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Circulation and upwelling off the coast of South-East Arabia

Circulation
Upwelling
Arabian Sea
Coast of Oman
IIOE

Circulation
Remontée d'eau
Mer d'Arabie
Côte d'Oman
Océan Indien

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ABSTRACT

Observations made during the International Indian Ocean Expedition provide the basis for a description of the summer circulation in the upper 500 m of the western Arabian Sea, off the coast of Oman. Under the influence of the south-west monsoon a pronounced geostrophic current develops along at least 1 000 km off the South-East Arabian coast between Ras Fartak and Ras al Hadd in May and the strong south-westerly wind brings about offshore transport of the surface layers between 55° and 60°E. Water is upwelled onto the continental shelf from depths of about 150 m and this creates a strong negative sea-surface temperature anomaly along the coast, reaching a maximum development in July-August. With the decline of the monsoon upwelling ceases in September. The origin of the upwelled water is traced and its distribution related to the direction of the wind and coastline, and the sea-bed topography. The distribution of the water masses at the surface and intermediate depths is described. Features of the upwelling are compared with those of other upwelling regions.

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RÉSUMÉ

Circulation et upwelling de la côte sud-est d'Arabie

Les observations faites pendant la campagne internationale dans l'Océan Indien ont été utilisées pour décrire la circulation estivale dans la couche superficielle de 500 m à l'ouest de la mer d'Arabie.

Sous l'effet de la mousson du Sud-Ouest, un courant géostrophique prononcé se développe, au mois de mai, sur plus de 1 000 km, le long de la côte sud-est de l'Arabie, entre Ras Fartak et Ras al Hadd ; le fort vent du Sud-Ouest entraîne les couches superficielles vers le large entre 55° et 60° E. De l'eau en provenance de 150 m de profondeur remonte sur le plateau continental et crée, le long de la côte, une forte anomalie négative de température, maximale en juillet-août. La remontée d'eau s'arrête en septembre, à la fin de la mousson. L'eau qui remonte est suivie à partir de son origine, et sa circulation est liée à la direction du vent, à celle de la ligne de côte et à la topographie du fond. La répartition des masses d'eau est décrite au voisinage de la surface et aux profondeurs intermédiaires. Les caractéristiques de la remontée d'eau sont comparées à celles de remontées dans d'autres régions.

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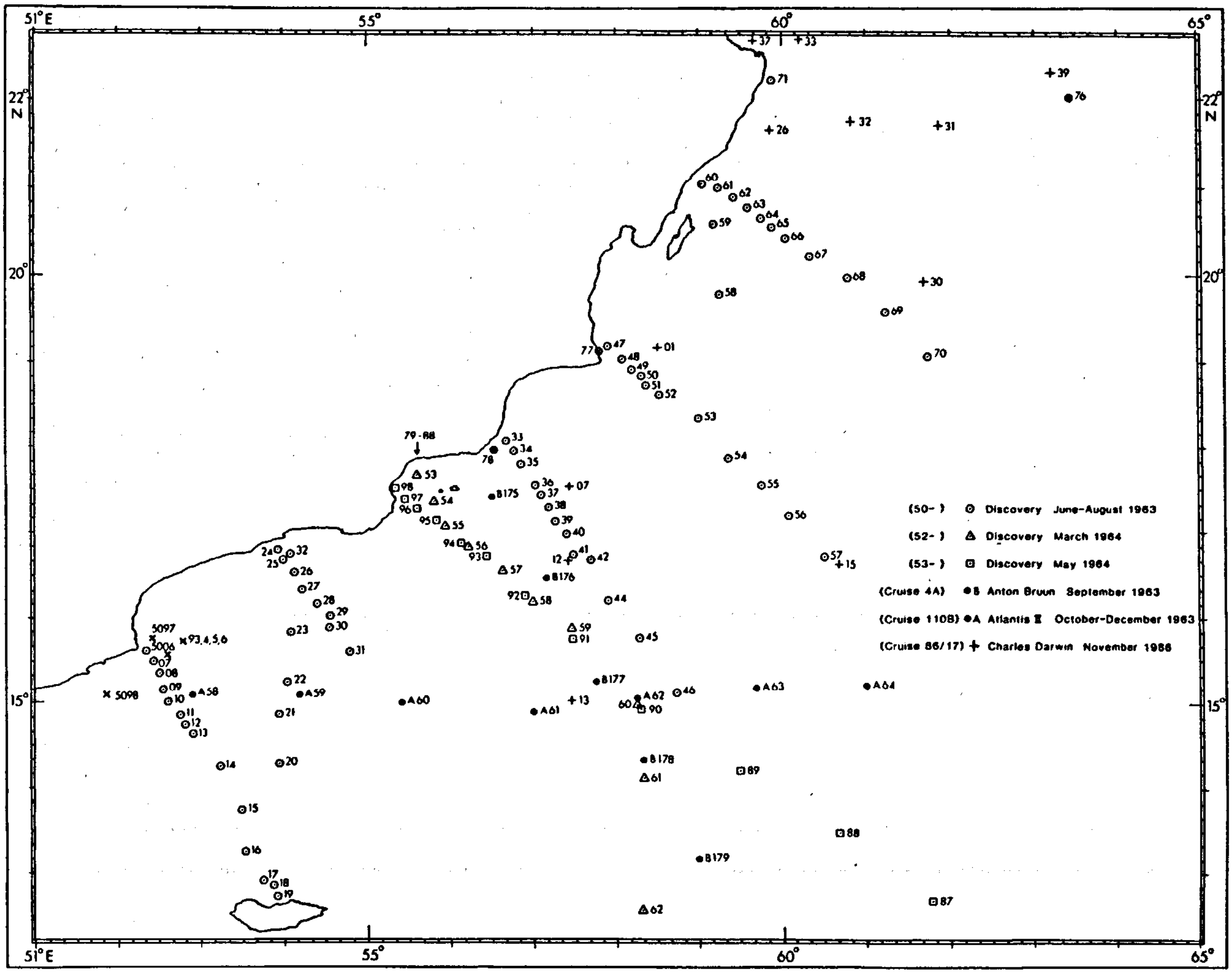


Figure 1

Positions of most of the hydrographic stations used in the present study. The positions of other stations used are given in the text.

INTRODUCTION

The extent of the south-east Arabian upwelling region has been recorded previously (Puff, 1890; Bobzin, 1922; Royal Society, 1963; Currie, 1964; 1965; Bottero, 1969; Currie *et al.*, 1973; Bruce, 1974; Smith and Bottero, 1977). The region occupies a length of nearly 1 000 km of the coast of Oman extending from Ras Fartak in the West, to Ras al Hadd at the mouth of the Gulf of Oman in the East, but the areas of most pronounced negative sea-surface temperature anomaly are found in the vicinity of the Kuria Muria islands and around Ras al Madraka.

The earlier German observations were derived from sea-surface temperature records in the log books of ships on passage through the region, held in the Deutsche Seewarte and from the Royal Netherlands Meteorological Institute monthly charts. Monthly sea-surface temperature charts were also published by the UK Meteorological office drawn on data from the years 1855-1943. None of these sources comprised any significant sub-surface observations.

During the International Indian Ocean Expedition (IIOE), however, a fairly large number of physical, chemical, and biological observations were made off the southern seaboard of Oman, most of which extend from the sea surface to the sea bed. Since the upwelling is a seasonal phenomenon associated with the south-west monsoon during the summer months, from May to October, the observations made by R.R.S *Discovery* in 1963 are of particular interest as they form a unique coverage of the area during the season of active upwelling and highest productivity. These data have been used by Smith and Bottero (1977) to compute the velocity field in the open ocean upwelling but it is felt that a broader statement of the hydrography is needed, particularly in relation to the coastal upwelling.

This paper is concerned, therefore, with presenting a fuller analysis of primarily the *Discovery 1963* data but use is made of relevant observations by other ships of the IIOE, *Vladimir Vorob'yev*, *Atlantis*, *Anton Bruun*, *Argo* and *Meteor*, and others made in more recent years. It is hoped that in view of therecent upsurge of interest in the living and non-living resources of the region, this will provide a descriptive background of strategic value. At the same time the unique character of the South-East Arabian upwelling, lying in a poleward flowing western boundary current provides an instructive comparison with the major upwelling regions on the western coasts of the continents, which occur on the coastal margins of equatorward flows of eastern boundary currents.

