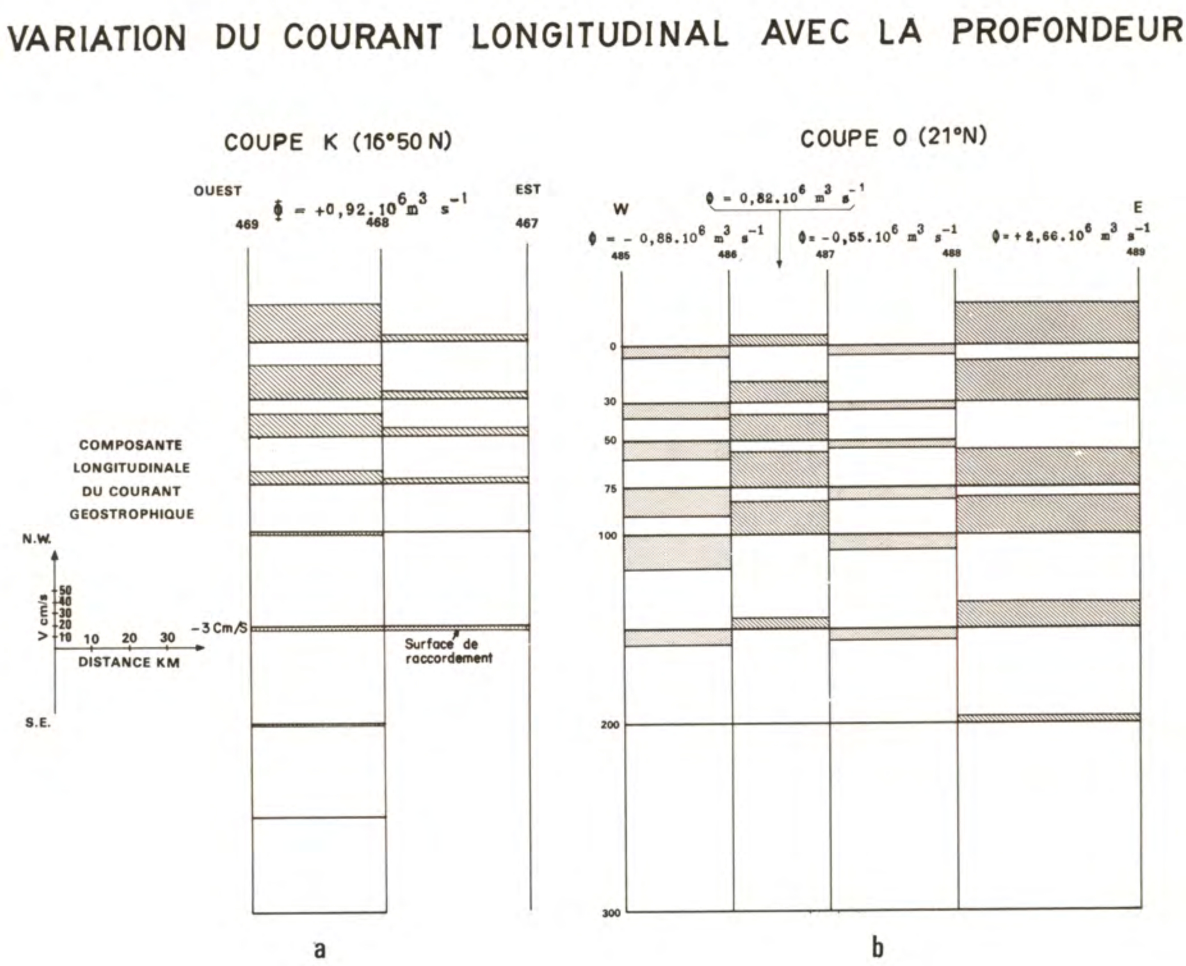


Fig. 3

2° - Flux d'eaux transportés et mouvements verticaux

Les flux d'eaux transportés entre 0 et 300 m à travers les diverses sections sont donnés en m^3/s dans le tableau suivant. Les signes + correspondent à des courants vers le NW, les signes - à des courants vers le SE. Nous avons aussi porté sur ce tableau les épaisseurs d'eau H intéressées par des vitesses de plus de 5 cm/s:

Tableau I

Position	Stations	H	Φ en m^3/s	
Coupe J - 15°50'N	465 - 463	75	+ $0{,}46.10^6$	+ $0{,}46.10^6$
Coupe K - 16°50'N	469 - 467	75	+ $0{,}92.10^6$	+ $0{,}92.10^6$
Coupe L - 17°30'N	474 - 473 473 - 470	150 100	- $1{,}44.10^6$ + $2{,}04.10^6$	+ $0{,}60.10^6$ *
Coupe M - 19°N	478 - 477 477 - 476	150	+ $1{,}25.10^6$ - $1{,}30.10^6$	- $0{,}05.10^6$ *
Coupe N - 20°N	483 - 482 482 - 481 481 - 480 480 - 479	150 150	- $0{,}28.10^6$ + $0{,}53.10^6$ - $1{,}24.10^6$ + $1{,}87.10^6$	+ $0{,}88.10^6$ *
Coupe O - 21°N	485 - 486 486 - 487 487 - 488 488 - 489	150 150 150 200	- $0{,}88.10^6$ + $0{,}82.10^6$ - $0{,}55.10^6$ + $2{,}66.10^6$	+ $2{,}05.10^6$
Coupe P - 24°N	491 - 494 494 - 496 496 - 497	200 200 100	+ $3{,}14.10^6$ - $1{,}98.10^6$ + $1{,}01.10^6$	+ $2{,}17.10^6$
Coupe Q - 25°N	499 - 502 502 - 504	200	- $1{,}50.10^6$ + $1{,}69.10^6$ **	
Coupe R - 27°N	506 - 508 508 - 510	200	- $0{,}51.10^6$ + $1{,}57.10^6$	+ $1{,}06.10^6$

* Les flux globaux calculés sont certainement très inférieurs à leurs valeurs réelles car les stations ont été effectuées trop loin de la côte Est.

** Les valeurs des flux sont très imprécises du fait de la difficulté de déterminer la surface de mouvement nul dans cette région.

Si l'on admet que par fonds inférieurs à 50 m, le flux d'eau permanent est négligeable, les sections J, K, O, P et R où la distance des stations extrêmes à la ligne de hauts fonds ne dépasse pratiquement pas 10 milles, permettent de calculer le flux moyen vers le NW. Celui-ci varie de section en section. Pour que l'équation de continuité soit vérifiée, il est nécessaire d'admettre des remontées d'eau dans tout le sud de la Mer Rouge jusqu'à la coupe O et des plongées d'eau au Nord de la coupe P. Sur les coupes O et P, le flux horizontal a sensiblement la même valeur. Dans le tableau suivant, nous avons porté la valeur de ces flux verticaux (en 10^6 m^3/s) et celle des vitesses verticales moyennes qui en découlent (en m/jour).

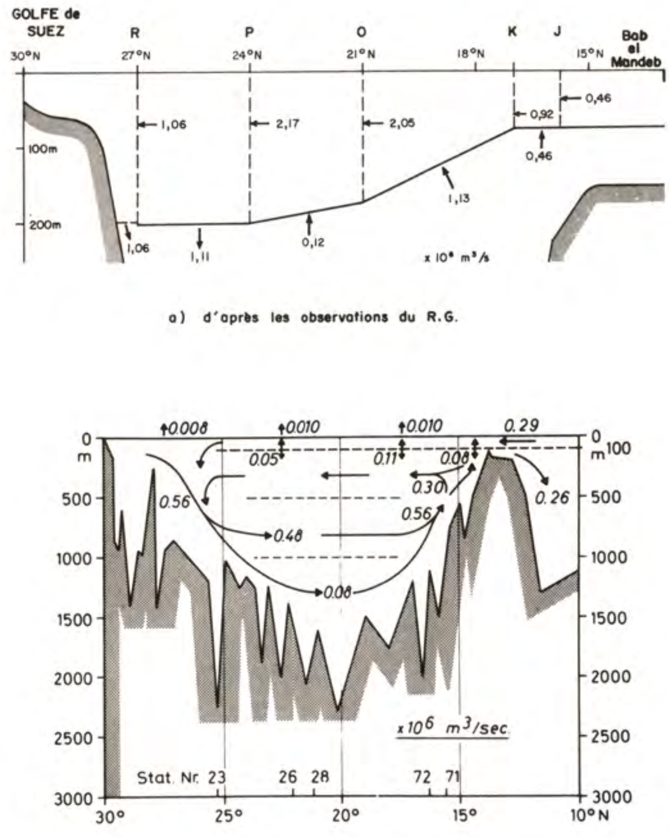
Tableau II

Région	Côte Nord Coupe R	R-P	P-O	O-K	K-J
Superficie $.10^9$ m^2	7,9	79,0	53,9	110,4	7,9
Flux vertical entre sections $.10^6$ m^3/s	- 1,06	- 1,11	+0,12	+ 1,13	+ 0,46
Vitesse verticale moyenne m/jour	- 11,6	- 1,2	+ 0,2	+ 0,9	+ 5,0

Ces résultats concordent très bien avec les conclusions de l'hydrologie et il est remarquable que l'on trouve précisément les plus fortes vitesses verticales vers les deux extrémités de la Mer Rouge. On peut résumer la circulation globale sur un schéma (Fig. 4 a).

En 1969, GRASSHOFF avait déjà donné un tel schéma à partir des données du "METEOR" (Fig. 4 b). Il admettait la conservation du flux dans la couche superficielle supposée d'épaisseur constante, entre 15°N et 25°N, l'évaporation étant négligeable devant les flux horizontaux et les échanges avec l'eau profonde mettant en jeu les mêmes quantités d'eau dans les deux sens. Les deux schémas sont donc assez différents. Cependant, le schéma de GRASSHOFF n'est fondé que sur l'examen d'une seule coupe longitudinale ; il ne donne donc qu'une hypothèse sur la valeur des flux. Les calculs présentés ci-dessus font, au contraire, appel à des données recueillies sur des coupes transversales : malgré l'incertitude qu'ils comportent, ils donnent au moins des résultats qualitatifs et un ordre de grandeur des phénomènes.

SCHEMAS DE LA CIRCULATION EN MER ROUGE



a) d'après les observations du R.G.

b) d'après GRASSHOFF 1969

Fig. 4

Conclusion

L'étude du courant géostrophique semble donner une bonne idée de la circulation générale en Mer Rouge car elle s'accorde, d'une part avec les données du GEK en surface, d'autre part avec les conclusions générales de l'hydrologie. Elle a permis de mettre en évidence ;

1 - l'existence de méandres dans le flux superficiel vers le NNW, où la vitesse moyenne est de 20 à 40 cm/s ;

2 - l'intensification de la circulation thermohaline du Sud au Nord de la Mer Rouge

le flux superficiel vers le NNW étant environ le triple au Nord de la mer de ce qu'il était au niveau du détroit de Bab-el-Mandeb ;

3 - l'amplification des mouvements verticaux aux deux extrémités de la mer, avec des vitesses moyennes de l'ordre du mètre par jour.

Cependant, il faut noter que ces résultats comportent une assez large marge d'incertitude, en particulier en ce qui concerne les flux et il est vivement à souhaiter de pouvoir disposer un jour d'un assez large réseau de mesures directes.

Un autre point qu'il n'a pas été possible d'élucider par ce réseau unique de stations dans le même hiver est la durée de persistance de méandres superficiels. Or, pour pouvoir étudier la genèse de ces méandres (effet du vent ou du relief des côtes), il est nécessaire de savoir si leur position varie ou s'ils sont stationnaires. Dans ce but, une observation à intervalles réguliers de la répartition de la température de surface pourrait déjà donner une bonne idée de la variabilité du phénomène.

Remerciements

L'auteur tient à exprimer ici sa gratitude à Monsieur MENACHE, chef de mission lors de la 5ème campagne du "Cdt. ROBERT GIRAUD", aux scientifiques et à l'équipage de ce navire, qui prirent part aux opérations. Elle remercie bien vivement le Professeur LACOMBE et le Professeur TCHERNIA, qui l'ont guidée et conseillée dans ce travail, ainsi que ses camarades du Laboratoire d'Océanographie Physique du Muséum, en particulier P. GUIBOUT et M. CREPON pour les données du GEK, l'équipe cartographique et le secrétariat.

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DISCUSSION AND COMMENTS

Dr. SHARAF EL DIN : Did you try different formulas for choosing the reference level ?

Dr. MAILLARD : I tried two methods.

1. To search for the level at which the flux through a transverse section was equal to zero. However, it is very difficult to find a reference level like this. The depth seems very variable and in many sections we do not have enough stations between the continental shelf and the open sea. Also we found that the velocities between some stations in deep water are too high to permit the use of this method.

2. We took the depth for which the ΔD variations between the neighbouring stations was negligible (the DEFANT's criterium). In fact, below 200-300 dbars, whatever the reference depth, the current pattern is almost the same (the incertitude of the value is about 3 cm/s).

For the fluxes this is not true, especially in the North of the Sea, so we have made the calculation with two possible reference levels : 300 and 500 dbars. When the difference between the two determinations was too high we have omitted the results.

Dr. SHARAF EL DIN : What did you do with regard to the shallow stations ?

Dr. MAILLARD : For these stations I have supposed that the velocity at the deepest level of the observations was equal to the velocity between the nearest stations at the same level.

In fact there were few stations in depths less than 300 meters. On the continental shelf, the water is very shallow with many coral reefs which makes it dangerous for navigation, so pratically no stations have been made there. After the continental shelf, the depth increases very abruptly and reaches 500-700 meters.

Dr. SHARAF EL DIN : Did you try to take one reference level for the whole Red Sea or did you choose different levels for each station ? Which do you think is better?

Dr. MAILLARD : We took the same level (300 dbars) for all of the Red Sea. For almost all of the Sea, except at the extreme northern and southern ends, this is a level of very little movement because it is the upper part of the oxygen minimum. It is only an approximation, but by not considering the variation of the depth of the reference surface in the Red Sea, we don't alter the result any more than the degree of incertitude of the geostrophic method itself.

Pr. WYRTKY : On the other hand, you must consider the fact that your stations are taken at one particular moment and the structure in the ocean and also in the Red Sea changes with time. A reference level is probably not existing in a synoptic situation over a short interval. A climatic mean may be existing.

One other thing, I was worried about. This is your figure 4. In one of the sections you had about one million cubic meters per second being included in the horizontal flux and the same magnitude for the vertical flux which gives a vertical velocity of about 5 m/day. That means that the surface layer (50-100 m in depth) will be drained in about 20 days. So it is difficult to operate with a big transport like that.

Pr. LACOMBE : This is a way to battle with existing observations.

Pr. WYRTKI : It's a problem. Reference levels are always something very difficult to choose.

Pr. LACOMBE : Another problem is how the gyres in the circulation are generated ?

Pr. WYRTKI : First of all, we have seen it from the meteorology that these are these bursts of southerly and northerly winds that are alternately occurring. Now, these winds can definitely cause gyres, both cyclonic and anticyclonic of the size shown on the diagrams. Secondly, I do not believe that this situation that was observed during the "Cdt. GIRAUD" cruise would be typical for all Novembers or Decembers. I think that in another year you may find the gyres somewhere different.

Dr. ROBINSON : Their position might move slightly.

Dr. WYRTKI : You see the gyres you find in a sea like the Red Sea, even if they could be generated in different locations, will be somewhat dependent on bottom topography. I would guess from the map that this place is definitely forming a gyre because of the shape of bottom topography. So the location of the gyres after they have been formed will then be affected by the topography of the sea. Also they will prefer places of development in the same way as the Mistral will always develop at the same place even if the atmospheric circulation may be slightly different.

Dr. ROBINSON : The maximum temperature does alternate between 14°N and 19°N or 15°N and 19°N and in TUNNEL's paper, where there are 2° averages I think it's from 14°N to 20°N. But it does do this and you can certainly see it in the charts. Also, in the North, where you have this transverse gradient across the sea, I think that this is the source and it does persist practically all of the time.

What surprises me in her results is the actual strength of the current on the right side rather than the current on the Arabian side. I am not surprised that we have these currents but that the strengths were as she showed them. This was a very interesting result to me.

Pr. WYRTKI : It is apparently a somewhat meandering flow that is chiefly concentrated on the Arabian side.

VOLUME AND HEAT TRANSPORTS BETWEEN THE RED SEA AND GULF OF ADEN, AND NOTES ON THE RED SEA HEAT BUDGET

William C. PATZERT *

Abstract

Estimates of the monthly mean transports of volume and heat exchanged over the shallow sill separating the Red Sea and Gulf of Aden below 100 m depth are calculated. During the winter monsoon season (October to May), the surface transport into the Sea and subsurface transport into the Gulf is approximately 0.44×10^{12} cm^3s^{-1}, while during the summer monsoon period (June to September) the exchange reverses and a surface outflow of Red Sea water and subsurface inflow of Gulf of Aden water of 0.14×10^{12} cm^3s^{-1} occurs. These volume transports are confirmed by volume transports calculated from direct current observations and by agreement of the calculated annual net heat transports with the annual net heat exchange between the Sea and atmosphere (YEGOROV, 1950), which are both close to zero.

Résumé : Transports d'eau et de chaleur entre la Mer Rouge et le Golfe d'Aden et notes sur le bilan calorifique de la Mer Rouge

Des estimations des transports moyens mensuels, d'eau et de chaleur au-dessus du seuil peu profond séparant la Mer Rouge et le Golfe d'Aden au-dessous de 100 m de profondeur ont été faites. Pendant la mousson d'hiver (octobre à mai), le flux superficiel dans la Mer Rouge et le flux subsuperficiel dans le Golfe d'Aden sont approximativement $0,44.10^{12}$ cm^3s^{-1}, tandis que pendant la mousson d'été (juin à septembre) les échanges sont inversés et on a un courant de sortie superficiel des eaux de la Mer Rouge et un courant subsuperficiel d'eau du Golfe d'Aden de $0,14.10^{12}$ cm^3s^{-1}. Ces valeurs des flux sont confirmées par les flux calculés à partir d'observations directes de courant et par l'accord que l'on trouve entre le transfert annuel de chaleur et la quantité de chaleur échangée annuellement entre la mer et l'atmosphère (YEGOROV, 1950), qui sont toutes deux proches de zéro.

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INTRODUCTION

The water masses of the Red Sea and Gulf of Aden are separated by a shallow sill (~100 m depth) which is located near Hanish Island at 13°40'N, 125 km NNW of the narrowest passage (only 27 km wide) of the Strait of Bab-el-Mandeb (Figure 1). Because in this region the Sea is both narrow and shallow, it is the most advantageous location to measure the exchange of water between the Sea and Gulf.

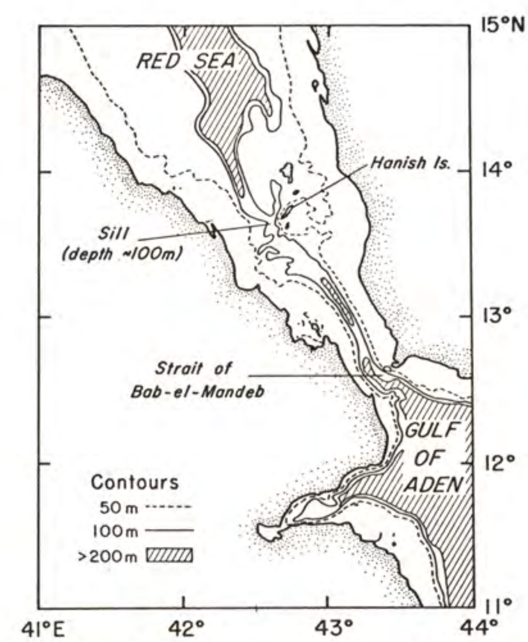

Figure 1. Bathymetric chart of the southern Red Sea and western Gulf of Aden (after chart in Morcos, 1970.)

The only quantitative estimates of this exchange are calculations by VERCELLI (1925) from 15 days of current measurements obtained during the March 1924 ARIMONDI cruise and by SIEDLER (1968) from moored recording current-meter observations taken during the November 1964 METEOR cruise. Both sets of current observations were obtained in the central channel of the Sea, south of the shallow sill and near the narrowest passage through the Strait. Vercelli's calculations for March 1924 showed a surface flow into the Red Sea of 0.58×10^{12} cm^3s^{-1} and a subsurface outflow of 0.48×10^{12} cm^3s^{-1}. Siedler's analysis showed a similar distribution, with a (November) surface inflow of 0.58×10^{12} cm^3s^{-1} and a subsurface outflow of 0.42×10^{12} cm^3s^{-1}. During other months the only quantitative information about the flow through the Strait is the calculated displacements between astronomical positions and "dead reckoning" positions (ship's drift) recorded by ships passing through the Strait. For the 13°-14°N latitude strip, within which the shallow sill is located, the Koninklijk Nederlands Meteorologisch Instituut (KNMI) Atlas (1949) summarizes over 7,100 ship's drift observations taken there and presents them as monthly mean surface current vectors. The ship's drift observations are combined with a recent discussion of the seasonal variations in the hydrographic structure over the sill (PATZERT, 1972) to calculate the monthly and annual mean heat and volume transports between the Red Sea and the Gulf of Aden. These transports are confirmed by :

a - Agreement of the calculated volume transports with volume transports calculated from direct current observations obtained in the Strait,

b - Calculating from the monthly mean temperature structure over the sill the gains or losses of heat within the Red Sea due to these transports, which agree with YEGOROV's (1950) conclusion that the annual net heat exchange between the water and atmosphere over the Sea is small.

Seasonal variations in structure and circulation over the sill

The following discussion of the seasonal variations in the exchange of water over the sill between the Red Sea and the Gulf of Aden is summarized from PATZERT (1972) and is explained in greater detail there. Figure 2 presents the monthly mean surface currents and surface winds for the 13°-14°N latitude strip (taken from KNMI, 1949) and the monthly mean changes in vertical temperature structure over the sill (taken from PATZERT, 1972).

Over the sill from October to May, the water exchange between the Red Sea and the Gulf of Aden is controlled by the winter monsoon winds over the southern Sea and Gulf. Direction of surface winds and flow between 13°-14°N is toward the NNW. From October to March, the strong monthly mean vector SSE winds of 6.7 to 9.3 m s^{-1} cause a warm, low-salinity (T ~25.5° to 30.0°C, S ~36.5 °/₀₀) surface inflow with a surface speed of 20 cm s^{-1}. Beneath this inflow, there occurs a subsurface outflow into the Gulf of Aden of warm, high-salinity Red Sea water (T ~24.0°C, S ~39.7 °/₀₀).

From early June to mid-September, the direction of winds over the southern Red Sea and Gulf of Aden are reversed, and the summer monsoon winds blow out of the Sea into the Gulf and toward the Arabian Sea. At the southern entrance to the Sea in the northwestern Gulf of Aden, the southwesterly winds cause an intense coastal upwelling beginning in July. The resulting drop in steric sea level in the Gulf of Aden causes the sea-surface slope through the Strait of Bab-el-Mandeb to drop towards the Gulf. This slope combines with the weak (2.4 m s^{-1}) NNW winds present between 13° and 14°N to cause a warm, high-salinity (T ~31.0°C, S ~ 37,3 °/₀₀), shallow (~ 20 m depth) surface outflow of 20 cm s^{-1}. Beneath this outflow, a cool, low-salinity (T ~18.0 to 24.0°C, S ~36.0 °/₀₀) inflow between 30- and 80-m depth of Gulf of Aden water is observed, but only from July through

September. This inflow of cool, low-salinity Gulf of Aden water is due to the reversal in the pressure gradient between 30- to 80-m depth over the sill. Two effects combine to reverse the pressure gradient ; the wind-induced coastal upwelling of cool, low-salinity water in the northwestern Gulf of Aden increases the density of the waters in the upper 100 m south of Bab-el-Mandeb, while the summer heating of the water column to approximately 80-m depth in the southern Red Sea decreases the density of the waters north of Bab-el-Mandeb. Beneath this layer, a third layer of highly saline Red Sea water continues to flow out of the Red Sea into the Gulf of Aden, as it does during winter, but its transport is much smaller during the summer than during the winter.

Calculation of volume and heat transports

During the winter, surface inflow is warmer than subsurface outflow, while during the summer the reverse is true : the subsurface inflow is cooler than the surface outflow (Figure 2).

Thus, during winter there is a net gain of heat in the Red Sea by advection and during summer a loss of heat by advection. This seasonal pattern of heat exchange by advection between the Red Sea and the Gulf of Aden suggests that the annual net exchange is small. These facts, as well as estimates of the monthly and annual mean volume transports between the Sea and Gulf over the sill, can be demonstrated quantitatively by the following simplified model : During any month the inflow or outflow of water in the surface layer must approximately equal that in the subsurface layer or layers. The small difference between the flows would be the water compensating for evaporation or for a regional change in sea level. For instance, the transport needed to compensate for an annual average loss of water due to evaporation of 200 cm yr^{-1} [estimates vary from 230 cm yr^{-1} (YEGOROV, 1950) to 183 cm yr^{-1} (PRIVETT, 1959)] over the surface area of the Sea (4.4×10^{15} cm^2) is only 0.03×10^{12} cm^3s^{-1}, as compared to the 0.58×10^{12} cm^3s^{-1} surface volume transports calculated by VERCELLI (1925) and SIEDLER (1968) from current observations.

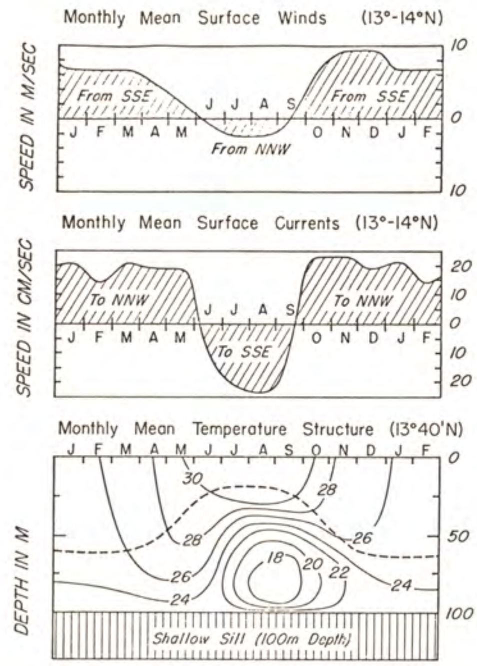

Figure 2. Montly mean vector winds near the sea surface between 13° and 14°N in the Red Sea (top), monthly mean surface currents as calculated from ship's drift observations between 13° and 14°N (middle), and monthly mean variation of thermal structure (°C) over the shallow sill at 13°40'N (lower). The mixed-layer depth, defined as the depth at which temperature deviates from surface temperature by 1°C, is indicated by the dashed line. January and February are repeated.

Data from coastal sea-level stations in the northern, central, and southern Red Sea indicate that the entire Red Sea exhibits a seasonal variation in mean sea level (PATZERT, 1972). The calculated monthly mean sea levels are at a maximum in winter and decrease from May to late summer, rising rapidly again in the fall. The range of this variation is approximately 30 cm. A difference in volume transport of 0.01×10^{12} cm^{3}s^{-1} is needed to cause the observed $\pm$ 30 cm variation in monthly mean sea level every six months. Thus, a maximum difference between the inflow and outflow of 0.04×10^{12} cm^{3}s^{-1} occurs during the fall, when mean sea level is rising, while from May to late summer this difference is only 0.02×10^{12} cm^{3}s^{-1}, because the evaporation can be partially accounted for by the drop in mean sea level. Since the differences between the inflows and outflows due to evaporation and sea level changes must be small, these will be ignored in the following calculations.

It should be noted that VERCELLI (1924) and SIEDLER (1968) calculated differences between the inflows and outflows of 0.10×10^{12} and 0.16×10^{12} cm^3s^{-1}, respectively. Differences of 0.10×10^{12} cm^3s^{-1} or 0.16×10^{12} cm^3s^{-1} during a month yield evaporations or rises in mean sea level of 68 cm or 110 cm during that month, or any combination of these two processes. Since the magnitudes of evaporation and mean sea level variation indicated by the 0.10×10^{12} cm^3s^{-1} or 0.16×10^{12} cm^3s^{-1} differences are not observed, one must conclude that both VERCELLI and SIEDLER did not exercise enough care with their calculations. In the calculations that follow, the question of whether their calculated inflows are too high or outflows are too low will not be answered. It should also be noted that calculated monthly mean transports that follow will be confirmed by comparing them with the SIEDLER and VERCELLI transports. Thus, the transports to be calculated will have the same uncertainty as the VERCELLI and SIEDLER transports, approximately $\pm$ 0.06×10^{12} to 0.12×10^{12} cm^3s^{-1} or $\pm$ 10 to 20 %.

As previously noted, exchange over the sill during winter is a two-layer system, but in summer this exchange becomes a three-layer system. Analyses by THOMPSON (1939), KHIMITSA (1968) and PATZERT (1972) indicate that during summer the outflow of Red Sea water over the sill is much smaller than during winter. Although no direct current observations exist for the summer outflow, it is reasonable to assume that this bottom outflow over the sill is an order of magnitude less than both the cool, low-salinity inflow and surface outflow above it. In the following calculation, this latter bottom summer outflow will be considered negligible.

Given the assumptions of a two-layer exchange with approximately equal and opposite transports, the continuity of water volume in the Red Sea as given by the flow over the sill during any month can be expressed approximately by

$$V_1 . b . d_1 = V_2 . b . d_2 \qquad (1)$$

where

V_1 = average velocity in surface layer
V_2 = average velocity in subsurface layer
b = width of Red Sea at 13°-14°N latitude
d_1 = thickness of the surface layer
d_2 = thickness of the subsurface layer.

The difference between the transport of heat by surface and by subsurface flows at Bab-el-Mandeb is the net heat gained or lost by advection in the Red Sea. This is expressed as

$$c_p \, \rho \, T_1 \, V_1 \, b \, d_1 - c_p \, \rho \, T_2 \, V_2 \, b \, d_2 = Q \qquad (2)$$

where

T_1 = average temperature in surface layer
T_2 = average temperature in subsurface layer
c_p = heat capacity of sea water
ρ = density of sea water
Q = net transport of heat (cal sec^{-1})

Substituting equation (1) in (2) gives :

$$c_p \rho \; b \; V_1 \; d_1 \; (T_1 - T_2) = Q \qquad (3)$$

By dividing Q by the surface area of the Sea (4.4×10^{15} cm^2) and multiplying Q by the number of seconds in a day (0.864×10^5), a new parameter Q' is defined. Q' is expressed as cal cm^{-2} day^{-1} so that the magnitude of the advective exchange Q' can be compared to the magnitude of the net heat gained or lost through surface exchange with the atmosphere over the Sea. Thus equation (3) becomes

$$c_p \; \rho \; b \; V_1 \; d_1 (T_1 - T_2) = Q' (\text{cal cm}^{-2} \text{ day}^{-1}) \qquad (4)$$

The shallow sill is located at 13°40'N. Consequently, the observations needed to calculate volume and heat transports, given by equations (1) and (4) respectively, are taken from the 13°-14°N latitude strip. The value used for b was the average width of the Sea between 13° and 14°N, approximately 60 km. T_1 and T_2 are the average temperatures of the two layers (see Figure 2). The observed vertical distribution of velocity in the Strait during two weeks in November-December 1964 shows that thickness of the inflowing surface layer corresponded approximately to the mixed-layer depth and the mean speed in this layer was approximately three-fourths of the mean surface velocity (SIEDLER, 1968) ; consequently, the value used for V_1 is three-fourths the mean surface velocity as given by ship's drift observations and d_1 is the mixed-layer depth (shown in Figure 2). Another justification for choosing V_1 as three-fourths the ship's drift velocities is that a choice of larger or smaller values of V_1 results in November and March surface transports that do not agree with SIEDLER'S and VERCELLI'S calculated transports. Since varying the depth d_1 has a small effect on the value of $T_1 - T_2$ in equation (4), the choice of the mixed-layer depth is less critical than the choice of V_1 to the calculation of heat transports. Table 1 shows the values used for V_1, d_1, T_1, T_2 and the tabulations of equations (1) and (4).

Table 1 - Approximate monthly mean transports in the surface layer, which are approximately equal to the oppositely directed subsurface transports, between the Red Sea and the Gulf of Aden and the net gains or losses of heat for each month due to these transports. Positive surface transports indicate flow into the Red Sea and negative indicate flow into the Gulf of Aden. Positive heat transports indicate heat gains and negative indicate heat losses.

Month	V_1 cm s^{-1}	d_1 m	T_1 °C	T_2 °C	T_1-T_2 °C	Net Heat Transport cal cm^{-2} day^{-1}	Surface Volume Transport $\times 10^{12}$ cm^3 s^{-1}
Jan	15.7	60	25.5	24.0	1.5	16	.57
Feb	11.1	60	25.5	24.0	1.5	12	.40
Mar	15.7	60	26.5	24.0	2.5	27	.57
Apr	14.1	50	28.0	24.0	4.0	32	.42
May	14.1	45	29.5	24.0	5.5	39	.38
Jun	6.3	20	31.0	24.0	7.0	-12	-.06
Jul	-15.7	20	31.0	21.0	10.0	-38	-.20
Aug	-17.4	20	31.5	20.0	11.5	-45	-.21
Sept	- 6.3	25	32.0	18.0	14.0	-24	-.09
Oct	17.4	50	30.0	21.0	9.0	90	.52
Nov	17.4	55	27.5	22.0	5.5	60	.57
Dec	14.1	60	26.5	24.0	2.5	24	.51
					Annual Net Advective Heat Exchange	15	

SUMMARY AND CONCLUSIONS

1 - Table 1 shows that monthly mean volume transports over the sill vary from a maximum surface inflow and subsurface outflow of approximately 0.57×10^{12} cm^3s^{-1} in November, January, and March to a maximum surface outflow and subsurface inflow of 0.21×10^{12} cm^3s^{-1} in August. The average magnitude of the October to May exchange (0.44×10^{12} cm^3s^{-1}) is more than three times larger than the June to September average exchange (0.14×10^{12} cm^3s^{-1}). During June and September, the transition months between the two different regimes of exchange over the sill, the transports between the Sea and Gulf are at a minimum.

2 - The transports calculated for November and March using the preceeding model (Table 1) are confirmed by SIEDLER'S (1968) and VERCELLI'S (1925) calculations of transports from current observations. Both SIEDLER'S and VERCELLI'S calculations indicated inflows of 0.58×10^{12} cm^3s^{-1} during November 1964 and March 1924. These transports agree closely with the November and March monthly mean transports of 0.57×10^{12} cm^3s^{-1} calculated from the simplified model (Table 1).

3 - VERCELLI (1925) estimated that the amount of Red Sea water that flows out over the sill and mixes first with Gulf of Aden and later with Arabian Sea water at intermediate depths is between 0.30 and 0.40×10^{12} cm^3s^{-1}. Assuming that a negligible amount of highly saline Red Sea water flows out from June to September, the average annual transport out of the Sea to intermediate depths in the Gulf, which occurs from October to May, is 0.30×10^{12} cm^3s^{-1}, which is simply the average surface transport in (0.33×10^{12} cm^3s^{-1}), minus the water lost by evaporation (0.03×10^{12} cm^3s^{-1}). This transport agrees with VERCELLI'S lowest estimate.

4 - From October to May, the Red Sea gains an average of 38 cal cm^{-2} day^{-1} by advection, while from June to September the Sea loses an average of 30 cal cm^{-2} day^{-1}. The annual net advective heat exchange is 15 cal cm^{-2} day^{-1} heat gain by currents. The important fact demonstrated here is that, given the observed variations of exchange over the sill and the associated temperature structure, the annual net heat gain by currents can only be large if the transports between the Sea and Gulf are increased by one order of magnitude.

5 - Since the advective heat exchange over the sill is represented in cal $cm^{-2}day^{-1}$, this exchange can be compared with the atmospheric heat exchange over the entire Red Sea calculated by YEGOROV (1950). Although the evaporation from the Red Sea is higher than that in most oceanic regions, the other heat budget components compensate for this heat loss, making the annual net heat exchange with the atmosphere -3 cal cm^{-2} day^{-1}. This must be compensated for by a heat gain by currents of 3 cal cm^{-2} day^{-1}. This agrees closely with the 15 cal cm^{-2} day^{-1} calculated using the simplified model and confirms both the heat and volume transports in Table 1. It is interesting that conditions in the atmosphere and the sea have adjusted themselves so that both the annual net exchange of heat with the atmosphere and by advection must be almost zero. This circumstance, together with the small size and geographic isolation of the Red Sea from the Indian Ocean, makes the Red Sea an ideal region in which to study seasonal heat-exchange processes.

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DISCUSSION AND COMMENTS

Dr. GORMAN : What was the cause of the large suppression of the lower outflowing layer of Red Sea water over the sill in late summer ?

Dr. PATZERT : The assumption in this is that the outflowing bottom layer does not exist, or is at least an order of magnitude less than in the two layers above it. This is purely a model assumption. Unfortunately, there are no observations at all in that bottom outflowing layer that I know of.

Dr. ROBINSON : I think that the B.T. curves in Fig. 10 of my paper confirm the existence of a 3 layer system across the Bab-el-Mandeb sill in summer. The flow may be intermittent or subject to tidal fluctuations, but it certainly does exist at times.

Dr. PATZERT : I am not saying that the third layer does not exist but that the implication of a third layer with significant flow is to lose less heat by advection during the summer, which means that to make the total heat budget balance you must have a very large evaporation (to make the sea-air heat budget negative) because the heat gained by advection is becoming larger. Clearly, if heat were gained by advection all the year round, you would be gaining a large amount of heat which means the atmosphere-sea heat budget would have to be negative. One of the ways to make that heat budget negative is to have a very high evaporation in the Red Sea. As a matter of fact, if the surface inflow-subsurface outflow persisted throughout the year, you would need an evaporation of approximately 300 centimeters per year, which is too high.

CIRCULATION BETWEEN THE RED SEA AND THE GULF OF ADEN IN LATE SUMMER

Everett N. JONES, John M. GORMAN and David G. BROWNING *

Abstract

Initial measurements conducted during October 1969 demonstrated the existence of a strong temperature inversion at a depth of 100 meters in the Southern Red Sea. To verify that the inversion was caused by an influx of water from the Indian Ocean a more extensive experiment was conducted during September 1971 to study the circulation between the Red Sea and the Gulf of Aden. Operating from the French Navy Ship LA DIEPPOISE, 16 oceanographic stations consisting of salinity-temperature-depth casts and current measurements were made in the Gulf of Aden, Strait of Bab-el-Mandeb, and Southern Red Sea. Seventy XBTs were taken during transits. Although cold water layering was sharply defined north of the sill, the circulation in the Strait of Bab-el-Mandeb was not characteristic of the three layer summer, monsoon current pattern. A strong tidal influence was observed, and as expected a bottom flow into the Gulf of Aden was detected.

Résumé : Circulation entre la Mer Rouge et le Golfe d'Aden à la fin de l'été.

Les mesures initiales effectuées en octobre 1969 avaient montré l'existence d'une forte inversion de température à 100 m d'immersion au Sud de la Mer Rouge. Afin de vérifier que cette inversion était causée par un courant d'entrée d'eau de l'Océan Indien, une expérience plus étendue fut effectuée en septembre 1971 pour étudier la circulation entre la Mer Rouge et le Golfe d'Aden. Opérant du navire de la Marine française "LA DIEPPOISE", 16 stations océanographiques furent exécutées, comprenant des prélèvements de salinité, température, immersion et des mesures de courant dans le Golfe d'Aden, le détroit de Bab-el-Mandeb et le Sud de la Mer Rouge. Pendant les trajets, 70 XBTs furent exécutés. Bien que la couche d'eau froide fut définie de manière très précise au Nord du seuil, la circulation dans le détroit de Bab-el-Mandeb ne fut pas caractéristique du modèle à trois couches de la mousson d'été. Une forte influence de la marée fut observée et, comme prévu, un courant de fond vers le Golfe d'Aden fut enregistré.

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INTRODUCTION

Prevailing NNW winds are characteristic over the entire length of the Red Sea during the summer monsoon season, roughly June through September. This persistent wind is believed to cause the highly developed inversion in temperature and salinity due to the influx of water near sill depth from the Gulf of Aden tunnelling under wind driven Red Sea surface water.