OBSERVATIONS

Puff (1890) identified four upwelling regions on the north-west side of the Indian Ocean: 1) the east coast of Africa from Cape Warscheik to Cape Guardafui; 2) the north and east coasts of Socotra; 3) the south-east coast of Arabia east of Ras Fartak; 4) the south-west coast of Arabia west of the Bay of Aden.

Puff, however, had very few observations from the south-east coast of Arabia. Bobzin (1922), on the other hand, used a total of 1690 ships observations held in the Deutsche Seewarte, made between the years 1906 to 1913, spread fairly evenly over the summer months. His results, summarised in his Plate 2, show the development and decay of the upwelling from May to October, reaching a peak in July and August.

The first *Discovery* cruise (Royal Society, 1963) was planned, as closely as ship time would allow, on the basis of Bobzin's work. Inevitably certain alterations and curtailments had to be made to the initial plan to accommodate exigencies of one kind or another. Five lines of stations, however, were worked normal to the coast at about 200 km intervals, varying in length up to about 400 km. The survey began on 25 June 1963, with a line of fourteen stations from Ras Fartak (56°20'E) across the Gulf of Aden to Socotra (*see* Fig. 1). Water sampling was conducted at standard depths, followed by a bathythermograph lowering to 270 m, a current-meter profile, using a direct-reading current meter (Swallow and Bruce, 1966), to 100 m and various biological observations. Underway observations between the stations consisted of continuous echo-soundings, continuous sea surface temperature recording and half-hourly bathythermograph lowerings. The second line of stations had to be shortened to about 175 km in length and ran roughly south-east from Ras Risut (54°E). The third line of stations was started on 5 July, after making a zig-zag course along the coast past the Kuria Muria Islands, at Ras Sauqara (51°41'E) and again ran roughly south-east for 400 km; it consisted of thirteen stations. The fourth line also ran south-east, commencing at Ras Madraka (57°55'E), for nearly 400 km and eleven stations were occupied. After returning to the coast the fifth section was started at Masira Island and eleven stations were worked running south-east for about 370 km. The first survey was completed at Ras al Hadd on 18 July.

The ship returned to the Arabian coast on 30 July and conducted a bathythermograph survey south-westwards from Ras Madraka to the Kuria Muria Islands where some days were spent making current measurements and undertaking detailed chemical work. Further such work was conducted off Ras Fartak following an unavoidable visit to Aden and the survey was completed on 18 August.

In October 1963, the R.V. *Anton Bruun* cruise 4A (US Program in Biology IIOE, 1965) worked six stations close to the line of the third *Discovery* section, extending from

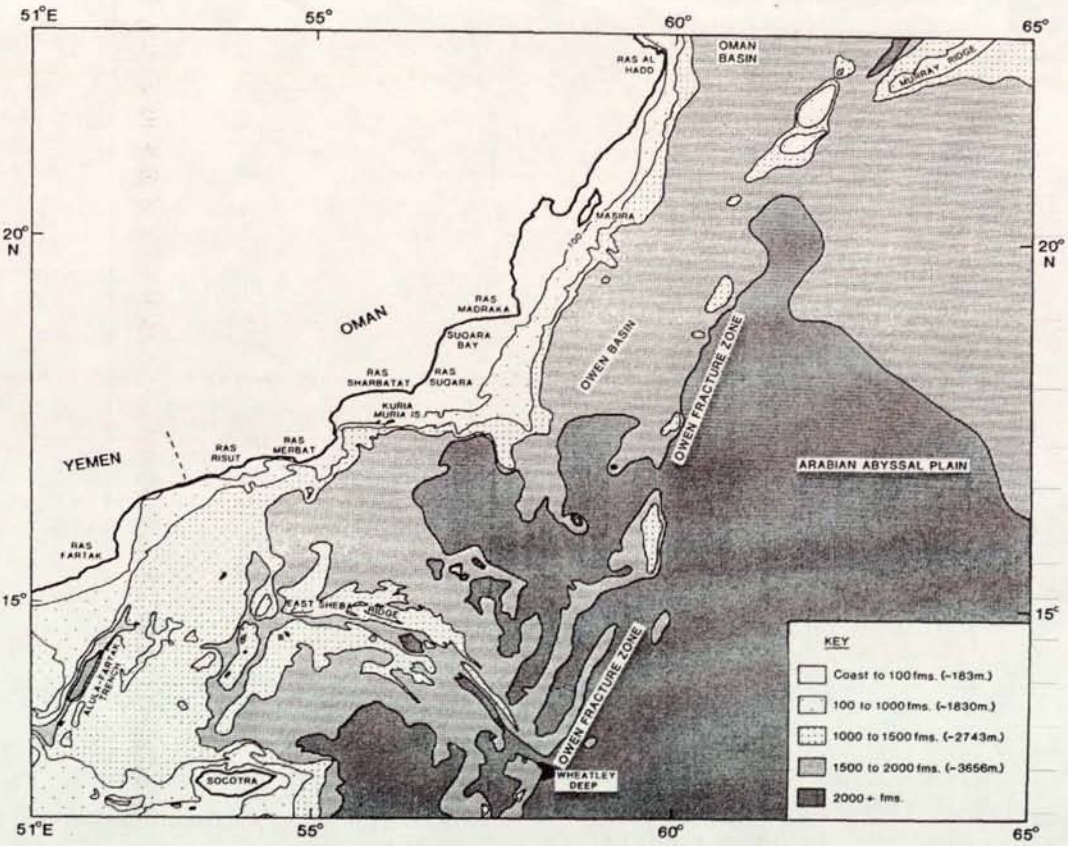


Figure 2

Bottom topography of the North-West Arabian Sea, simplified from the National Institute of Oceanography chart of the Gulf of Aden, prepared by A.S. Laughton et al. *(1970) and a contour chart prepared by the late Cdr. R.G. Nesbitt, R.N. based on available soundings in 1963.*

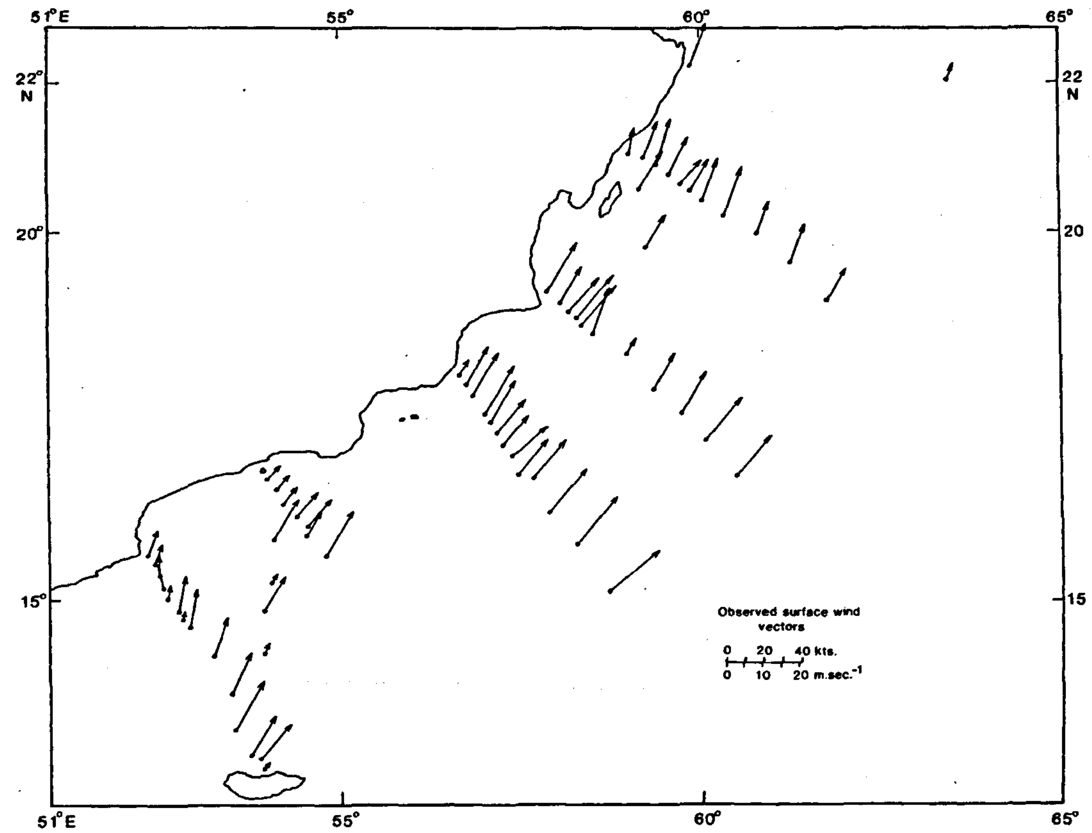


Figure 3 *a*

Surface wind vectors recorded at hydrographic stations on the Discovery 1963 *survey. Wind velocities are indicated by the length of the arrows according to the scale given.*

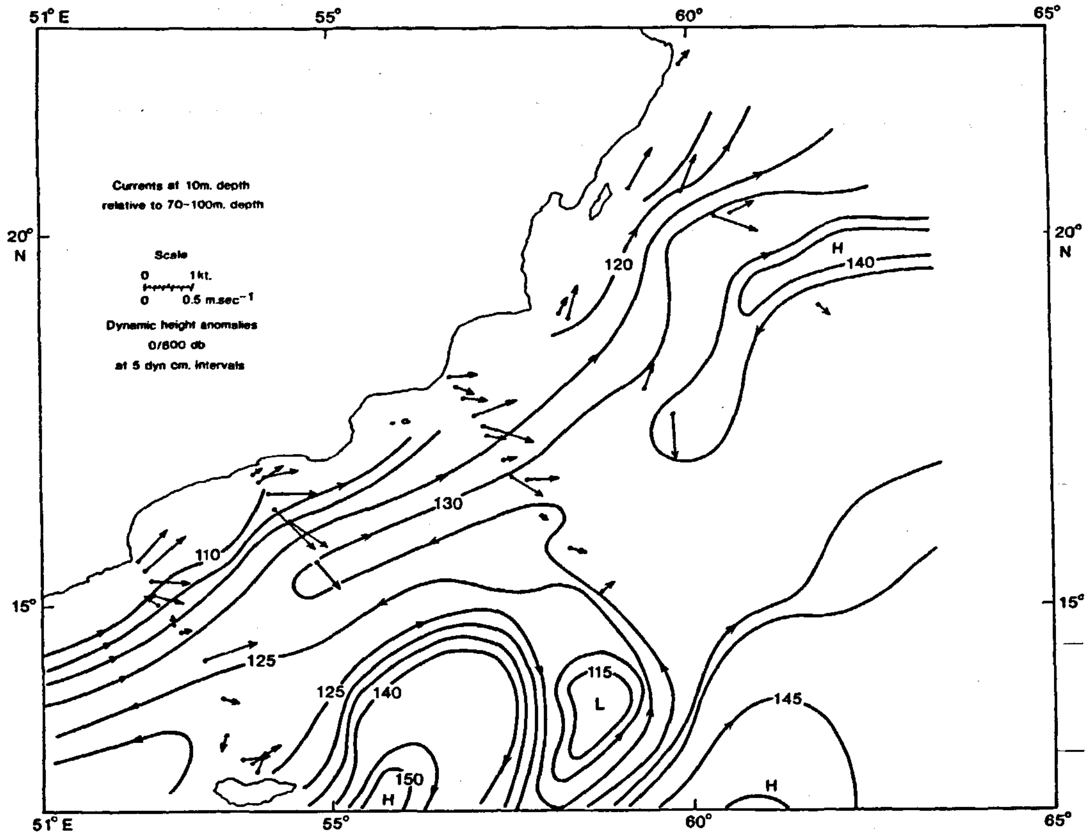


Figure 3 *b*

Sea surface currents at 10 m relative to 70-100 m depth from the Discovery 1963 *survey. The length of arrow represents the current velocity. The topography of the sea surface, relative to the 800 db surface is copied to the Mercator projection from Düing's (1970) chart and is given in dynamic centimetres.*

the coast to 12°15'N, 59°42'E. At about the same time (October-December) the R.V. *Atlantis II* worked some stations eastwards from the Gulf of Aden along approximately 15°N to the coast of India (data from NODC Washington).

The second *Discovery* cruise (Royal Society, 1965) provided an opportunity to repeat observations close to the third 1963 section, in March and May, 1964 when eight or nine stations were worked on each occasion.

Observations during the North-East (winter) monsoon period which have been used for comparison or amplification were made by the *Vladimir Vorob'ev* in 1961 (Seryi and Khimitsa, 1963), F.S. *Meteor* in 1965 (Koske, 1972) and by the R.R.V. *Charles Darwin* in 1986 (Shimmield *et al.*, 1988). The *Vladimir Vorob'ev* worked four lines of stations to 750 m depth, one across the Gulf of Aden (4 stations), one from Ras Fartak to Socotra (5), one south-east from Ras Sauqara (5) and one east from Masira Island (4) on course to Bombay. The F.S. *Meteor* conducted a survey of the Persian Gulf with about twenty-two stations in the Gulf of Oman and the R.R.V. *Charles Darwin* worked sixteen hydrographic stations to the east of 57°E.

A chart of most of the stations used in this paper is given in Figure 1. The positions of other stations used is given in the text.

BOTTOM TOPOGRAPHY

To understand the bottom topography of the waters off the Oman coast, it is helpful to look at the main structural features of the region. Oman lies on the eastern corner of the Arabian Plate which extends east to the Owen Fracture Zone, a line of displacement across the mid-Indian Ocean ridge. The branch of that ridge running north-west over the Arabian Sea, the Carlsberg ridge, is displaced about 200 miles northwards along the fracture and continues west as the Sheba ridge into the Gulf of Aden. The Sheba ridge forms the boundary between the Arabian and African plates and lies axially in the Gulf of Aden where it is broken by a number of lateral fracture zones lying more or less parallel to the Owen Fracture Zone. The principal feature is a deep trench from Cape Guardafui to Ras Fartak, the Alula Fartak Trench, with a maximum depth of 5 360 m (Laughton *et al.*, 1970).

The basin off Oman (Fig. 2) is thus somewhat isolated at a depth of 2 000-3 000 m from the abyssal plains of the northern Indian Ocean by the Sheba ridge and the Owen Fracture Zone which continues north-east towards the Indian continent as the Murray ridge. This southern extension of the Oman Basin, the Owen Basin, is some 160- 320 km wide, about 1 000 km long, and some 3 000-4 000 m deep. East of the Owen Fracture Zone the abyssal plain descends from the Indus Fan to the Carlsberg ridge at about 4 500 m.

The south-east coast of Arabia eastwards from Aden runs roughly 65°T as far as 55°E then becomes more northerly orientated to 30°T to Ras al Hadd. The Oman coast east of 55°E evidently closely follows the line of a late Palaeozoic axis (the Huqf axis) and the shelf and shelf break are characterised by younger downfaulted blocks (Clarke, 1988).

The principal features of the coast are a series of prominent headlands - Ras Fartak (52°25'E), Merbat (55°E), Ras Sharbatat (56°20'E), Ras Madraka (57°50'E) and Masira (58°30'E). In the vicinity of these promontories the shelf is generally very narrow and the continental slope particularly steep. In the embayments between them, however, the shelf extends some 25-80 km offshore. The main areas of shelf lie between the Kuria Muria islands and Ras Madraka, and north and south of Masira Island.

The continental slope is particularly steep south of the Kuria Muria islands where from the shelf break it drops at a dip of about 35° to depths of 3 000 m. East of Ras Sharbatat there is a large promontory of the continental shelf which forms a major underwater feature of the coast. Shimmield *et al.* (1988) report the occurrence of a number of small silled intrashelf basins south of Masira, with accumulations of diatomaceous ooze and have evidence of current scour on the outer shelf.

METEOROLOGY

There is an extensive literature on the monsoon regime over the Indian Ocean, not the least because of its profound climatological consequences for the countries bordering the ocean. This is particularly true in the northern part of the ocean, the Bay of Bengal and the Arabian Sea.

The uniqueness of the alternating six-monthly change in wind direction and its resultant effects attracted particular attention during the IIOE and gave an impetus, albeit in a somewhat opportunistic manner, to the collection of data which had hitherto been scanty.