In a previous set of measurements in October, 1969, (JONES and BROWNING, 1971) we observed a pronounced temperature inversion at 16°30'N and traced it using expendable bathythermographs (XBT) to 18°10'N where this characteristic structure became indistinguishable within the water column. Since the cold water layer must originate in the Gulf of Aden, it was assumed that the inversion would be present far to the south if not as far as the Strait of Bab-el-Mandeb itself, despite the onset of SE winds of the winter monsoon.

Various investigators (THOMPSON, 1939 ; MUROMTSEV, 1960 ; NEUMANN and Mc GILL 1961 ; TUNNELL, 1963) have hypothesized and commented on a three-layer current system in the area of Bab-el-Mandeb. The three-layer model is based on numerous observations of temperature, salinity, and in some cases dissolved oxygen concentrations, which all suggest sill depth inflow from the Gulf of Aden. The three-layer current system is supposedly limited to the summer monsoon period when the NNW wind system provides the force required for driving the surface layer of this circulation model. Our objective was to test the effectiveness of the three-layer model by not only demonstrating the presence of temperature and salinity inversions in the southern Red Sea but to measure currents and correlate water mass flow with the inversions.

In September 1971 we had the opportunity to conduct a joint survey of Bab-el-Mandeb and the Red Sea sill with the French Navy using the French Minesweeper LA DIEPPOISE based at Djibouti. Our purpose was to investigate the circulation patterns by determining temperature and salinity profiles and by making current velocity measurements at pertinent depths.

MEASUREMENTS

The measurements consisted of salinity/temperature/depth (STD) casts, 6 to 13 hour current observations at anchor in depths as great as 185 m, and XBT tracks made in the Red Sea, Gulf of Aden and Gulf of Tadjoura. Figure 1 shows the location of the stations occupied by LA DIEPPOISE during the three-week experimental period of September 1971.

Wind conditions were observed hourly during measurements. The general wind behaviour conformed to no particular pattern and could not be associated with either the summer or winter monsoons. A high degree of variability in direction and speed was observed suggesting unsettled weather during the transition between monsoon seasons.

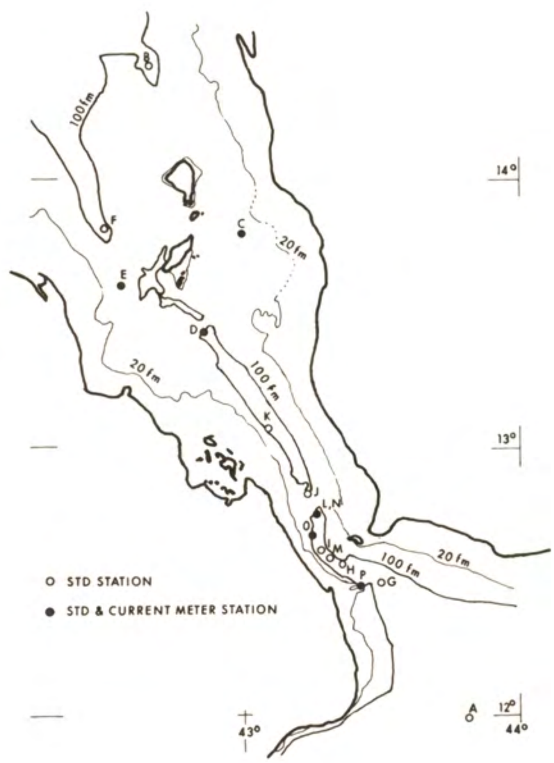


Fig. 1 - Location and designation of stations occupied by LA DIEPPOISE 7-27 September 1971.

RESULTS AND DISCUSSION

General observations

Evidence of a strong influx from the Gulf of Aden was found beyond the sill in the Red Sea. Station data showed highly developed temperature and salinity inversions characteristic of mid-depth inflow layered beneath Red Sea surface water, which resulted in a three-layer system as shown on Figure 2. It is probable, when considering other available records for September and October (JONES and BROWNING, 1971), that the intermediate layer caused by a tongue of colder (17°), less-saline (36.1°/₀₀) water from the Gulf of Aden extends NW along the Red Sea basin for over 350 km at very nearly the same depth.

In the Strait of Bab-el-Mandeb the water movement was not clearly defined. Temperature and salinity inversions were observed but were not as prominent as is shown in figures 3 an 4. Instead, our measurements show that the circulation in the Strait was variable with strong tidal influence and conformed neither to the three-layer nor to the two-layer current scheme.

Southeast of the Strait, in the Gulf of Aden, a single STD cast to 550 m revealed water of slightly higher salinity and temperature underlying water of the gulf. This water appears to be the shallowest extent of Red Sea outflow and is the water that flows along the bottom of the sill spilling out into the Gulf of Aden. Figure 5 shows this property. The data seem to agree closely with R/V ATLANTIS station data (Woods Hole Oceanogr. Inst. 1963) and serves to demonstrate the presence of the two water masses ; the cooler, less saline gulf water overlaying the outflowing Red Sea water. Of interest here is the structure of the salinity profile from 210 to 510 m, which is indicative of a substantial mixing between Red Sea and gulf water. The S-T diagram of Figure 6 further illustrates this point.

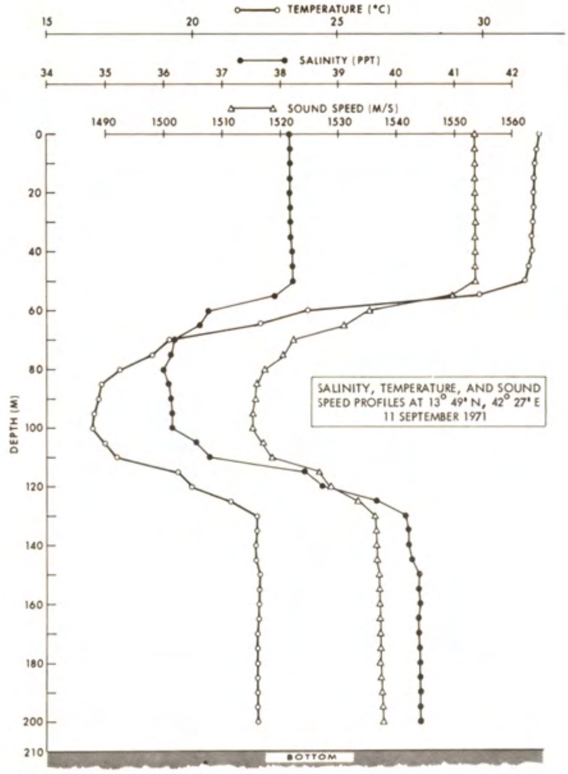


Fig. 2 - Vertical profiles of temperature, salinity and sound speed north of the sill in the Red Sea.

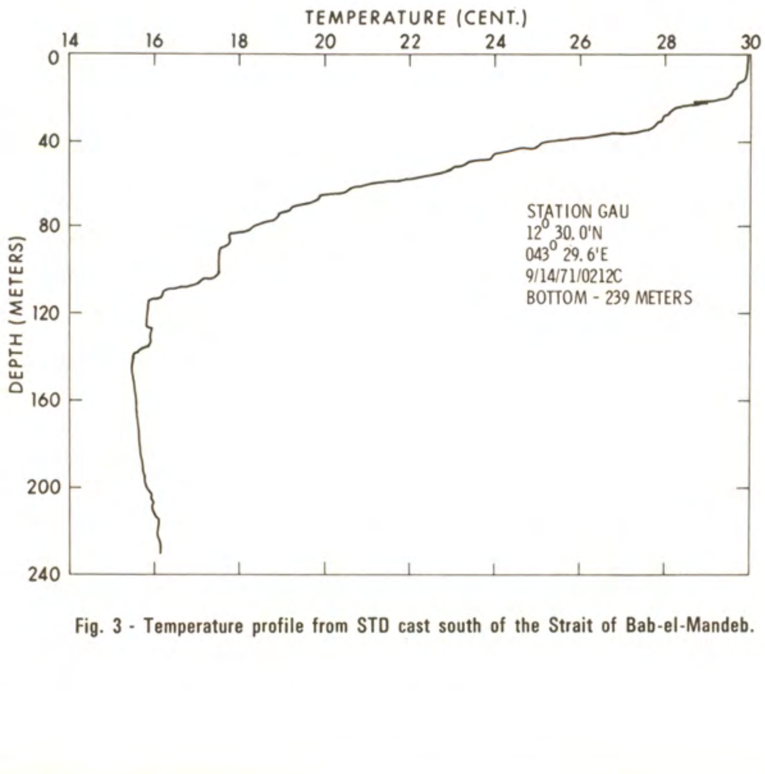


Fig. 3 - Temperature profile from STD cast south of the Strait of Bab-el-Mandeb.

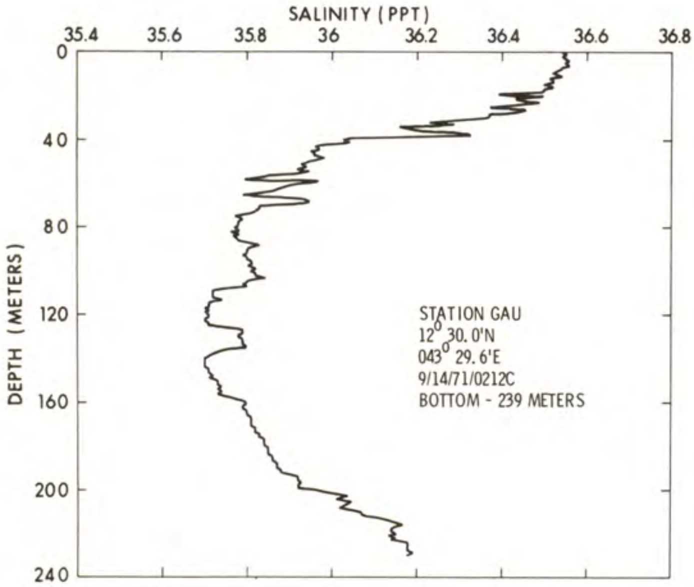


Fig. 4 - Salinity profile from STD cast just south of Bab-el-Mandeb at station G.

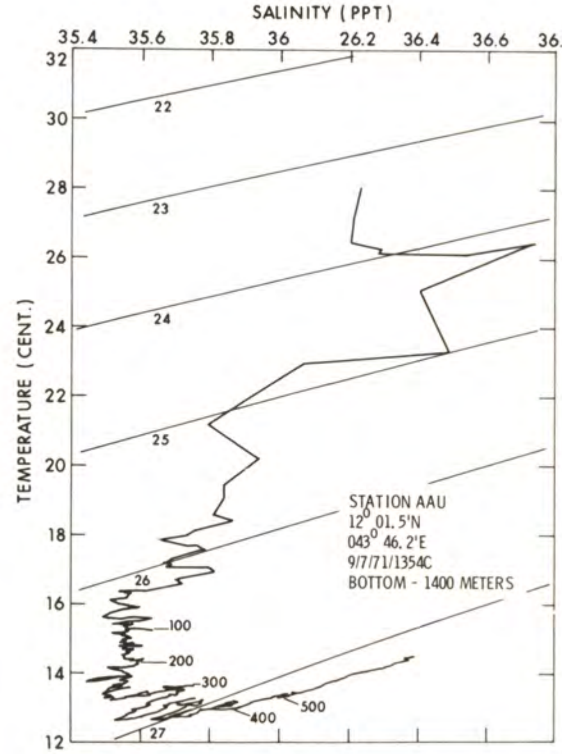


Fig. 6 - Salinity-temperature diagram for station A in the Gulf of Aden. Depths are identified every 100 m.

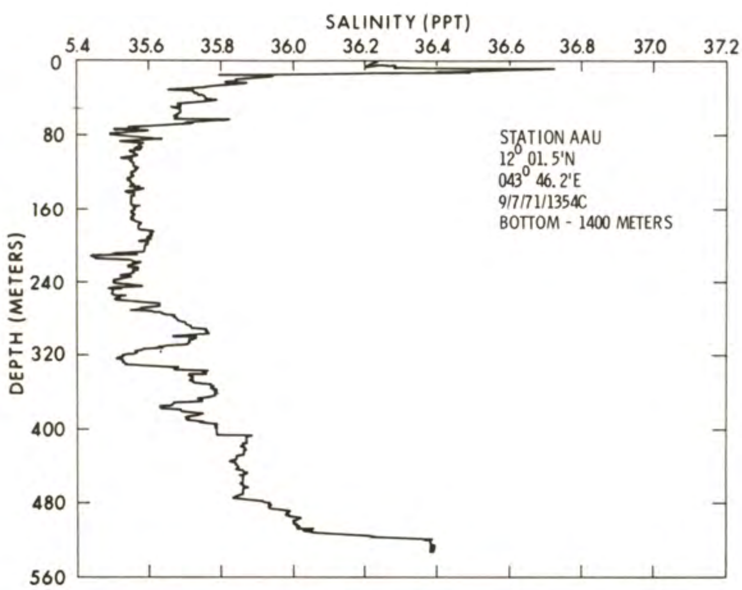
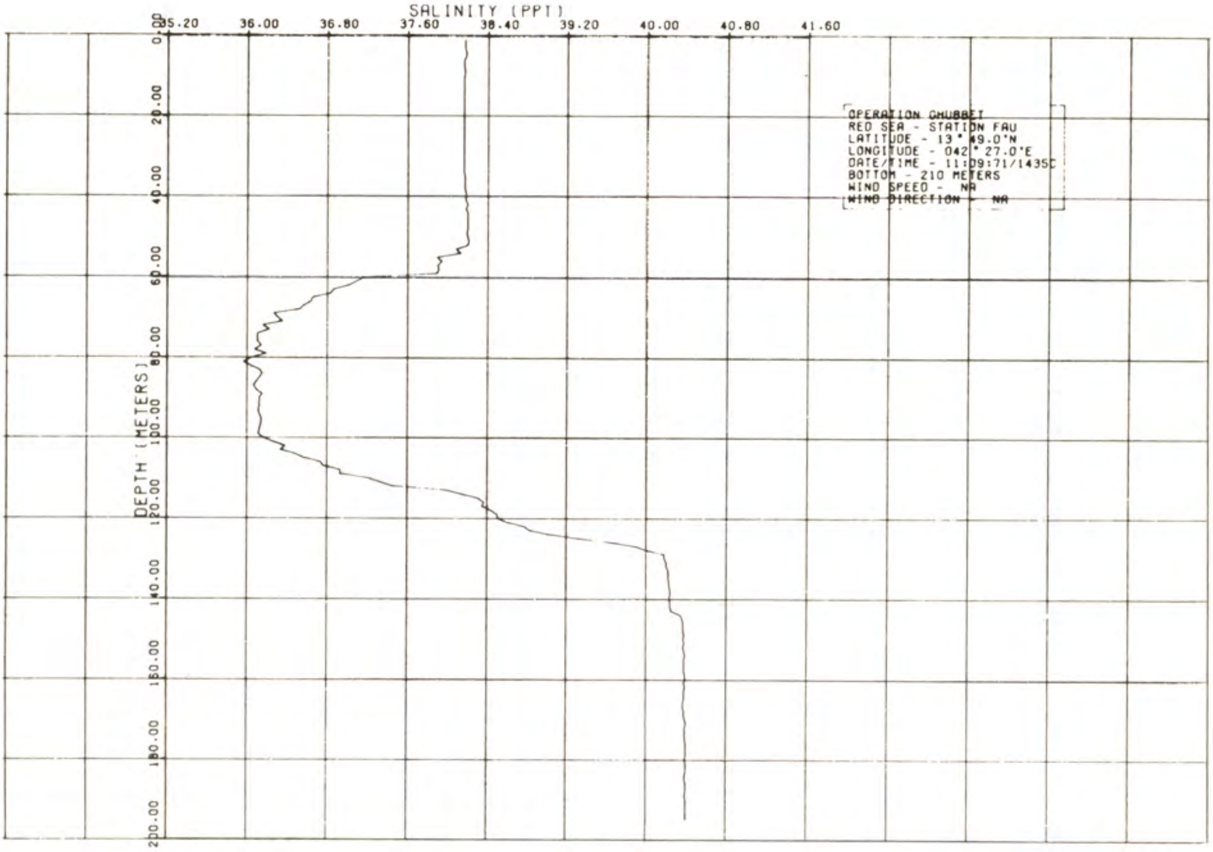


Fig. 5 - Vertical profile of salinity at station A in the Gulf of Aden.

The sill and Bab-el-Mandeb

The strong temperature and salinity inversions observed at northern stations F and B, both within the 100 fathom contour line in the Red Sea, are almost identical in character. Figures 7 and 8 show the temperature and salinity minimums are at a slightly greater depth at station F than at B. The formation of the cold water layer at B can occur by two mechanisms. Water from the Gulf of Aden can cross into the Red Sea west of Hanish Island, flow northward filling out along lines of constant density in areas where sufficient depth exists. In this way the cold water responsible for the layer can find its way to B, perhaps dispersing somewhat due to flow around bathymetric obstacles. It is also possible that cold water can creep along the shallow channel east of the islands of Hanish and Zugar, and arrive at B to form the observed temperature and salinity inversions. To determine whether significant inflow occurs in the shallow channel, current measurements at two depths were made at Station C. Figures 9 through 12 are typical of the reduced data for our current monitoring. Although a great deal of variability is evident due to semidiurnal tides and motion introduced by the anchored ship, a weak residual surface outflow and deep inflow is apparent. This net flow must be characterized as having an insignificant effect on the stable temperature and salinity inversions beyond the sill in the Red Sea. The temperature minimums at stations F and B correspond well and are in both cases 1,5° less than the lowest temperature recorded at C over a six-hour period.



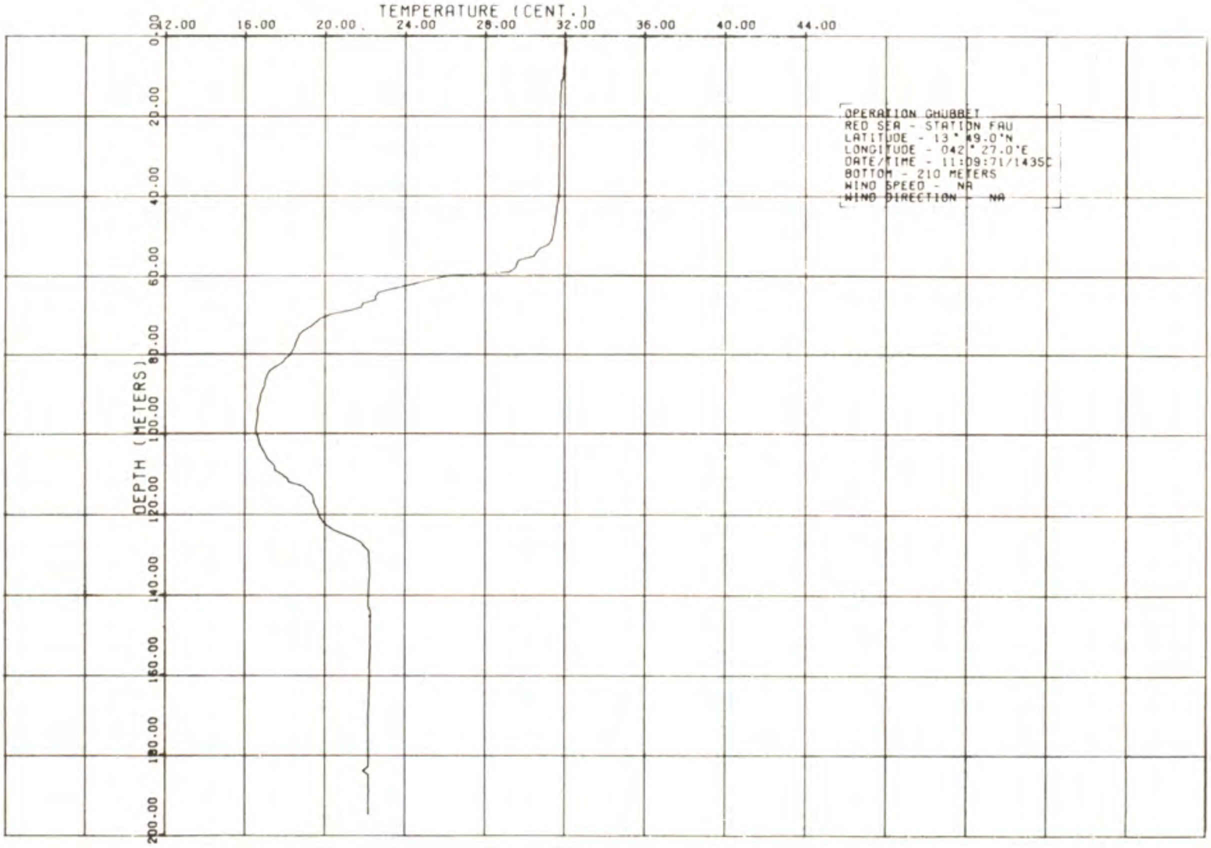
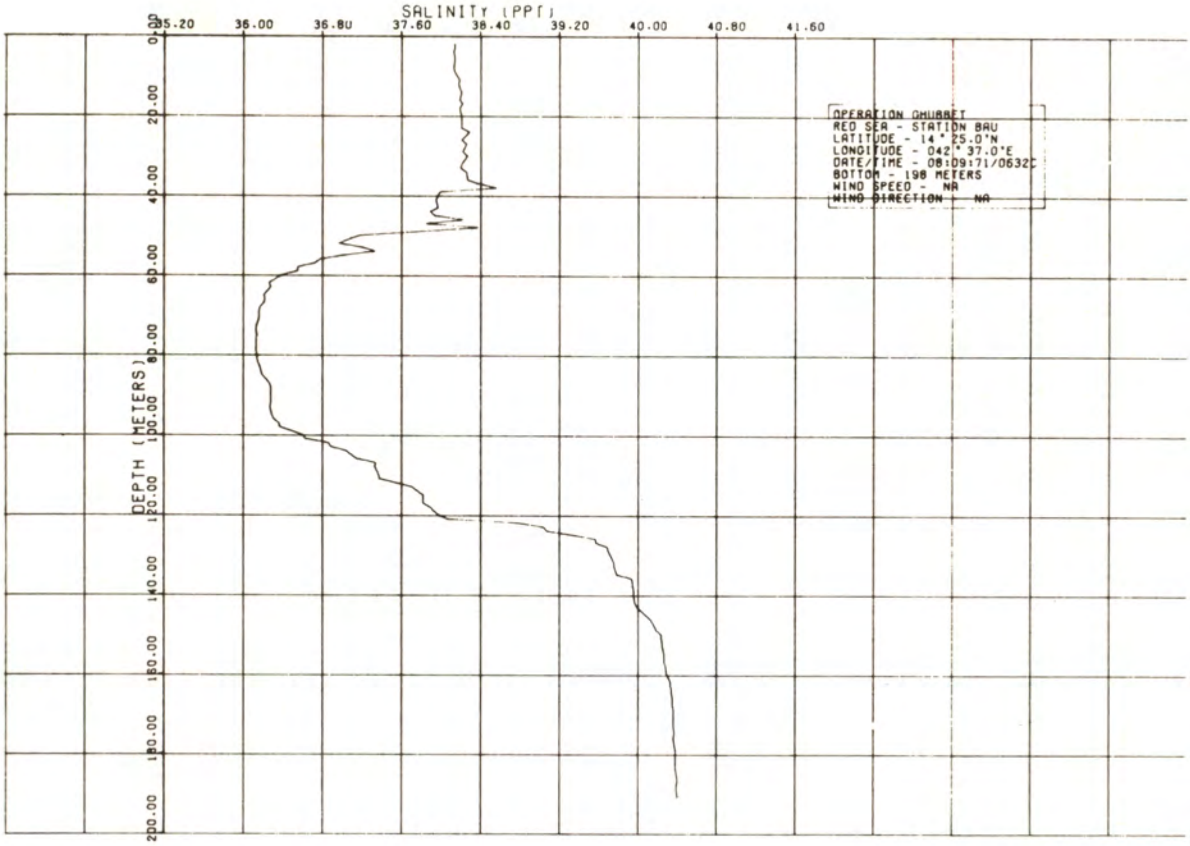


Fig. 7 - Vertical profiles of temperature and salinity at station F in the Red Sea.



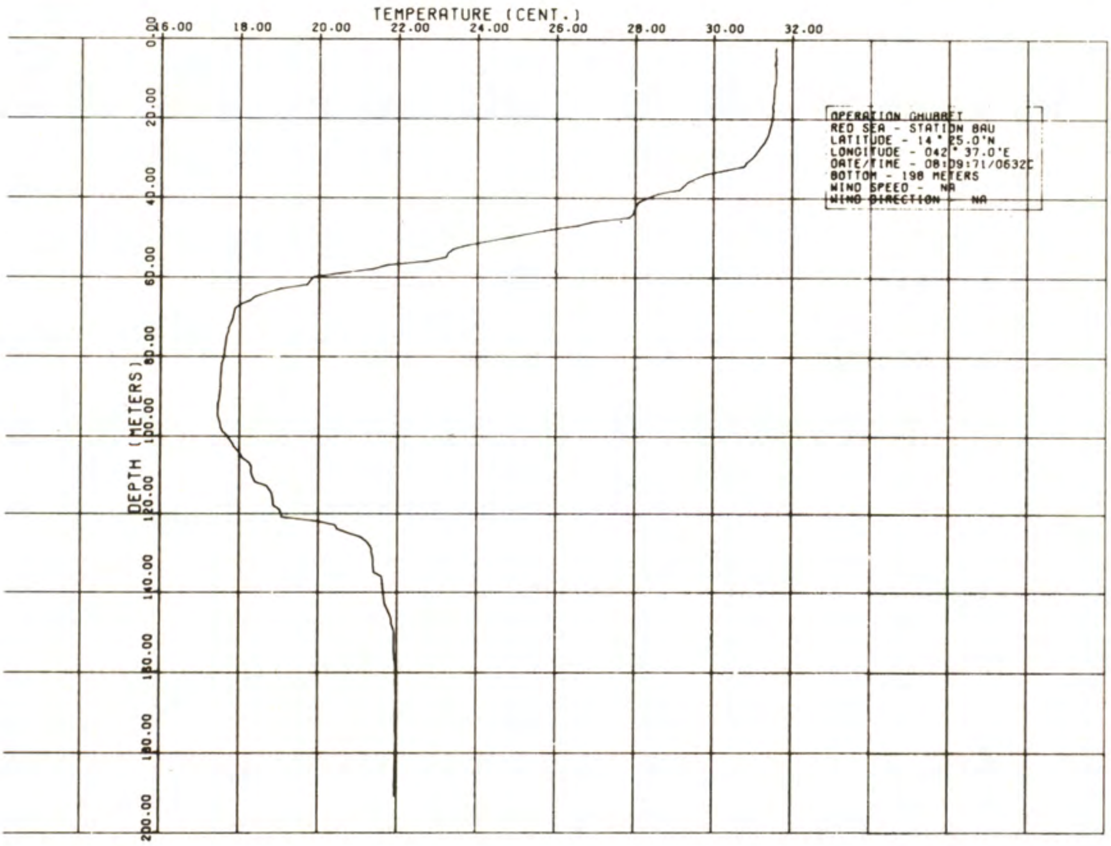


Fig. 8 - Vertical profiles of temperature and salinity at station B in the Red Sea.

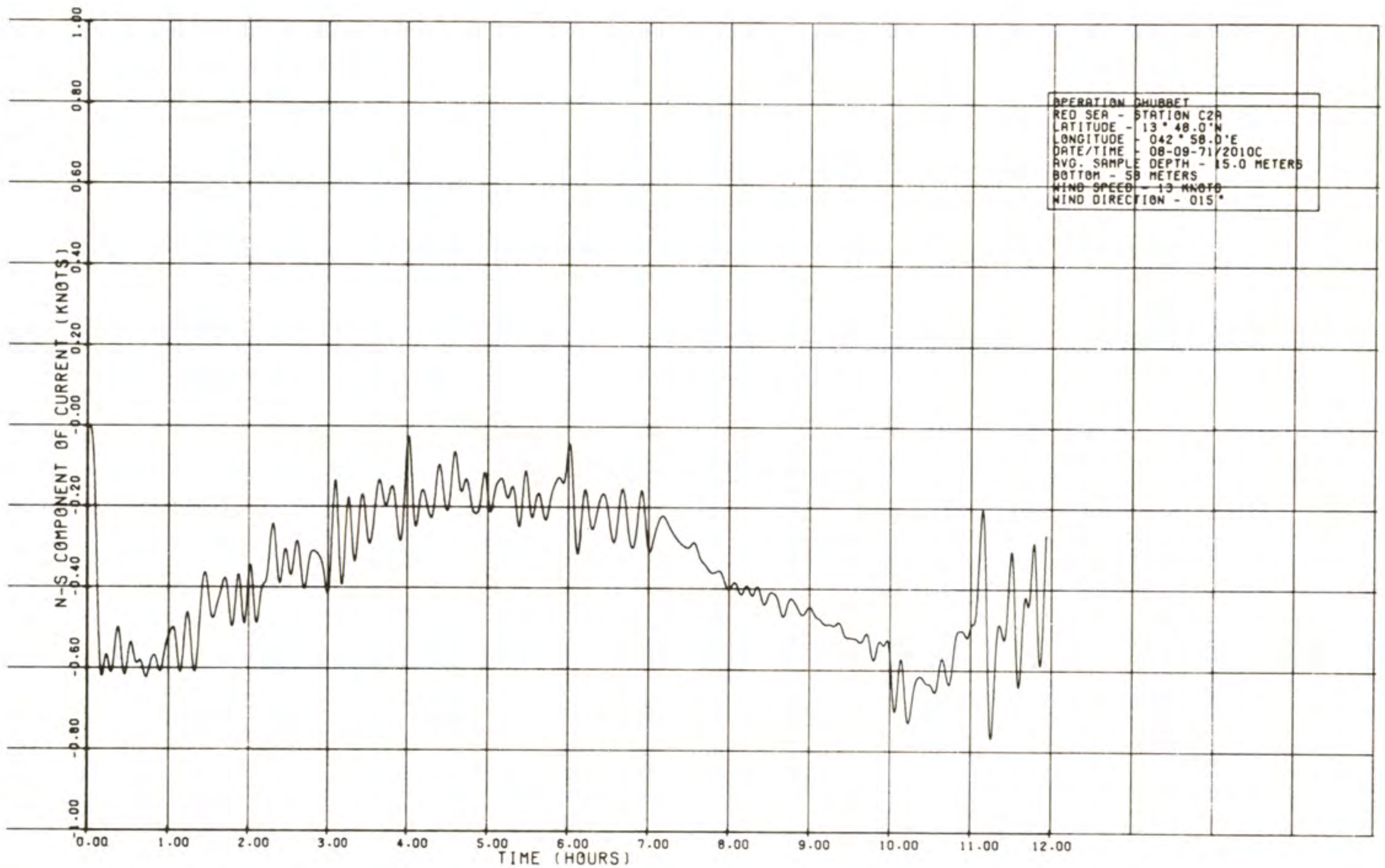


Fig. 9 - Time plot of north-south component of current at 15 m depth at station C east of rhe Hanish Islands. The average N-S component speed is -0.37 knots directed to the south. The data have been low-pass filtered (cut-off frequency = 8.57 cycles per hour or period of 7 min.).

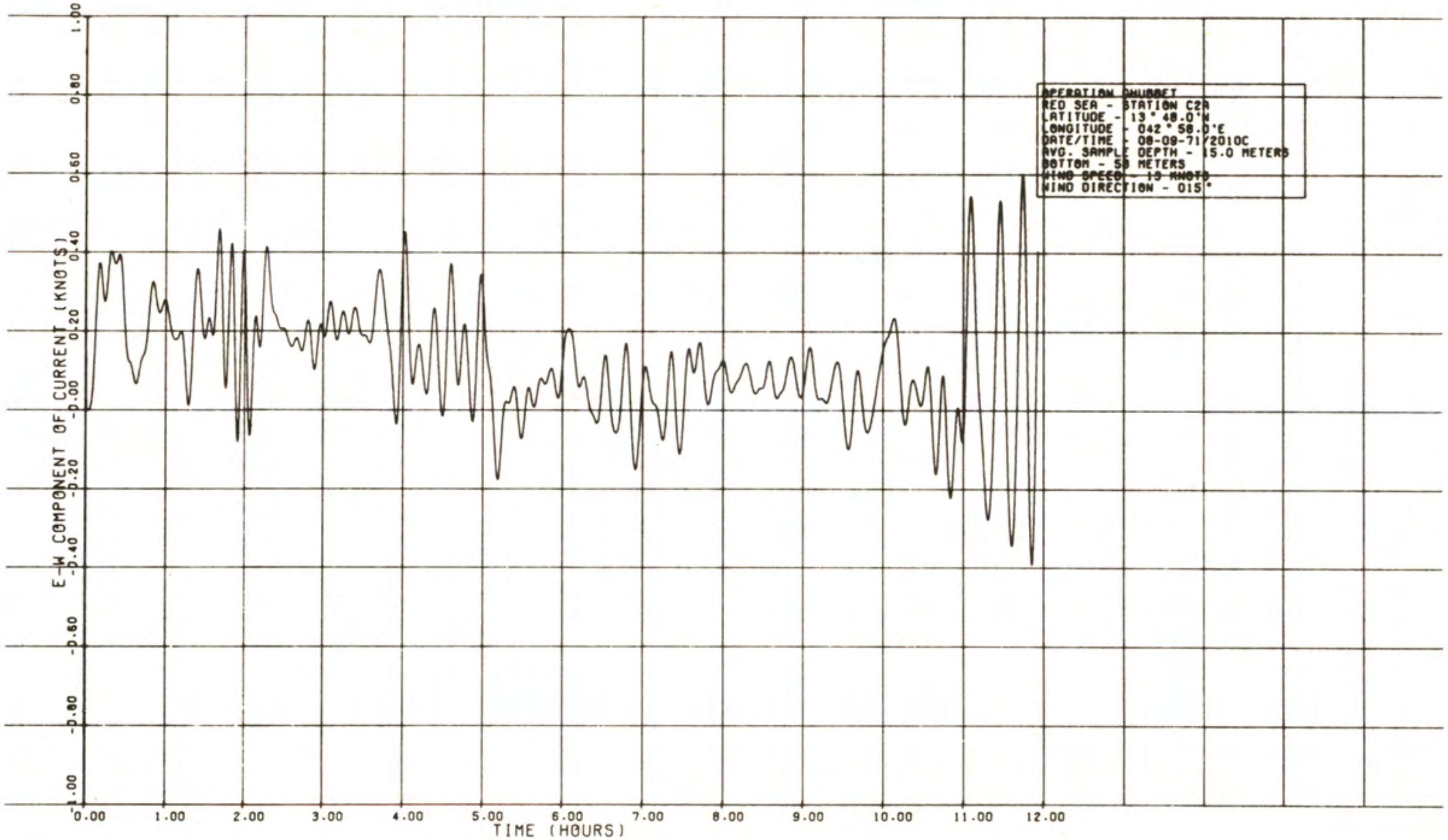


Fig. 10 - Time plot of east-west current component at 15 m at station C. The average E-W component speed is + 0.12 knots directed to the east. The data have been low-pass filtered (cut-off frequency = 8.57 cycles per hour or a period of 7 min.).

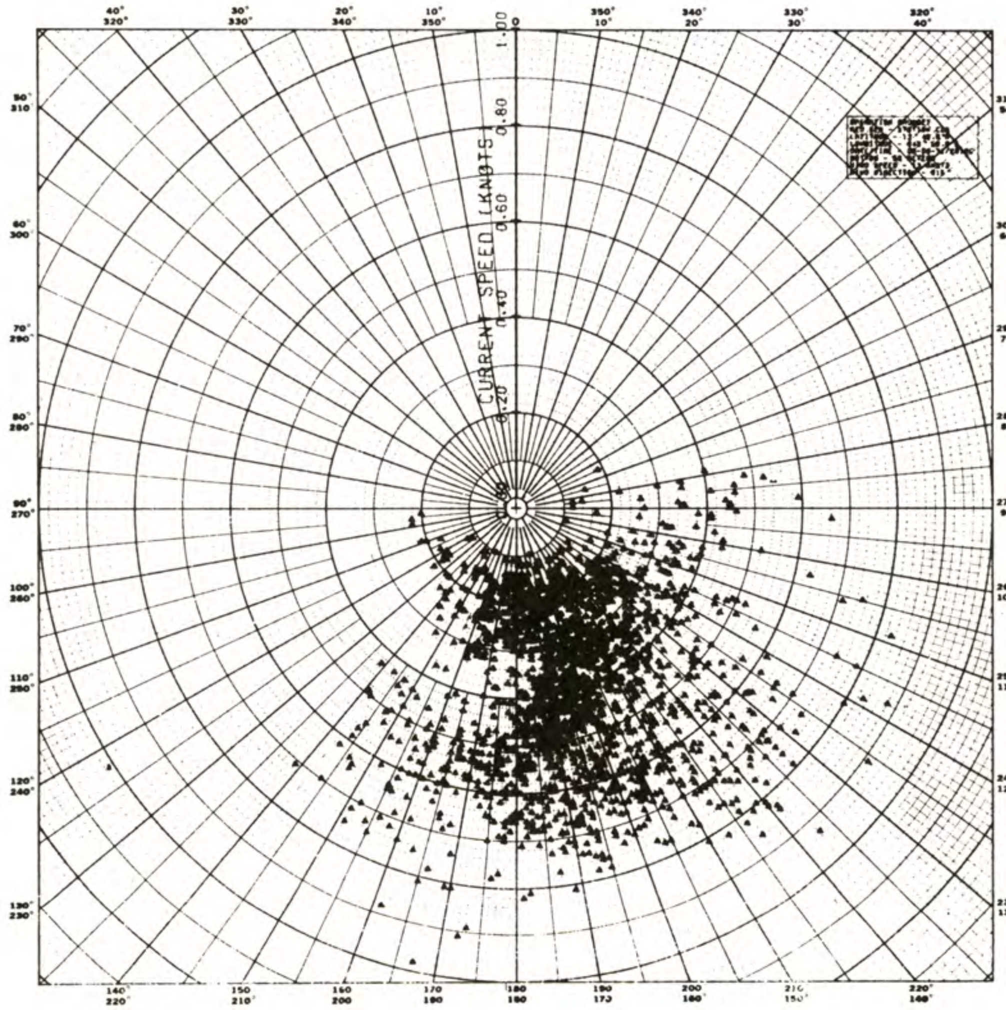


Fig. 11 - Current speed and direction scatter diagram at station C, 15 m deep.

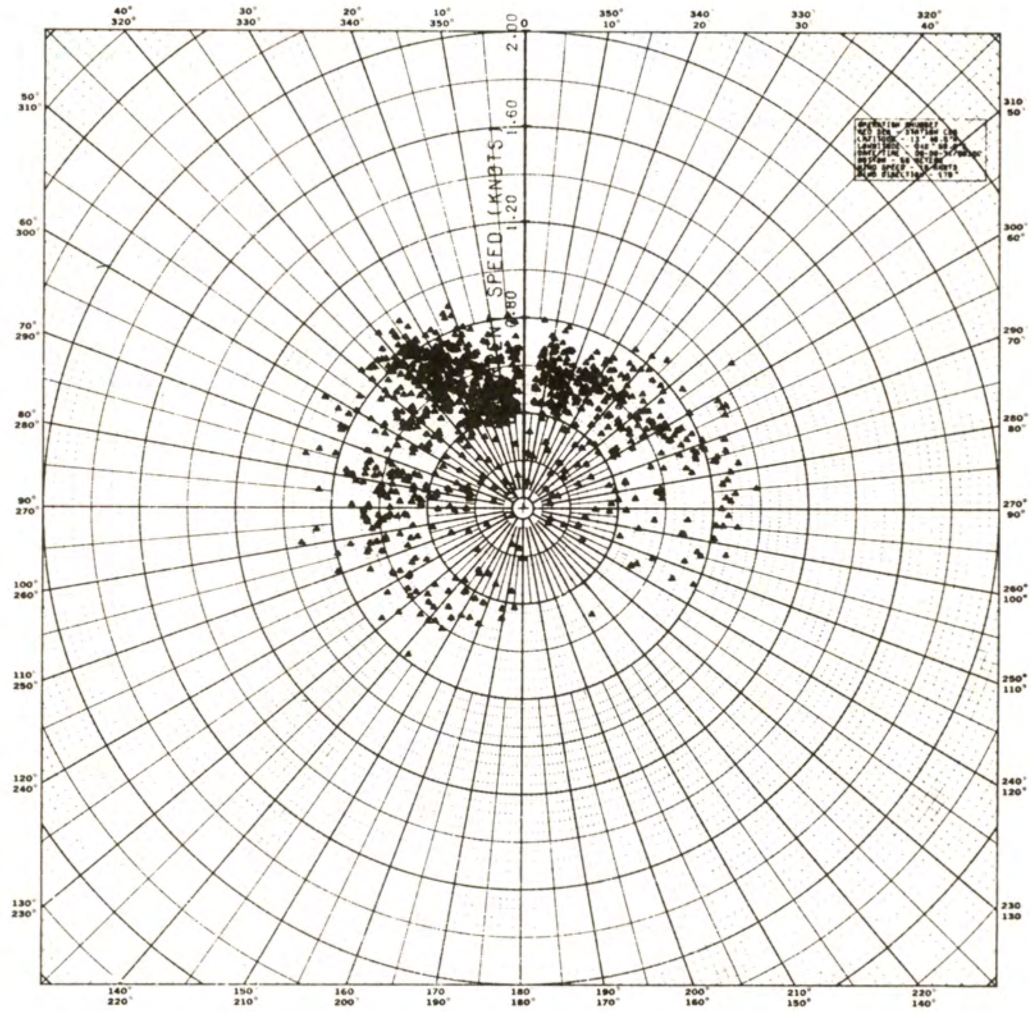


Fig. 12 - Current speed and direction scatter diagram at station C, 43 m deep.

Our attention now shifts to the deeper channel west of Hanish. Intermediate inflow is strongly indicated by the stratified water north of the sill and by the presence in the gulf of water with the same temperature and salinity. Figure 13 shows a vertical salinity section from the edge of the basin in the Red Sea to a deep water station south of Bab-el-Mandeb in the gulf. Salinity inversions exist throughout most of the section. The sill depth is somewhat obscured by our use of station data taken out of the deep channel. The actual sill depth appears to be at least 135 m deep. Water representative of intermediate depth Red Sea water with a salinity of 40,5°/oo does not cross the sill in this section. In fact, salinities no greater than 37,5°/oo were observed south of the sill, even in the deeper holes we encountered between Hanish Island and Bab-el-Mandeb. The core of low salinity water is shown penetrating to the north of Bab-el-Mandeb. However, the section through the Strait is distinguished by a pinching-off of the core water, seemingly eliminating water of salinities below 36°/oo from progressing as far north as the Hanish Islands. From the surface to 80 m the water column is in a state of flux. It appears that a small parcel of 37°/oo water, which originated at the surface farther to the north in the Red Sea has become isolated in the vicinity of Perim Island. This behavior is indicative of a tidal influence. The tides appear to have been exerting a greater influence than the surface outflow of the supposed three-layered current models which may have been weakened by the lack of persistent northerly winds.

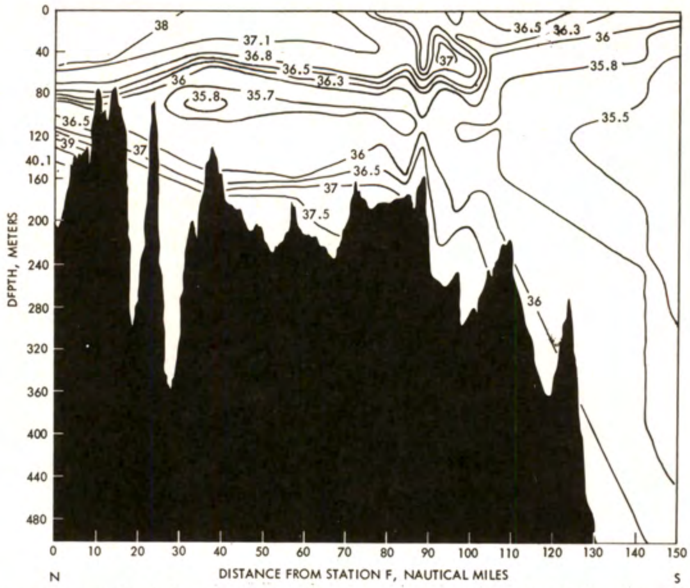


Fig. 13 - Salinity section starting north of the sill and running to the Gulf of Aden through the channel west of Hanish Island.

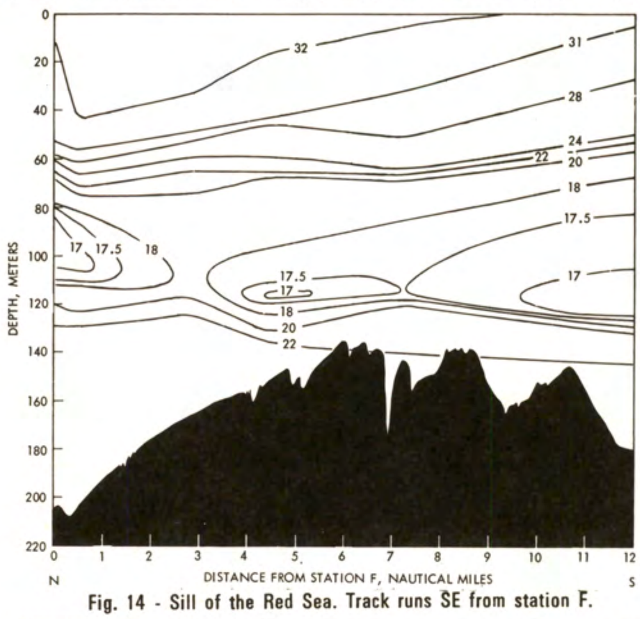


Fig. 14 - Sill of the Red Sea. Track runs SE from station F.

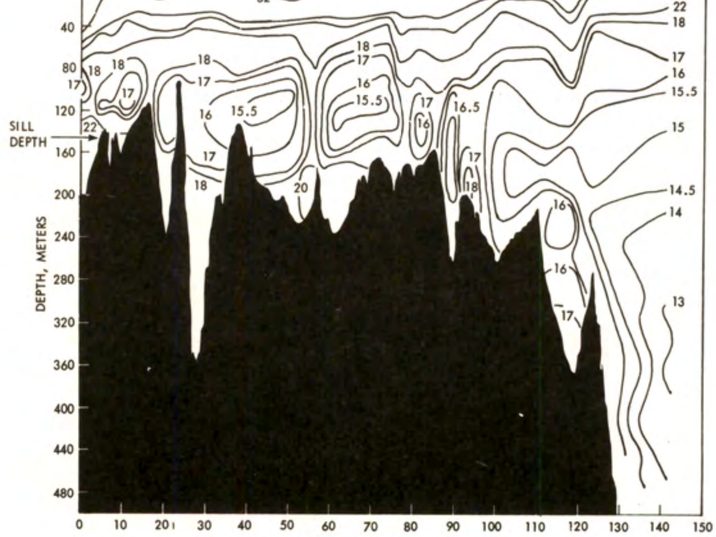


Fig 15 - Temperature section from north of the sill to the Gulf of Aden.

Two temperature sections are presented here ; first (figure 14) is a detailed temperature contour across the sill located west of Hanish Island. The contours were constructed from XBT measurements taken at approximately 2 nautical mile intervals. A continuous record of the bottom profile was made simultaneously. The passage represented the deepest channel that we found in the barrier between the Red Sea and the Gulf of Aden. The actual sill depth is therefore 135 m or greater. Temperature inversions occur all the way across the sill. Thus, a 135 m sill is not a barrier to inflowing water from the gulf, nor does this depth restrict the outflow of 22° Red Sea water. The second temperature section covers approximately the same track as the salinity section but follows a slightly deeper route (figure 15). These contours were constructed mainly from XBT records gathered nearly one week before the STD stations. Disturbances in the intermediate water are more noticeable here than in the case of the salinity section. Twenty degree water is in evidence as isolated pools along the bottom between the sill at Hanish and Bab-el-Mandeb. Twenty-two degree water, although crossing the sill, is not found far south of the sill. The temperature section is based on more measurements just south of the sill than is the salinity section. It appears possible that saline intermediate Red Sea water exists in the 20° pools observed with XBT's south of the sill. The coolest water found north of Bab-el-Mandeb is 15,5° but water of this temperature was only traced to within 40 nautical miles southeast of station F at the time of measurement. The many isolated water regimes with temperatures of 15,5 to 18° suggest that tidal effects were modulating the inflow of gulf water.

Currents

Current speed and direction data generally show the lack of sustained flow patterns. Tidal influences were very strong and residual currents did not always corroborate either a well defined two or three-layered model. Good examples are the measurements at stations L and N essentially at the same location, at the center of the Strait, where strong currents were in evidence. At 30 m we find a net inflow (to the north) while at 127 m the residual flow is to the south. Temperature and salinity casts at the same station show that 30 m is above the thermocline and 127 m well below it yet not deep enough to be associated with increasing temperature and salinity values near the bottom. Figures 16 through 20 show the results. For the three-layer model the surface and bottom layers should flow toward the gulf and the intermediate flow toward the Red Sea. The two-layer model would have bottom outflow and inflow throughout the rest of the water column. Such is not the case. Even though the STD casts here suggest three layers with particular stability in the deepest 20 m (figure 21) current measurements in two of the layers points up the failure of the water movement models for late summer. Apparently no persistent monsoon type flow pattern had been established yet. Current velocity data accumulated from our other stations, both to the north and outside Bab-el-Mandeb supports the same conclusion-that of high current variability and inconsistency with either model.

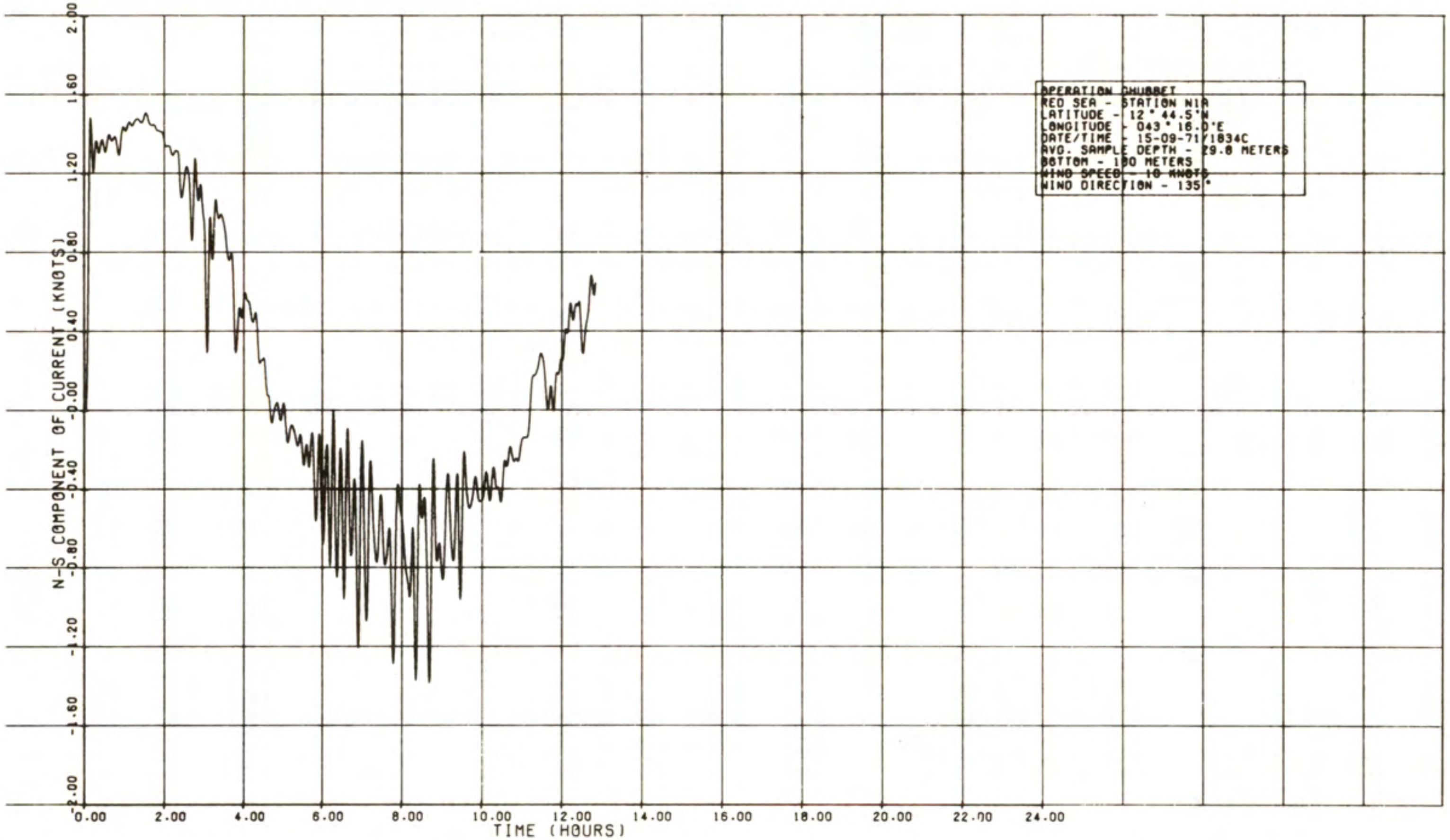


Fig. 16 - Time plot of north-south current component at 30 m at station N in the Strait of Bab-el-Mandeb. The average N-S component speed is + 0.19 knots directed northward. These data have been low-pass filtered (cut-off frequency = 8.57 cycles per hour or a period of 7 min.).

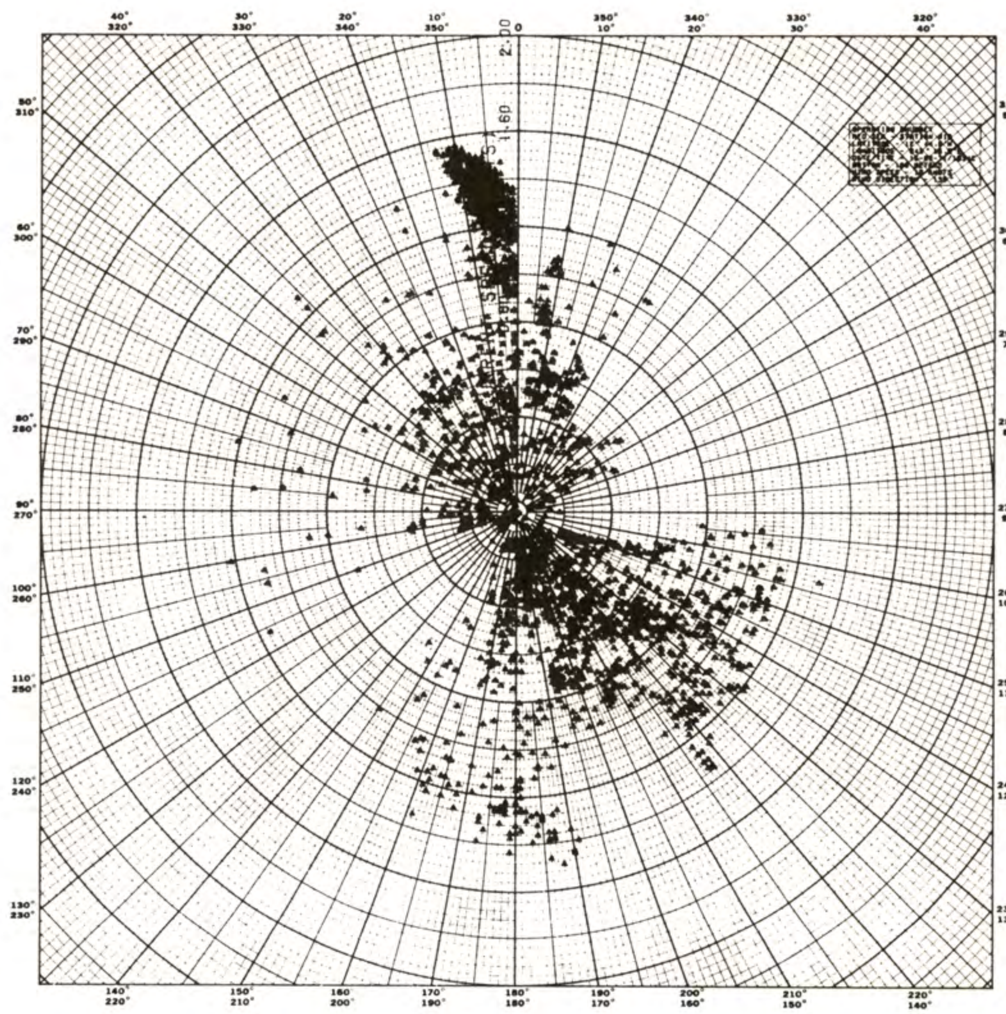


Fig. 17 - Speed and direction scatter diagram at station N, 30 m deep.

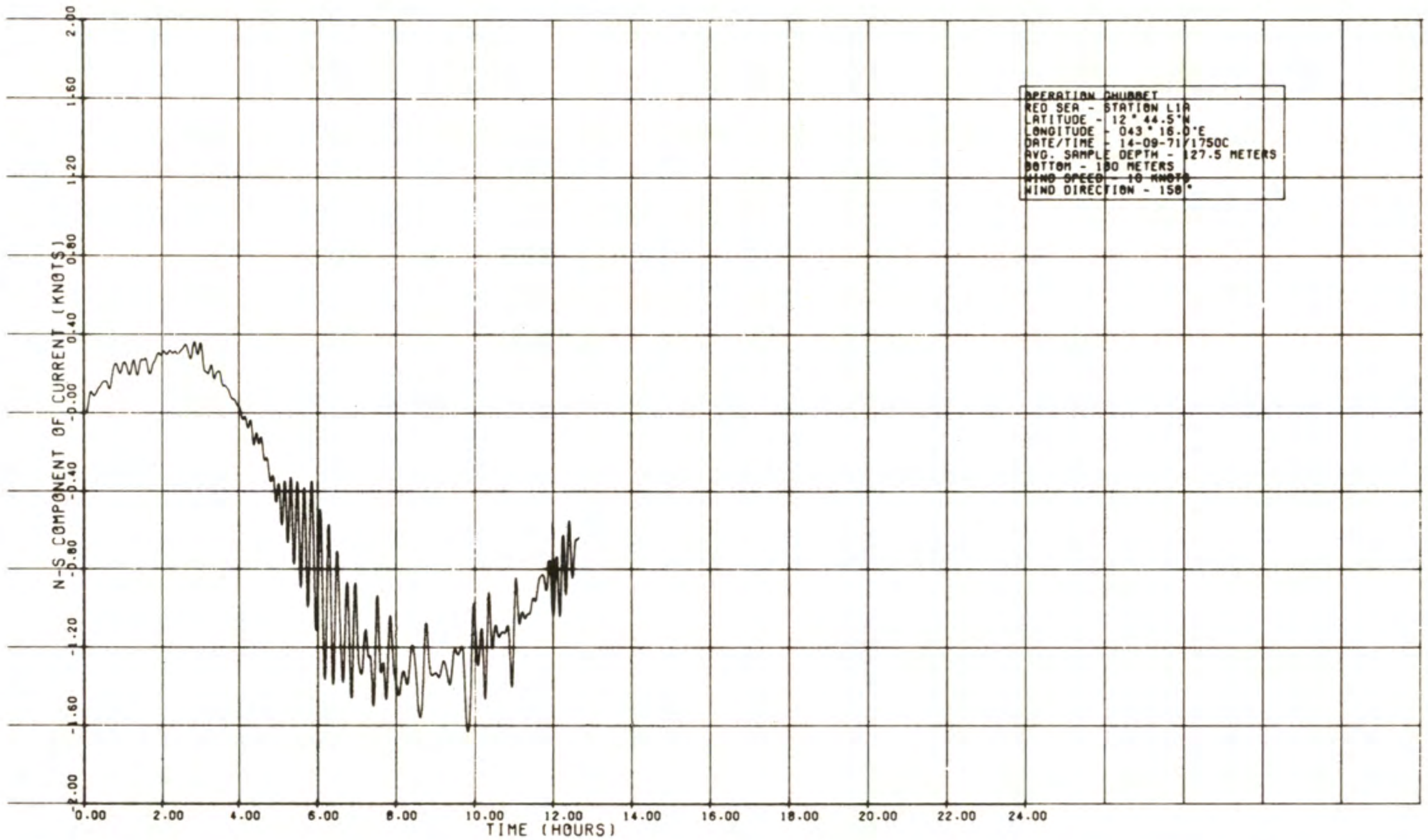


Fig. 18 - Time plot of north-south current component at 127 m at station L (same location as N). The average N-S component speed is - 0.59 knots directed to the south. These data have been low-pass filtered (cut-off frequency = 8.57 cycles per hour or a period of 7 min.).

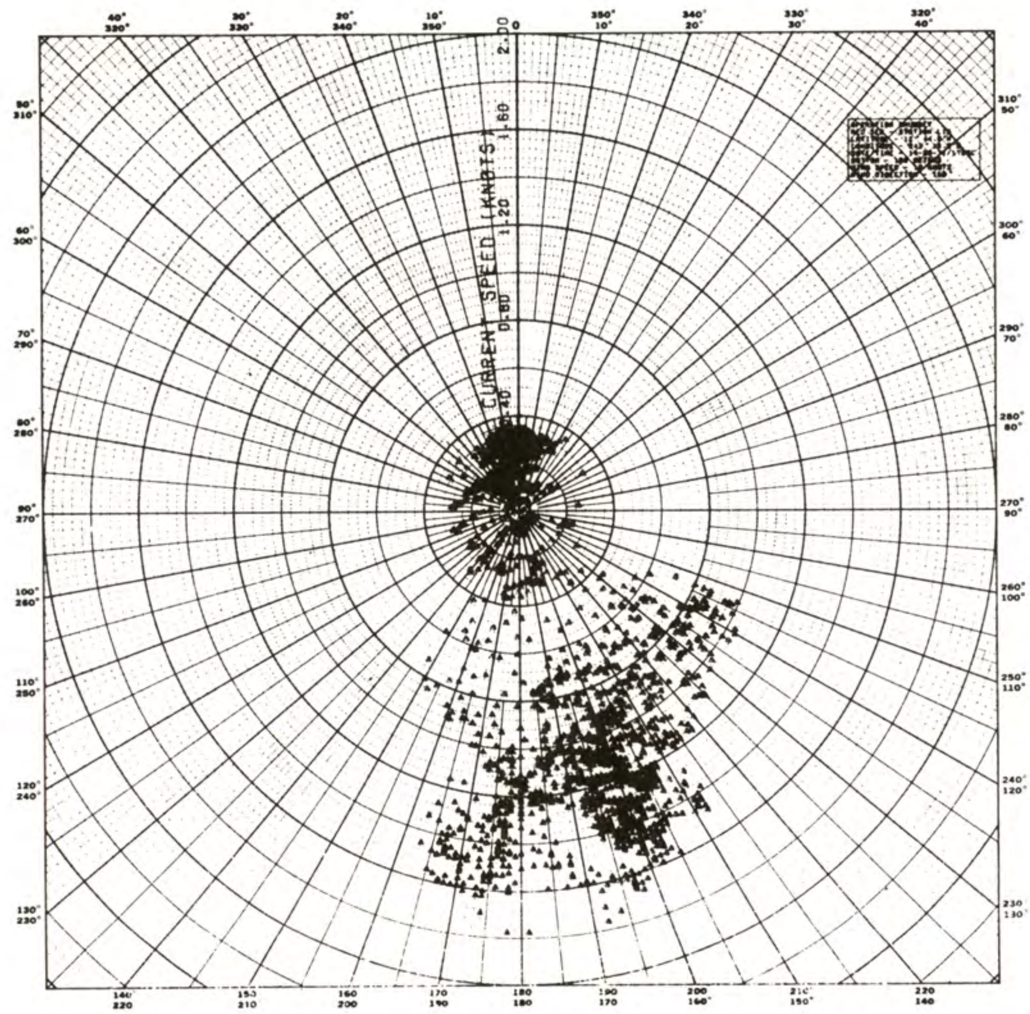


Fig. 19 - Current speed and direction scatter diagram for station L, at 127 m.

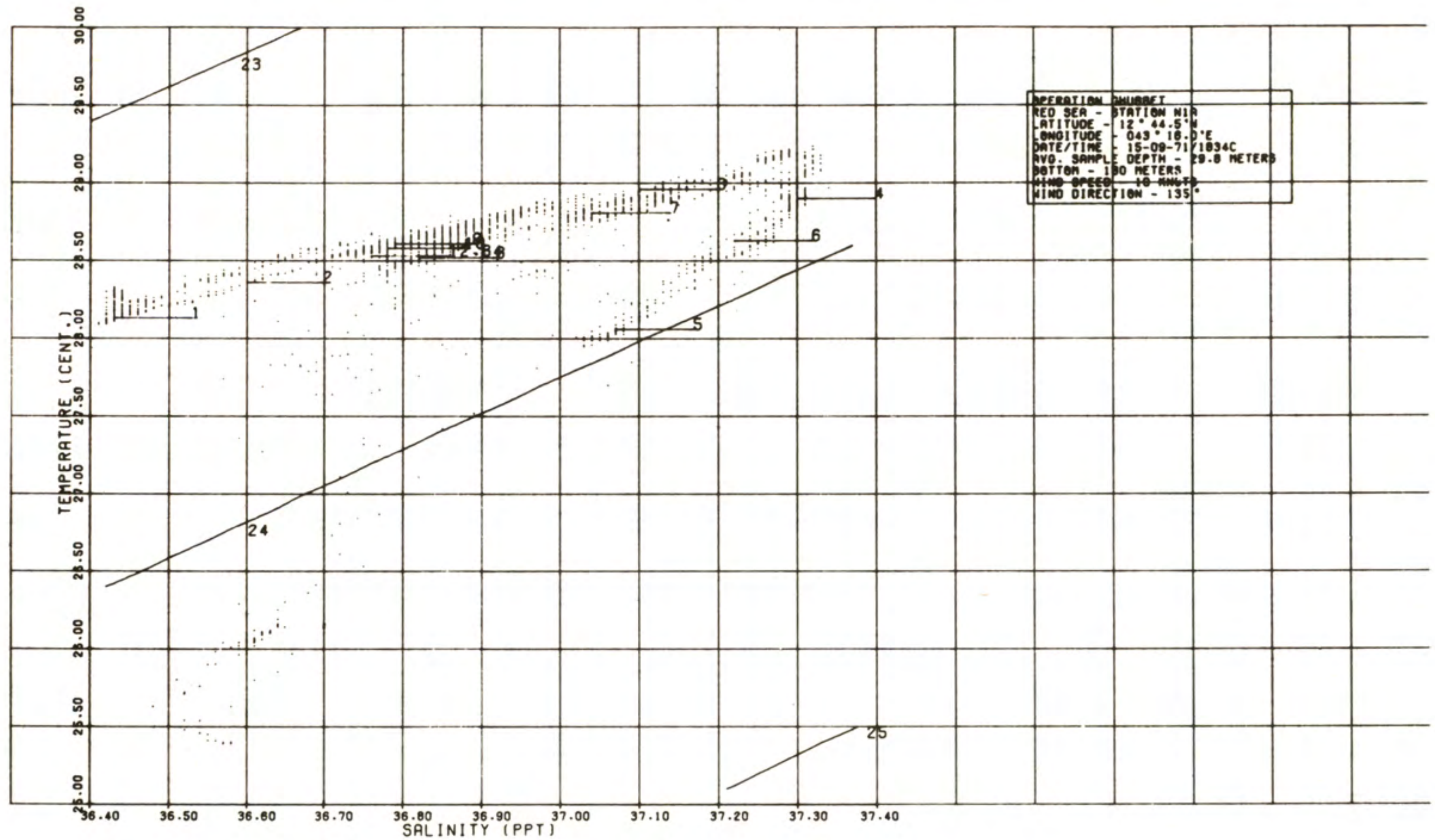


Fig. 20 - Salinity-temperature diagram as a function of time at a constant depth of 30 m at station N. Labels are hourly intervals.

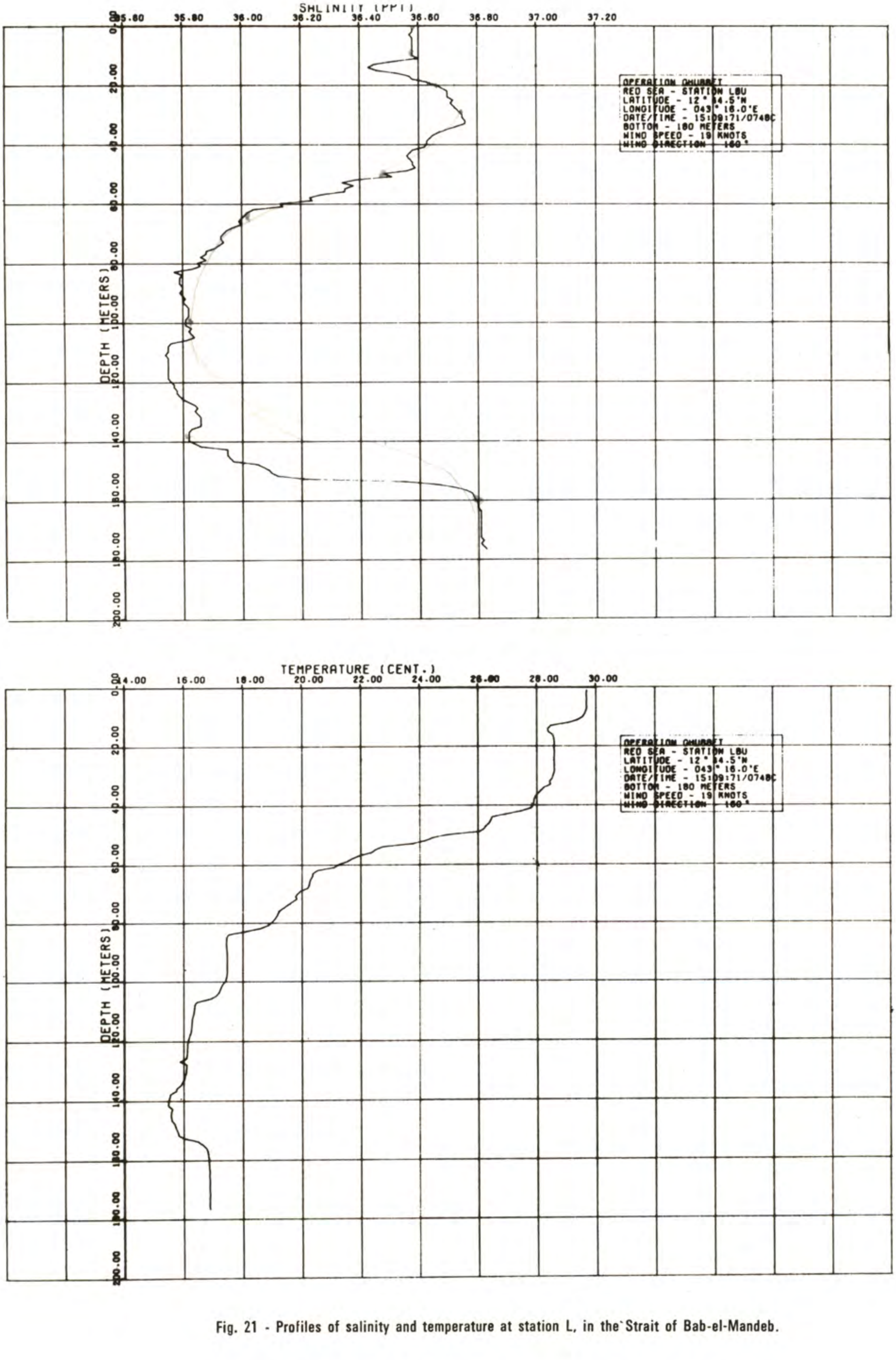


Fig. 21 - Profiles of salinity and temperature at station L, in the Strait of Bab-el-Mandeb.

CONCLUSIONS

The strong inflow from the Gulf of Aden which results in salinity and temperature inversions throughout the southern Red Sea had been weakened by tidal activity in the Strait at the time of our measurements. We also found little evidence to support a three-layered current pattern in Bab-el-Mandeb at least during late summer. Tidal behavior, coupled with the decided absence of NNW monsoon winds, led us to believe the winter current pattern (the two-layer model) would soon be evident in the Strait.

The water column north of the sill was in every case highly stratified and appears stable despite the variable weather conditions encountered. It is uncertain whether current measurements will demonstrate the behavior predicted by the idealized three-layer scheme in the area from Bab-el-Mandeb to the sill, even if measurements were made during a time more representative of the summer monsoon, such as July. Gulf water may cross the sill in an irregular fashion as experienced by us and become layered as a continuous flow only north of the sill where its core tunnels northward for hundreds of kilometers without appreciable loss of identify.

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DISCUSSION AND COMMENTS

Dr. ROBINSON : I am interested in just how 22°C, 39°/oo water observed north of the sill becomes the characteristic Red Sea water in the Gulf of Aden and Indian Ocean with a salinity of 36,5°/oo. Is the bottom water, say 40 nautical miles north of Bab-el-Mandeb a result of mixing with the water immediately above it due to tidal movement over the rugged bottom topography ?

Mr. GORMAN : It is our feeling that the mixing, as demonstrated by reduced temperature and salinities of the bottom water (compared to values north of the sill at Hanish Island), is due mainly to the tidal and topographic features. This mixing, as seen in figures 13 and 15, results in large cells of cooler, less saline water, as well as the apparent trapping of Red Sea water in various bottom depressions.

Dr. ROBINSON : It appears to me that what we are seeing at this time of year is only a remnant of the water exchange that has taken place before because the water pockets between Hanish Island and Bab-el-Mandeb give rise to temperature and salinity inversion, but nothing has really passed through the area. Is it a case of tidal mixing all the way through and an absence of a persistant flow pattern ?

Mr. GORMAN : There seems to be tidal mixing all the way through the Strait-sill area, but as shown in figures 16 and 18 there exists substantial residual currents, which are modulated by the tidal current field. Thus we think it fair to say that there was tidal mixing all the way through the Strait especially in the vertical where it had a distinct effect in moderating the high temperature-high salinity characteristics of the outflowing (to the south) Red Sea water, but that effective net transport was accomplished by means of the residual flows.

Dr. PATZERT : Well, the way I would interpret these observations is that during October the summer circulation pattern begins to break down. What you see are strong winds entering at the surface in the Red Sea and you can describe the surface flow to the north from your current observations, and, the cool low salinity water that entered during July, August and September is now beginning to back out. The upflowing from the Gulf of Aden has ceased. So what you are seeing is the water that entered during the summer beginning to back out which is what your current measurement showed. It is the beginning of the winter circulation scheme with the remnants of the summer scheme being flushed.

Mr. GORMAN : It wasn't our intention to be there in this season. We had desired to be in the middle of the summer circulation scheme in August but because of logistics and other difficulties we were delayed one month almost exactly and we didn't anticipate this sort of pattern at all.

Dr. PATZERT : What happens is that some of this water is going to be trapped further North in the Red Sea but what you're seeing in the water over the sill is the circulation scheme reversing and the remnants of the summer water over the sill being flushed out.

Dr. MORCOS : What do you think is the best period of the year for such measures ?

Mr. GORMAN : You mean to observe a classical summer situation. Well, Neumann and Mc Gill tried it in June and they did't see it. Muromtsev made measurements in September and they have seen it and we, unfortunately, didn't see it in the same period. So that leaves only July and August.

Dr. PEDGLEY : The optimum time for examination of flow patterns over the sill would probably be late July to early August, when summer wind and water circulations are likely to be well-established, and days with southerly winds are infrequent. The southerlies become more frequent in late August and September (although these days still form only a small fraction of the total) and may confuse the motion of surface water.

OBSERVATIONS OF THE EXCHANGE OF WATER IN THE STRAIT BAB-EL-MANDEB IN 1967

VAN AKEN H.M.* and OTTO L.**

Abstract

Serial observations and current measurements made in March 1967 in the Strait Bab-el-Mandeb are described. The serial observations show a good agreement with the results of previous observations.

The main finding of the observations at an anchor-station near the shallow sill close to Great Hanish Island is the presence of an outward residual current at 15 m as well as at 60 m depth. This deviation from the current pattern normally assumed for this time of the year apparently is due to abnormal winds (northerly instead of southerly).

Using a theorical approach developed by GROEN (1971) an explanation for the observed pattern is suggested and a tentative circulation pattern for the Strait is sketched.

Résumé : Observations sur les échanges d'eau dans le Détroit de Bab-el-Mandeb en 1967

Dans cette étude sont décrites les séries d'observations et les mesures de courant faites en mars 1967 dans le Détroit de Bab-el-Mandeb. Les séries d'observations sont en bon accord avec les résultats des observations précédentes.

Le principal fait nouveau apporté par les observations à la station près du seuil peu profond près de la Grande Ile Harnish est la présence d'un courant résiduel de sortie à 15 m aussi bien qu'à 60 m. Cet écart avec le modèle de courant normalement admis pour cette époque de l'année est apparemment dû à des vents anormaux (du Nord au lieu du Sud).

En utilisant l'approche théorique développée par GROEN (1971), une explication est proposée pour la circulation observée et un modèle de circulation est proposé et discuté pour le détroit.

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INTRODUCTION

In spring 1967 oceanographic observations were carried out in the Indian Ocean and Red Sea by a Belgian-Spanish-Netherlands group under direction of M. Steyaert on board of the MV. "Magga Dan" when returning from Antarctica. The Netherlands contribution included a programme of serial and current observations in and near the Strait of Bab-el-Mandeb. This programme aimed at a further understanding of the exchange processes between the Red Sea and the Gulf of Aden.

Quite a number of investigations have already been made in this region. A summary of the present knowledge concerning the exchange processes has been given by MORCOS (1970).

The Hanish Sill, located at some 80 n.miles inward from the narrowest section of the Strait, is the shallowest part in the connection between the Red Sea and the Gulf of Aden. The depth of the sill is given in literature to be about 100 m ; more accurate figures apparently are lacking. On the southeastern side of the Strait the channel branches into two channels, a relatively narrow and shallow one ($\simeq$ 500 m) in the north and a deeper and wider one (> 1 000 m) in the south.

Seasonal variations of the wind-field over the southern Red Sea and Gulf of Aden give rise to seasonal variations of the pattern of currents in the Strait.

In winter (October-April) SSE-ly winds are prevailing over the Red Sea south of 20° latitude, and easterly winds are found over the Gulf of Aden. This wind-field causes an inward surface current into the Red Sea while pressure gradients cause an outward bottom current of high saline water (THOMPSON, 1939 a, b). The presence of this two-layer current system has been confirmed by current measurements (SIEDLER, 1968).

In summer (June-September) NNW-ly winds are blowing all over the Red Sea, and westerly winds over the Gulf of Aden. The observations of water properties indicate the presence of a three-layer system : an outward current both at the surface and near the bottom, and an inward current into the Red Sea at an intermediate level (THOMPSON,1939 b). The influence of this intermediate inflow was found north to 18°10'N by JONES and BROWNING (1971).

NEUMANN and Mc GILL (1961) conclude from the distribution of water masses in the Red Sea as observed in June, that in this month the two-layer current system characteristic for the winter situation is still present. So there would be a time lag between the reversal of the wind direction and the change in the current system. However, no current observations are known that confirm this conclusion.

1 - The programme of observations

At the end of March 1967 measurements were made on board MV. "Magga Dan" in the Strait Bab-el-Mandeb and at nearby positions in the Red Sea and the Gulf of Aden (figure 1). As only normal serial observations could be made, the great vertical variability that is observed in this region from recordings of T-S-D probes could not be detected. But in order to have at least some indication of this phenomenon some extra sampling levels were included in the casts.

At a position 6 miles west of Great Hanish Island, at 3 nautical miles distance from the shallowest sill in the connection between the Red Sea and the Gulf of Aden, an anchor-station was occupied for about 24 hours. Here current observations were made with two self-recording current meters (Plessey) suspended from the ship at 15 and 60 m depth. During this period six serial observations were made in order to study the time variations of the water properties at different levels.