Ramage (1969) summarised the annual sequence of events as they are now seen: during the winter months in the Arabian Sea (November to April) northerly or north- easterly winds flow out from the continental anticyclone and the sea surface loses more heat to these cool dry northerlies than it gains by radiation through near cloudless skies. This cooling reaches a maximum in December and as the monsoon weakens, sea-surface and air temperatures equilibrate and the net heat gain to the sea surface rises, reaching a maximum in April. As the south-west monsoon develops, a tropical maritime air flow is established over the Arabian Sea, increasing in strength as continental air pressure over Arabia and India decreases, to a peak in July and August but the increased amount of cloud counteracts solar heating and can lead to more heat loss from the sea surface in August than in any other month. After mid-September the south-westerly winds become weaker until the continental high pressure is re-established.

Against this background, the surface winds observed at the stations on the *Discovery 1963* survey (Fig. 3 *a*) do not depart significantly from the mean situation in these months and emphasise the strength and constancy of the wind over the area. Close to the coast, however, there was a tendency to more variability and the atmospheric conditions typical of upwelling regions - cool, humid, misty or even foggy airs were frequently encountered. In the region west of Merbat (55°E) the wind in the coastal region was weak and mainly onshore, whereas east of Merbat it was consistently longshore and of much greater strength. This difference will be seen to play an important part in relation to the upwelling (p. 57).

CURRENTS

Prior to the IIOE, our knowledge of the current systems of the Indian Ocean was based on observations of ship's drift and several maritime nations had prepared and published current charts for the use of navigators. The most detailed are those published by the Royal Netherlands Meteorological Institute (Koninklijk Netherlands Meteorologisch Instituut, 1952). Such charts show the general features of the monsoonal circulation but the sparsity of data and scale of presentation precludes much detailed analysis although some smaller-scale features do become apparent. However, the observations generally spanned periods of several years and show the mean currents from which it is possible to see how far observations in any one year deviate from the mean.

Swallow and Bruce (1966), reported on direct current measurements and geostrophic calculations of currents off the Somali coast in the summer of 1964 and described the anticyclonic nature of the path of the Somali current, diverging from the African coast in about 9°N and flowing east to at least 55°E and then south. To the north of this gyre, they produced strong evidence of another anticyclonic circulation immediately south of Socotra. Their observations did not, however, extend beyond 55°E.

Wooster *et al.* (1967), replotted data for each month from the Royal Netherlands Meteorological Institute charts, in two-degree quadrangles, which indicated that in July a continuous north-easterly flow is present from the Somali region to the mouth of the Gulf of Oman, parallel to the South-East Arabian coast.

Düing (1970), used the IIOE hydrographic observations to study the dynamic topography of the sea surface and describe the monsoonal circulation and its underlying mechanisms. Data from a number of years had to be used, but in the Arabian Sea he was able to base his analysis on the period July to September, 1963, including the *Discovery 1963* observations. He revealed a greater complexity than hitherto supposed; instead of the large-scale gyres characteristic of the North Atlantic and North Pacific Oceans, there was a complex pattern of anticyclonic and cyclonic circulations centred around high and low areas of sea-surface topography.

Düing's chart of the Arabian Sea for the summer of 1963 is of particular interest. East of Africa and towards India, and relative to reference levels at 200 and 800 db, there is a series of cells of alternately high and low dynamic height aligned on roughly south-west to north-east axes. The first of these, east of Socotra, is a high with an associated anticyclonic circulation between Socotra and the south Arabian coast. The slope of the sea surface along the Arabian coast, the geostrophic current, more or less follows the direction of the coast (Fig. 3 *b*).

The identity of the two distinct anticyclonic circulations south of Socotra observed by Swallow and Bruce (1966) in 1964 is not evident in Düing's chart of 1963 but this may merely be a shortcoming of the station coverage at his disposal. Alternatively, it may not have been present in 1963. During the *Discovery 1963* survey, both indirect and direct current measurements were made. The observations and preliminary results were reported on briefly in the report of the cruise (Royal Society, 1963).

Surface current vectors were determined on 81 occasions from discrepancies between dead reckoning and observed positions, allowing for leeway using a factor determined by current meter observations with the ship lying-to. These observations showed a considerable degree of scatter, but a distinct dominance of north-easterly flow in the vicinity of the coast with eddies evident near Kuria Muria Bay and off Ras Madraka.

Offshore, there was a clear tendency to a south-easterly or even more southerly flow, but again with a great degree of variability.

Vertical profiles of relative currents were made on 70 positions, using direct-reading current meters, generally to 100 m but some to 200 m depth. The currents at 10 m relative to those at 70-100 m have been plotted in Figure 3 *b* and show a similar pattern to the surface currents with a dominantly north-easterly flow at the coast but, by contrast with the surface currents, less of a southerly component offshore. For comparison, the dynamic height anomalies at 0 db relative to 800 db , computed by Düing (1970), have been included in the figure. Bottero (1969) and Smith and Bottero (1977) also computed the absolute dynamic topography of the 100 and 300 db surfaces and found good agreement with those computed by Düing. Conclusions about water movements from an analysis of dynamic topography, however, are subject to the implicit assumptions in the method and thus have to be treated with caution where conditions depart from a steady state and in particular where wind drift and vertical movements may play a significant role in the circulation. This probably accounts, at least in part, for the discrepancies between the observed relative currents and those expected on geostrophic grounds.

Where it was possible to measure currents in relation to an anchored buoy, or where accurate radar fixes on the land could be obtained, the currents at about 75 to 100 m depth near the coast show a distinct flow towards the coast. A few measurements, generally made with neutrally buoyant floats, at about 200-300 m depth were generally weak and towards the coast. On three occasions they were opposed to the surface current direction.

OBSERVED DISTRIBUTION OF TEMPERATURE AND SALINITY, *DISCOVERY 1963*

The horizontal distribution of sea surface temperature (Fig. 4 *a*) shows a tongue of warm water extending eastwards from the Gulf of Aden. Inshore of this, the development of an area of progressively colder water is evident, particularly marked east of Ras Merbat. A fairly large eddy is evident east of Sauqara Bay, perhaps associated with the easterly promontory of the continental shelf, from the Kuria Muria Islands (*see* Fig. 2).

The repetition of the survey between Ras Madraka and the Kuria Muria islands, some two weeks later and in somewhat greater detail (Fig. 5), indicates an even smaller scale, of the order of 50 km, in the pattern of eddies of water movement in this area.

Further offshore, there is a general, if rather irregular, rise of surface temperature towards the central and eastern Arabian Sea.

Sea-surface temperature is, of course, subject to many influences, radiation balance, evaporation, mixing and advection. On the short time scale of these surveys, with predominantly overcast and humid weather, it seems unlikely that variations in radiation balance and evaporation played a major role in determining the sea-surface temperature and it is quite clear that the depression of the sea-surface temperature along the coast is associated with the vertical advection of cooler, deeper water to the surface.

On a number of occasions, sharp fronts associated with very sudden changes of sea-surface temperature over short