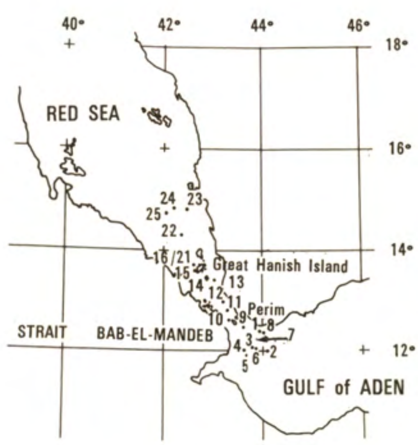


Fig. 1

2 - Weather conditions

It has to be noted that during the period these measurements were made the wind, contrary to the prevailing conditions in this time of the year, was blowing from northerly directions (table 1).

Table 1 - Wind direction and speed, measured on board MV. "Magga Dan" during measurements near Strait Bab-el-Mandeb.

date	time G.M.T.	wind direction (°)	wind speed (Knots)	remarks
23/3	06.00	250	03	
	12.00	050	02	
	18.00	330	20	
24/3	00.00	310	20	
	06.00	300	25	
	12.00	290	29	
	18.00	320	25	
25/3	00.00	330	18	
	06.00	330	19	ship at anchor-station
	12.00	340	22	ship at anchor-station
	18.00	290	15	ship at anchor-station
26/3	00.00	340	20	ship at anchor-station
	06.00	320	21	
	12.00	330	24	
	18.00	340	21	

According to a series of daily weather maps for this period, received from the "Service Méteorologique" at Djibouti, this abnormal situation was due to the penetration of a low-pressure area over the south of Arabia from the northeast.

3 - Discussion of the serial observations

a - General notes

In order to investigate the importance of time variations in the water structure we may compare two pairs of stations (1 and 8 as well as 3 and 6), made at approximately the same position, with time differences of 23 hours and 8 hours respectively. Temperature, salinity and sigma-t profiles are given in the figures 2-7. Although the density variations in both cases are relatively small temperature and salinity variations are important, especially for the pair of stations 3 and 6. These large variations, certainly those at the latter pair, can be attributed to the laminated structure of the water. Both the chance of sampling each time in a different layer and the possibility of internal waves may lead to variations as observed here. We may conclude with previous workers, that "only broad features of a section can be accepted provided that almost quasi-stationary conditions prevail during a reasonable period of time. (MORCOS, 1970).

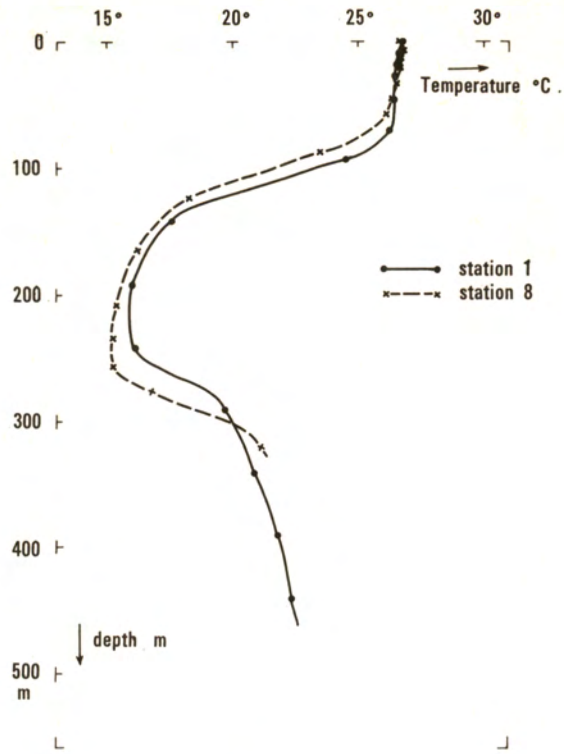


Fig. 2

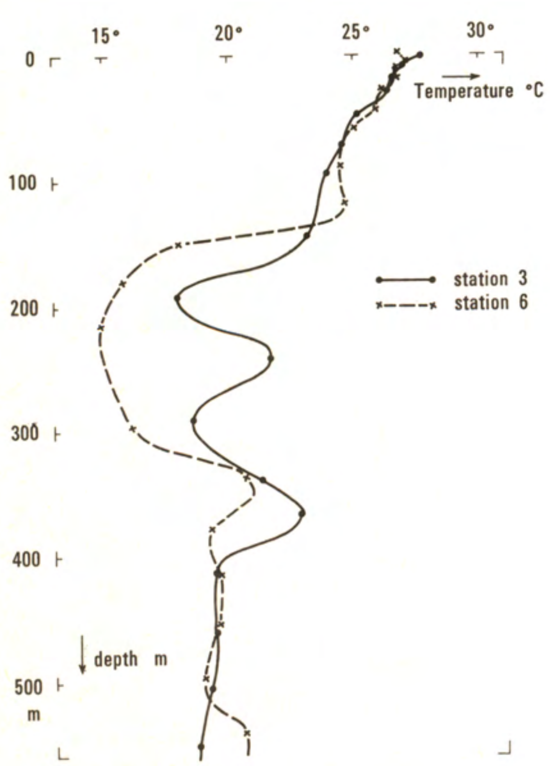


Fig. 3

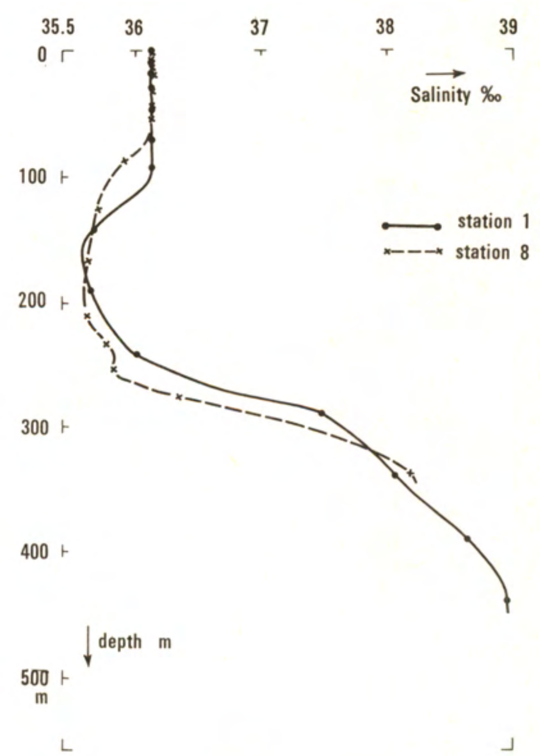


Fig. 4

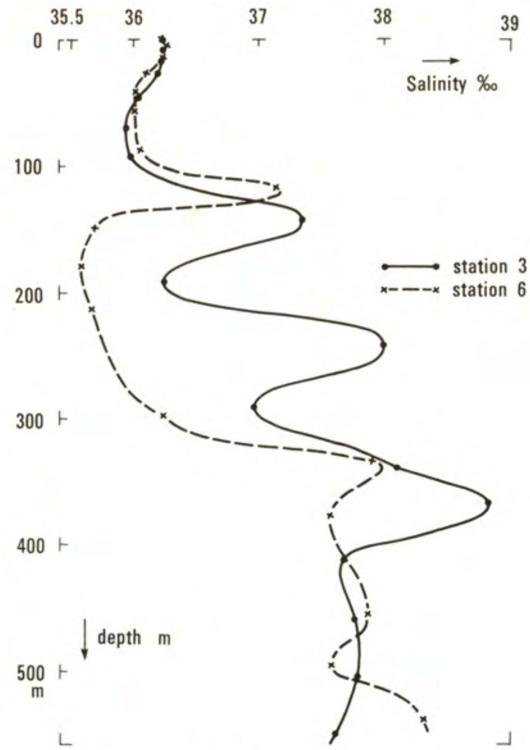


Fig. 5

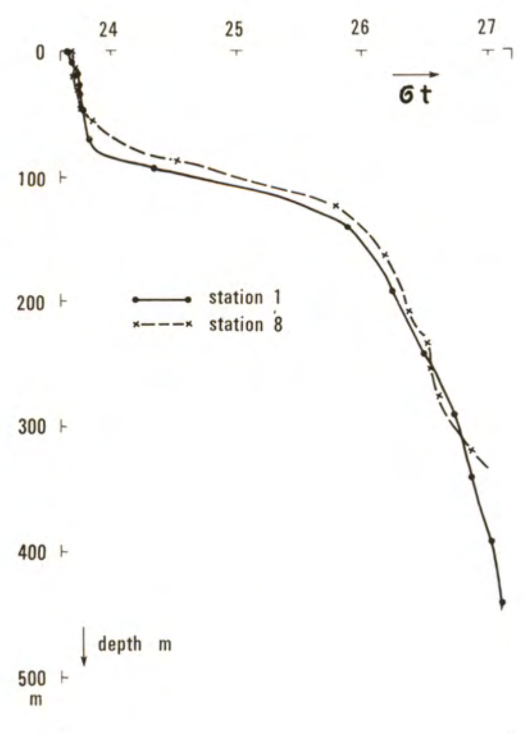


Fig. 6

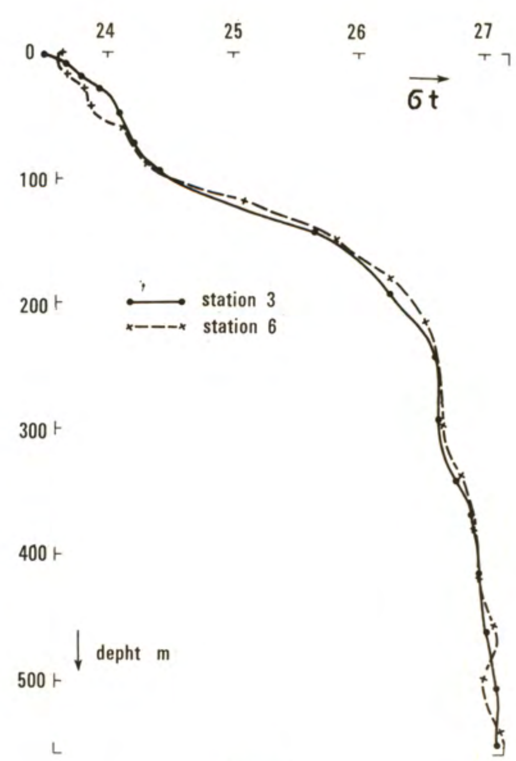


Fig. 7

b - The longitudinal section (stations 2, 9-12, 14-16, 22, 24)

In figures 8, 9, 10 and 11 the temperature, salinity, oxygen concentration and sigma-t values are given for the longitudinal section through the Strait. The bottom topography is indicated schematically, based on echo-sounding at the stations. The sill-depth is likely to be larger than the measured 82 meters.

The temperature section (figure 8) conforms to the description given by THOMPSON (1939 b). One can distinguish the deep water in the Red Sea, characterized by a temperature just below 22°C. Water with temperatures from 22° to 23°C is found on both sides of the sill. We also notice the warm surface water with temperatures up to 27°C and, on the right side of the figure, an intrusion with cold subsurface water in the Gulf of Aden at a depth of ± 240 m. Below this intrusion we find a laminated structure and at a depth of ± 650 m the relative warm water leaves the bottom, in accordance with the sections described by SIEDLER (1968).

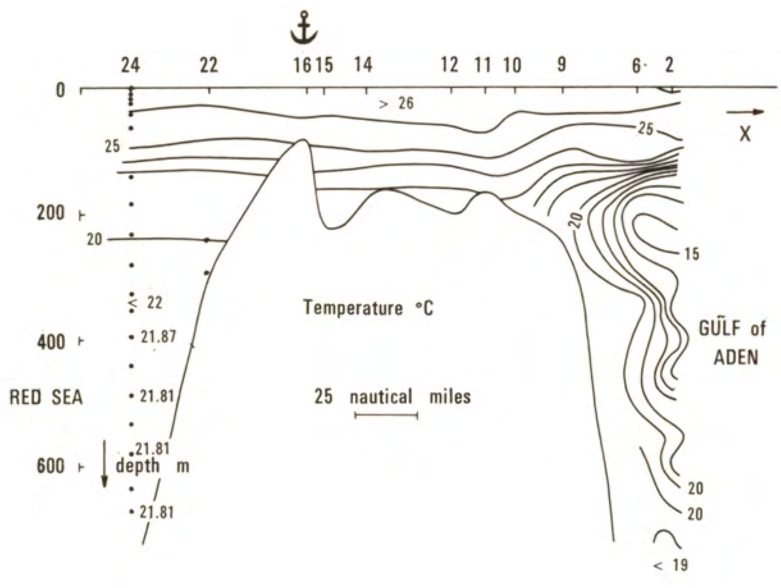


Fig. 8

The salinity section (figure 9) equally shows much analogy with the findings of THOMPSON (1939 b). In the Red Sea the 40°/oo isohaline coincides more or less with the 23°C isotherm. But only at 40,6°/oo the water is homogeneous. At the same depth the temperature becomes homogeneous, just below the 22°C isotherm. We can consider the water above the 40,6°/oo isohaline as a mixing product of the Red Sea water and the surface water with lower salinity and higher temperature. In other parts of this section the same features are observed as in the temperature section. Here we also distinguish surface water, in this case marked by a relatively low salinity (< 37,0°/oo). The subsurface intrusion in the Gulf of Aden with even lower salinities (< 36,0°/oo) coincides with the already mentioned low temperatures. Here again the laminated structure is well developed where the high salinity water from the Red Sea mixes with the low salinity subsurface water in the Gulf of Aden.

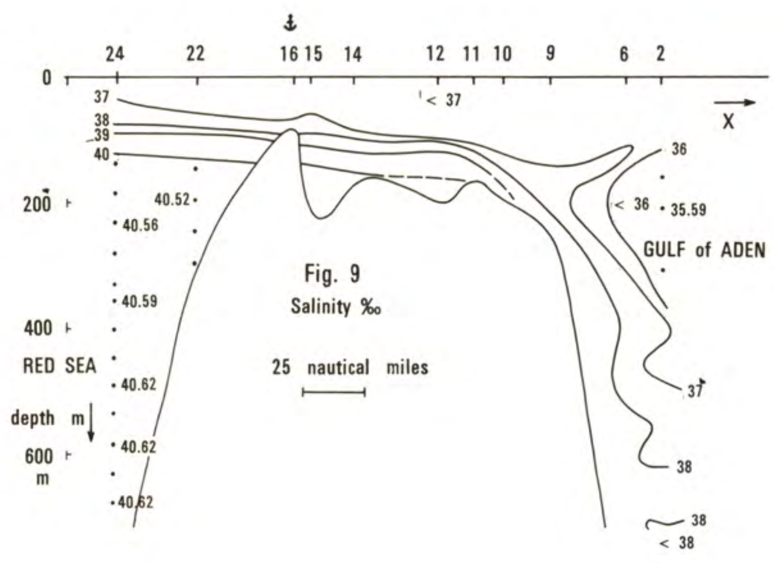


Fig. 9
Salinity ‰

In the Red Sea the oxygen maximum, described by THOMPSON (1939 b), is distinguished, but in our case at a deeper level (viz. ± 450 m) (fig. 10). The water from the Red Sea, flowing over the sill and the bottom of the Strait into the Gulf of Aden has more elevated oxygen values and gives rise to an oxygen maximum at 650 m.

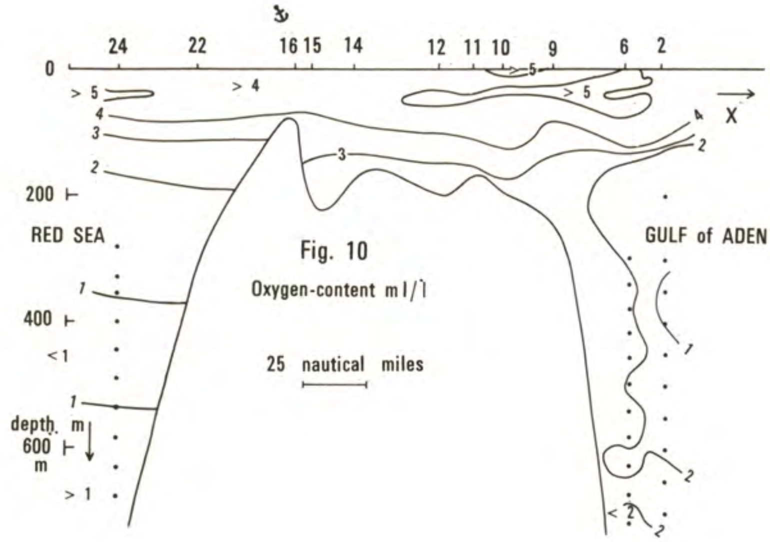


Fig. 10
Oxygen-content ml/l

A strong vertical density gradient is observed at the boundary between the surface water and the deeper water in the Red Sea. In the Gulf of Aden the presence of the Gulf of Aden water causes a less strong gradient (fig. 11). In this figure we observe a downward bulging of the isopycnals between the stations 10 and 12 (North of Perim). Although because of the time variations we have to be careful in attaching too much weight to smaller details in the observed water structure, this might be considered as an indication of converging motion in the surface layers, especially in connection with the discussion in the following sections of this paper (see section 7).

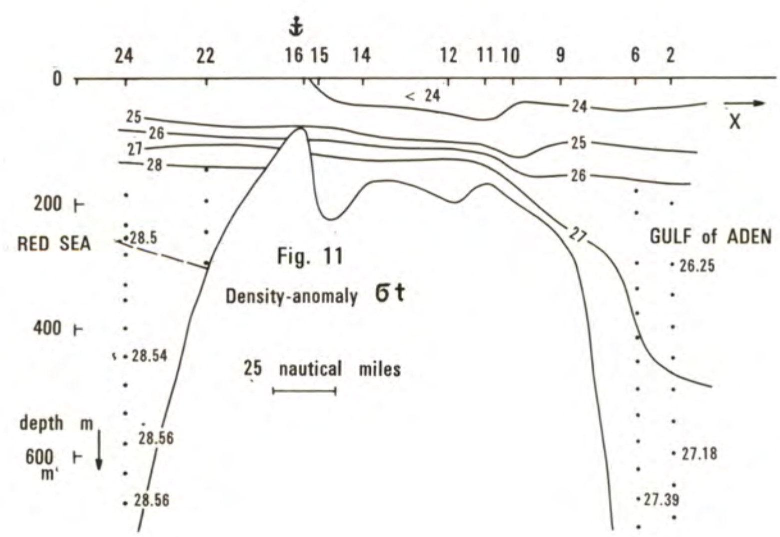


Fig. 11
Density-anomaly σ_t

c - The cross-section in the Gulf of Aden (stations 5-8)

As mentioned earlier, there are two channels in the Gulf of Aden, separated by a shallower ridge. The northern channel is relatively narrow and shallow.

The figures 12-15 give a picture of the different properties in a section crossing both channels.

At the upper levels warm surface water is observed down to a depth of about 100 m (fig. 12). The cold Gulf of Aden water is present at the 240 m level, with a strongest development in the southern branch. The warmer water from the Red Sea is observed at different levels, agreeing with the laminated structure mentioned before.

According to KRAUSE (1968) such structures do not appear in the northern channel in contrast with the southern one. Our results at least do not contradict this opinion, but data from the deepest region are lacking.

The salinity distribution (fig. 13) is conform to the temperature distribution with respect to the distribution of the various water masses.

As regards the oxygen distribution (fig. 14) the areas of low oxygen concentration (< 1 ml/l) at about 200 m depth deserve special attention. At this level the Gulf of Aden water is predominant, but the oxygen minima do not exactly coincide with the temperature minima.

No special features are found in the density distribution as given in figure 15.

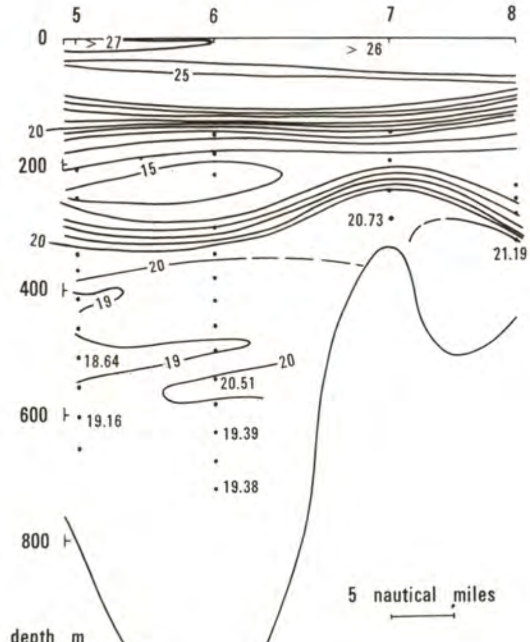


Fig. 12
GULF of ADEN
Temperature °C

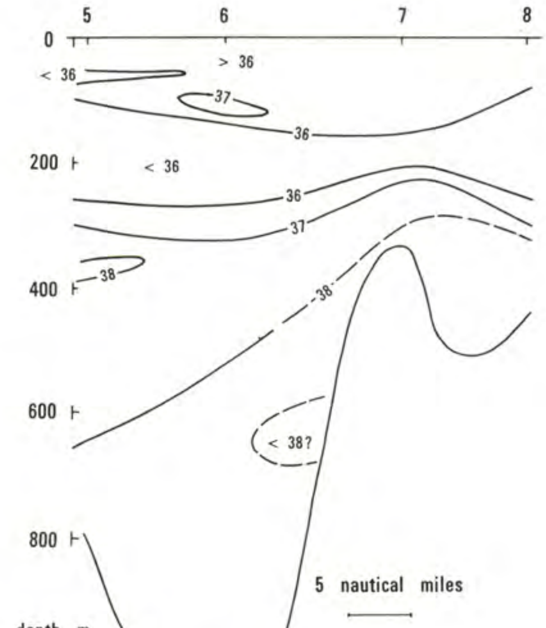


Fig. 13
GULF of ADEN
Salinity ‰

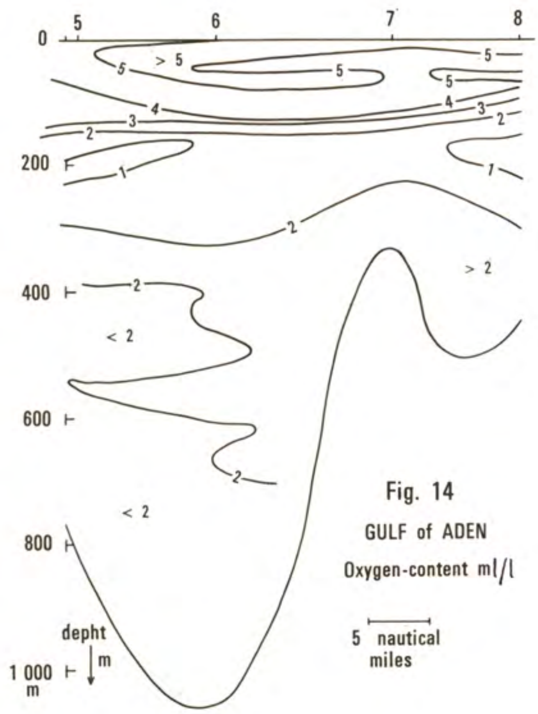


Fig. 14
GULF of ADEN
Oxygen-content ml/l

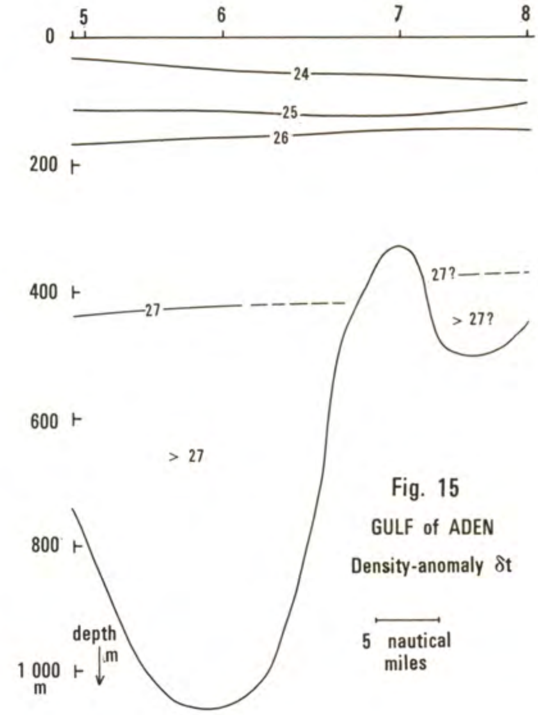


Fig. 15
GULF of ADEN
Density-anomaly δt

d - <u>The cross-section in the Red Sea (stations 23-25)</u>

The distribution of water properties in a cross-section in the southern part of the Red Sea is given in figures 16-19. There are no important lateral variations in the general distribution of the water masses. A more detailed discussion of these observations e.g. in terms of geostrophic calculations is not given, as for such a discussion a more complete set of observations is needed.

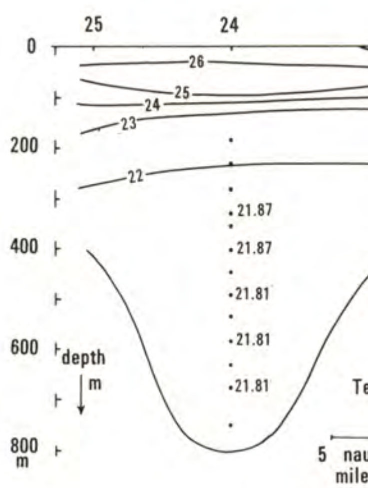


Fig. 16
RED SEA
Temperature °C

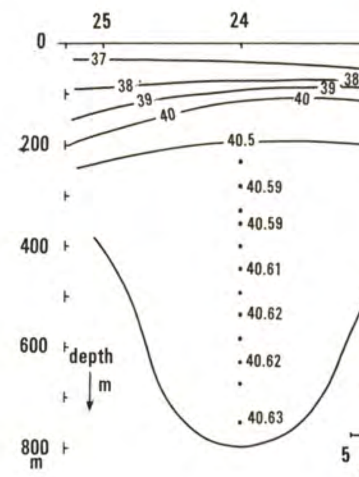


Fig. 17
RED SEA
Salinity ‰

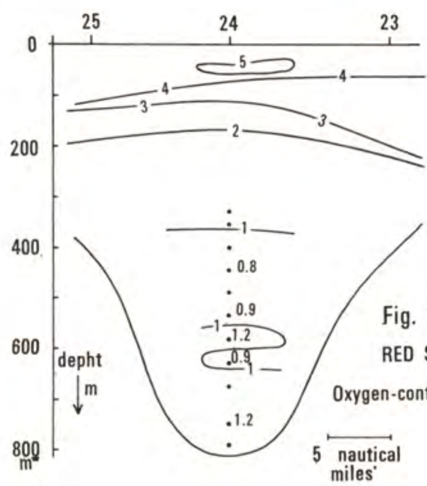


Fig. 18
RED SEA
Oxygen-content ml/l

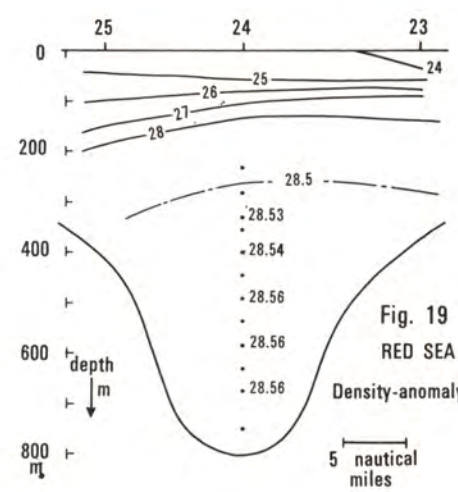


Fig. 19
RED SEA
Density-anomaly δt

5 - Distribution of different water-types

In a T-S diagram, shown in figure 20, observations from a selected group of stations have been plotted. Looking at the positions of these points in the diagram, we may consider the water-masses as mixing products of three primary water-types, called Red Sea water, surface water and Gulf of Aden subsurface water.

Surface water

The oceanographic atlas of the international Indian Ocean expedition (WYRTKI, 1971) gives, for the season in question, a surface temperature of 28°C and a salinity of 36,1°/oo in the eastern part of the gulf of Aden. According to THOMPSON (1939 b) the surface water comes from the Gulf of Aden and in that Gulf the surface current is directed westward in this season (Koninklijk Nederlands

liver

Meteorologisch Instituut, 1949). So we can accept this water as a primary water-type. (elle évolue d'une saison à l'autre)

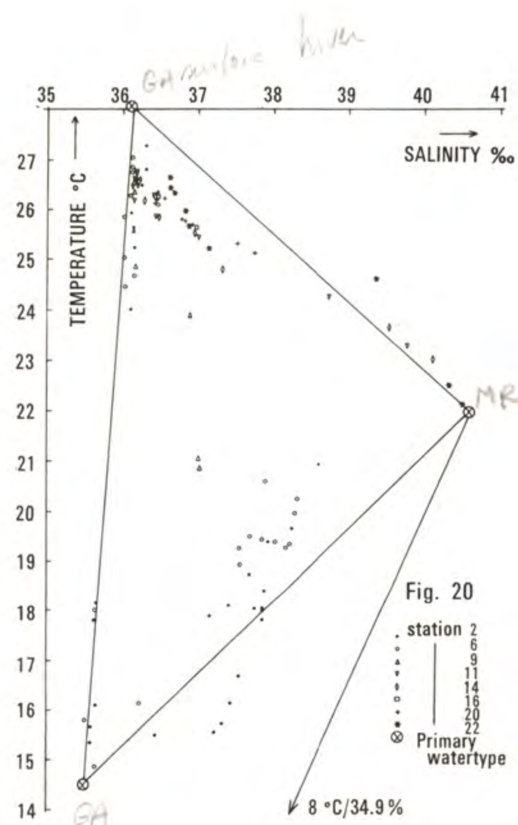
Gulf of Aden subsurface water

NEUMANN and Mc GILL (1961) define this watertype by a salinity of 35,5°/oo and a temperature of 14,5°C. These values fit very well with our observations and could be accepted for our purpose.

Red Sea water

In the already discussed temperature sections we found the "pure" Red Sea water marked by a temperature of 22°C and a salinity of 40,6°/oo, which values have been taken as characteristic for this water-type.

NEUMANN and Mc GILL (1961) indicate the mixing of the water from the Red Sea outside this sea with a fourth water-type at greater depths. This is perceived in the T-S diagram for station 2 (fig. 20). For this water-type a temperature of about 8°C and a salinity of about 34,9°/oo tentatively can be considered as characteristic, on the basis of the results presented by ROCHFORD (1964). However, as this mixture is only observed at station 2 we will not pay more attention to this aspect.



For the points within the triangle of figure 20, we assume that their temperature and salinity values are caused only by the mixing of the three water-types. The proportion of these water-types to the mixture can easily be calculated. Of course we have to bear in mind that the primary water-types defined here are an abstraction and that in reality the properties of the water are the result of mixing, heat exchange and evaporation or precipitation, and therefore may vary somewhat over a larger region.

In figure 20 some points fall just outside the triangle. This may be the result of observational errors, variability of the properties of the primary water-types, admixture of small quantities of other water-types or of exchange of heat or moisture with the atmosphere. These points have been considered to lay in fact on the triangle.

The results of the calculations are presented in figures 21-26.

It appears that the water flowing from the Red Sea into the Gulf of Aden consists for over 50 % of primary Red Sea water, mixed with 10-20 % surface water and 30-40 % Gulf of Aden water.

The surface water penetrating into the Red Sea does not consist of "pure" primary surface water, but it contains about 10 % Gulf of Aden water.

In the cross-section (figs 24-26) the upper 250 m appears to be a mixture of surface water and Gulf of Aden water. The concentrations decrease, respectively increase. In the southern branch the "laminated" structure is clearly shown.

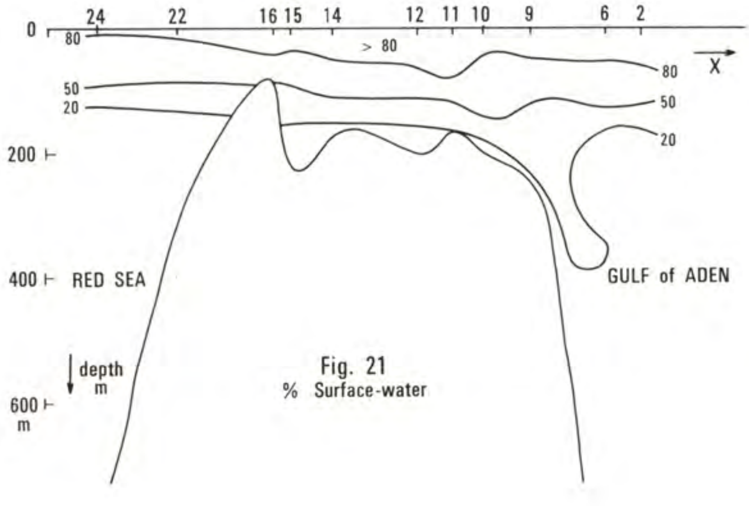


Fig. 21
% Surface-water

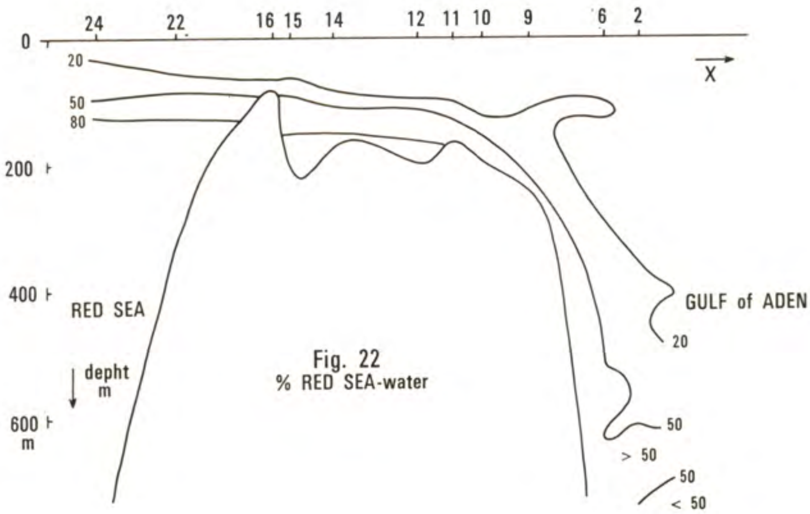


Fig. 22
% RED SEA-water

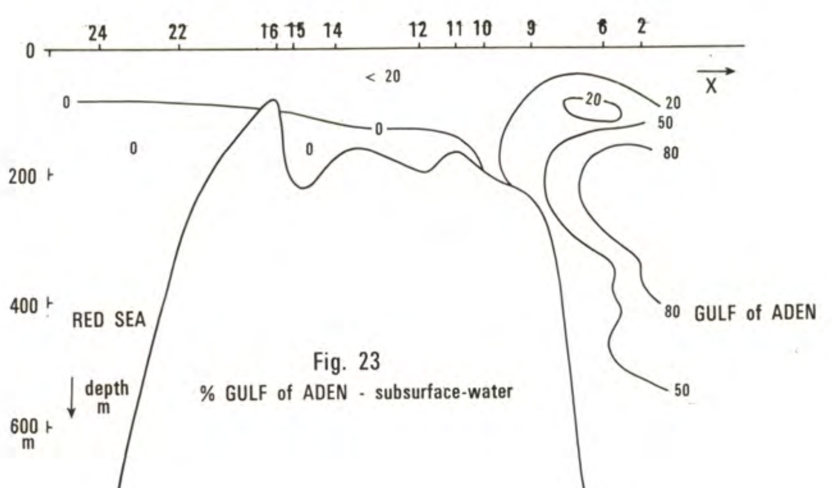


Fig. 23
% GULF of ADEN - subsurface-water

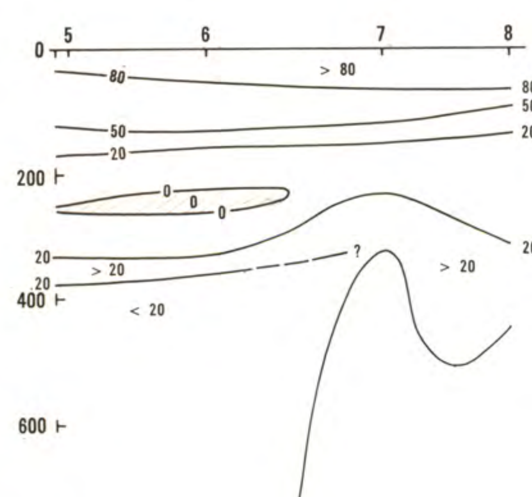


Fig. 24
GULF of ADEN
% Surface-water

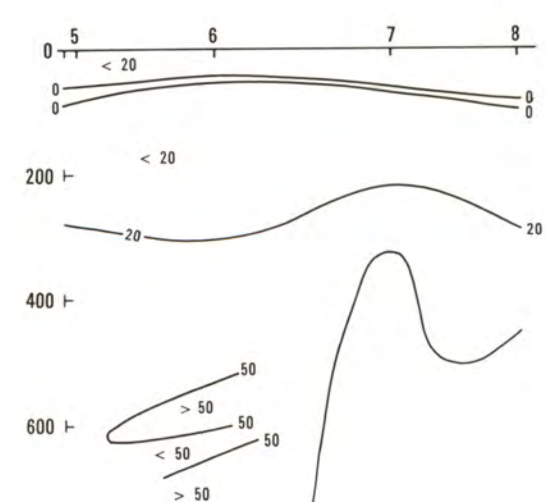


Fig. 25
GULF of ADEN
% RED SEA-water

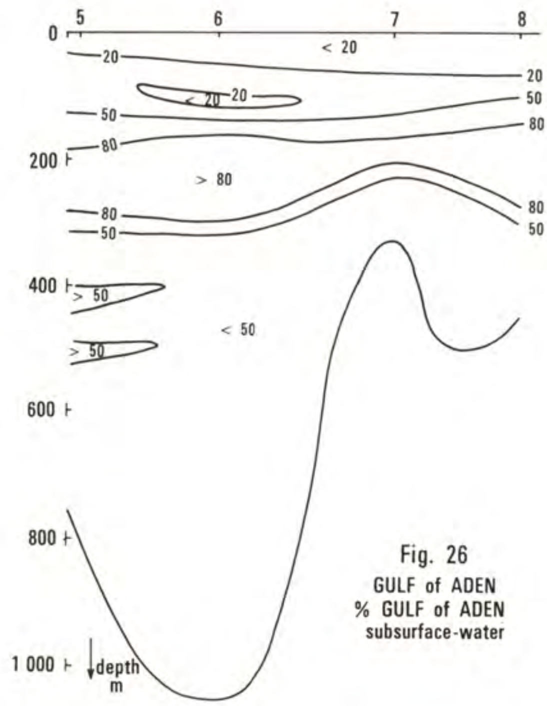


Fig. 26
GULF of ADEN
% GULF of ADEN
subsurface-water

6 - Observations at the anchor-station

From 25 th March 1967, 03 GMT to 26 th March, 03 GMT the ship anchored at position 13°41'N, 42°45'E. The depth indicated by echosounder was 82 m. So this means that the ship was not at the deepest part of the sill. Moreover the maximum sampling depth was 70 m. Therefore the variation of the water properties near the bottom and especially at the deepest point of the sill remains unknown.

The variation of temperature, salinity, oxygen content and sigma-t is shown in figs 27-30.

Surface values of temperature and oxygen content exhibit diurnal variations that may be related to solar influences (heating and phyto-plankton activity), while salinity, the temperature below 30 m and the oxygen content below 60 m show predominant semi-diurnal variations, apparently due to tidal influences.

The maximum salinity observed coincides with the lowest temperature (hydrographic station no. 20 at 70 m depth). This means that at this depth only 38 % Red Sea water is present at that time. Since south of the sill values with percentages over 50 % are quite normal, the core of the outflow apparently is not observed.

The current observations (recordings of direction and mean current made at 10 minute intervals) showed a relatively large variability. It is impossible to say whether this variability is due to motions of the meters or to real variations of the current. However, hourly means clearly show a semi-diurnal periodicity.

The variation of the northward component of the current is shown in figure 31, together with the depth of the 36,5°/oo isohaline.

It is seen that the isohalines move upward during most of the inflow period and downward during most of the outflow period. The same was found by VERCELLI (1925) in his measurements further to the south, in the narrower part of the Strait.

station 16 13° 41' N 42° 45' E

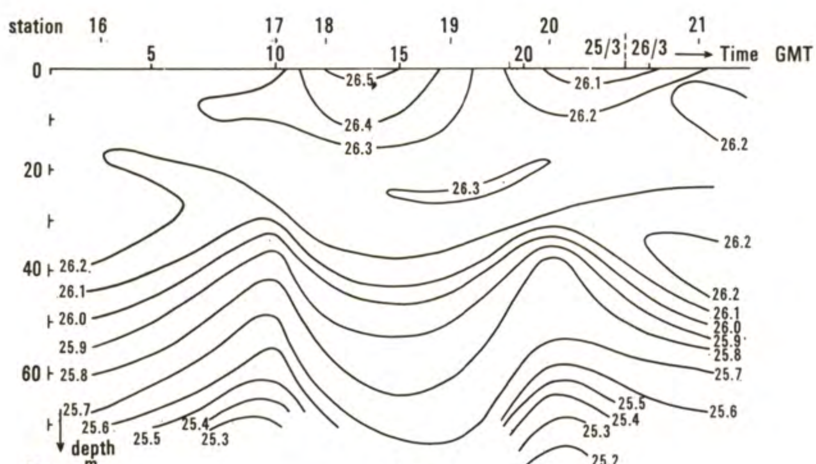


Fig. 27
Anchorstation Temperature °C

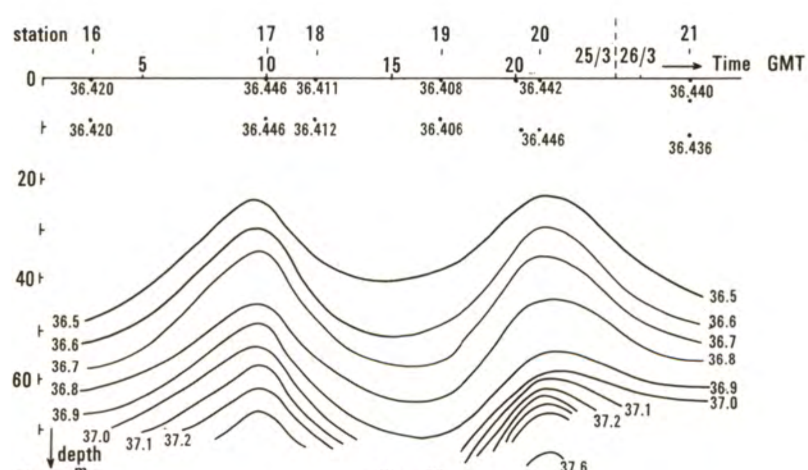


Fig. 28
Anchorstation Salinity ‰

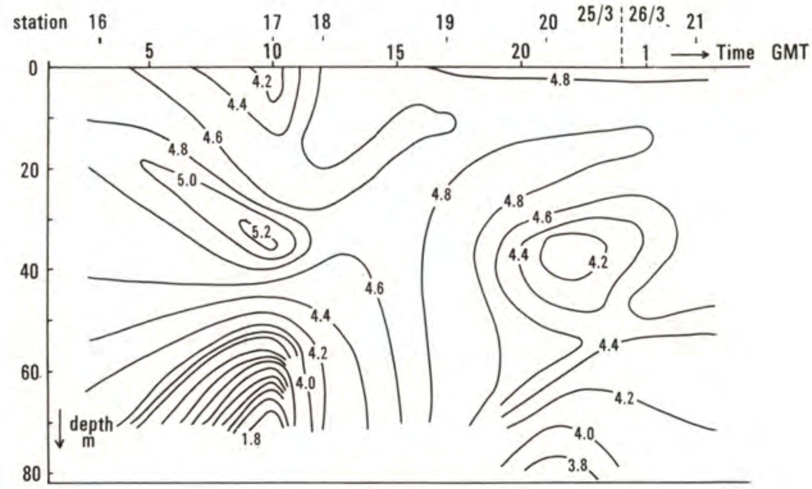


Fig. 29

Anchorstation Oxygen-content ml / l

station 16 13° 41 N 42° 45' E

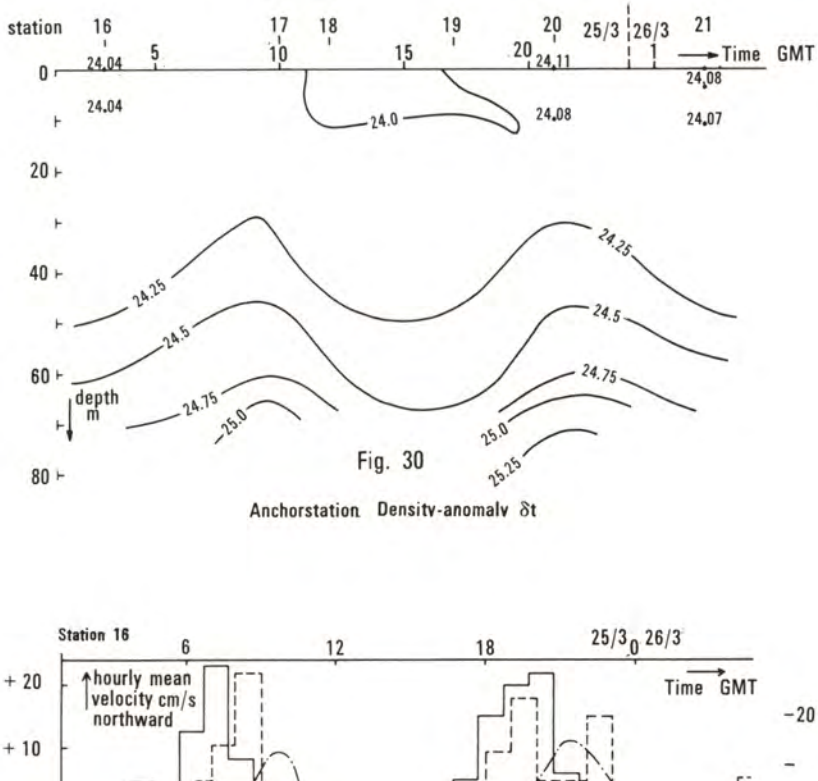


Fig. 30

Anchorstation Density-anomaly δt

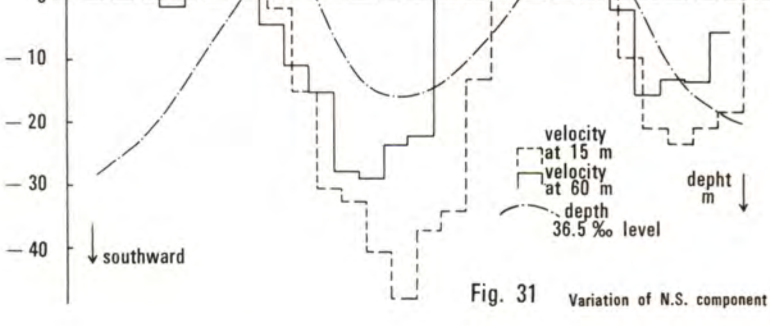


Fig. 31 Variation of N.S. component of current

The current variations suggest for the north component the presence of semi-diurnal tides with an amplitude of the order of 25 cm/s, and diurnal tides with an amplitude of the order of 10 cm/s, superimposed on a residual current. For the east-west component (not represented in fig. 31) the amplitudes are about 15 cm/s and 10 cm/s for the semi-diurnal and diurnal components respectively.

Usually the residual current can be estimated by taking the average over a full tidal period, but as the period of the reliable current measurements for the observations at 15 and 60 m is only 21h 40 mn and 23 h 50 mn respectively, this procedure cannot be followed here.

Therefore a slightly different method was adopted. At first the east and north components of the current (U and V) were averaged over the first 12 h 30 mn and the last (partly overlapping) 12 h 30 mn of the record. By this procedure the semi-diurnal tide and its higher harmonics are nearly eliminated. The two means for U and V were again averaged. This procedure does not sufficiently eliminate the diurnal tide, as there is an overlap in the middle of the period and similar stretches of time are missing at the beginning or the end. The difference with a residual calculated as an average over 24 h 50 mn is extreme when the diurnal tide is maximal or minimal during the period of overlapping. An estimate of this maximum deviation D for small values of the overlap n is about.

$$D = 2a \frac{n}{25}$$

where a is the amplitude of the diurnal tidal current.

Assuming for a, for both east and north components, a value of 10 cm/s it is found that the mean residual current becomes

depth 15 m	$U = -2 \pm 3$ cm/s	(westward)
	$V = -12 \pm 3$ cm/s	(southward)
depth 60 m	$U = +2 \pm 1$ cm/s	(eastward)
	$V = -4 \pm 1$ cm/s	(southward)

These estimates show that on both levels there is a residual current with an outward component. For the 60 m level this agrees with the observed outflow of Red Sea water. However the strong outward component at 15 m depth contradicts the assumed surface inflow, for it appears highly improbable that between 15 m and the surface there could be a reversal of the direction of the residual current. It is rather likely that this strong residual current is due to the strong northerly wind that was already blowing for about $1\frac{1}{2}$ day (see table 1).

Although the possibility of a locally different current system cannot be ruled out completely, it appears as if the situation is already conform the summer conditions, and in that case one may envisage the presence of a return flow somewhere between 15 and 60 m depth. However, if such a rapid response of the current pattern to the change of the wind occurs, it has to be explained how NEUMANN and Mc GILL (1961) could conclude that the surface inflow continues for some time after the end of the southeast monsoon, the more so as the atlas "Red Sea and Gulf of Aden, oceanographic and meteorological data" (Koninklijk Nederlands Meteorologisch Instituut,1949) shows that for June already a marked outward surface current exists. In other words, the observed outward currents and the apparent inflow of surface water have to be reconciled.

7 - Combined effect of an anti-estuarine circulation and a counteracting wind drift

The above-mentioned situation may be described by a simplified model developed by GROEN (1971). In this theory the influence is elucidated of the water depth on the circulation pattern in the case of anti-estuarine conditions and a counteracting wind drift.

Assuming a vertical eddy viscosity coefficient $A(z)$ which is a parabolic function of the depth z, and a horizontal density gradient $\partial\rho/\partial x$ which is independent of depth, an expression for the longitudinal current velocity U is found as a function of z with the depth h, the density gradient $\partial\rho/\partial x$ and the surface stress τ as parameters satisfying the imposed conditions that at the bottom $U = 0$ and that the net water transport is zero.

Three current regimes are possible, dependent on the magnitude of z, h and $\partial\rho/\partial x$:

1 - surface outward flow, bottom inward flow
2 - surface outward flow, bottom outward flow, intermediate inward flow
3 - surface inward flow, bottom outward flow.

The case (2) is similar to the normal current regime in Strait Bab-el-Mandeb in summer and to the special situation described here as well. The limiting case between situation (2) and (3) is given by the approximate relation (Groen, eq. 15)

$$4\ \tau h^{-2}\ \ln(h z_0^{-1}) = -g\ \partial\rho/\partial x$$

Here z_0 is the roughness parameter for the water surface.

The limiting case between situation (1) and (2) is given by the approximate relation (Groen, eq. 16)

$$-\tfrac{1}{4} g\ \partial\rho/\partial x\ h^2 = \tau$$

Application of these formulae to our observations at the anchor-station demonstrates the influence of the bottom depth on the circulation pattern. Such an application appears to be justified although the schematic nature of Groen's model is recognized. Especially the vertical variation of the eddy viscosity A_z is expected to be more complicated because of variable density gradients.

The density gradient $\partial\rho/\partial x$ is estimated using observations made at station 15, at about 12 km from the anchor-station, and at the anchor-station itself 23 hours later (this eliminates as good as possible the effect of tidal variations). It is found that the depth mean of the density gradient is

$$\partial\rho/\partial x = -12{,}5.10^{-6}\ \mathrm{kg/m^4}$$

With a mean wind speed during the anchoring period of 19 knots (9,5 m/s) we find, assuming a drag coefficient 0,0013 (see e.g. BROCKS and KRÜGERMEYER, 1970) a surface stress

$$\tau = 0{,}14\ \mathrm{kg/m\ s}$$

Adopting furthermore $z_0 = 0{,}25$ cm we find that situation (2), viz. the three-layer circulation, occurs at sea depths

$$200\ m > h > 70\ m$$

According to these values at the position of the anchoring station the situation would be within this range, thus a three-layer system with surface outflow can be expected.

Although the density gradient and the wind stress at other parts of the Strait will be more or less different from the values used here, one may presume that outside the Strait where depths rapidly increase, conditions are more favourable for a two-layer system with surface inflow, even if opposing winds do occur.

The wind velocity at which the three-layer circulation over the sill (assumed depth 100 m) may occur if the other conditions remain unchanged, is 4,3 m/s, but of course at this low wind velocity only a superficial layer would be affected.

The current system that can be assumed from this theory for moderate or fresh opposing winds is sketched in figure 33, in which a closed cell of streamlines is indicated, superimposed on the normal in-and outflow. A convergence area may develop at the Gulf of Aden side and a divergence area at the Red Sea side of the system. As mentioned in section 4.b there is observed a downward bulging of isopycnals near Perim which perhaps may indicate such a convergence. Only if wind becomes stronger or the density gradient is closer to zero, the cell will extend over the deeper parts and the inflow and outflow of different watermasses may be affected significantly.

As a final question we may ask how frequently such abnormal conditions might occur. From climatological data (Koninklijk Nederlands Meteorologisch Instituut, 1949) it is found that winds favourable for such conditions occur with a frequency of something like 2 % in the months of March and April.

8 - Conclusions

For a better understanding of the water exchange between the Red Sea and the Gulf of Aden the details of the current pattern in Strait Bab-el-Mandeb deserve more attention. Studies of the distribution of water masses alone are insufficient for this purpose. On the other hand, as it is likely that a circulation pattern as described in the previous section (fig. 33) affects the mixing of the water in this region, the development of such a pattern may be of importance for the constitution of the resulting water masses.

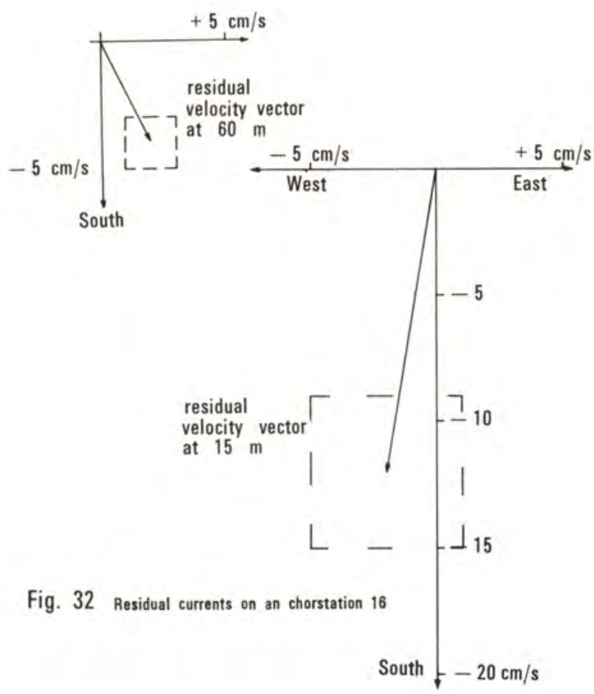


Fig. 32 Residual currents on an chorstation 16

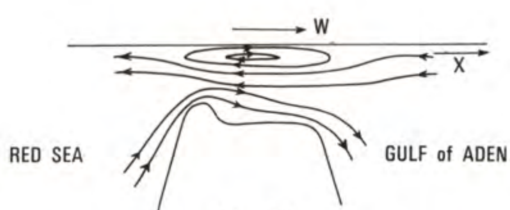


Fig. 33

Sketch of the current system near STRAIT BAB-EL-MANDEB

Acknowledgements

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Mr. H. BOSCHLOO and Mr. J.P.H. VAN AMEYDE were responsible for carrying out the observations. We gratefully acknowledge the support of the leader of the "Magga Dan" expedition, Dr. M. STEYAERT, of Dr. A. BALLESTER, who did much of the analytical work, of the other members of the scientific staff and of the captain and crew of the ship.

Much preparatory work for this study was done by Mr. H. BOSCHLOO and Mr. A.J. MEERBURG.

The Director in Chief of the Royal Netherlands Meteorological Institute and Professor R. DORRESTEIN, professor in oceanography at the State University of Utrecht, gave their permission to publish this paper.

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INDIRECT ESTIMATION OF THE SEASONAL VARIATION OF THE WATER EXCHANGE THROUGH BAB-EL-MANDEB

A.K. BOGDANOVA*

Abstract

Some peculiarities of the water exchange through Bab-el-Mandeb connected with the seasonal variation of the level, evaporation, level difference on the strait ends, wind, and "piled-up" circulation on the near-strait regions of the Red Sea and Gulf of Aden are discussed.

The effect of monsoonal winds and "piled-up" circulation in the two Bab-el-Mandeb adjacent regions on the water exchange between Red Sea and Gulf of Aden is concerned in a new fashion.

The annual level variations slope of level surface concerning with mean annual position and evaporation from sea surface are analyzed. According to annual evaporation variation and mean monthly sea level change, the positive component of water exchange through Bab-el-Mandeb is calculated.

The maximum sea level difference is observed in summer months (VI-VIII) with a maximum in July. The maximum Aden waters inflow shifts to September.

According to a level surface slope and wind field the qualitative characteristic of water exchange intensity through Bab-el-Mandeb is given. It is shown that an annual variation of the total water exchange has different variations as compared with the variation of a positive water exchange component.

The water exchange through the strait is increasing in winter months when level surface slope and tangential wind stress coincide in their direction.

When the surface water is moved away from the southern part of the Red Sea and upwelling occurs, the lower current is increasing in the strait. By simultaneous increasing of both flows the difference between Aden and Red Sea discharges is decreasing.

The intensity of water exchange through the strait slacks off in summer. The upper flow is weakening since the level surface slope and tangential wind stress have opposite directions. The Aden waters move as an intermediate layer breaking a resistance of the upper and lower current. However, the lower Red Sea current is weakening also since the summer North-North-West winds give rise to the piling up in the South of the Red Sea and, therefore, generate a deepening of the water masses interface in the sill region. However, the increasing of a positive water exchange component points out the greater weakening of the lower Red Sea flow as compared with Aden waters flow.

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Résumé : Estimation indirecte de la variation saisonnière de l'échange d'eau à travers Bab-el-Mandeb

Certaines particularités de l'échange d'eau à travers Bab-el-Mandeb, liées à la variation saisonnière de niveau, à l'évaporation, à la différence de niveau entre extrêmités du détroit, au vent et à l'accumulation des eaux dans les régions voisines du détroit entre la Mer Rouge et le Golfe d'Aden sont discutées ici.

L'effet des vents de mousson et de l'accumulation des eaux au voisinage du détroit sur l'échange d'eau entre la Mer Rouge et le Golfe d'Aden est traité d'une nouvelle manière.

Les variations annuelles du niveau et de la pente de la surface vis-à-vis de la position moyenne annuelle et de l'évaporation sont analysées. La composante positive de l'échange à travers Bab-el-Mandeb est calculée en fonction des variations annuelles de l'évaporation et des variations de la moyenne mensuelle du niveau de la mer.

L'écart maximal entre le niveau de l'eau et la position moyenne est observé en été avec un maximum en juillet. Le maximum du flux d'entrée des eaux d'Aden se trouve en septembre.

Les caractéristiques de l'intensité de l'échange d'eau à travers Bab-el-Mandeb sont données qualitativement en fonction de la pente de la surface de l'eau et du champ de vent. On montre que la variation annuelle de l'échange d'eau total est différente de celle de la composante positive de l'échange.

L'échange d'eau à travers le détroit croît en hiver quand les effets de la pente de la surface et du frottement des vents s'ajoutent.

Quand les eaux superficielles se retirent de la région Sud de la Mer Rouge et qu'il y apparaît un upwelling, le courant inférieur est renforcé dans le détroit. Du fait de l'accroissement simultané des deux courants, la différence entre les écoulements dans le Golfe d'Aden et dans la Mer Rouge diminue.

En été, l'intensité de l'échange à travers le détroit diminue. Le courant supérieur décroît parce que la pente de la surface de l'eau et le vent sont en opposition. L'eau d'Aden progresse dans une couche intermédiaire tout en freinant les courants inférieur et supérieur. De plus, le courant inférieur de la Mer Rouge décroît aussi car les vents d'été de NNW tendent à accumuler les eaux au Sud de la Mer Rouge et à engendrer ainsi un abaissement de l'interface entre les masses d'eau dans la région du seuil. Toutefois, l'accroissement de la composante positive de l'échange met alors en évidence l'encore plus important affaiblissement du flux inférieur d'eau de la Mer Rouge.

INTRODUCTION

The Red Sea regime is conditioned by the climatic conditions and water exchange with the Gulf of Aden through Bab-el-Mandeb and with the Mediterranean through the Suez Canal. The climat of the Sea is of a monsoonal character but owing to its position between deserts of Arabian peninsula and North Africa it is notable for high dryness. Negative water balance causes the highest salinity of the Red Sea waters as compared with the other seas of the globe.

To study the hydrological regime of these regions the Institute of Biology of the South Seas Ukrainian Academy of Science carried out two oceanographical expedition in 1961-1962 and 1963 (fig.1).

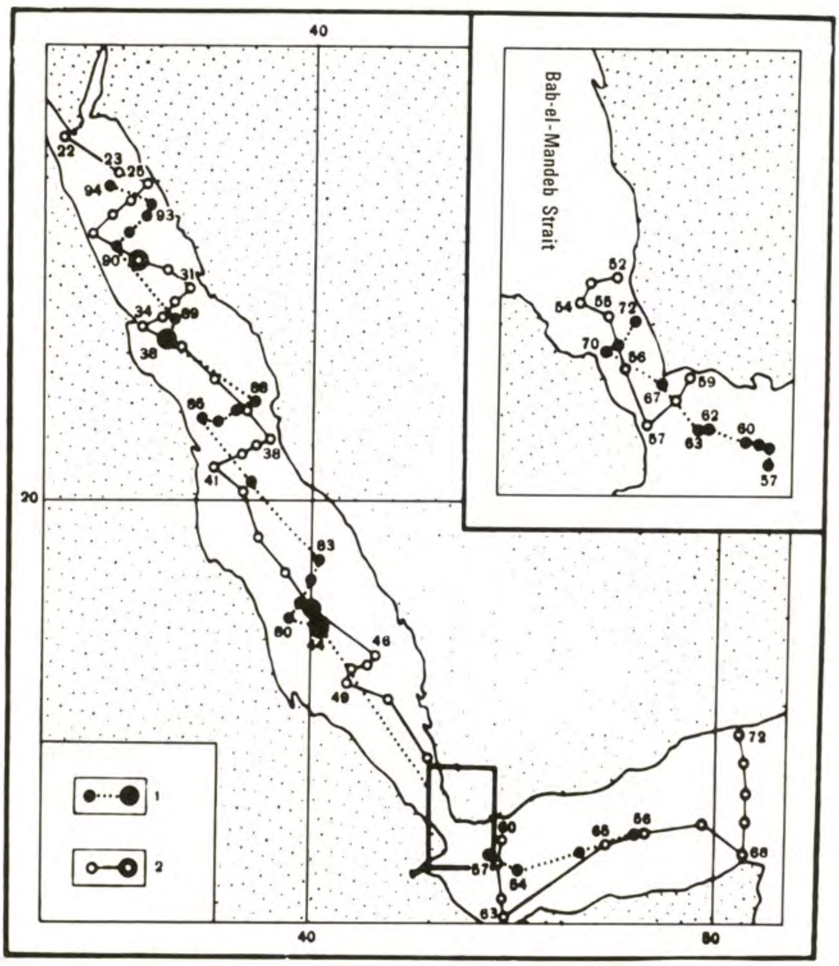

fig 1 - Hydrological samples taken by "Academician A. KOVALEVSKY" during
1) December 1961-1962
2) October - November 1963

The low depths in the sill region situated in the South of the Red Sea (the maximum depth is 125 meters) limit the exchange between the Red Sea and Gulf of Aden to the waters of a comparatively small upper layer. Under such conditions, the effect of a "piled-up" circulation in the near-strait regions on the intensity of water exchange and on the thermohaline characteristic of the lower and upper (or intermediate) current is rather considerable. During the winter monsoon the reccurence of the water "driving away" on the South of the Sea in the sill region and the "piling-up" in the near-strait region of the Gulf of Aden is increasing. It was traced that in this case the deeper highly saline Red sea waters were entrained into the lower current and, vice versa, the surface Aden waters were carried into the Red Sea. In summer when the north-north-western winds blow over all Red Sea and the south-south-western - over the near-strait region of the Gulf of Aden the reccurence of the piling-up is increasing in the South of the Sea and recurrence of the driving away - from the Gulf od Aden.

Due to the piled-up thickening of the surface layer in the sill region the low current is formed by more surface Red Sea waters. On the contrary, the intermediate current carring Aden waters into the Red Sea is formed by the relatively deep Gulf waters which are upwelled near to the surface as affected by the wind drived effect. In this case the Aden waters are found not only in the surface layer of the Red Sea but also in the intermediate layers at the depth from 90-100 to 300-400 m. Thus, the piled-up circulation changes not only the discharge quantity of the Aden and Red Sea waters but also their thermohaline characteristic what causes in turn the immersion depth of the Red Sea waters in the Gulf of Aden and that of the Aden waters in the Red Sea (BOGDANOVA, 1966).

A current in the strait is appeared as affected by tide-forming forces : wind, level-and density differences on strait ends. If one eliminates the tidal currents, which don't effect on the averaged discharge quantities of the Red Sea and Aden waters the residual current in the surface layer depends on wind (its strength and direction) and level difference at the ends of the strait.

The lower current is determined by the density difference between the Red Sea and Aden waters at the sill level.

According to DEFANT (1961) the mean density difference is egual to 1.5 conventional units. Depending on high tide, wind, and season a density of the lower flow varies within 23,94-27,74 con.units.

It was reported that winds are causative factor of circulation in the Red Sea and strait (VERCELLI, 1931 ; THOMPSON, 1939). In winter when a south-south-eastern wind predominates over the south part of the Red Sea the Aden waters are transferred into the Red Sea by the surface current.

The lower current of Bab-el-Mandeb carries the subsurface warm and more saline Red Sea water into the Gulf of Aden. In summer when the north-north-western wind predominates over all Red Sea the Aden water enters into the Red Sea by the intermediate layer. The residual current in the surface layer and near the bottom is directed from the Red Sea to the Gulf of Aden.

NEUMANN and McGILL (1961) have pointed out that in the middle of June 1957 the surface current in Bab-el-Mandeb was directed from the Gulf into the Red Sea. The authors have assumed that in the first half of summer the water circulation in the Red Sea and in the strait was conditioned, on the whole, by no wind but by a level difference caused by evaporation. In July, August and September the surface current in the strait was directed into Gulf, i.e. it coincided with the predominant north-north-western wind what was possible only by the decrease of evaporation from the sea surface (NEUMANN, McGILL, 1961).

Our analysis of level values in the Suez, Sudan, Perin and Aden (north, central part of the sea, Bab-el-Mandeb, and north-east region of the Gulf of Aden) and of evaporation averaged by 3 coastal stations : Tor, Sudan, Suakin (according to VERCELLI, 1926) indicated that the character of variation of the yearly sea level and level surface slope and evaporation data didn't confirm this interpretation.

PRINCIPAL FEATURES OF THE RED SEA SEASONAL LEVEL VARIATIONS

The level reflects a resultant effect of all forces influencing upon the sea surface. Therefore to obtain the characteristic of the seasonal water exchange variation the monthly values of evaporation, sea level difference between Aden-Perim and Aden-Sudan were accounted for. The level difference between the Red Sea and Gulf of Aden depends on following factors : on a real decrease of water volume due to intensive evaporation from sea surface, on the variation of a positive component of water exchange through Bab-el-Mandeb and Suez Canal and on water redistribution in the sea due to the wind and piled-up circulation.

In winter the monthly level of the Red Sea is higher than the yearly one what points out the absolute increase of the sea water volume during this season. In the north and central sea part the level is higher than the yearly one from November to May. In Suez (in the North) two maxima are recorded - in December and April (12 cm), in Sudan - one peak in January (13 cm). In the strait region (Perim) and in the north-western region of the Gulf of Aden (Aden) the level is higher than the yearly one from December to June with a peak in Perim in May and in Aden in April and in May (10 cm). In summer the Red Sea level is lower than the yearly one (fig.2). A minimum occurs in August when the level in the North of the Sea is lower than the mean one by 21 cm, in the middle - by 22 cm, in Aden - by 14 cm. In the strait (Perim) the minimum is observed in September (15 cm).

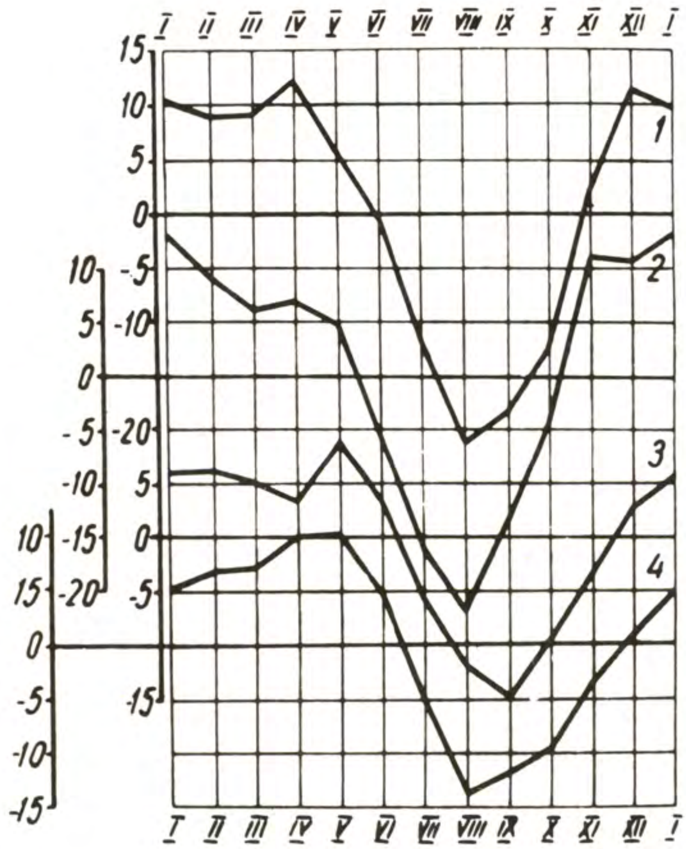

fig 2

Unfortunately, the numbers of observations on these stations were unlike ; it was used a 12-year set for Suez, 37-year set for Sudan, 6-year one for Perim, 25-year one for Aden, i.e. monthly and yearly sea level were of a different accuracy. The monthly sea level and level differences between the north and south sea regions and its central part, between Aden and Perim, are summarized in Table 1.

Table 1.- The annual variation of the Red Sea level relative to the many-year yearly value and level difference between central sea part, its north and south/cm/ sea part

Point of observations	Set of observations	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Amplitude
Suez	12	10	9	9	12	6	0	-12	-21	-18	-12	3	12	33
Sudan	37	13	9	6	7	5	-5	-16	-22	-14	- 4	11	11	35
Perim	6	6	6	5	3	9	3	- 6	-12	-15	- 9	-3	3	21
Aden	25	5	7	7	10	10	4	- 6	-14	-12	-10	-3	1	25
						Level difference /cm/								
Sudan-Suez		3	0	-3	-5	-1	-5	- 4	- 1	4	8	8	1	13
Sudan-Aden		8	2	-1	-2	-5	-9	-10	- 8	- 2	6	14	10	24
Sudan-Perim		7	3	1	4	-4	-8	-10	-10	1	5	14	8	24
Perim-Aden		1	-1	-2	-7	-1	-1	0	2	- 3	1	0	2	9

The general view of a longitudinal profile of level surface according to the yearly sea level (fig.3) indicates that it slopes from South to North during the warm season. However, in the middle of the sea (Sudan) the level is some lower than in the North (Suez), it seems to be associated with the transversal level surface slope which we leaved out of account.

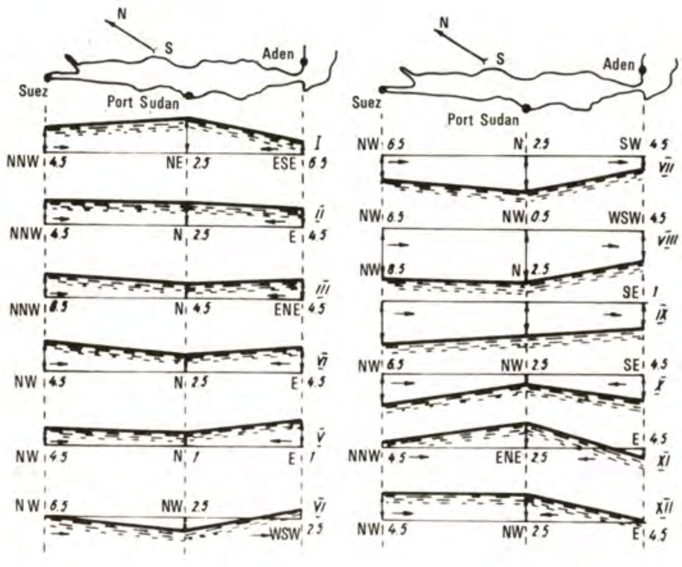

fig 3 - Annual variation of the longitudinal profile of the Red Sea surface height, relative to its mean annual value - (wind velocity in m/s Height scale ⟼ = 10 cm)

Level decrease all over Red Sea during the warm season is related to the evaporative loss excess over the Aden inflow, i.e. over the positive water exchange component through Bab-el-Mandeb. The most rapid level decrease in the Red Sea is found from June to August to be in North of the Sea 21 cm, in the middle -17 cm, in the South (Perim) -15 cm. The lessening of level decrease from North to South has to do with the north-north-western wind tide.

Sea level increase begins from September and continues to January what points out the water exchange positive component increasing. Some level increase is also observed from March to April. In September the monthly sea level is already higher than the yearly one on the head of the Suez Canal by 3 cm, in the central sea part - by 11 cm, only in the south, in the strait (Perim) it is yet by 3 cm lower than the sea level datum. During the cold season sea level surface increases from North and South to the central part where surface waters are piling-up. In the North half of the Sea the most level difference is observed in October-November and is 8 cm from Sudan to Suez. In the south half of the sea the most level difference between Sudan and Aden is recorded in October-November with peak in November being 14 cm.

A convex form of the level surface in the central part of the sea is the most distinct in November and a concave one in June. The Red Sea level surface is smoothed out and approximates to some extent to horizontal one in April and November, i.e. during the monsoons slackening and their direction change.

The surface current direction (a residual component) is determined in this period mainly by level differences resulting from the evaporative loss from Red Sea surface. Such a pattern of the level surface relief variation is conditioned by the seasonal wind field change, annual variation of evaporation intensity and that of the water exchange components through Bab-el-Mandeb and, partly, through the Suez Canal. In this case the most rapid change of the level surface relief seems to be concerned with wind. If the wind factor was neglected the level surface relief variation would occur more smoothly.

SOME FEATURES OF EVAPORATION AND WATER EXCHANGE THROUGH BAB-EL-MANDEB

There are few data on evaporation in the literature and they are inconsistent. Some investigators supposed that the most evaporation from sea surface may be in summer (SCOTT, 1929). According to PRIVETT the most evaporation in the Red Sea was observed in winter. NEUMANN and McGILL pointed out that Red Sea level in winter was to be high decrease due to intensive evaporation in order that a surface current in Bab-el-Mandeb would to meet wind at least to a half of June. The level decrease is observed in fact in summer with minimum in August and it agrees well with the inverse trend of an evaporation curve plotting according to VERCELLI (1926). According to PRIVETT (1939) and NEUMANN (1952) the evaporative water loss throughout the year amounts to 2,10 m or 17,5 cm/month. According to EGOROVA N.' measurements by R/V "Shokalsky" in September 1959 and by R/V "A. Voeikova" in July 1960 monthly evaporation from Red Sea surface amounted to 21,9 cm (MUROMTSEV, 1960, 1962).

Table 2.- The annual variation of evaporation on coastal stations (mm/24 hours)

Points	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Mean
Tor	6,25	6,85	8,11	8,83	9,18	10,89	10,11	9,68	8,83	6,93	6,73	8,22	8,22
Sudan	7,10	6,07	7,61	8,66	9,97	13,06	13,27	12,70	10,47	6,71	7,12	7,40	9,26
Suakin	4,38	4,71	4,86	5,25	6,68	10,38	12,78	11,60	7,81	4,68	4,69	4,62	6,87
Mean dayly (mm/24h.)	5,91	6,21	6,86	7,58	8,61	11,44	12,05	11,33	9,04	6,11	6,18	8,12	8,72
Mean monthly (mm/24 hours)	18,32	17,39	21,27	22,74	26,69	34,32	37,37	35,12	27,12	18,94	18,54	18,85	24,72

Since the evaporation values from sea surface throughout the year were not available we used VERCELLI evaporation data from three coastal stations : Tor, Sudan, Suakin (Table 3) when calculating the Red Sea water balance and positive water exchange component through Bab-el-Mandeb. According to these data the maximum evaporation is observed in June-August, the minimum one in winter when it is almost halving. The minimum sea level was found, on the contrary, in summer, the maximum one in winter, therefore evaporation data at the coastal stations given above describe rather right the yearly water loss variation from Red Sea surface due to evaporation. Curves of the level and evaporation changes have a reverse trend but it is not wholly that seems to be associated with water exchange variations through Bab-el-Mandeb.

Table 3.- The annual variation of evaporation (cm/month, km³/month), averaged Red Sea level (cm) and positive water exchange component (ΔQ_A km³/month)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
h_E	18,85	18,32	17,39	21,27	22,74	26,69	34,32	37;37	35,12	27,12	18,94	18,54
$Q^{x)}$	86,33	83,91	79,65	97,42	104,15	122,24	157,19	171,11	160,85	124,21	86,74	84,91
Level	9,4	8,3	7,4	9,8	7,0	- 0,3	-11,2	-19,0	-14,6	- 8,6	3,7	8,1
ΔQ_A	92,29	78,87	75,52	108,41	91,32	88,81	107,26	135,38	181,0	151,69	143,08	105,06
$\Delta Q_A - Q_E$	5,96	-5,04	-4,13	10,99	-12,83	-33,43	-49,93	-35,73	20,15	27,48	56,34	20,15

x) Evaporation data are shifted to right, e.g., evaporation for January is related to February

Q_E the yearly evaporation from all sea surface = 1358,6 km³/year

h_E the layer thickness of the monthly evaporation from the Red Sea surface=24,72 cm

H_E the layer thickness of the yearly evaporation = 2,96 m

The positive water exchange component through Bab-el-Mandeb was calculated by means of a formula $\Delta Q_A = \Delta h.S + Q_E$

Δh sea level change from month to month (cm)

S Red Sea surface area = 458.10^3 km³

The level decrease from April to August is related to an evaporation excess over the Aden water inflow, i.e. $\Delta Q_A = Q_A - Q_K > Q_E$. Estimation of the positive water exchange component through Bab-el-Mandeb was carried out by means of monthly water volume losses due to evaporation and sea level variation from month to month. The latter is know to be an integral expression of all water balance components of the sea, wind effect and water density variation. Out of water balance components the water loss due to evaporation and Aden water inflow are taken into account. Precipitation and river discharge for the Red Sea are known to be rather little, they are supposed to be compensated for an outflow through the Suez Canal into Mediterranean. The wind effect was eliminated by means of level averaging all over the sea. Since the water density variation effect upon the yearly level change is little it is neglected.