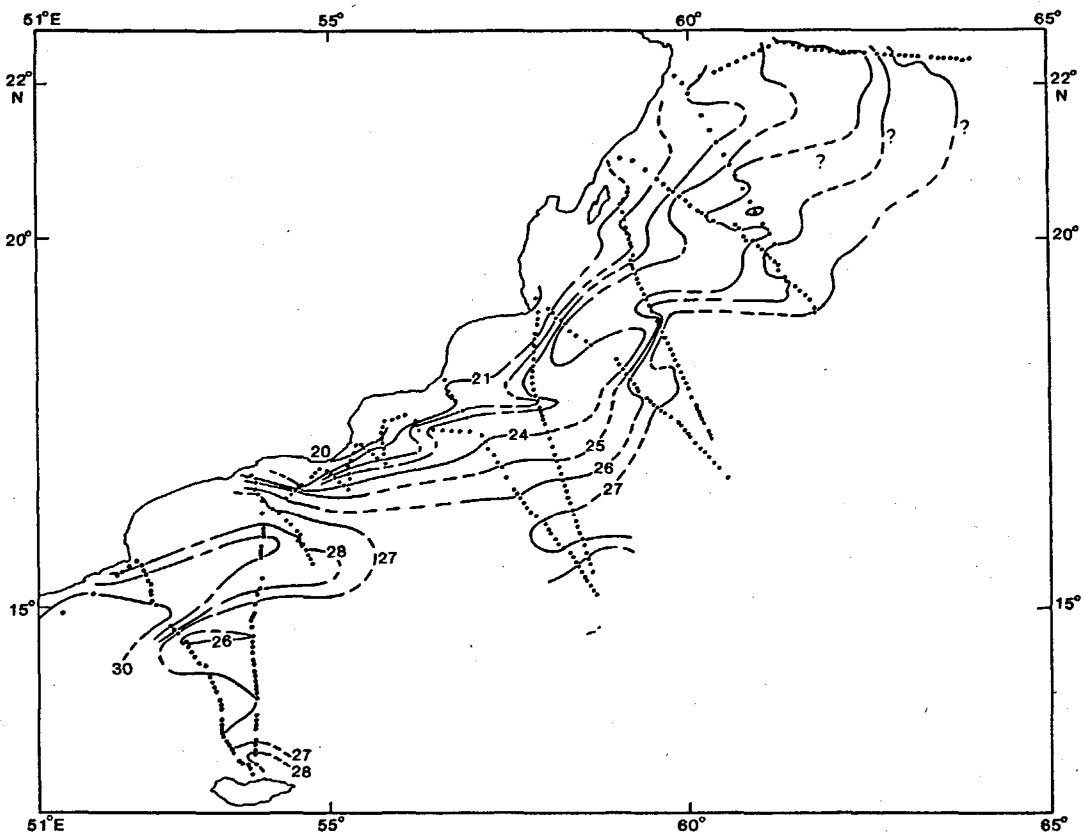


Figure 4 *a*

Sea surface temperature (°C) recorded by bathythermograph and distant reading thermograph during the Discovery 1963 *survey. The isotherms are shown as broken lines where the contouring is uncertain.*

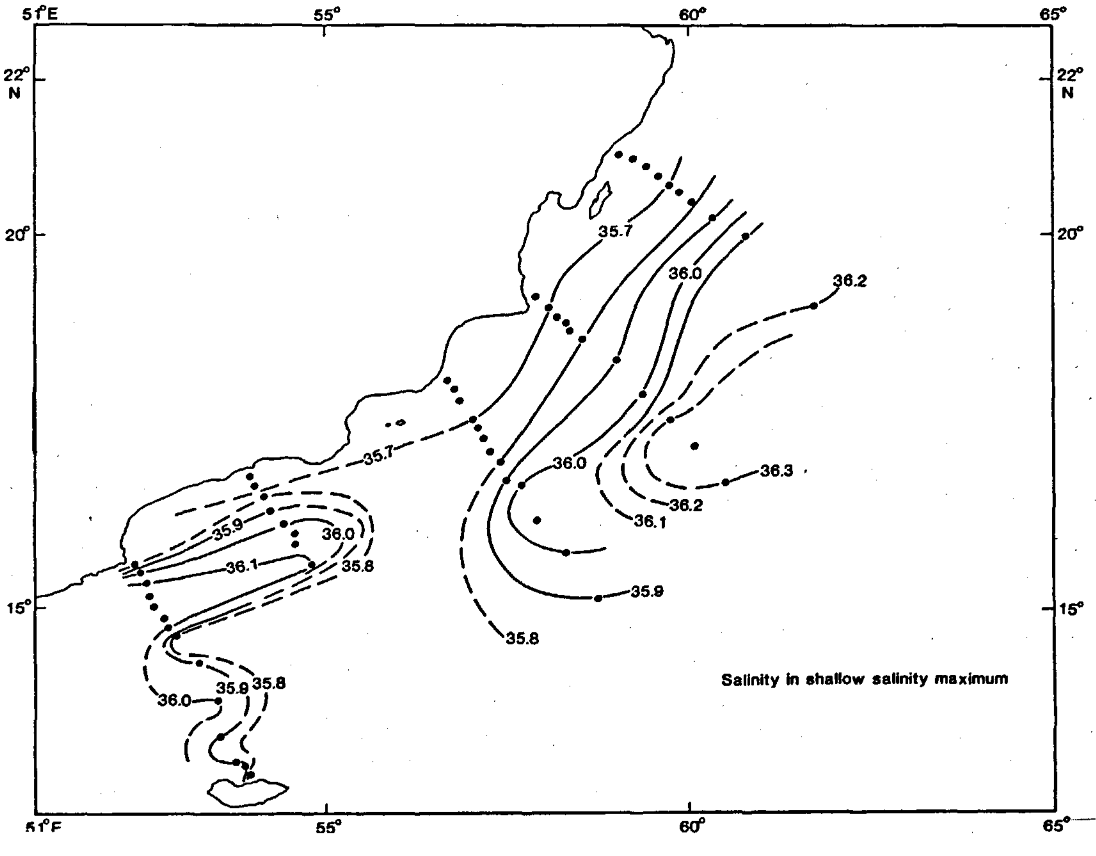


Figure 4 *b*

Horizontal distribution of salinity in the shallow salinity maximum during the Discovery 1963 *survey.*

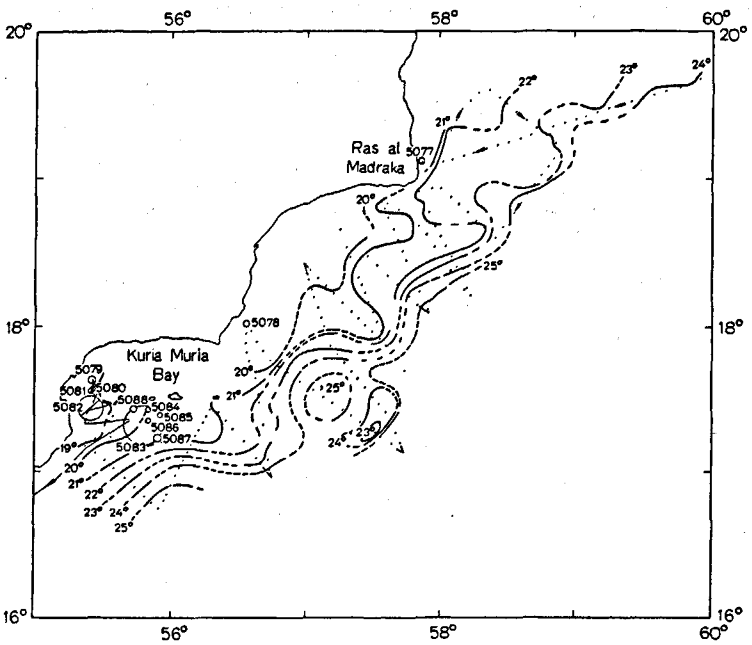
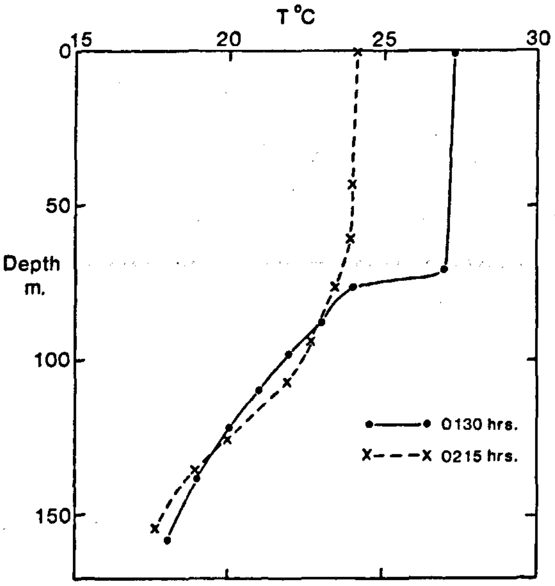


Figure 5

Sea surface temperature (°C) recorded by bathythermograph during the Discovery 1963 *survey on passage between Ras Madraka and the Kuria Muria islands, 30 July to 7 August.*

Figure 6

Bathythermograph records on either side of the front encountered between station 5057 and Masira Island. The two records were separated by a distance of about 6 km.



distances were encountered, particularly south of Masira island (Fig. 6), where a well mixed warm surface layer underlain by a strong discontinuity lay adjacent to cooler coastal water without any marked thermocline. The potential convection between these two upper layers over a distance of only four miles emphasises the dynamic nature of the circulation.

Salinity observations were restricted to those made on station positions and therefore much less detail of its distribution can be resolved. The salinity in the upper layer of maximum salinity has been plotted (Fig. 4 *b*) in preference to the surface salinity, as in the eastern Arabian Sea the salinity maximum tends to occur at sub- surface depths and its distribution is obscured at the surface. The wide separation of the lines of stations makes the contouring of the isohalines somewhat uncertain, but the distribution broadly reflects the distribution of sea-surface temperature with high salinities associated with the warmer surface waters.