The seasonal water density variations for different sea regions are ranged from 1.6 to 2.5 con.units and envelop only an upper 50 meter layer. So, for estimation of the positive water exchange component and its seasonal variation the following equation was used :

$$\Delta h.S = Q_A - Q_K - Q_E = \Delta Q_A - Q_K$$

from which

$$\Delta Q_A = \Delta h.S + Q_E$$

where Δh level variation from month to month (cm) ;
S Red Sea surface area equal to 458.10^3 km^2;
Q_A mean monthly Aden water inflow into the Red Sea ;
Q_K the Red Sea outflow into Gulf of Aden ;
Q_A positive water exchange component through the strait ;
Q_E water volume loss due to evaporation.

The results are summarized in Table 3. The positive water exchange component through Bab-el-Mandeb has a two-peak curve of annual variation (fig. 4B). The Aden inflow increase begins in July and continues to September when ΔQ_A amounts to 181 km^3/month.

Maximum inflow is observed in September at a moment when the summer monsoon slacks off. In winter in a transitional period from winter to summer monsoon some exceeding increase of Aden inflow into the Red Sea over the outflow into Gulf is observed. (ΔQ_A = 108,4 km^3/month). The maximum sea level difference is observed in summer monthes /VI-VIII/ with a peak in July, while the maximum Aden waters inflow ($Q_A - Q_K$) shifts to September due to wind meeting the level surface slope.

The north-north-western wind slackening in September under level surface slope directed to the Red Sea seems to be accompanied by the surface current increase in the same direction. In this case the flattening of the level surface and increasing of water masses interface in the sill region and, consequently, some increasing of the lower flow take place. In April under south-south-eastern wind slackening the intensity not only of upper but also of lower current is lessening, since the water masses interface and density difference on sill level decrease. However, the difference between Aden inflow and Red Sea outflow is some extending in April as compared with March and May.

The annual variation of Red Sea water balance (fig.4 B) has also two peaks - in November and April, and two minimums - in July and in February-March. In summer,when a maximum level surface slope is observed the water balance of the sea is negative. From September to January it is positive. The maximum inflow excess over evaporation ($\Delta Q_A - Q_E$ = 56,34 km³/month) is noted in November. Some inflow excess from Gulf of Aden over evaporation (10,99.km³/month) is observed also in April.

In February and March water loss due to evaporation is in some excess of Aden water inflow (5,04 and 4,13 km³/month). From May to August the negative water balance is observed in the Red Sea. It doesn't make up for the water losses due to evaporation with Aden waters in this period. The most deficit equal to 49,93 km³/month is recorded in July. During the negative water balance the sea level decrease and minimum is noted in August.

The positive water exchange component values obtained don't pretend to absolute accuracy since the calculations are based on evaporation data that are known to be the most difficult determined of all water balance components.

The yearly value of the positive water exchange component through Bab-el-Mandeb (1 359 km³/year) proved to be close to our previously obtained value (1 197 km³/year) by means of a saline balance equation (Bogdanova, 1966). Since the different methods were used this small disagreement (13 %) suggested that a monthly and yearly value of Aden waters inflow into the Red Sea obtained holded rather true the general nature picture.

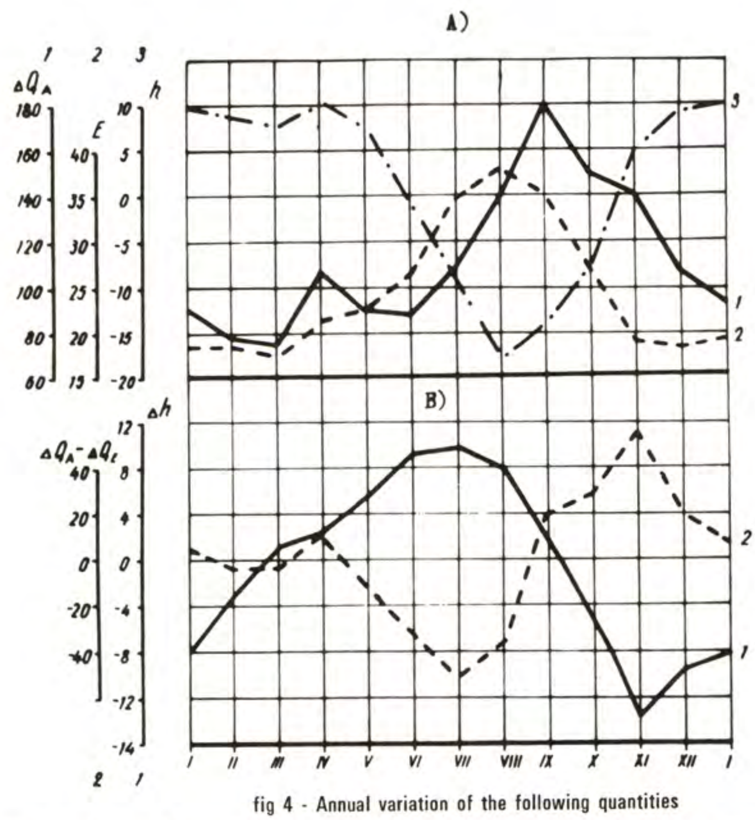

fig 4 - Annual variation of the following quantities

A) 1 positive component of water exchange through Bab-el-Mandeb Strait (km³/month)
2 Evaporation (cm/month)
3 Surface height averaged over three stations (Suez, Port Sudan, Aden)

B) 1 Surface height difference between Aden and Port Sudan (cm)
2 Water budget of the Red Sea (km³/month)

A QUALITATIVE CHARACTERISTIC OF WATER EXCHANGE THROUGH BAB-EL-MANDEB

The inflow change of Aden waters into the Red Sea certainly doesn't reflect a total picture of water exchange through the strait. An analyse of the level variation, its slope and seasonal wind field change over the sea indicates that an annual variation regularity of the Aden and Red Sea flow intensity is different as compared with the positive water exchange component change. The most intensive water exchange through Bab-el-Mandeb seems to be during the winter monsoon when the upper flow is forming by two forces of the same directions : by the level surface slope and tangential wind stress. At the time the lower flow is also increasing since the winter winds in the south sea part (SSE) drive away the surface and upwell the deep Red Sea waters in the sill region, i.e. density gradient - a moving force of the lower flow is increasing.

In summer the surface current forming forces are of opposite direction. The level surface slope is directed to the Red Sea, the tangential wind stress - in opposite direction. The surface current decreases and changes its direction. Along the Arabian coast the surface current is directed to the Gulf of Aden, along the African - to the Red Sea /instrumental observations by VERCELLI, 1931/. In this case the Aden waters get into the Red Sea as a intermediate layer - along Arabian coast, and as a surface layer - along African coast. The lower current carring the Red Sea waters into Gulf of Aden is also decreasing since the prevailing summer winds (NNW) pile up the surface waters in the near-strait region of the Red Sea (in the sill region) and drive away the water from the Gulf of Aden. It is attended by the density difference reduction on the strait ends. In this manner the water exchange intensity increases in winter when the discharges of the upper and lower current are extended. However, the excess of Aden water inflow over the Red Sea water outflow decreases at the time.

In summer the water exchange intensity through Bab-el-Mandeb decreases but since June the Aden water inflow increases due to more decrease of the lower Red Sea flow relative to the upper one.

Conclusions

To check up the results obtained it is necessary to organize the instrumental observations on current in the strait by means of self-recorders installed from self-contained buoy stations. It is desirable to carry out investigations on current field in the strait at different seasons. The long-term sets of velocity recordings will allow to obtain the average discharge values of the Red Sea and Aden flows and their variability depending on wind field and seasonal sea level difference.

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CIRCULATION AND MEAN SEA LEVEL IN THE SUEZ CANAL

by S.A. MORCOS* and M.A. GERGES**

Abstract

Three sections along the Suez Canal in April 1964, September 1964 and September 1966 are presented. The first two sections indicate that the general scheme of circulation in the Canal remained unchanged during the ten years since the last monthly sections 1954-1955 of MORCOS (1960). The two sections of September 1964 and September 1966 show opposite conditions. The usual reversal ofcurrent to the south which had taken place every September, did not occur in September 1966.

The monthly mean sea level at Port Saïd and Port Tewfik (Suez) in 1964 and 1966 were computed and compared. The factors influencing the seasonal variation of mean sea level e.g. wind, atmospheric pressure and water density were investigated with respect to the two ends of the Canal. After the completion of the Aswan High Dam the high amount of Nile discharge in the Mediterranean has stopped. Before 1966 the peak of flood in September is followed by a sharp decrease in salinity and density and,as a result,by an increase in the specific volume and mean sea level. The high salinity which appeared at the southern end due to the current from the Bitter Lakes favoured a decrease in specific volume and mean sea level. On September 1966 the salinity was subjected neither to decrease in the north or increase in the south. The importance of this factor requires further investigations in future.

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Résumé : Circulation et niveau moyen dans le Canal de Suez

Trois sections le long du Canal de Suez en avril 1964, septembre 1964 et Septembre 1966 sont présentées. Les deux premières sections montrent que le schéma général de circulation dans le canal n'a pas varié depuis les dernières sections mensuelles effectuées en 1954-1955 dix ans auparavant par MORCOS (1960). Les deux sections de septembre 1964 et septembre 1966 sont dans des conditions opposées. Le renversement habituel de courant vers le Sud qui s'opère chaque mois de septembre ne s'est pas produit en septembre 1966.

Les niveaux moyens mensuels à Port Saïd et Port TeWfik (Suez) en 1964 et 1966 ont été calculés et comparés. Les facteurs qui influencent les variations saisonnières du niveau moyen, par exemple le vent, la pression atmosphérique et la densité de l'eau ont été évalués en considérant les deux extrêmités du canal. Après l'achèvement du grand barrage d'Assouan, le fort débit d'eau du Nil s'écoulant en Méditerranée fut stoppé. Avant 1966, le pic des crues en septembre était suivi d'une forte diminution de salinité et de densité et, en conséquence, d'une augmentation du volume spécifique et du niveau moyen de la mer. Les fortes salinités qui apparaissent à l'extrêmité Sud et qui sont dues au courant issu des Lacs Amers favorisent une diminution du volume spécifique et du niveau moyen de la mer. En septembre 1966, on n'observait ni diminution de salinité au Nord, ni accroissement au Sud. L'importance de ce facteur nécessite de nouvelles investigations dans l'avenir.

INTRODUCTION

During the period 1953-1955 the senior author (MORCOS, 1959,1960) made monthly cruises along the Suez Canal in order to study the stratification and circulation of water in the canal in relation to the main physical factors affecting them. Ten years after these observations, it was desirable to make a new investigation in order to reveal any change in the oceanographic conditions of the Canal. These cruises were carried out by one of us (S.A.M.) in April 1964, September 1964 and September 1966. Sections of salinity along the Canal in these three months are represented in fig.1. The choice of the time of three cruises was based on the experience gained from the monthly cruises of 1953-1955.

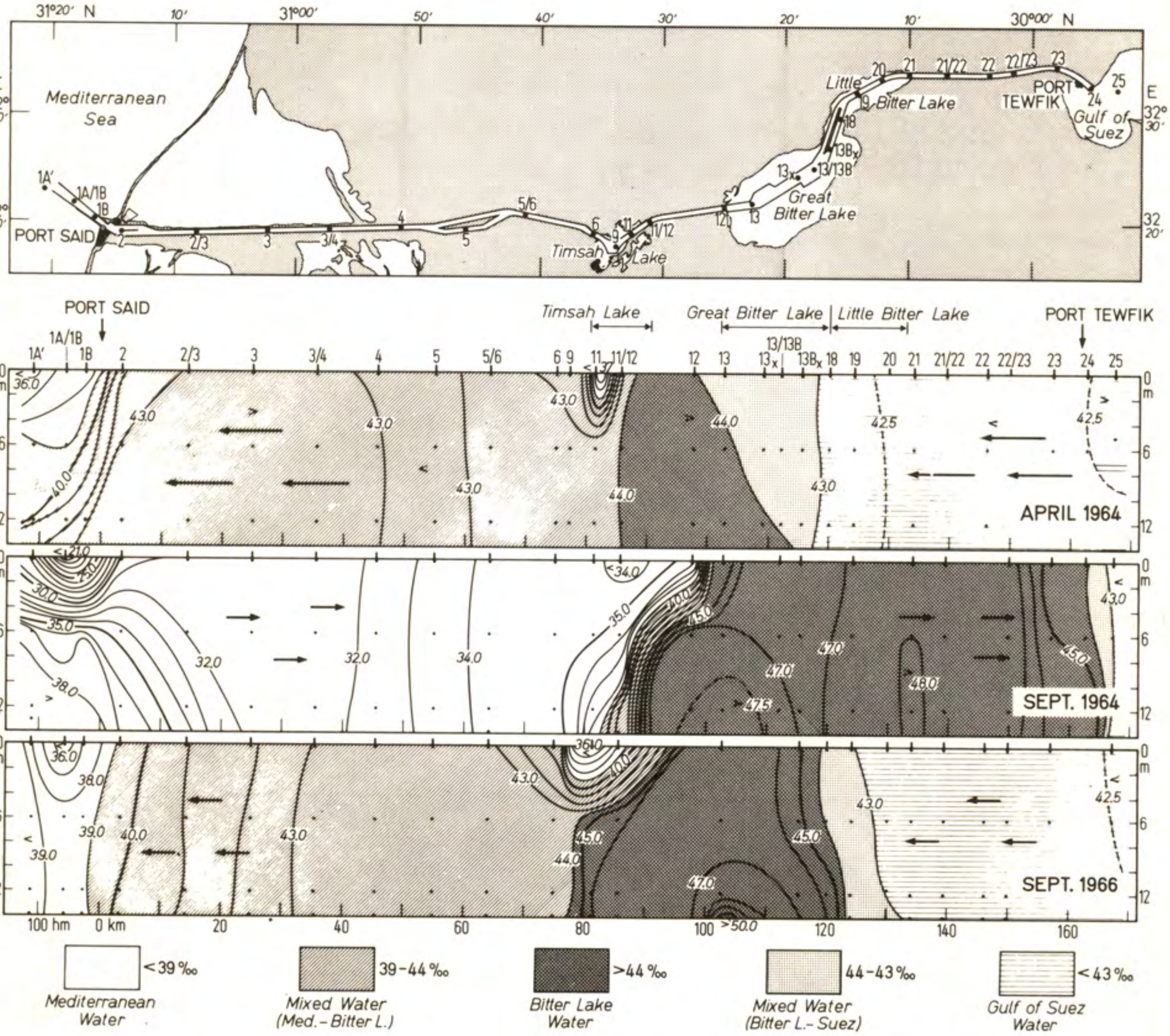

Fig. 1 - Vertical Sections of salinity (°/..) along the Suez Canal in :

April 1964

September 1964

September 1966.

The hydrographic conditions in the Suez Canal undergo a spectacular seasonal variation. The extreme opposite and well defined pictures are best represented by April and September observations. In April the mean sea level in the Suez Bay (Port Tewfik) is higher than the Mediterranean (Port Saīd), the current is strongly northward, and the salinity in the Great Bitter Lake shows its lowest values (∿44 ‰). In September, the reverse conditions prevail, the mean sea level being higher at Port Saīd than Suez, the current being mainly southward, and the salinity in the Great Bitter Lake reaching maximum values (∿ 48 ‰).

In the present study, comparison is made between the observations of April and September 1954 and those of April and September 1964. In addition, the cruise of September 1964 represents a very significant occasion, since it was made during the peak of the last Nile flood before the completion of Aswan High Dam. The Nile rises considerably from July to December with a maximum in September. During this period immense quantitites of fresh water were discharged in the Mediterranean through the Rashid (Rosetta) and Damietta branches. The latter opens only 60 kms west of Port Saīd.

Table 1 - Monthly Discharge of the Nile River at Rosetta "Rashid" (R) Damietta (D) and total discharge (T) (in million m^3)

	1964			1966		
	R	D	T	R	D	T
Jan.	3086	407	3493	3175	0	3175
Feb.	1349	0	1349	686	0	686
Mar.	281	0	281	104	0	104
Apr.	11	0	11	42	0	42
May	3	0	3	77	0	77
June	3	0	3	50	0	50
July	660	0	660	1710	0	1710
August	9153	3124	12.277	148	0	148
Sept.	13.582	5709	19.291	1487	0	1487
Oct.	9343	3957	13.300	3866	0	3866
Nov.	6156	2750	8.906	1018	0	1018
Dec.	2404	1470	3.874	1290	0	1290

The flood of 1964 was exceptionally high (Table 1 and fig.2) and the section of September 1964 (fig.1) demonstrates very clearly the effect of the Nile flood on the distribution of salinity in the northern part of the Canal.

A third cruise was made in September 1966, also representing a significant occasion, since it provides the first observations made under the new conditions imposed by the completion of Aswan High Dam. In 1966, the Nile water discharge in the Mediterranean was greatly reduced as shown in fig.2. The two cruises of September 1964 and September 1966 furnish a good basis of comparison between the conditions before and after the completion of Aswan High Dam. A preliminary account of this problem was given by MORCOS (1967) and commented by EL-SABH (1968, 1969).

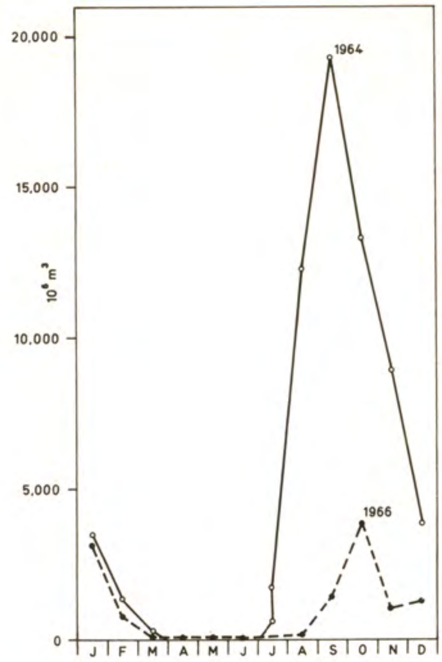

Fig. 2 - Seasonal variation in the discharge (10^6 m^3/Month) from the Nile River (Rosetta "Rashid" + Damietta branches) in 1964 Rashid Branch only in 1966 No discharge from Damietta branch in 1966.

The problem was considered again by MORCOS and MESSIEH (1973 a, b) in their study of the southern part of the Suez Canal. The present communication provides the complete set of the three salinity sections in April 1964, September 1964 and September 1966 which will be examined in the light of new information on the mean sea level at the two ends of the Canal in 1964 and 1966, and the main meteorological and oceanographic factors influencing the seasonal variation of the mean sea level in the Canal.

<u>The Main Water Masses</u> :

According to Morcos' (1959, 1960) definition, five water masses are distinguished in the three salinity sections along the Canal (fig.1) :

1. Great Bitter Lake Water Mass (G.B.L.) having salinity higher than 44 ‰.
2. Mediterranean waters of Port Saïd (P.S.) of salinity less than 39 ‰.
3. Suez Bay waters (S.B.) of salinity less than 43 ‰
4. Mixed waters in the Northern Canal (M_1) of salinity between 39 ‰ and 44 ‰
5. Mixed waters in the Southern Canal (M_2) of salinity between 44 ‰ and 43 ‰.

The salinity of the waters over the salt bed in the Great Bitter Lake never decreases below 44 ‰ in winter. Thus the isohaline 44 ‰ is taken to define this water mass. Although the Mediterranean waters along the Egyptian coast may exceed 39 ‰ by few decimals, we consider here waters over 39 ‰ to represent Mediterranean waters mixed with the more saline waters of the Great Bitter Lake.

Comparison of the section of April 1964 with April 1954 and September 1964 with September 1954 shows that the same trends in salinity distribution and circulation which were prevaling in 1954 were still holding in 1964. The April sections demonstrate the strong northward current prevailing in winter. The Suez Bay waters penetrate northward in the Canal to occupy the Southern Canal and the Little Bitter Lake. Mixed water (M_2) fills the southern part of the Great Bitter Lake while the Great Bitter Lake water mass proper (G.B.L.) is pushed northward to fill the northern part of the Lake and the central canal. The mixed water (M_1) fills the Northern Canal and flows below the less saline Mediterranean water of Port Saīd (P.S).

In September 1964, the diluted waters of the Mediterranean flow in the Canal and penetrates south to reach the Central Canal. The much enlarged water mass of the Great Bitter Lake (G.B.L) flows south to fill the Little Bitter Lake, the Southern Canal and even reaches the Suez Bay where it sinks below the less saline waters of the Gulf of Suez.

The contrast between April and September 1964 sections is very evident. The Great Bitter Lake water mass (G.B.L) shows a spectacular change from April to September, a change which can be easily linked with the direction and velocity of current in the Canal. In fact, this water mass is very significant for the study of the circulation in the Suez Canal. The following characteristics of the Great Bitter Lake water mass demonstrate the above concept :

1. This water mass has the highest salinity of surface waters in free connection with world oceans. It is easily identified since it is distinctly higher than waters from the Red Sea or Mediterranean origin.
2. It undergoes seasonal variation in salinity in a very regularly manner which is rarely encountered in nature. Salinity increases from about 44 ‰ in April to about 48 ‰ in September, then decreases regularly again to the minimum of 44 ‰ in March-April. This annual range is very large compared to any oceanographic standard.
3. The increase in salinity of the water mass is accompanied by an increase in its volume from April to September. This is clearly demonstrated by the monthly cruises of MORCOS (1960). Figure 1 shows that this water mass occupies only part of the Great Bitter Lake in April 1964 while it bulges in September 1964 to occupy the Great and Little Bitter Lakes, the Southern Canal and flows as bottom water of the Suez Bay. The combination of the two factors, i.e. the increase of salinity and volume of this water mass, illustrates the extreme change in the salt content from April to September.
4. The increase of salinity and volume of the water mass is accompanied by a definite displacement of the position of the water mass. The small, less saline, water mass of winter occupies the northern part of the Great Bitter Lake and is displaced northward to the Central Canal. The larger, more saline, water mass of July to September occupies the entire Great Bitter Lake, the Little Bitter Lake and the Southern Canal.

MORCOS (1960) introduced the concept of the point of maximum salinity along the Suez Canal. This point lies within the water mass of the Great Bitter Lake. It exhibits a clear trend of displacement towards the north in winter and towards the south in summer. Within a narrow canal like this and considering the relatively small volumes of water involved one should take into consideration other interfering factors including dilution by external factors which may alter the values of salinity at certain points along the Canal. This may tend to make slight

alterations in the position of the isohalines. However, the water mass of the Great Bitter Lake is the least affected for various reasons including its absolute high values of salinity and its relatively large volume. The large volume of this water mass (which is subject to seasonal variation) is best demonstrated by the fact that the Great Bitter Lake represents 78 ‰ of the total volume of the Suez Canal.
EL SABH (1969) argued that the concept of the point of maximum salinity along the Canal is not very meaningful. The main objection is that a highly stratified layer occurs immediately above the rough bottom of the salt bed in the Great Bitter Lake. Slight variations of the position of the boat, caused by the swinging of the buoy and of the boat tied to it, resulted in the sample being taken from different relative heights above the bottom. Taking into consideration that the salt bed lies now at about 14 to 16 m below the surface and that the samples were collected at 0,6 and 12 m, one would expect that the disturbance, produced by the salty pockets and the highly stratified layer immediately over the salt bed would not extend to 12 m i.e. 2 to 4 m above the bottom. The influence diminishes at 6 and 0 m levels. Comparison of salinity at different points along the Canal at 6 m level as applied by MORCOS (1967) would be the best method of ascertaining the point of maximum salinity at a given section. This will minimize the influence of the highly stratified layer hugging the bottom and avoid any minor influence of local intrusion of fresh water on surface salinity.

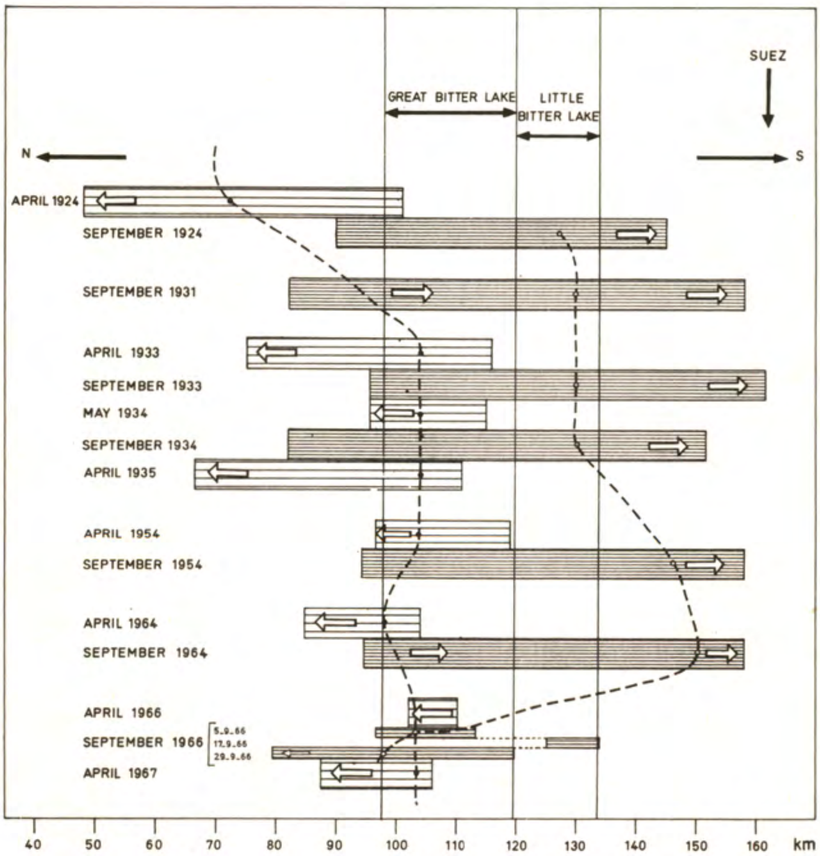

Fig. 3 - Displacement of the Great Bitter Lake water mass and the point of maximum salinity along the Suez Canal at 6 m level in the cruises made from 1924 to 1967 in April and September.

Figure 3 represents a simple application of this approach. The Great Bitter Lake mass (> 44 ‰) is represented by rectangular blocks which shift either northward or southward along the Canal during all the April and September cruises carried out in the Suez Canal from 1924 to 1967. The boundaries of the G.B.L. water mass in each section are represented in fig.3 by the position of the southern and northern 44 ‰ isohalines at the intermediate level of sampling. The point of maximum salinity along the Canal at this level is also represented. This intermediate level varies according to the levels of sampling in the various cruises : 3 m in 1920's cruises, 5 m in 1930's cruises and 6 m in the cruises from 1954 to 1967. The salinity decreased sharply in the Bitter Lakes in early years. The 1924 values are particularly high, so that the water over 44 ‰ salinity would occupy a large part of the Canal. For this reason the G.B.L. water mass in April and September 1924 is represented in fig.3 by the 46 ‰ isohalines. Another difficulty in applying this method to observations extending over more than 40 years, is that the network of observations was made up of fewer stations in the 1930's compared with the more dense observations in the cruises of 1950's and 1960's. This makes the positions of the boundaries of the water mass and the point of maximum salinity less accurate in 1930's sections. However, these positions undergo such a large seasonal variation that the overall picture represented in fig.3 is not altered by this factor. It is obvious that better results would be obtained if the same network of closer stations is repeated every month. Figure 3 shows clearly that the G.B.L. water mass shifts to the north in all April cruises. It shifts to the south in all September cruises except in September 1966. In this month, two cruises were made. The first cruise made by El-Sabh (1969) was divided into two legs : the southern boundary of the water mass was determined by observations made on 17 September 1966 while the northern boundary was determined by observations made on 4-6 September 1966. The second cruise made by MORCOS (1967) covered the whole water mass in one day. An obvious conclusion from the three sets of observations is that the G.B.L. water mass was definitely in a different position along the Canal, being much more displaced to the north in September 1966 compared with any preceeding September section since 1924. However, a detailed study of the three sets of observations elucidates the problem of movement of this water mass during the month of September 1966 :

a) On 4-6 September 1966 the northern boundary of the water mass appeared north of the Great Bitter Lake resembling the conditions of preceeding September months, and indicating that the G.B.L. water mass was held within the Lake by a southward current in the northern Canal. Moreover, the distribution of salinity in the Lake during these early days of September shows that the point of maximum salinity at 6 m level lies at the Northern Light Buoy. The northern part of the Lake is more saline than the southern part. Two anchored stations were carried out at the Southern Light Buoy (Km 113) on 3-4 September 1966 and at the Northern Light Buoy (Km 103) on 5-6 September 1966 (El-Sharkawi, 1968). The salinity at the Northern Light Buoy was higher. The averages of 9 observations taken every three hours over 24 hours period were 45.94 ‰ and 45.78 ‰ at 6 m level at the Northern and Southern Light Buoys respectively. This shows that already at the beginning of September 1966 the salt was accumulating at the northern part of the Lake, and that there is no evidence of a southward movement of salt similar to the preceeding months of September.

b) On 17 September 1966, the southern boundary of the G.B.L. water mass appeared at the southern end of the Little Bitter Lake. This is another indication of a northward movement of water. The Southern Canal is filled with waters from the Suez Bay in reverse to any preceeding observation of September when the G.B.L. water mass moved southward to occupy a considerable part of the Southern Canal. As a a result of that southward flow the salinity at the southern end of the Canal and in the Suez Bay showed higher values. Up to 1965 the salinity levels in the bay increased every summer to values as high as 47 ‰, and were never lower than 44 ‰, but in 1966 they never rose above 43 ‰ as illustrated by fig.4 (MORCOS and MESSIEH, 1973). Fortnightly cruises made by Meshal (1967) in 1966-67 in Suez Bay confirm the above observation.

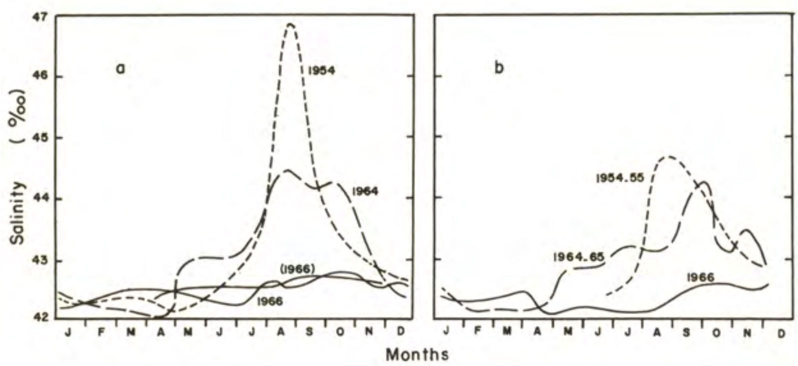

Fig. 4 - Seasonal variation of salinity in Suez Bay before and after 1965.

a. At Station 24 (Km 162.4, most southern buoy of the Suez Canal) b. At Station 25 (Km 164.8 Newport (Zenobia) Rock Lighthouse (after Morcos and Messieh, 1973 b).

c) On 29 September 1966, the G.B.L. water mass moved further to the North indicating a unique condition. The northern direction of the current is similar to the conditions in winter, but the volume of the water mass is considerably large and similar to the conditions in summer. Figure 3 indicates that the volume of the G.B.L. water mass is small during the April cruises and much larger during September cruises. Moreover, the salinity of this water mass shows a minimum in March-April and a maximum in September. The velocity of the current over the salt bed can be inferred from the characteristics of the G.B.L. water mass over the salt bed. It is the salt balance of the Great Bitter Lake and the residence time of water over the salt bed that play the major role in producing the relatively smooth curve of annual change in salinity in the Lake (MORCOS, 1959,1960). In April, the velocity of the northward current is strong, thus allowing a short residence time over the salt bed. In September, the southward current is very weak and thus permits a longer contact between the water mass and the salt bed. Evidence for salt dissolution from the salt bed was obtained by MORCOS (1967b, 1968) and MORCOS and RILEY (1966) who found a deviation in the chemical composition and physical properties properties of the G.B.L. water mass from those of proper sea water.

The rather smooth curve of increase of salinity from April to September is explained by studying the Salt budget of the Great Bitter Lake. From April to September the total salt content of the Lake increases gradually due to the fact that the salt gain exceeds the salt outflow, while the reverse takes place from September to April. The main sources of salt in the Lake are evaporation and dissolution of salt from the salt bed two factors which are very strong in summer. The main factor for loss of salt from the lake in winter is the strong northward current resulting in an inflow of less saline water in the lake compared with the highly saline water leaving the lake.

The succession of events in summer 1966 may be descrived as follows. At the beginning of September the current in the Northern Canal was reversed to the South and water of salinity less than 39 ‰ reached Lake Timsah. However, the usual reversal of the current regime in the whole Canal did not occur as usual. The G.B.L. water mass did not reach the Suez Bay as occured previously since the salinity in the bay remained unchanged as shown in fig.4 (MORCOS and MESSIEH,1973b). On 17 September 1966, the Southern boundary of the G.B.L. water mass was spoted at the southern end of the Little Bitter Lake. By that time a northward current existed in the Southern Canal, while the current in the Northern Canal either continued to be southward as it was in the beginning of the month or had been reversed. It is not difficult to understand a situation where water flows from both ends of the Canal in the Great Bitter Lake where it temporarely accumulates. Also, excessive evaporation in summer from the surface of the Lake may induce a weak stream of water from both ends of the Canal. As a result the G.B.L. water mass will be trapped over the salt bed for a longer time and will increase in salinity and volume. This swelling water mass will gradually push its boundaries to the north to the Central Canal and to the south of the Little Bitter Lake. However, its influence on the Little Bitter Lake is more likely since this Lake is a part of the Bitter Lake basin and can be regarded as the shallow shelf water of the Great Bitter Lake. The fact that the Little Bitter Lake was filled with the G.B.L. water mass in mid September 1966 is not an indication of a southward flow, it rather shows a standstill condition in the Bitter Lakes with a very slow northward current in the Southern Canal. The slow inflow of water from south and from north is compensated for by evaporation and the G.B.L. water mass increases in volume and salinity. The southward current in the Northern Canal was observed in the beginning of September 1966. We possess no indication as to how long it did last. It may have already diminished by 17 September 1966, when the northward current in the Southern Canal was evident. On 29 September 1966, the current in the Canal became predominantly northward both in the Southern and Northern Canals. The G.B.L. water mass was shifted northward, and the Northern Canal was filled by mixed water (M_1) of salinity much higher (39-40 ‰) than the Mediterranean. The distribution of the water masses (fig.1) strongly ressembles the conditions in April 1964, except that the G.B.L. water mass is much larger and more saline. This is taken as an evidence of unsual history of this water mass before the 29 September 1966 section as well as an indication of the slow velicity of this northward current (MORCOS, 1967).

It should be emphasized that what we mean by the <u>reversal of the regime of current</u> in september 1966 is the <u>reversal in the net outflow from the Canal</u>. Experiments with continuous recording current meters over one year showed that, before 1966, there was a net outflow from the Red Sea into the Mediterranean in winter, and a net outflow from the Mediterranean into the Red Sea in summer. For example, in 1935, there was a net outflow of 5,250 x 10^6 m^3 into the Mediterranean during most of the year and 150 x 10^6 into the Red Sea in summer. (Anonymous, 1936). It can be safely stated that this net outflow from the Canal into the Gulf of Suez did not take place in summer 1966. In the various parts of the Suez Canal, currents change direction over periods of hours and days due to tidal and non tidal factors, but the main and over all criterium which has a seasonal character is the net outflow from the Canal.

Mean Sea Level at the two ends of the Canal

Reduction of tidal records by applying numerical filters to observational data (24 readings a day) for eliminating the contribution due to tides is considered to be the best way to obtain reliable values of Mean Sea Level (MSL) (ROSSITER, 1958 ; LISITZIN, 1963). A computer program adopted by LENNON (1965) for this prupose was used for the computation of the MSL at Port Saīd and Suez using the electronic digital computer IBM-1620 in Alexandria University. The program eliminates all the possible tidal contributions and retains the contribution from the meteorological forces and other perturbing influences affecting the sea level.

The two available tide gauges at Port Saīd and Suez (Port Tewfik) supplied us with the daily tidal curves for 1964 and 1966 and made it possible, by applying the above-mentioned program, to obtain the daily and monthly MSL values at both locations to a good degree of accuracy (Table 2).

Table 2 - Mean Sea Level (MSL) at Suez (Port Tewfik) and Port Saīd in 1964 and 1966

	1964			1966		
	Port Tewfik (m)	Port Saīd (m)	P.T-P.S. (m)	P.T. (m)	P.S. (m)	P.T.-P.S. (m)
Jan.	18.311	17.951*	+ 0.360	18.472	18.254	+ 0.218
Feb.	18.326	18.199	0.127	18.301	18.205	+ 0.096
Mar.	18.438	18.174	0.264	18.338	18.052*	+ 0.286
Apr.	18.330	18.088	0.242	18.398	18.074	+ 0.324
May	18.222	18.069	0.153	18.313	18.048	+ 0.265
June	18.246	18.226	0.020	18.201	18.169	+ 0.032
July	18.131	18.269	- 0.138	18.147	18.300	- 0.153
Aug.	18.127	18.319	- 0.192	18.139*	18.321	- 0.182
Sep.	18.002*	18.272	- 0.270	18.146	18.278	- 0.132
Oct.	18.184	18.227	- 0.043	18.293	18.250	+ 0.043
Nov.	18.290	18.212	+ 0.078	18.419	18.261	+ 0.158
Dec.	18.397	18.169	+ 0.228	18.577	18.306	+ 0.271
Annual Average	18.250	18.181	+ 0.069	18.297	18.210	+ 0.087

This enables us to investigate the seasonal variations of mean sea level at both ends of the Canal. Moreover, description of the slope of water surface, and hence the current, along the Canal could be discussed.

The computer results for the 1964-MSL showed that from July to October, the sea level at Port-Saīd is higher than that at Suez. The mean difference between the two ends of the Canal is about 16 cm, with a maximum difference in September (27 cm). During the rest of the year, the MSL is higher at Suez than at Port Saīd.

The maximum difference is 36 cm in January. This is considered to be a typical situation of the sea level in the Canal (Table 2, Fig.5).

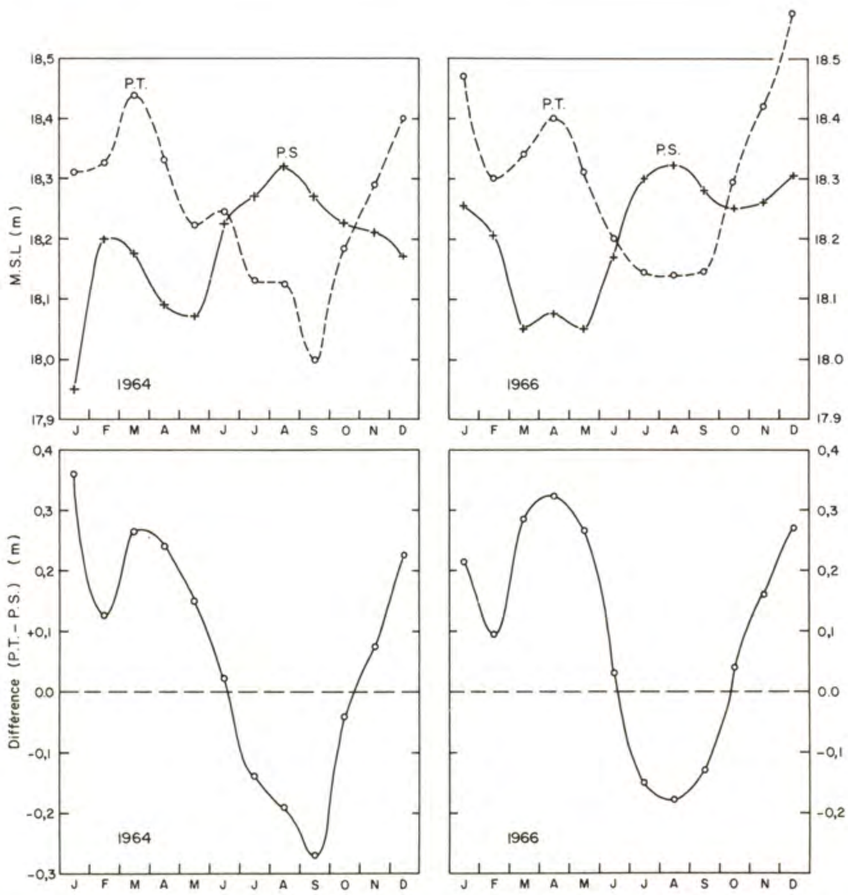

Fig. 5 - Monthly Mean Sea Level at Suez, Port Tewfik (P.T.) and Port Saïd (P.S.) and the difference between them (P.T.-P.S.) in 1964 and 1966.

Considering the MSL difference between the Canal extremeties, and hence the slope of water surface of the Canal, as one of the main factors influencing the current and its direction in the Canal, it could, therefore, be concluded that the current in the Canal should be southward during the four months (July to October) and northward for the rest of the year, when Suez is higher in level than Port-Saïd. This picture agrees well with that concluded from the salinity distribution along the Canal in the sections of April and September 1964 (fig.1) which are typical for the winter and summer situation in the Canal.

The MSL in the Canal is generally higher in 1966 (fig.5). The phenomenon of the September reversed regime of circulation in the Canal, illustrated in fig.1 by the salinity section of September 1966 is not reflected by the values of sea level at Port-Saïd and Suez. The sea level at Port-Saïd was still higher than at Suez in the summer months of 1966 (Table 2, Fig.5) and according to the above discussion, one might expect a summer southward flow, as usual. This, however, was not observed. The only noticeable feature for 1966, as shown in fig.5 and table 2 is that the summer situation (P.S. higher than Suez) lasts for a shorter period and the amplitude of the difference in sea level between Port-Saïd and Suez is relatively smaller than in 1964. The main physical factors contributing to the seasonal change in the mean sea level are : (1) the barometric pressure, (2) the wind stress on the surface and (3) the variation of water density. Effects (1) and (2) together are described as the atmospheric or meteorological effect. Some authors emphasize that the two principal causes for the seasonal variation of sea level in a region are the change in specific volume of sea water (Steric effects) in that region, and the fluctuations in the local atmospheric pressure (isostatic adjustment of sea surface). Although the effect of each of these three factors is already well known, the whole is a very complicated problem and it is generally not easy to separate the influence of the different factors influencing the slope of water surface in a region, i.e. the pressure, the wind and the density (Lisitzin, 1958,1963,1972).

A brief description of the seasonal variation in these three main factors at the two ends of the Canal is given below :

1. Atmospheric Pressure :

The atmospheric pressure has an appreciable influence upon the annual cycle of mean sea level. It is now fully recognized that the water surface responds to the local pressure changes as an "inverted barometer" standing at a low level when the atmospheric pressure is high and vice versa. The effect is nearly 1 cm change in water level for each 1-mb change in atmospheric pressure (Lisitzin, 1961, Lisitzin and Pattullo, 1961).

Table 3 - Atmospheric Pressure at Suez and Port-Saīd in 1964 and 1966

	1964		1966	
	Pressure at Suez (mb)	Pressure at Port Saīd (mb)	Pressure at Suez (mb)	Pressure at Port Saīd (mb)
Jan.	1021.1	1020.8	1017.2	1016.4
Feb.	16.7	16.3	17.3	16.9
March	13.7	13.7	15.9	15.7
Apr.	13.7	14.3	12.2	12.5
May	13.9	14.1	14.0	14.6
June	09.3	09.3	10.2	10.9
July	07.9*	07.7*	07.8*	08.0
Aug.	08.0	07.9	07.8*	07.7*
Sep.	13.3	12.5	11.9	12.0
Oct.	15.6	16.4	13.9	14.3
Nov.	17.1	16.8	15.2	15.7
Dec.	17.8	17.5	16.6	15.9

Table 3 gives the monthly average values of atmospheric pressure at Suez (Port Tewfik) and Port-Saīd for 1964 and 1966. The annual cycles at both ends of the Canal show highest pressure in winter (January-February) and lowest in summer (July-August). From the curves of the monthly variation in the mean sea level (fig.5) it can be seen that the sea levels do respond to the corresponding pressure changes as inverted barometer. Nevertheless, the relation is clearly not a one-to-one mirror image as is frequently the case in open oceanic areas. Comparison of differences in the monthly values of M.S.L. 1966 minus those of 1964 with the corresponding differences in atmospheric pressure (fig.6) shows two inverted curves which reveal the great influence of pressure when comparing the 1964 with the 1966 values of M.S.L.

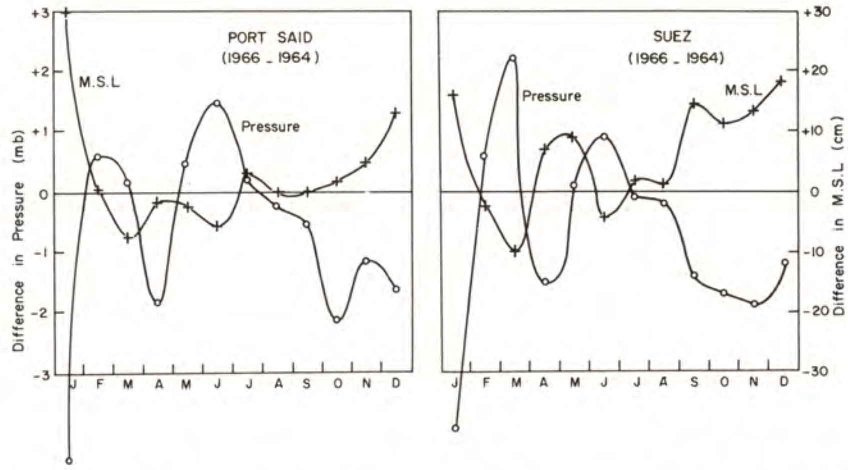

Fig. 6 - Difference (1966-1964) in mean sea level (MSL) and atmospheric pressure (P) in Port Saïd and Suez (Port-Tewfik).

2. Wind

The average surface wind speeds in different months of the years 1964-1966 at both Port-Saīd and Suez (Port Tewfik) were studied. The most important for our discussion however, is the wind data collected at the northern entrance of the Canal at Port-Saīd. The prevailing winds in this region of the Mediterranean Sea have a NNW direction, for most of the year, and this obviously is the main wind component which plays a major part in piling water in front of the Canal at Port-Saīd. Thus, comparing the annual cycles of the average surface wind speed at Port-Saīd for these years, we notice that for the summer months of 1966, the average speeds are generally greater in magnitude than those of 1964. However, the M.S.L. in Port-Saīd was practically the same in 1966 as 1964 in the months of August and September. This is the time when the maximum Nile discharge in the Mediterranean used to occur. It may be questioned if the increase in the wind speed from 1964 to 1966 was compensated by the absence of the usual Nile discharge.

3. The density effect

Variations of the density within a water column, from which steric sea level can be calculated, are dependent on the thermal and haline variations within the column. Thus, the steric sea level is high when water is warm and/or less saline and low when it is cold and/or more saline. In other words an increase in salinity of a water mass will produce a corresponding increase in its density and hence a decrease in its specific volume. When speaking of a limited sea region, the decrease in specific volume of the sea water implies a lower water level and hence a slope of water toward this region. That is why the change of density of sea water plays such an important role in the water circulation in any sea area. It is in our case an important factor in producing the circulation regime in the Canal.

In September 1966 there was in the Port-Saīd region of the Mediterranean Sea, a drastic change of water salinity, and hence density and specific volume.

This was mainly due to the absence of the regular huge amount of fresh water discharge from the Nile River which used to be ovserved yearly during the Nile flood period from July to October, with a peak in September (fig.2). The natural consequence of the Nile flood was an accumulation in the neighbouring area of Port-Saīd of a large amount of fresh water, which mixes with the Mediterranean waters producing a mixed water of lower salinity, lower density and higher specific volume. This has usually produced a slope of water surface in the Canal towards the south, causing a southward flow of water through the Canal in the summer months as observed up to 1964. Later, the Nile River High Dam at Aswan was completed and put an end to the yearly Nile flood. This clearly gives an opposite situation. A water mass of relatively higher salinity occupies Port-Saīd region in the summer. The consequence is an increase in density, decrease in specific volume and hence a decrease in water level at Port-Saīd.

On the other hand, conditions at the southern end of the Canal show an opposite picture. A remarkable increase of salinity to values such as 44-46 ‰ was usually observed at Suez Bay every summer due to the southward outflow of the highly saline waters of the Great Bitter Lake into Suez Bay. In the summer of 1966, the salinity at the southern end of the Canal continued to be less than 43 ‰ (MORCOS and MESSIEH, 1973b, 1973b). These new conditions in 1966 would result in a relatively lower density or higher specific volume which tends to increase the mean sea level at Suez.

After the completion of Aswan High Dam the salinity at the two ends of the Canal changed considerably. Compared with previous years, the salinity increased at the north and decreased at the south. A relative change in the mean sea level could be expected in summer at the two ends of the Canal. The mean sea level at the northern end tends to decrease, while that at the southern end tends to increase. Such a situation would influence the water level in the Canal to slope from south to north. This is compatible with the observation that the current regime in the Canal continued to be northward in September 1966.

Slope of water level along the Canal :

The results of the computed M.S.L. at the two ends of the Canal showed that the water level in the Canal in September 1966 would slope from north to south while the current regime is northward. It is therefore suggested that the 1966-reversed system of summer circulation in the Canal is not a direct result of an absolute inversed situation in sea level at the two ends of the Canal. It is rather the result of the influence of several physical factor combined together. One of these factors might be the fact that the difference in sea level between Port-Saīd and Suez in summer of 1966 was less than in summer 1964 especially in the month of September. However, any discussion on the currents in the Suez Canal as a result of MSL differences between its ends must take into consideration the existence of the huge water mass of the Bitter Lakes, which represents about 80 % of the whole water mass of the Canal. The Bitter Lakes form some kind of discontinuity in the slope of the sea surface along the whole length of the Canal. This adds more to the complexity of the whole phenomenon.

Reliable information on the slope of water along the Canal could only be gained from observations of M.S.L. at selected points along the Canal especially in the region of the Bitter Lakes in addition to observations at the two ends of the Canal. In 1935, 1936 and 1937, three tide gauges were installed at the following three points along the Canal :

Deversoir (Km 98) at the northern end of the Great Bitter Lake
Kabret (Km 121) between the Great and Little Bitter Lake
Geneffe (Km 134) at the southern end of the Little Bitter Lake.

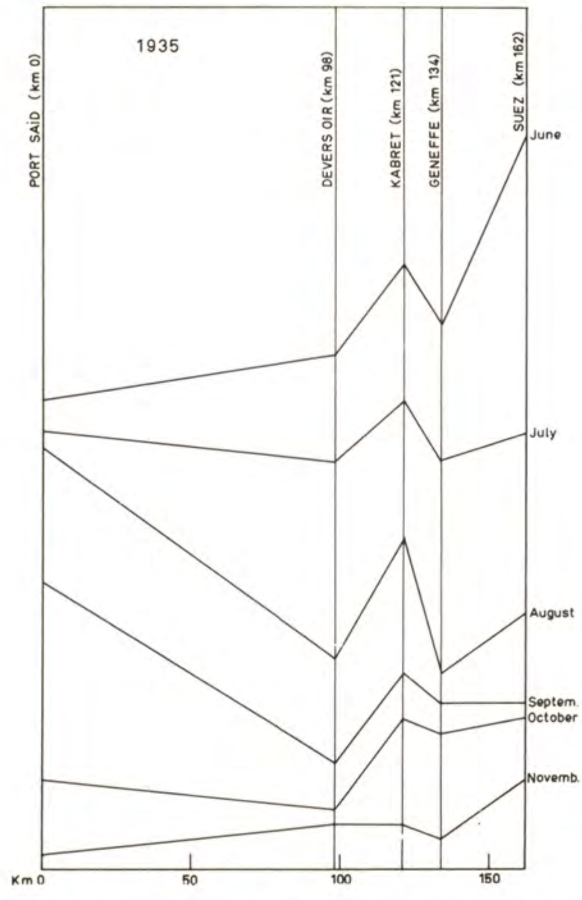

Fig. 7 - The slope of water level along the Suez Canal in each month from June to November 1935.

Fig.(7) represents the slope of water level along the Canal at the six months between June 1935 and November 1935. The data of these three years show that in most cases the Bitter Lakes occupy an intermediate height between the Red Sea and the Mediterranean when the current is predominantly northward in winter or predominantly southward in the month of September. However, in some transitional months the Bitter Lakes are either higher or lower than the M.S.L. at both ends of the Canal. According to Baussan (1938) the 1935-1937 observations give the following patterns of circulation :

a) From winter to early summer the current flows from the Red Sea to the Mediterranean as indicated by the slope of water in June 1935.

b) This is followed by a reversal of current in the Northern Canal with waters flowing from the Mediterranean to the Bitter Lakes while the current in the Southern Canal continue to be northward from the Red Sea to the Bitter Lakes (e.g. July-August 1935, June, July, August 1936, June 1937). In these months the waters flow from both ends of the Canal towards the Bitter Lakes.

c) This is followed by a predominant current established between the Mediterranean and Red Sea (e.g. September 1935, September 1936 and September 1937).

d) The current in the southern Canal regains its original direction from the Red Sea to the Bitter Lakes while the waters of the Mediterranean continue to flow from the Mediterranean to the Bitter Lakes (e.g. October 1935, October 1936).

e) Finally, the current is reversed between the Mediterranean and the Bitter Lakes and regains its initial northward direction along the whole Canal (November 1935 - November 1936).

Conclusions

The above discussions give support to the following conclusions :

a) In the first half of September 1966, waters were flowing from the Mediterranean to the Bitter Lakes in the Northern Canal, while the current continued to be northward from the Red Sea to the Bitter Lakes in the Southern Canal. This ressembles the conditions in the transitional months July-August in 1935 and 1936 observations.

b) In the second half of September 1966, and instead of attaining the complete reversal of currents as occurred in the preceeding years, the current changed from the transitional condition in the beginning of this month to the predominantly northward current in reverse to what had prevailed in all the preceeding months of September.

c) The slope of water in the Canal could not be simply deduced from observations of M.S.L. at the two ends of the Canal but from additional observations at significant points along the Canal especially at the region of the Bitter Lakes. The Great Bitter Lake represents about 80 % of the total volume of the wasers of the Suez Canal and it plays a significant role in altering the slope of water and the current regime in the Canal.

e) A complete change in the direction of the current regime occured for the first time in summer 1966 after the completion of the Aswan High Dam. Whether this change in the current regime is entirely linked to the Aswan High Dam, and whether this change continued to occur every September after the summer of 1966, are questions open to future investigations.

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DISCUSSIONS AND COMMENTS

Dr. ROBINSON : I have some inquiries and questions to Dr. MORCOS.
Would you please make some additional comments concerning the depth over the salt-bed in the Bitter Lakes from the beginning of flooding when salinities were 168 ‰, and dissolution of the bed appeared to be taking place, and conditions which are currently present ?

Dr. MORCOS : Yes, before digging the Canal, the Great Bitter Lake was a dry basin occupied by a huge salt-bed. Aillaud, one of De Lesseps scientists, told us that this saline plateau "rises suddently as a piece of coin placed on a level surface", and that numerous pools of clear transparent waters surrounded its base at a depth of about 2m below the surface of the plateau. This water yielded 310.40g/l on evaporation.

The Mediterranean water was first introduced into the dry basin on March 18, 1869, followed after five months by the Red Sea water. The operation was completed in in eight months, when the lakes were filled to sea level on November 17, 1869. This operation was accompanied by a decrease of salinity and increase of depth over the salt-bed. Three months after the starting of the operation, i.e. when Mediterranean water only was flowing, the salinity was 168.8g/l by evaporation, compared with 43.8g/l for the inflowing water from the north. It was concluded that every litre of the inflowing water had dissolved 125 g of salt. The estimated volume of the salt-bed which had dissolved since the start of filling agreed closely with the observation that a layer of 40 cm of the salt-bed went into solution.

It became certain that the salt-bed was dissolving. In fact, there was a conflict between the engineers of the project at that time.

One group wanted to avoid the Bitter Lake on the assumption that the very important evaporation in the area would result in a continuous deposit of salt and the blocking of the canal.

The other group said that as the Bitter Lake constitutes one-third of the length of the canal they would make an economy of one-third of the distance to be dug and they went on with the project.

The investigations started in this area and the results showed that evaporation was not excessive enough to cause precipitation. De Lesseps /1/2/ presented two papers to the Académie des Sciences de Paris and showed that this precipitation would never occur so long as there is a continous flow between the two seas.

Dr. ROBINSON : How deep was the salt-bed ? Was it one meter or two meters ? What was the change in depth of the salt-bed ?

Dr. MORCOS : In November 1869, when the Canal was opened to navigation the depth over the salt-bed was between 7 and 8 meters which was just enough to let the ships of that time passing through. The Canal itself was deepened in successive programmes of improvement to accomodate larger ships. However, no dredging was made over the central part of the Great Bitter Lake where the salt-bed exists. The depth over the salt bed increased due to the natural process of dissolution of salt.

Because of its practical importance, the Canal authorities kept a fairly good record of the depth over the salt bed. It increased relatively quickly in the early years to about 10 m at the beginning of this century and to about 12 m in the thirties. It is now about 14 m with some deeper spots. However, there is some sort of "apparent depth" and "real depth" of the salt-bed. When I say that it is 14 or 15 m in depth, the measurement really extends below the bottom because there is a layer of sediments overlying the salt-bed.

There are two different processes going on in the Bitter Lakes : one is the dissolution of the salt, and the other one is precipitation. You will find that what is always quoted as the depth of the salt-bed in the literature is actually the apparent depth. The real depth of the salt-bed is a larger figure, i.e. the apparent depth + the thickness of the sediment layer.

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/2/ De Lesseps, F., 1876
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FURTHER STUDIES ON TIDES AND THE HYDROGRAPHY OF THE SUEZ CANAL AND ITS LAKES

S.H. SHARAF EL DIN*

Abstract

Between April 1966 and April 1967, five cruises were taken to study the seasonal hydrographic variation in the Suez Canal, the Lakes and the Suez Bay. Also tidal current and tidal elevation were recorded during 1966 at Ginefa and Shallufa. In the Suez Canal the reversal of the northerly current in the summer season is primary due to the wind and not to the effect of the Nile flood. A steady northward flow of water in the southern part of the Canal is directed into the Bitter Lakes is due to evaporation and dissolution of the salt bed. The increase in the Canal area has no apparent effect on the tides and the tidal currents.

Résumé : Nouvelles études des marées et de l'hydrologie du Canal de Suez et de ses Lacs.

Entre avril 1966 et avril 1967, cinq campagnes furent entreprises pour étudier les variations saisonnières dans le Canal de Suez, les lacs et la baie de Suez. De plus, les courants de marées et les variations de niveau dues à la marée furent enregistrées en 1966 à Ginefa et Shallufa. Dans le canal de Suez le renversement du courant vers le Nord dans la saison d'été est essentiellement dû au vent et non à l'effet des crues du Nil. Dans la partie méridionale du canal, un courant stationnaire vers le Nord s'écoule vers les Lacs Amers pendant la majeure partie de l'année sauf à la fin de l'été. Le maximum de salinité dans les Lacs Salés est dû à l'évaporation et à la dissolution de la couche de sel du fond. Cet accroissement de sel dans le canal n'a pas d'effet apparent sur les marées et le courant de marée.

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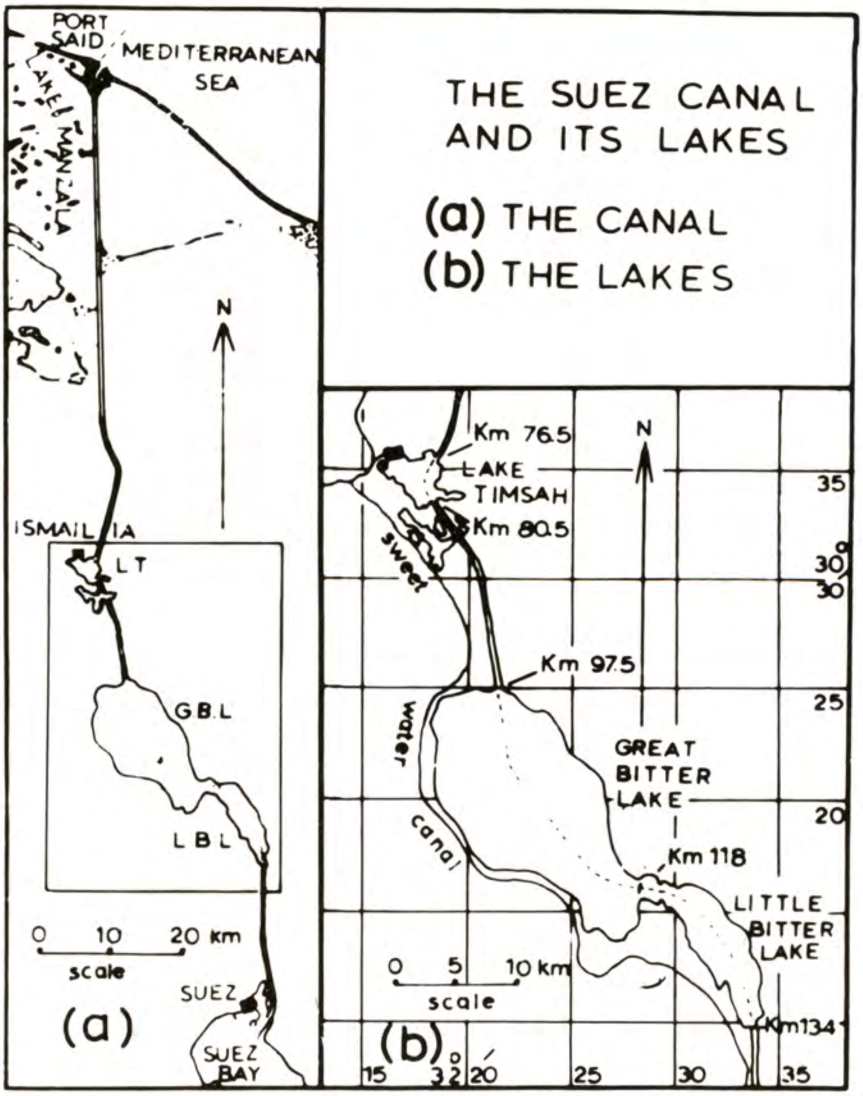
INTRODUCTION

Between April 1966 and April 1967, five cruises were taken to study the seasonal hydrographic variation in the Suez Canal, the lakes and the Suez Bay (Fig.1). These five cruises were taken on April, May, September, December of 1966 and April 1967. The hydrographic stations in the canal were occupied every 5 km and, 14 stations were taken in the lakes, 10 stations in the Great Bitter Lakes and two in both Lake Timsah and the little Bitter Lake. Water samples and temperature were taken at 0, 3, 6, 9, 12 m and current observations were made every other station. Also tidal current and tidal elevation were recorded in the region of the Bitter Lakes down to Suez during the second half of 1966 for a continuous six month-period at two stations Ginefa and Shallufa (Fig.1). The current measurement were recorded every half hour at different depths. Besides, an old measurements taken by the Suez Canal Company on 1929, from 1933 to 1935, and from 1944 to 1950 were also used for comparison with the results of the new data.



- Fig. 1 -

The hydrography of the Suez Canal

Analysis of the results of five cruises show the expected pattern of northerly drift of Red Sea water in the Suez Canal most of the year (El Sabh 1967,1968, 1969). The northern section, always contains some Mediterranean water (table 1). In summer time the flow pattern becomes weaker and reverses in the northern section at least. Different investigators studied the distribution of salinity along the canal. They found that for most of the year the mean sea level is higher at Suez than at Port-Saīd, which causes a steady northerly current. During the Nile flood, this circulation pattern changed giving a southerly flow as a result of the intrusion of the flood water to the canal. But after the building of the first stage of the Aswan High Dam in 1966, which put an end to the seasonal discharge of the Nile flood, two cruises were taken. One on 14 September 1966 by El Sabh followed by another one on 28 September of the same month by Morcos. The result of the two cruises are different from each other although they were taken within the same month. The wind direction was in the North direction during the two cruises with different magnitude in speed. Morcos stated that the Nile flood is the major parameter in the southerly flow in the Suez Canal during the summer which is disappeared during his cruise (Fig.2)

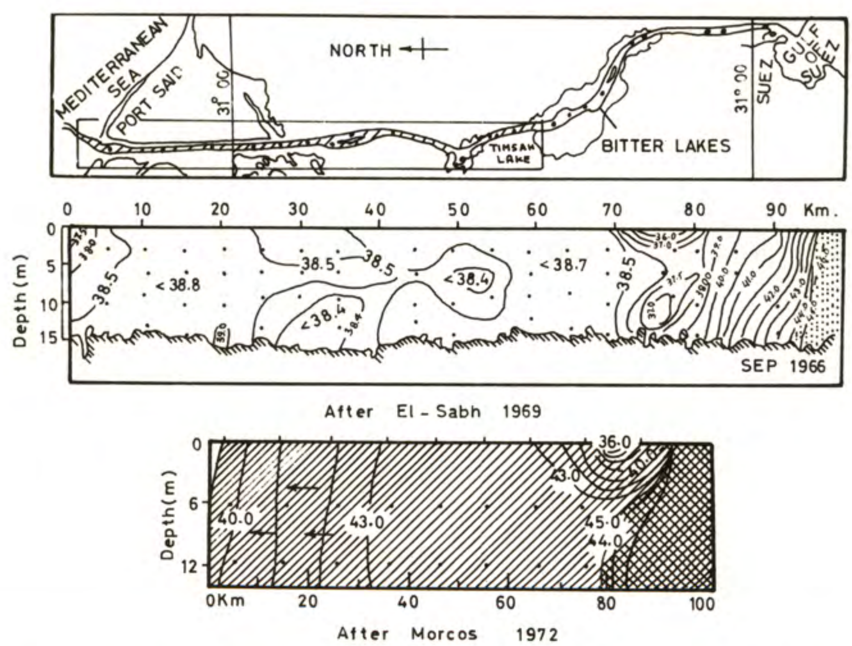


Fig. 2 Salinity variations along the Suez Canal during September 1966, by Es Sabh (14 September) and by Morcos (28 September)

The average salinity of the Northern section of the canal increased from 38.43 ‰ in early September to 42.72 ‰ at the end of that month (El Sabh 1969). El Sabh showed from his result the evidence of the southerly current during his cruise (Fig.2) which is similar to that which occured each year before the building of the Aswan High Dam. He concluded that the prime factor in the southerly flow is the wind stress on the water and not as previously thought to be caused by the Nile flood. His conclusion is based on, a very careful look in the wind records at that area. The southerly section is affected more than any other section by the tidal cycle. The tide range has an average of 110 cm at Port Tewfik (near Suez) which forces the Gulf water northward at High Tide and the canal water into the Gulf at low water, this enhances the exchange between the Gulf and the Bitter Lakes With the proposed enlargement in the canal cross-section after opening, the exchange will change radically and it needs more complete observations.

Table 1 : Percentage of the Mediterranean and Lakes waters in the Northern section of the Canal (after El Sabh 1968).

Cruise N°	Month	Per cent of Mediterranean water	Per cent of Lakes water
1	April 1966	18	82
2	May 1966	11	89
3	Sept. 1966	95	5
4	Dec. 1966	3	97
5	April 1967	4	96

Hydrography of the Canal lakes

Again from April 1966 to April 1967, five cruises were taken to cover fourteen hydrographic stations in each season, 10 stations in the Great Bitter Lakes and two stations in both Lake Timsah and the Little Bitter Lakes. At these stations temperature, salinity and current measurements were taken at different depths.

The analysis of these observations show a steady northward flow of water in the southern part of the Canal (42.3 ‰) into the Bitter Lakes most of the year except in late summer. The Great Bitter Lake water is driven in an anticlockwise sense. In September, the southward flow of water give a smaller salinity of 38.5 ‰ in the northern part of the canal and the lake water is driven southwards under the effect of the reversed flow as the maximum salinity occurs south of the Great Bitter Lake. The maximum salinity (46.5 ‰) in September is due to the combined effect of excess evaporation and dissolution of the salt-bed of the Great Bitter Lake (El-Sharkawy 1969). The effect of the salt bed was so great in the past compared to the present that the salinity at the first beginning was 168 gm/l in 1869 when the depth of the water over the salt-bed was as yet 1.14 m. From the previous salinity data, the yearly decrease of salinity was shown to be asymptotic. This indicates a gradual decrease in the rate of dissolution of salt. This can be attributed to : a) contraction of the salt-bed, b) black mud on top of the bed and c) the least soluble salts at the bottom of the bed which are now to be dissolved.

The salt-bed is now of a minor effect on the salinity of the lake, and the annual change in salinity is mainly due to the effect of evaporating. A rough calculation shows that the salinity increase of the lake water due to evaporation is about three times greater than that due to the salt-bed. Thus, the salinity of the water in the Great Bitter Lake will be always higher than that in the southern part of the Canal, even in absence of the salt-bed, by 1.25 ‰. This contradicts the suggestion of Wust 1935 of the mean salinity between the Mediterranean and Red Seas.

The speed of the current in the Little Bitter Lake is close to that in the southern part of the Canal. Enlargement of the Canal would result in increasing the speed of the current, and thus decreasing the time spent by the water in the Great Bitter Lake.

Consequently, the salinity extremes in the lake would be lower than that observed before enlargements.

Tides and tidal currents in Suez Canal :

The tides and tidal currents in the southern part of the Suez Canal was investigated by the Suez Canal Laboratory. The data used in these investigations based on the tidal current and tidal elevation measured in the region of the Bitter Lakes down to Suez during 1966 for a continuous six month-period at two stations, Ginefa and Shallufa.

The current measurement were measured every half hour at different depths. Besides, an old measurement taken by the Suez Canal Company on 1929, 1933 to 1935, and 1944 to 1950 were also used for comparison with the new data. From the analysis of the six months data during 1966 (Shukry 1968) concluding remarks can be summarized as follows :

1 - The vertical velocity distribution of the tidal current follows the logarithmic distribution.
2 - The horizontal distribution of tidal current follows a parabolic distribution across the Canal, with minimum velocity over the berms and maximum velocity at the canal axis.
3 - The main four harmonic constants for the tidal current were determined, allowing the prediction of the tidal currents within $\pm$ 15 %.
4 - The prediction of tidal currents can be improved by taking records for one complete year, and determining a correction factor for each month, because of seasonal variations.
5 - The main four harmonic constants for the tidal elevation were determined allowing the prediction of the tidal elevation within $\pm$ 20 %. However, the tidal range can be predicted with an accuracy of $\pm$ 2 %.
6 - The prediction of tide elevation can be improved by taking records for one continuous year to get more harmonics.
7 - The friction reduction ratio C/C_o was found to be 0.92 in the southern part of the Suez Canal. ($C = \sigma/K$, $C_o = \sqrt{g\ h_o}$)
8 - The effect of increasing the cross-section of the Suez Canal on tides and tidal currents were studied. Also the expected cross-section of the Suez Canal in its future widening was taken into consideration. It was found, in confirmation with previous and present records, that the increase in the canal area has no apparent effect on the tides and tidal currents within the range of the studied areas.

From the temperature and salinity measurements taken from the different stations occupied in the Red Sea, during the last fifty years, the seasonal variations of the water masses will be studied during the different seasons of the year.

The water characteristics will be studied qualitatively and quantitatively from one season to another. This will show the effect of the meteorological parameters on the water masses during the year.

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THE BITTER LAKE SALT BARRIER (1)

A.R. MILLER and R.G. MUNNS (2)

Résumé : La barrière de sel du Lac Amer.

Les eaux salées (43 à 47 o/oo) du Grand Lac Amer forment une "barrière de sel" empêchant le passage des espèces marines de l'Est à l'Ouest. Un fait significatif obtenu durant les dernières campagnes dans cette région, en particulier par l'"ATLANTIS II" (juillet 1963 et février 1965) et le "CHAIN" (octobre et novembre 1966), est que les dépôts de sel du Grand Lac Amer semblent être épuisés et que le maximum de salinité est probablement dû à l'évaporation (3,9 à 6,5 mm/jour dans les Lacs Amers).

Cette barrière de sel semble être un phénomène saisonnier, contrôlé, en partie par les conditions météorologiques et, en partie, par l'intensité de la circulation dans le Canal.

Abstract

The saline waters (43 to 47 o/oo) of the Great Bitter Lake make a "salt barrier" inhibiting the transfer of species between East and West. One significant fact obtained during the last cruises in this region, especially by the "ATLANTIS II" (July 1963 and February 1965) and the "CHAIN" (October and November 1966) is that the salt deposits of the Great Bitter Lake seem to be exhausted and that the maximum salinity is probably due to evaporation (3,9 to 6,5 mm/day in the Bitter Lakes).

This salt barrier seems to be a seasonal phenomenon, controlled, in part, by meteorological elements and, in part, by the rapidity of the circulation through the Canal.

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(1) Contribution n° 2972 of the Woods Hole Oceanographic Institution.

(2) Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, U.S.A.

INTRODUCTION

From ancient times the Bitter Lakes, intervening between the northern and southern portions of the Suez Canal, appear to have been affected by the needs and demands of mankind. Aside from geological considerations, their very existence as bodies of salt concentration was linked to economic and political necessity, first, as part of the system connecting the Nile River with the Red Sea, then, as part of planning and eventual operation of the passage between the Mediterranean and Red Seas. In the time of the Pharaohs (from about 2 000 B.C. to 600 B.C.) an ancient canal provided communication and transportation to other parts of the Near Eastern world and this waterway, passing through Great and Little Bitter Lakes, was the practical means for alleviating famine threatened by drought. The canal system was also important for safety of empire being strategically important successively to the Persian, Ptolemaic, Roman and Caliphate regimes (KIMROSS, 1969). Eventually, with the falling into disuse, with the silting up of entrances, and with probable subsequent geologic events, the Bitter Lake depressions were isolated and dried up leaving behind a thick salt bed whose dissolution would ultimately affect the circulation of the present day canal and present an osmotic salt barrier (FOX, 1926) inhibiting the transfer of species between East and West. Ferdinand De Lesseps had estimated that before the opening of the Suez Canal the thickness of the salt bed inGreat Bitter Lake was about 13 meters (WÜST, 1951).

In the Moslem era following the Arab conquest of Egypt a canal was again opened up to connect the Nile River with the Red Sea in order to move corn from Egypt to Arabia (Nadvi, 1966). The Arabs and their predecessors were able to predict future harvests by measuring the crest of the Nile flood. The height of the flood determined whether there would be bounty or scarcity. Ritual breaking of the dams at the crest was also accompanied by directing of flow through the canal towards the Isthmus of Suez (STEWART, 1968). In the recent millenium prior to the opening of the present Suez Canal the old canals were filled in by silt and the Bitter Lakes sealed off from the Gulf of Suez. However, traces of the old canals remained and had considerable influence on the plan of the present-day canal (BURCHELL, 1966).

WÜST (1934) has shown that the dissolution of salts in the lake bed of Great Bitter Lake and its subsequent deepening correlated with the gradual decrease of salinity in the Bitter Lake waters. He had estimated from the rate of solution that by 1970 the salt beds would be exhausted. The Canal was broached in 1869 and its original depth was dug to 26.3 feet. However, in 1939, to accomodate larger and deeper draft vessels, dredging was cut to depths of 32.8 to 42.7 feet with a bottom width increased from 72.2 to 196.9 feet. In 1959 further dredging increased canal depths from 36.1 to 49.2 feet with bottom widths to 283 feet, or, four times the width of the original cutting (BURCHELL, 1966). Maximum permissible draft of vessels passing through the Canal in 1961 was 34 feet (H.O. Chart N° 2431). These dredgings, presumably, should have accelerated the dissolution of the Bitter Lake salts. Further, the annual Nile flooding has been brought under control of the Aswan High Dam since late 1964. This has its influence on the salinity of the Suez Canal through the "sweet water" canal connecting with Lake Timsah, north of the Great Bitter Lake. It is the intent of this paper to examine the waters of the

Mediterranean and Red Sea entrances, the Canal itself, and the Bitter Lakes to determine the extent of the salt barrier as it may exist today.

Background

MORCOS (1960) has shown through repeated surveys of the Canal that, invariably, the highest salt concentration throughout the length of the Canal is in the Bitter Lakes area. The focus of this concentration moves north or south according to season. In Figure 1 we have extrapolated Wüst's correlation of salt concentration of surface and bottom waters with the depth of the Bitter Lakes using more recent data. This figure demonstrates an assymptotic curve towards latest values. Since these latest values vary between 43 ‰ and 48 ‰ and compare easily with those several decades earlier, it may be argued that the dissolution is complete and that the depth of the Lakes is stable. The dredgings of 1939 and 1959 may have contributed towards quicker dissolution of the salt beds ; nevertheless, the still high concentration of the Bitter Lakes deserves some explanation and methodical study. It is this concentration which has inhibited the migration of Indo-Pacific species into the Atlantic-Mediterranean regime. The weakening of the salt barrier presents a migratory possibility with ecological signifiance, for the Canal is the sole sea-level water-way link between the great oceans, other than the cold high-latitude accesses around the continents.

In contrast, another semi-tropical waterway, the Panama Canal linking Pacific and Atlantic regimes, gives access only through the high fresh waters of Gatun Lake, a prohibitive barrier for the migration of species. Some fish, such as tarpon, and other marine organisms have survived the Panama Canal transit presumably hitch-hiking by means of ship's hulls or bilges (B.H.Ketchum ; Personal Communication). More and more Red Sea species have been identified in the Eastern Mediterranean (BEN-TUVA, 1964). Broadly, if the salinity transition from the Pacific to the Indian Ocean and, then, to the Red Sea presents no migratory problems one might assume that the transition from the Red Sea to the Mediterranean Sea should present no problem either, for the demand for osmotic adjustment would not be very great. However, if the scale of change in salinity more than 3 parts per thousand is biologically significant, then, the Bitter Lakes are still effective in restraining free migration of Eastern and Western organisms. The leaching of the Bitter Lake salt beds cannot go on forever so another mechanism for salt concentration is required ; otherwise, the Canal waters are destined to be simple mixtures of Red Sea, Mediterranean Sea, and Nile River water and thus no barrier at all.

Observations

In late July, 1963, the Research Vessel ATLANTIS II passed through the Suez Canal on its way to the Indian Ocean. Through the courtesy of the Suez Canal Authority, the ship and its small work boat conducted an hydrographic survey of Great Bitter Lake during the traffic lay-over for the north-bound convoy. A second survey was carried out in February, 1965, more extensively, with an in-depth sampling program throughout the entire length of the Canal together with deep hydrographic stations at the Mediterranean and Red Sea entrances. In 1966, October and November passages of the R.V.CHAIN provided autumn data for the length of the Canal.

One significant fact was obtained during the 1965 cruise worth mentioning at this point. Core samples (three) and grab samples from the bottom of the Great Bitter Lake showed that the salt deposits were probably exhausted. Mud and gypsum crystals were the main constituents of the cores.

In the interval between 1963 and 1965 the completion of the Aswan High Dam eliminated any further natural effects of Nile flooding, henceforth to be controlled by engineering decisions. Its significance for the Suez Canal lies in the Sweet Water Canal entering Lake Timsah at Ismailia, and in the Canal entrance at Port-Saīd. Figures 2 and 7 show the salinities along the length of the Canal as observed in 1963 and 1965. The ordinate extends north and south beyond the Canal to show the background salinities of the Mediterranean and Red Seas. The transit of July 29, 1963, during the time of Nile flooding shows that the background salinity of the Mediterranean surface water was 39.0 ‰ . The effect of the Nile is very close to shore and extends north only a few miles beyond the Port-Saīd breakwater where it succeeds in lowering the surface salinity to 37 ‰ . Its influence, or else the influence of the Mediterranean, extends into the Canal as far as Ras el'Ish, or about 20 kilometers. From here to kilometer 70 the surface salinity varies between 41.5 to 42 ‰ and is abruptly lowered to 36.5 ‰ at Lake Timsah. Further southward the salinity climbs steeply and assymptotically to 47 ‰ in Great Bitter Lake. It drops sharply to less than 46 ‰ in the southern part of the Canal at the end of which salinity values are lowered steeply to 42.5 ‰, presumably the background surface salinity of the Gulf of Suez. During this transit, surface temperature in the confined areas rose to 29.5° C and 30.5° C in the Bitter Lakes from referential surface temperatures of 26 and 26.5°C in the Mediterranean and Red Seas. Probably the prevailing north winds have influenced the distribution. This is suggested by the abrupt northerly discontinuities and tapered southerly changes with respect to the two fresh water sources. It should be noted, too, that the greatest Great Bitter Lake surface salinity was observed in the southern portion of the Lake.