Vertical distribution of properties

Temperature and salinity profiles for the five lines of stations on the *Discovery 1963* survey are shown in Figures 7 *a* to 7 *e*, progressing from west to east. The profiles are drawn, with the Arabian coast on the left, to a depth of 500 m since we are concerned primarily with the upper layer circulation.

Section I (Ras Fartak to Socotra, Fig. 7 a)

The tongue of warm water extending east from the Gulf of Aden which was evident in the sea-surface temperature chart (*see* Fig. 4 *a*) is characterised by comparatively high salinity > 36.1 and by a mixed layer deepening to about 30 m offshore. Close to the Arabian coast both the isotherms and isohalines rise from depths of about 100 m to the surface. Cooler and less saline water occurs in the upper layers in the middle of the section while both temperature and salinity again increase towards Socotra. At intermediate depths the section is occupied by water of salinity between 35.6 and 35.7.

Section II (Ras Risut, Fig. 7 b*)*

It appears that the outermost stations lay in the warm saline tongue from the Gulf of Aden. Closer to the coast, however, cooler and less saline water was present beneath a very thin warm surface layer and the isoline patterns are again indicative of uplift from deeper layers towards the coast. As in section I, the intermediate depths were largely occupied by water of salinities between 35.6 and 35.7.

Section III (Ras Sauqara, Fig. 7 c*)*

Lying to the east of the Kuria Muria islands, this third section traversed the area of broadening continental shelf. Inshore surface temperatures below 20°C were found, equivalent to the temperature at 100 m depth some 150 km offshore. Offshore, the warm, high salinity water in the upper layers is probably a westward extension of the warm, more saline waters of the upper layer of the north-eastern Arabian Sea, since except at the surface it has a significantly different T-S relationship from the Gulf of Aden water (Fig. 8). Indeed, there is reason to suggest a north-south continuity of cooler and less saline water between the coast and equatorial region to the south. Again in the intermediate layers, there is a uniformity of salinity between 35.6 and 35.7 but between 150 and 200 km offshore an intrusion of more saline water > 35.8 is evident.

Section IV (Ras Madraka, Fig. 7 d*)*

The warm, high salinity surface layer across this section is well developed, extending between 100 and 400 km from the coast, while inshore some of the coolest surface waters encountered on the survey, < 19°C, were found at the station closest to the coast (5 047). At intermediate depths, salinities are generally higher than on section III, largely between 35.7 and 35.8.

Section V (Masira Island, Fig. 7 e*)*

The offshore high salinity layer in this section is overlain by lower salinity water, generally about or less than 36.0, and between 200-400 km offshore the salinity maximum occurs at about 100 m depth. The lower salinity water is also significantly cooler, < 26°C, indicating that it arises from offshore transport and mixing of upwelled water. The inshore part of this section in the upper layers is extremely confused, with alternating parcels of higher and lower salinity waters and at intermediate depths there is an overall increase of salinity over that at comparable depths on section IV although low salinities persist close to the continental slope.

WATER MASSES

Rochford (1964) described five salinity maxima in the north Indian Ocean, to three, possibly four, of which he ascribed origins in the Arabian Sea. Warren *et al.* (1966) discussed the water masses of the Somali basin in some detail, while Wyrtki (1971) in the Indian Ocean Atlas drew conclusions about the spread of core layers from the wide collection of IIOE and earlier data covering the whole Indian Ocean. These authors show broad agreement on the general characteristics of the water masses of the Arabian Sea although the interpretation of the precise origin of some still remains open to question.

Wooster *et al.* (1967) plotted distributions of properties from mainly IIOE data, on various surfaces across the whole Arabian Sea and their charts form a useful background to the interpretation of the *Discovery* data.

Surface waters

The structure of the surface layer of the Arabian Sea during the 1963 survey has been seen in the distribution of surface temperature (*see* Fig. 4 *a*) and the salinity in the upper layer of maximum salinity (*see* Fig. 4 *b*).

Two areas of high salinity were evident, one extending east from the Gulf of Aden and the other occupying the eastern part of the area covered by the observations. The latter appears to extend across to the western coast of India (Wooster *et al.*, 1967). Seryi and Khimitsa (1963) designated these two high salinity water masses as the Aden surface water and the North Arabian surface water. Between the two and extending along the Arabian coast, salinities and temperatures are lower and exhibit the characteristics of the water at intermediate depths.

The characteristics of the surface layer of the Gulf of Aden are best seen (Fig. 8) at *Discovery* station 5 566 (13°07.8'N, 50°21.2'E). The surface was very warm > 29.9°C and highly saline > 36.4. There is an almost linear decrease in the temperature-salinity relationship from the surface to the salinity minimum of the sub-surface water, with a thermocline at about 70 m. This layer is evident on the *Discovery 1963* sections I and II. The absence of stations in the area between 55° and 57°E makes it difficult to say how far it extended to the east but it does not occur at Atlantis station.

The higher salinity water in the upper 100 m or so in the eastern part of the area surveyed (Fig. 8, station 5 070) has similar characteristics to the Gulf of Aden surface water but it is cooler and more saline and clearly associated with the area of high salinity extending southward, across the eastern and central parts of the Arabian Sea, shown to be present both at the surface and on the δt 300 surface by Wooster *et al.* (1967). This appears to correspond with Rochford's (1964) salinity maximum "D", the origin of which is ascribed to the excess of evaporation over precipi tation in the North- East Arabian Sea.

On *Discovery* sections III, IV and V, the salinity maximum is overlain on the coastal side by water of somewhat lower salinity and the inflexion of the isohalines at about 200 km from the coast suggests this is a result of offshore transport of upwelled water at the surface.

To the south of the area surveyed there is a reduction of salinity in the surface layer towards the equator which appears to be associated with a westward intrusion of low salinity water along the equator from the south of India (Warren *et al.*, 1966; Wyrtki, 1971).

There is also a decrease of salinity towards the coast and the horizontal temperature-salinity relationship at 50 m depth shows reasonably close similarity to the vertical temperature-salinity relationship at the stations about 100 km from the coast, suggesting that close to the coast, the temperature-salinity characteristics are largely determined by divergence of the sub-surface layers rising along surfaces of equal density (Fig. 9).

Intermediate layers

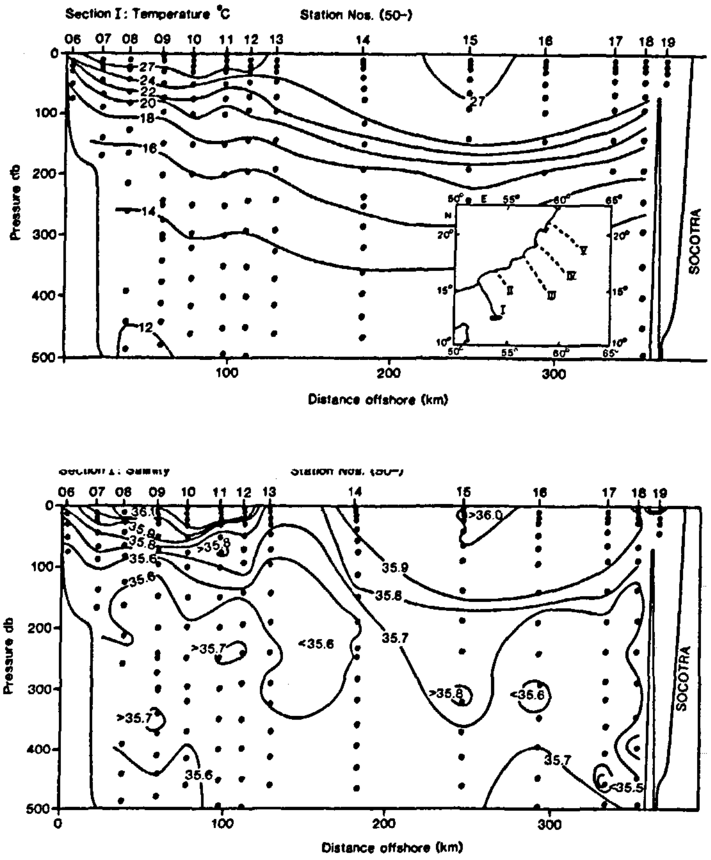
Beneath the surface 100 m or so, the water is characterised by a number of salinity minima lying between the more saline waters of the surface layer and the more saline waters associated with the outflows from the Gulf of Oman and the Red Sea. The occurrence of these minima tends to be erratic in depth and often more than one minimum is found: Warren *et al.* (1966) described a similar situation in the Somali basin as "disorderly". Three minima in particular, however, show some continuity in distribution.