An in-depth survey of the Great Bitter Lake for July 29, 1963 does not show the effect of north winds. In fact, the greatest salt concentration appears to be north of the central part of the Lake at Station 35. Figure 3 shows three profiles, east, central and west, across the length of the Lake. They show that the salinity distribution is lens-shaped with the thickest part, representing maximum salinity, in the northern third of the Lake with the greatest salinity trending to the west. However, the least salinity gradient occurs in the eastern profile which, accordingly, shows higher salinity values than the peripheral features of the western side. This seems to indicate that there was a counter-clockwise circulation within the Lake superimposed over influences from the north and south. A northerly flow on the eastern side and a southerly flow on the west seems to be borne out by the distortions of the salinity distributions.

There is a marked contrast to summer in the winter distributions (fig.4) of February 13-14, 1965. Surface salinities in the Canal are remarkably low and the influence of the Nile is meager, if present at all. Again, Mediterranean surface water is at 39 °/oo, although at a short distance from the Port-Saīd breakwater it is lowered to 38 ‰ . This might be due to the Nile influence but, more probably, it is part of the general coastal distribution (MILLER et al, 1970).

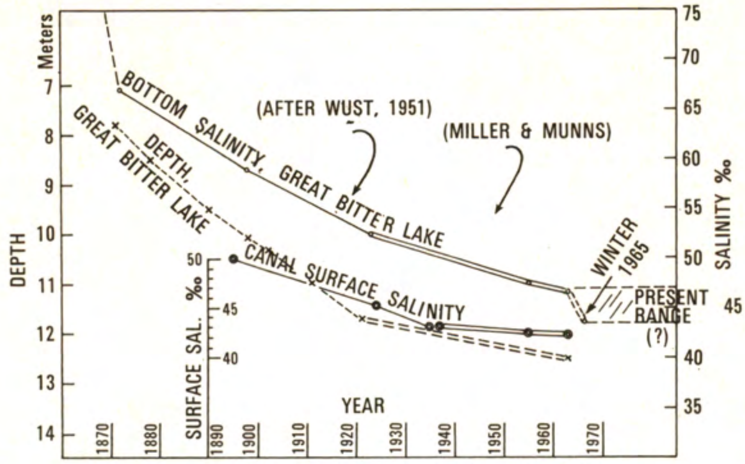

Figure 1. Salt concentration and depth of the Bitter Lakes

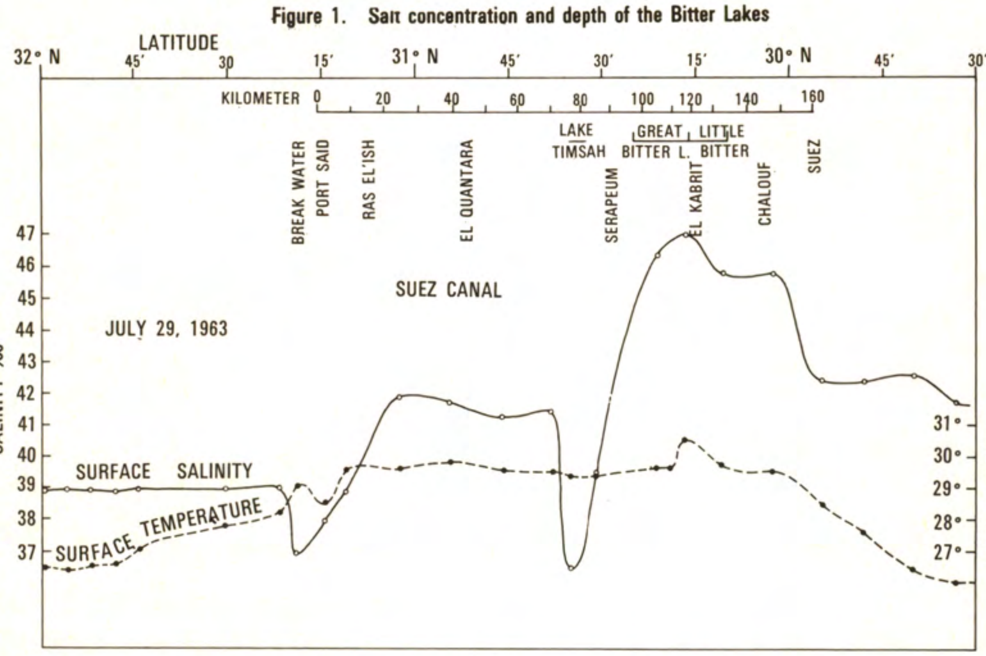

Figure 2. Surface salinity and temperature during transit of Suez Canal, July 29, 1963

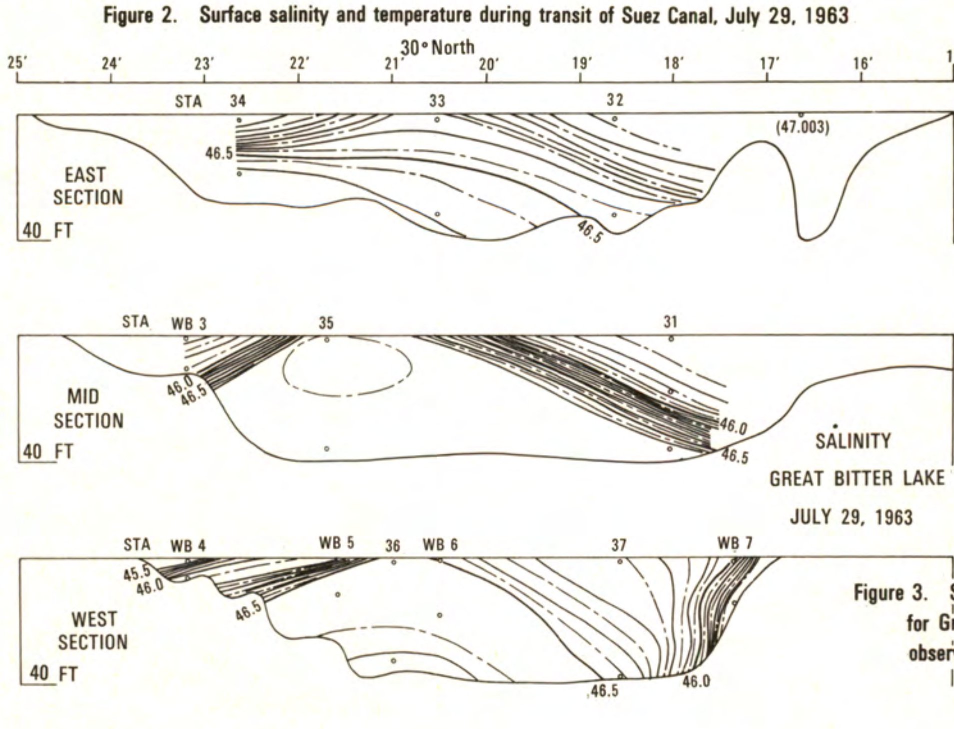

Figure 3. Salinity profiles for Great Bitter Lake observed July 29, 1963

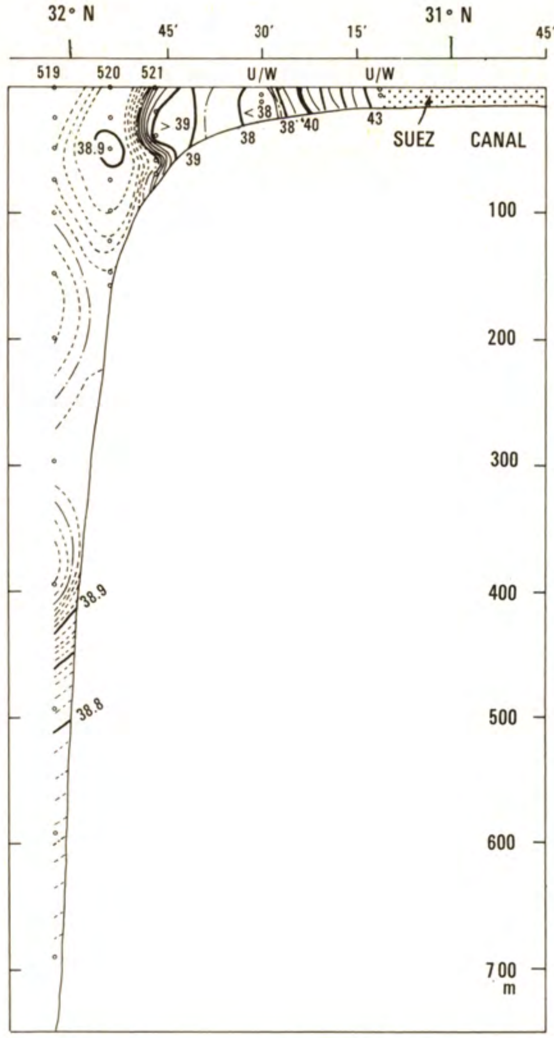

Figure 4. Surface salinity and temperature during transit of Suez Canal, February 13-14, 1965.

There is very little salinity gradient throughout the length of the Canal, although there appears to be an appreciable gradient in Lake Timsah. Water was sampled at the surface, at hull depth (15 feet) and from a towed "fish" at 23 feet. The greatest salinity values were obtained from Great Bitter Lake at 43.5 ‰ and curiously, from the northern extremity of the Canal at kilometer-20. At El Kabrit, between Great and Little Bitter Lakes, the salinity drops to 42 ‰, the value representative of the Gulf of Suez. An enlarged profile (figure 5) shows that salinity greater than 43 ‰ extends from El Kabrit to Ras el'Ish, practically to Port-Saïd, with a slight lowering at Lake Timsah.

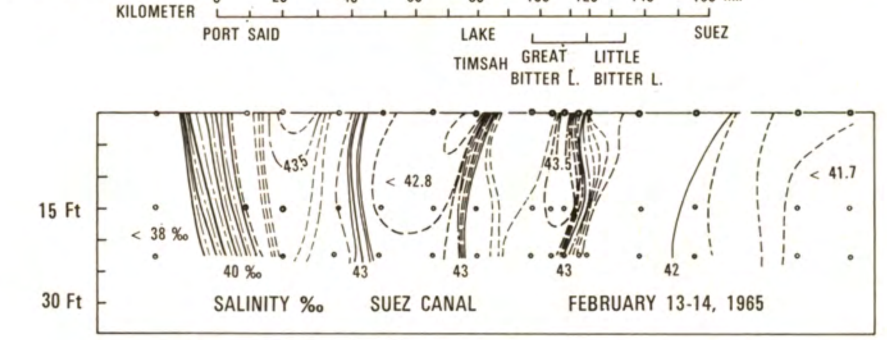

Figure 5. Salinity profile for Suez Canal, February 13-14, 1965.

The Bitter Lake survey for this period (figure 6) shows, again, a lens-shaped distribution but with two thick foci rather than one as in figure 3. Otherwise, and with the exception of lowered salinity values and smaller gradients, its distribution is similar to the summer survey of 1963. The suggestion of cyclonic circulation is still apparent with low salinity forced to the north in the eastern sector and a sharp southerly surface discontinuity in the western sector.

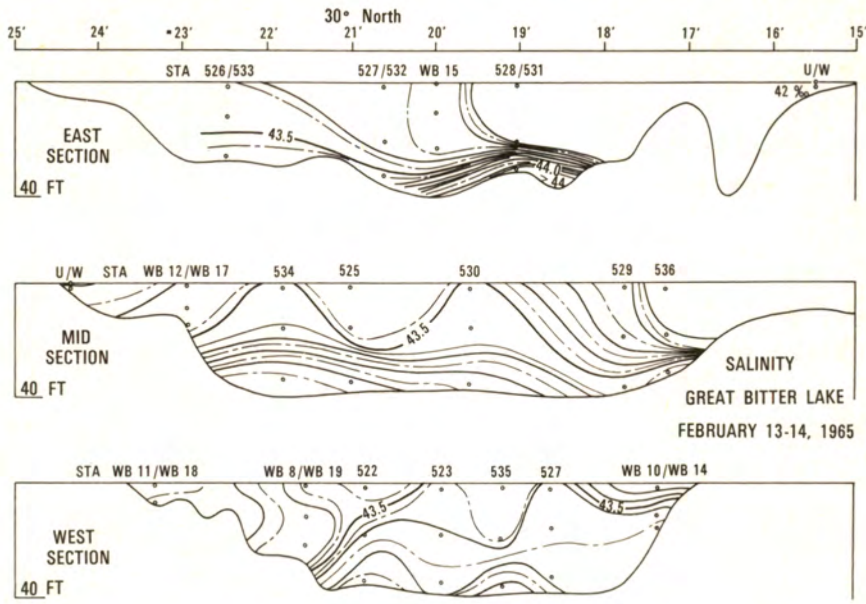

Figure 6. Salinity profiles for Great Bitter Lake observed February 13-14, 1965.

In general, the winter distribution appears to be northerly through the Canal. With a relatively weak salinity increase in the Bitter Lake, the winter season appears to favor the migration of Red Sea species into the Mediterranean. However, this influence seems, if anything, to favor the near-shore, for there is very little influence of Canal circulation on the Mediterranean Sea Proper. Figure 7 shows a deep salinity profile of the Mediterranean at the approaches to Port-Saïd. There is little effect, if any, to be noted from either the Canal or the Nile River on the salinity distribution.

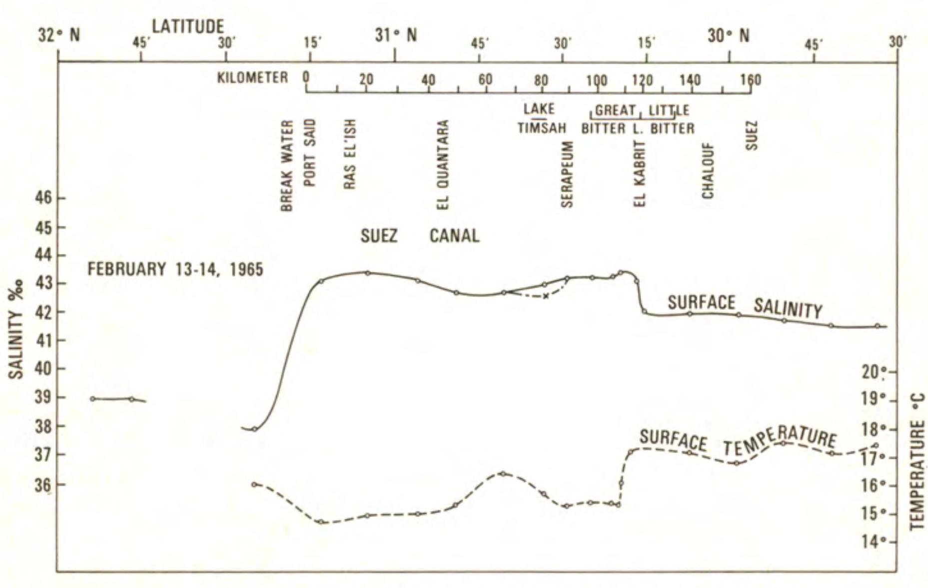

Figure 7. Salinity distribution at Mediterranean entrance to Suez Canal, February, 1965.

In the Red Sea, in order to show deep salinity distribution, it was necessary to go beyond the Gulf of Suez to get into deep water. Figure 8 shows the vertical distribution at the southern end of the Gulf. This figure markedly demonstrates that the entering salinity values are between 40 and 40.5 ‰. Salinity between 40.5 and 41 ‰ extends deep into the Gulf, whereas the 41 ‰ isohaline reaches southward only as far as the Continental Shelf. The volume of water represented by those values over 41 ‰ in the Gulf of Suez must have had its source in local origins but it is unlikely that that the source should be attributed to the leaching of the Bitter Lake salt beds. The large area of the Gulf of Suez, exposed to conditions probably more conducive to evaporation than any other maritime area, is, no doubt, responsible for its increased salinity. On this basis, it is worth examining the Bitter Lake region for its evaporation potential.

Evaporation

The period of the greatest source of energy is the summer time, so, for this purpose, data from 1963 is used. Measured solar radiation from shipboard for the Canal transit of July 29 was 694 gram calories. This figure will be used for computing the number of calories available for evaporation during that day.

In order to determine the various factors in the heat budget equation, it was necessary to calculate volumes and areas of various parts of the Canal, determine probable flows, and reduce observed parameters to average values. Thus, for the Great Bitter Lake the following average values apply for July 29, 1963.

Temperature	29.5°C
Surface Temperature	29.7°C (Vap.Press.41.75 mb.)
Dry Air Temperature	27.1°C (Vap.Press.35.90 mb.)
Salinity	46.2 ‰
Density (σ_t)	30.35

Volumes and areas are as follows :

North of Great Bitter Lake	32,258,000 m^2
Great Bitter Lake	188,428,000 m^2
Little Bitter Lake	44,010,000 m^2
South of Little Bitter Lake	7,097,000 m^2
Total	271,793,000 m^2
Great and Little Bitter Lakes give	232,438,000 m^2 or
85.5 % of the total area.	
Great Bitter Lake (Km.97 to 32°29'E)	1,385,712,000 m^3
Little Bitter Lake (32°29'E. to Km.135)	93,521,000 m^3
Lake Timsah (Km.76.5 to Km.81)	41,646,000 m^3
Canal (except above)	299,268,000 m^3
Total	1,829,147,000 m^3
Great and Little Bitter Lakes give	1,479,233,000 m^3 or
81.3 % of the total volume.	

As there were no figures for flow during this transit, representative flows from the period, July-August, were used for an estimate (Courtesy of Dr.S. MORCOS, University of Alexandria).

Monthly Average Maximum Velocities in cm/sec :

	Chalouf		Geneffe		El Kabrit	
	N	S	N	S	N	S
July	93.98	97.76	87.95	89.37	20.58	16.47
Aug.	90.12	89.62	84.84	91.84	21.36	17.53
Average	92.05	98.19	86.40	90.60	20.97	17.00

These are maximum velocities, therefore they are not representative of total transport. However, at Kabrit in Little Bitter Lake an available duration factor may be considered as applicable to the maximum values. The M^2 tidal amplitude at Suez is about 56 cm ; tidal friction is probably responsible for the reduced velocities at Kabrit (Grace, 1931).

Monthly Average Durations in Hours

	Northward current Minima	Southward current Maxima
1933	4.19 (June)	5.16 (Sept.)
1934	4.41 (Aug.)	5.08 (Aug.)
1935	5.00 (July)	5.30 (July)
Average	4.5 hours	5.2 hours

For computing the transport at Kabrit we used the following :

	North	South	
cm/sec	20.97	17.00	
or Velocity m/hr	754.9	612.0	
x Cross-section (m^2)	1440.	1440.	
Transport	1,087,056	881,280	m^3/hr
x Sine Wave Corr.	.7	.7	
	760,939	616,896	
x Ave. Duration	4.5	5.2	
	3,424,226	3,207,859	m^3/tidal cycle
or	6,848,452	6,415,718	m^3/day

Therefore, the estimated excess northerly inflow into the Great Bitter Lakes for July-August was 432,734 m^3/day.

No accuracy is claimed for this amount of transport, particularly as the durations are from old data and dredgings since then have deepened and widened the Canal. However, for estimation of the evaporation potential, the figures are useful. Accuracy, also, is not especially applicable to the following elements of the heat budget equation, but the resulting computations can be considered as reasonably approximate.

From Sverdrup, Johnson and Fleming (1946) the heat budget equation is given as

$$Q_s - Q_r - Q_b - Q_e - Q_h + Q_v + Q_\theta = 0$$

The available heat, Q_s, at 694 gm.cal/cm²/day is reduced by reflected radiation, Q_r, or albedo, by the empirical equation

$$Q_r = 0.15\ Q_s - (0.01\ Q_s)^2$$

from Laevastu (1963). This value is 56 gm.cal/cm²/day.

Back radiation, Q_b, was estimated to be 216 gm.cal/cm²/day by taking the mean values from Laevastu (1963) and Sverdrup (1951). From Laevastu, 187, and Sverdrup, 245, the mean value for back radiation was 216 leaving 422 gm.cal/cm²/day for the remaining elements of the heat budget. (As an alternative choice, the Laevastu figure is preferred. Budyko, 1963, gives 147 for Cyprus and 160 for Aden ; thus, the Laevastu figure may be more realistic).

Heat convected back to the atmosphere, Q_h, is given by the equation

$$Q_h = 39\ (0.26 + .077\ V)\ (T_w - T_a)$$

from Laevastu (1963). Using 2.5 m/sec for V and 2.6°C for $(T_w - T_a)$ $Q_{h\ max.}$ becomes 46. However, 5 hours out of the 24 air temperature was greater than sea temperature, so 46 less 5/24 (46) becomes 35 gm.cal/cm²/day. This equation is similar to Bowen's ratio. (Alternatively, if the sense of the heat convected in those 5 hours is in the opposite direction, Q_h is further decreased to 24 gm.cal/cm²/day).

Heat consumed in the temperature rise from the Red Sea inflow, Q_v, was 10 gm.cal/cm²/day. It was derived by multiplying the total daily inflow, 6,850 x 10^9, by the specific heat, C_p = .92, and the temperature rise, 3,5°C, and divided by the total area of the Bitter Lakes (2,324.38 x 10^9).

Finally, the heat used up in local warming, Q_θ, was calculated as 152 gm.cal/cm²/day (Sverdrup, 1951). First, local warming from 24 hours observation at El Kabrit was determined at 0.26°C. Then, the volume of Great Bitter Lake (1,479.2 x 10^{12}) was multiplied by the specific heat, C_p = .92, and divided by the area (232.4 x 10^{10}). (Alternate views might be taken by asserting that the real value for local warming is one-half of 0.26°C. This gives 76 gm.cal/cm²/day).

The remaining element, Q_e, as a residue, gives 225 gm.cal/cm²/day as the amount of heat available for evaporation. (Or, alternatively, 339 gm.cal/cm²/day, if one chooses the bracketed estimations).

There are several ways of estimating the amount of evaporation.

From the energy balance (SVERDRUP, 1951)

$$E = Q_e / L$$

Where L is the latent heat of evaporation and

$$L = 596 - .52\ T \quad (\text{For } 30°C,\ L = 579.2)$$

$$E = 225 / 579.2 \quad \text{or} \quad \underline{3.88\ \text{mm/day}}$$

which is equivalent to 1.42 m/year. (The alternative, Q_e = 339, gives 5.85 mm/day, or 2.14 m/year).

The simpler approach, using the moisture deficiency in the air over the water as the primary factor, is given by a number of equations.

From JACOBS (1951)

$$E = .142 (e_w - e_a) V$$

Substitution of 41.8 as vapor pressure of the water and 23.1 as vapor pressure of the air, with 2.5 m/sec as wind speed, gives E = 6.64 mm/day, or

From Sverdrup, Johnson & Fleming (1946)

$$E = 3.7 (\overline{e}_w - \overline{e}_a) \overline{V} / 365$$

and $$E = 4.74 \text{ mm/day, or}$$

From LAEVASTU (1963)

$$E = (0.26 + 0.077 V) (0.98 e_w - e_a)$$

and E = 8.08 mm/day. The average of these is 6.48 mm/day equivalent to 2.36 m/year.

It is interesting to compare the evaporation potentials derived from the energy balance and the moisture deficiency with the assumption that all the daily inflow entering from the Red Sea is transformed into the salt concentration as observed in the Bitter Lake. The average salinity of Great Bitter Lake on July 29,1963 was 46.2 ‰. Salinity in the Red Sea from ATLANTIS II Station 38 at 28°50' N, 32°59' E was 41 ‰. Assuming that this value was the inflow contributor, the following holds :

Northward transport	6,850,000 m^3/day	
Multiplied by	0.0410	(incoming salinity)
And divided by	0.0462	(observed salinity)
Gives	6,079,000 m^3/day	(amount of 46.2 ‰ water available for south transport)
Or	771,000 m^3/day	to be evaporated.

This represents an evaporation requirement of

3.32 mm/day,

which is much less than the evaporation potential which ranges from 3.9 to 6.5 mm/day.

The fact that the net outflow southward from the Great Bitter Lake was roughly computed to be 6,416,000 m^3/day as compared to the daily salt budget amount 6,079,000 m^3/day suggests that the difference could be made up with contributions from Mediterranean or Nile indrafts. These are only calculated speculations made from available data. A summary discussion is required to consider the significance of the calculated values.

Discussion

The Research Vessel CHAIN passed through the Canal on October 12, 1966. Bitter Lake salinity was greater than 47 ‰ as shown in Figure 9. The effect of Nile water was strong in Lake Timsah with a sharp vertical gradient within the depth of the ship's hull. On November 15, 1966 the CHAIN returned through the Canal. Its samplings are shown in Figure 10 where Bitter Lake salinity was reduced to 45.5 ‰ with high value salinity appearing in the northern part of the Canal in spite of the strong intrusion of fresh water at Lake Timsah. The effect of the controlled Nile outflow was observed outside the Port-Saīd Breakwater.

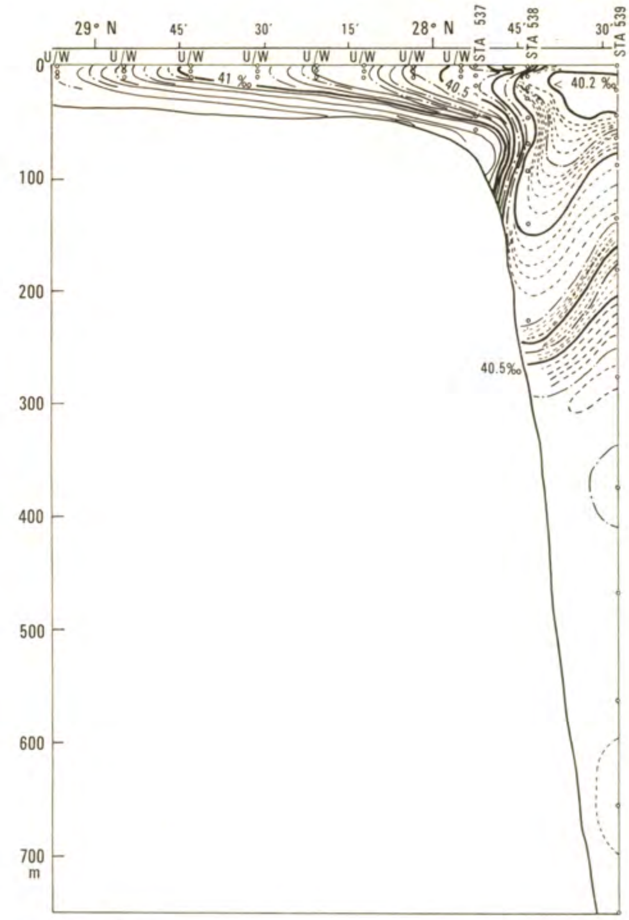

Figure 8. Salinity distribution at Red Sea entrance to Suez Canal, February, 1965.

To sum up, it appears that there is a general net inflow into the Canal from the Red Sea. The tidal oscillation at the southern end, the extra head of sea level provided by the Gulf of Suez entrance as compared to the Mediterranean entrances as shown by WÜST (1934), and the possible evaporation demands of the Bitter Lakes as demonstrated by the energy budget, combine to demonstrate a net influx. With this net inflow from the south, one would expect that the Mediterranean side should show a net outflow. In the summer period this is not the case, and winter outflow, if any, is not appreciable. Both Morcos (1967) and El-Sabh (1968) affirm that sea level at Port-Saīd is higher than at Suez during the period, July-October, and currents are southerly. WÜST (1934) shows that during the major part of the year Suez sea level is higher than Port-Saīd by as much as 42 cm. From the results of five cruises from April, 1966 to April, 1967 El-Sabh concluded that the southerly flow in summer is due to the wind stress of the prevailing north winds. There appears to be very little influence of high salinity Canal water on the Mediterranean side where any outflow could become confused by mixing with the Nile effluent. On the other hand, the salinity gradient in the shallow Gulf of Suez and tidal mixing in the southern end of the Canal indicate that the products of the salt concentration in the Bitter Lakes are normally drawn off to the south.

The seemingly contradictory evidences of net inflows into the Canal from both the northern and southern ends of the Canal in the same period, together with extra volumes of Nile water entering at Lake Timsah, are reconciled with the excessive evaporation potential of the Bitter Lakes region which, in the removal of

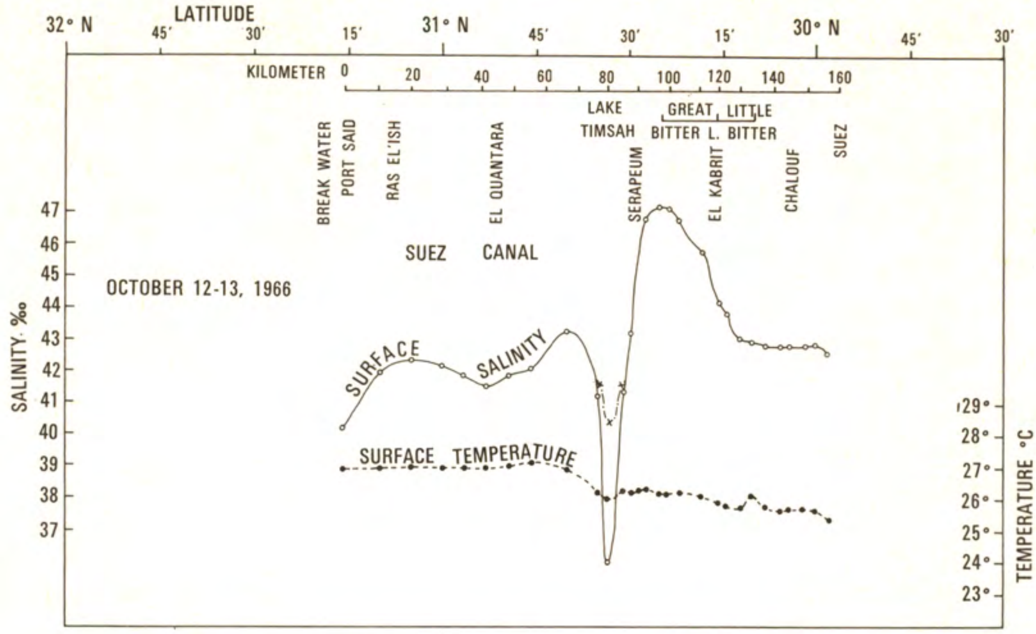

Figure 9. Surface salinity and temperature during transit of Suez Canal, October 12, 1966.

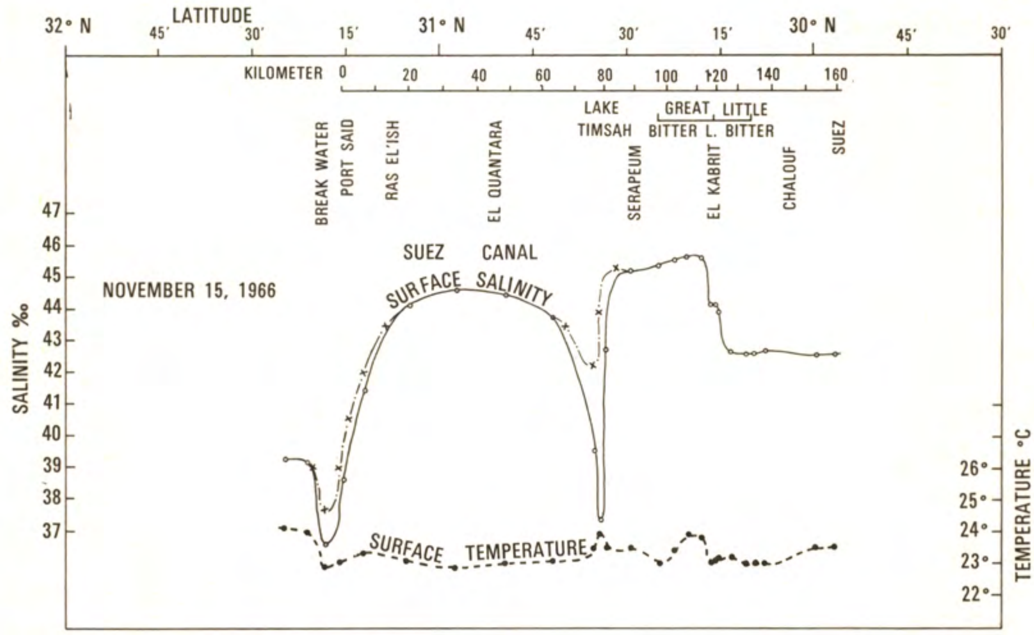

Figure 10. Surface salinity and temperature during transit of Suez Canal, November 15, 1966.

fresh water by evaporation, concentrate the salt waters locally. This suggests that the Salt Barrier is a seasonal phenomenon controlled, in part, by meteorological elements and, in part, by the rapidity of the circulation through the Canal. In microcosm, the Suez Canal System is not unlike the Mediterranean-Red Sea entity where there is net inflow into the Mediterranean through the Strait of Gibraltar and net inflow into the Red Sea through the Strait of Bab el Mandeb. The salt-bed dissolution is no longer a factor and the Barrier is minimal or non-existent in the winter. Further deepening of the Canal with the consequent greater flushing to be expected might virtually wipe out this ecological water gate as an effective biological barrier unless, by some engineering feat, the evaporation potential is used to advantage.

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The Suez Canal.
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Salzgehalt und Wasserbewegung im Suezkanal.
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DISCUSSIONS AND COMMENTS

Dr. MORCOS : What Professeur WÜST said earlier on the problem of decrease of salinity in the Suez Canal appeared in a paper published in 1925. In this paper /1/ WÜST found by extrapolation that the salinity of the Canal will decrease by 1970 to the average value of both the Mediterranean and Red Sea salinities. In a second paper, WÜST, (1951) noted from salinity observations along the Canal in April 1935 and April 1937 that the rate of decrease of salinity over two years is too small compared with the rate of decrease in the early decades after opening the Canal and concludes that the salinity is decreasing asymptolically and not linearly.

On another point, can I understand that the calculations were made on the small net flow in El-Kabrit which shows a net flow to the north in summer although the net flow was southward in the two other points (Chalouf and Geneffe) ?

Dr. MILLER : Yes, to the north.

Dr. MORCOS : Continuous record of currents in the Canal was made by Idrac current-meter at two points south and north of the Bitter Lakes during three years (1933-1935) /2/. This record shows a net flow towards the north in summer and a net flow towards the south in winter. The summer current is very small in magnitude compared with winter. The winter flow occurs for 9 to 10 months while in summer it only occurs for 2 to 3 months. One should take the whole annual picture into considerations.

/1/ WÜST, G. 1935
Fortschreitende Salzgehaltsabhahme in Suez Kanal. Ann. Hydrogr. Maritime Meteorol., Bd, 63, H.10, S. 391-395

/2/ MORCOS, S.A., 1960
The tidal currents in the southern part of the Suez Canal.
Symp. Int. Ass. Phys. Oceanogr. Helsinki 1960, M. Publ. Int. Ass. Sci. Hydrol., Comm. Surface Waters, 51 ; 307-316

ALLOCUTION DE CLOTURE

Professeur H. LACOMBE

A la conclusion de ce Symposium, il convient de rendre hommage au Professeur Paul TCHERNIA à qui revient l'idée de notre réunion. Le nombre de communications annoncées (16) et présentées (14) montre bien que le sujet de l'Océanographie Physique de la Mer Rouge, au sens strict, valait la peine d'être abordé. Le recueil des exposés constituera, malgré l'absence de nos collègues allemands, une utile synthèse de notre connaissance physique de cette aire marine.

La communication de M. PEDGLEY a discuté la météorologie synoptique de la Mer Rouge mais aussi les perturbations à échelle moyenne, de dimensions de 10-100 kms. En raison de l'expérience personnelle de la région qu'a l'auteur, il a présenté une description très vivante des effets superposés des anticyclones subtropicaux permanents de grande échelle et des traits à plus petite échelle résultant de la canalisation provoquée par les reliefs élevés des plateaux de part et d'autre de la Mer Rouge ; les effets dynamiques et thermiques qui en résultent jouent un grand rôle dans la variabilité de la météorologie de la Mer Rouge.

Les variations saisonnières de température de la Mer Rouge (Mrs.ROBINSON) telles qu'elles apparaissent à la lumière de l'étude statistique des bathythermogrammes collectés dans la région, fournissent pour la première fois une description très complète, dans l'espace et dans le temps, de la distribution thermique dans les 150 m superficiels. Les principaux traits de la circulation marine décrite d'après des données individuelles sont confirmés par la distribution thermique ici présentée. En particulier, les dissymétries Est-Ouest, aussi bien de la circulation superficielle que de la distribution thermique mises en évidence par les cartes saisonnières, sont loin d'être exceptionnelles.

De telles dissymétries sont à l'origine de courants traversiers qui apparaissent clairement dans l'étude de C. MAILLARD, fondée sur les stations occupées par le "Cdt. ROBERT GIRAUD" (janvier 1963) et, pour le Nord de la Mer Rouge, dans celle de S.A. MORCOS et G.F. SOLIMAN, fondées sur les mesures du "MABAHISS" (janvier 1935).

La claire corrélation, mise en évidence par l'exposé de W. PATZERT entre les variations mensuelles de la force d'entraînement du vent et de la circulation de surface dans la mer, indique que cette circulation est très fortement conditionnée par le vent, l'écoulement superficiel pouvant se faire dans le sens du vent, à l'opposé de la pente de la surface marine.

L'exposé du Professeur WYRTKI sur la circulation profonde de la Mer Rouge fournit une très intéressante évaluation de la vitesse de formation de l'eau profonde de la Mer Rouge, fondée sur les bilans de diverses propriétés et sur leur répartition.

Sur les hauts fonds qui bordent les côtes, il se forme des eaux denses qui plongent à des immersions intermédiaires entre l'eau superficielle et l'eau profonde. Sur les hauts fonds du Golfe de Suez, l'accroissement de densité est particulièrement élevé, si bien que l'eau formée est susceptible de renouveler l'eau profonde, après mélange avec les eaux sub-superficielles du Nord de la Mer Rouge. Dans l'hydrologie de la Mer Rouge, les deux Golfes de Suez et d'Aquaba jouent un rôle privilégié, en particulier en ce qui concerne la formation de l'eau profonde. Les valeurs des flux d'eau échangés entre ces golfes et la Mer Rouge proprement dite (C. MAILLARD, D. ANATI) et qui proviennent de déterminations récentes sont un apport intéressant de ce colloque.

Un complément important à la connaissance de l'hydrologie du Nord de la Mer Rouge a été apporté par les études de MORCOS et GERGES, MILLER et MUNNS, et SHARAF EL DIN dans le canal de Suez, d'où il ressort que le canal se comporte à la fois comme une pompe d'eau de la Mer Rouge vers la Méditerranée et comme une source de sel pour la Mer Rouge. En effet, bien qu'il semble que la couche de sel des Lacs Amers ait été entièrement dissoute, l'évaporation intense de cette région (salt barrier) crée une masse très salée qui s'écoule sur le fond.

A l'extrêmité opposée, en dépit de l'absence malheureuse de nos collègues allemands, des contributions importantes ont été apportées à la connaissance de la variabilité saisonnière des échanges avec le Golfe d'Aden par W. PATZERT (II), J. GORMAN et les textes de VAN AKEN et A.K. BOGDANOVA. Ces études, en particulier celle de W. PATZERT, ne sont pas limitées aux échanges d'eau mais aussi au bilan thermique, dont le rôle dans la climatologie de la région est prépondérant.

Il me reste maintenant l'agréable devoir de remercier les auteurs des communications, qui ont bien voulu nous communiquer le résultat de leurs travaux et les participants, qui ont alimenté les discussions.

Enfin, merci à l'UNESCO, au SCOR et à l'IAPSO qui, par les subventions accordées, ont permis le déplacement de nombreux participants étrangers.

Je déclare clos le Symposium sur l'Océanographie Physique de la Mer Rouge.

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