The upper one spans a range of densities but seems most marked at a density of about σt 25.7 (Fig. 10) and appears to overlie the salinity maximum ascribed to the Gulf of Oman outflow and underlie the North Arabian Surface Water; it shows a west to east increase in salinity. It was not recorded at station 5 556 close to the Somali coast and the 15°N Atlantis section suggests that its main North-South continuity occurs around 57°E.

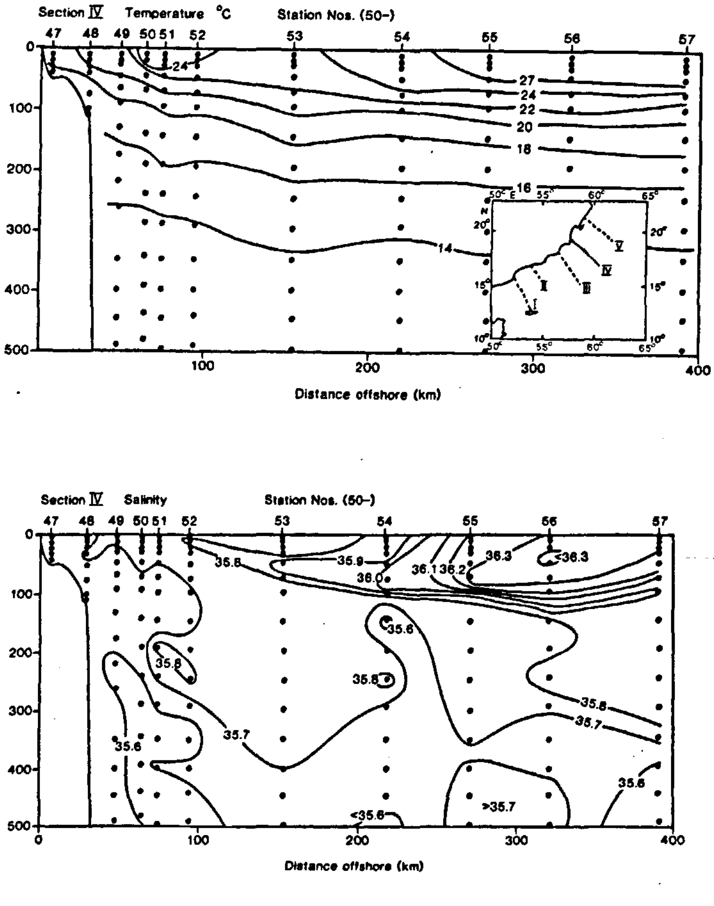
The next minimum is most pronounced in the south west of the area surveyed (Fig. 11) and occurs on the σt26.6-26.7 surface. On section I, north of Socotra it is only identifiable at stations 5 013 and 5 016 with salinities about 35.6 but south of Socotra and between Socotra and the African coast it is well developed. At *Discovery* station 5 556 (10°54.9'N, 51°48'E) there is an extensive minimum < 35.2 at 140 m depth. It does not appear at Atlantis station 61 but is very marked in the Gulf of Aden at the SCOR/UNESCO reference station 12 (*Discovery* station 5566) where it was recorded at a depth of 300 m on the σt 26.6 surface. It appears to correspond with the water type defined by Neumann and McGill (1961) as Gulf of Aden sub-surface water, with a temperature of 14.5°C and salinity of 35.5, a definition accepted by Van Aken and Otto (1974) at their stations close to the straits of Bab el Mandeb at a depth of about 200-300 m. It thus appears that the main continuity in this layer between the Gulf of Aden and the Arabian Sea lies through the channel between the Somali coast and Socotra rather than to the east and north of Socotra. The sill depth in this channel is about 1000 m (*see* Fig. 2).

The third minimum at a density of about 27.0 σt lies immediately above the salinity maximum of the Red Sea water and is widespread, and identifiable on all sections, mainly at the stations furthest from the coast. It is also well marked across section I and to the south of Socotra but not in the Gulf of Aden. It can be traced southwards beyond the equator in 60°E at the Anton Bruun stations 145-149.

Warren *et al.* (1966) discussed at some length the origins of the low salinity water in the Somali basin. Following their reasoning there appear to be three possible sources of low salinity water in the Arabian Sea: 1) low salinity



a



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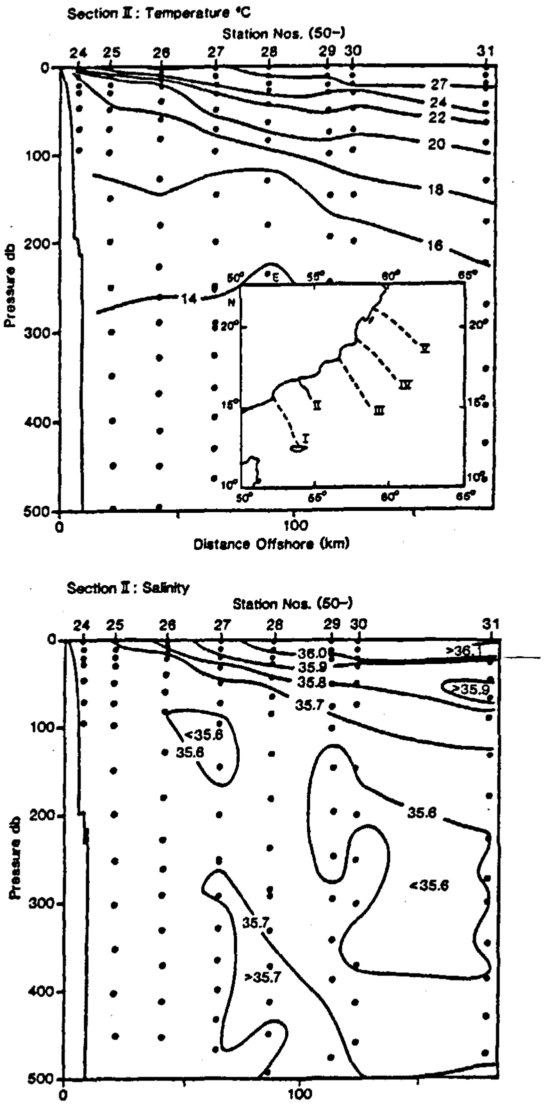
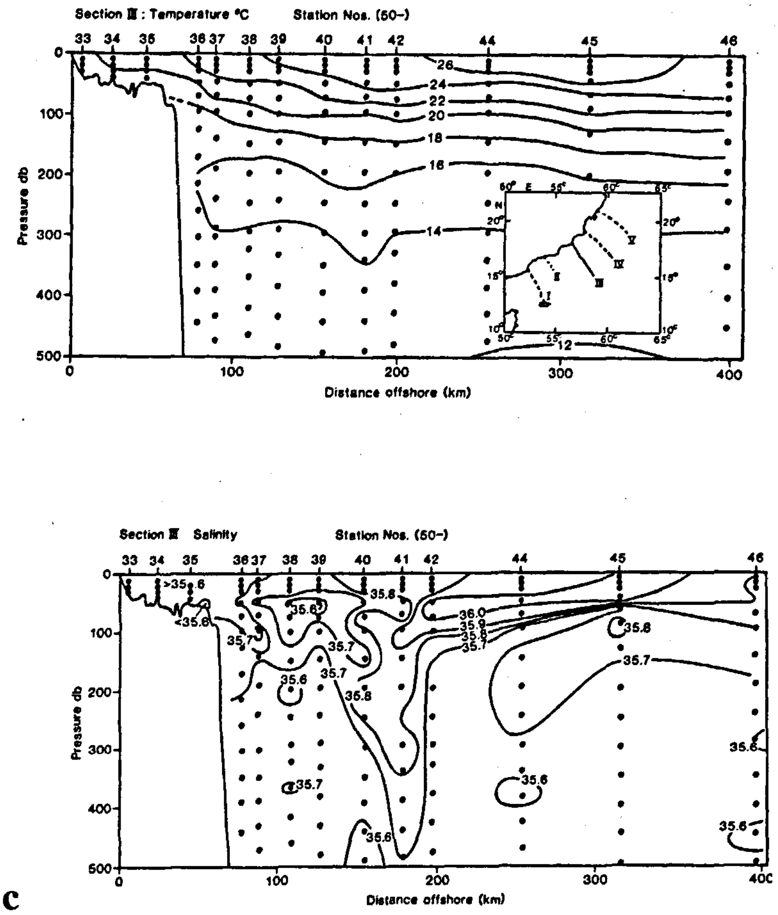
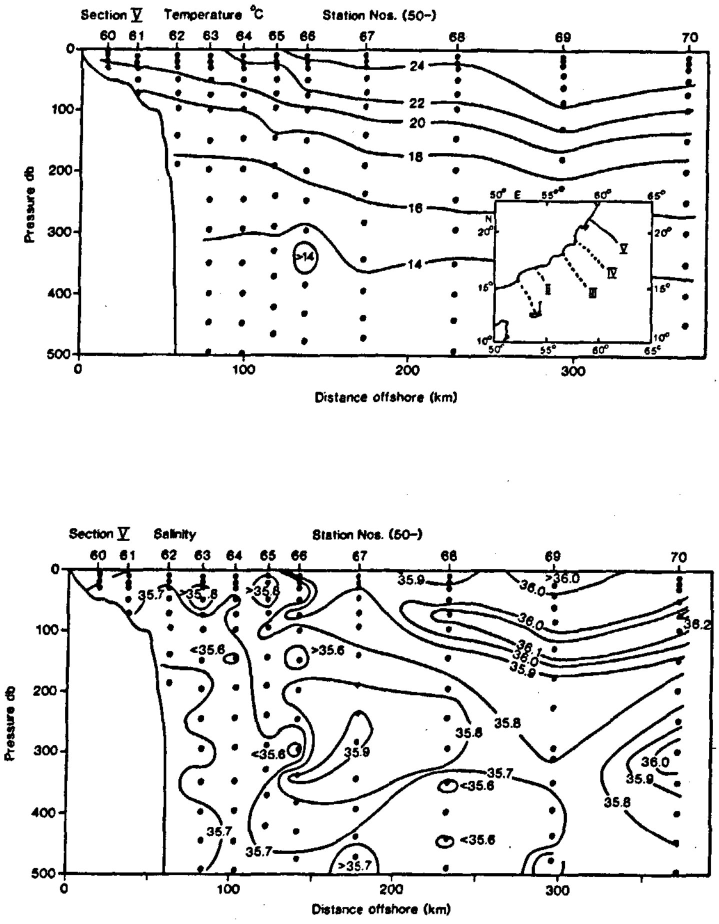


b



c



e

Figure 7

a: Discovery 1963 *section I: vertical distribution of temperature and salinity.*

b:*Section II.*

c: *Section III.*

d: *Section IV.*

e: *Section V.*

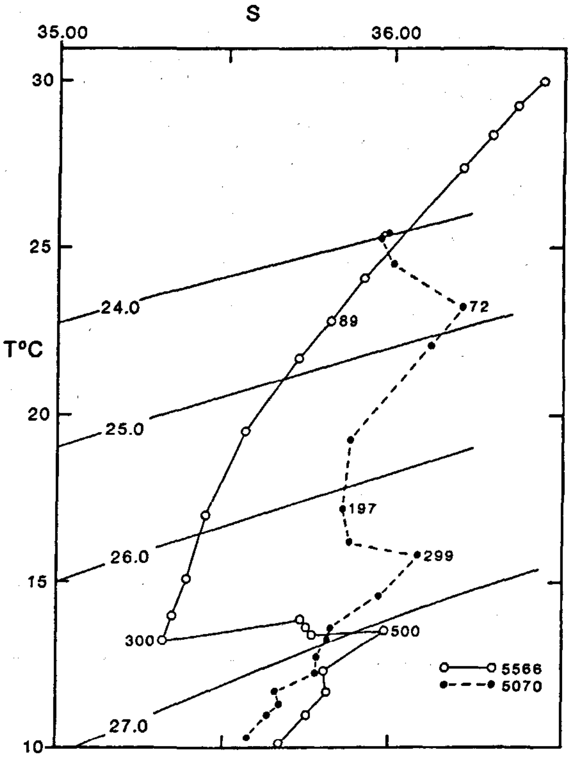


Figure 8

Temperature-salinity relationships of the Gulf of Aden and north-east Arabian Sea upper layers (see Fig. 11 for location of station 5566).

water originating from the Bay of Bengal and eastern equatorial Indian Ocean, carried westwards in the South Equatorial Current; 2) Subtropical Subsurface Water flowing northwards across the equator from the southern Indian Ocean; 3) the Antarctic Intermediate Water.

The shallowest salinity minimum is of greatest interest in the present paper since, as will be shown later, it occupies the depths from which upwelling takes place. The most likely source of this seems to be in the equatorial Indian Ocean water.

Warren *et al.* (1966) did not differentiate salinity minima at 26.6-26.7 σt and 27.0 σt in the Somali basin. They pointed to an anomaly in the Indian Ocean by comparison, for example, with the Atlantic Ocean, in that, while Antarctic Intermediate Water sinking at the Antarctic Convergence in the Indian Ocean is characterised by the lowest salinity minimum as in the Atlantic Ocean, it is not, as in the Atlantic, accompanied by the highest mid-water oxygen content; indeed the latter lies significantly shallower in the Subtropical Subsurface Water. It is evidently formed by sinking along surfaces of equal density in the region of the Subtropical Convergence about 40°S latitude. The coincidence of the salinity minimum and oxygen maximum in the Somali basin led them to conclude that the water mass is identified with the northward transport of Subtropical Subsurface Water, rather than Antarctic Intermediate Water.

Clearly the upper minimum (26.6-26.7 σt) in the present observations is identifiable with the Subtropical Subsurface Water, but although the characteristics of the deeper minimum would be consistent with those of Antarctic Intermediate Water there is no associated lower oxygen content which would be expected from that origin.

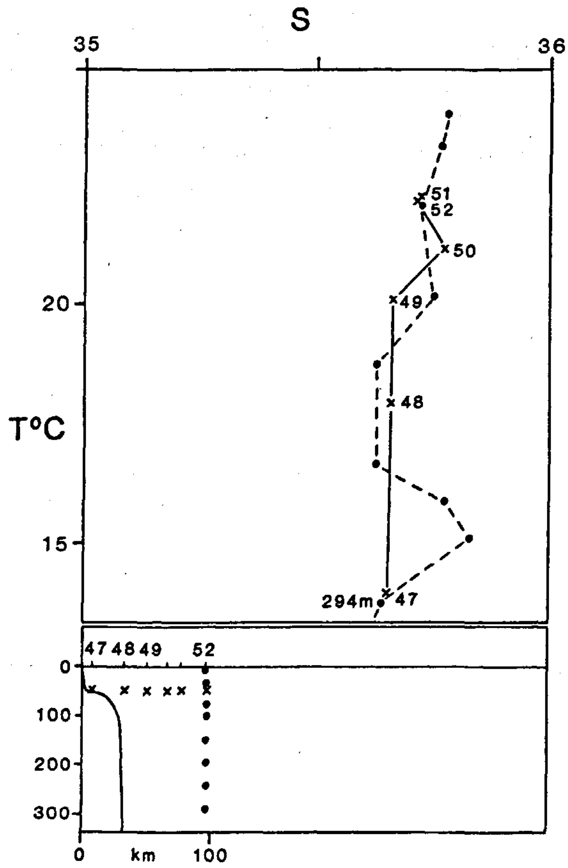


Figure 9

Horizontal and vertical temperature-salinity relationships on section IV. The vertical T-S curve is for station 5 052 and the horizontal curve is at a depth of 50 m at stations 5 047 to 5 052. The positions of the stations on the section is shown in the lower part of the figure.

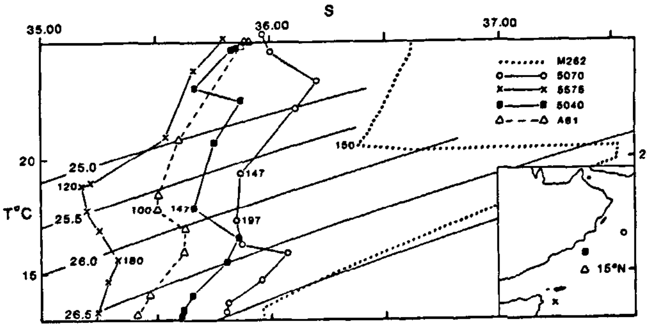


Figure 10

Temperature-salinity relationships in the shallow salinity minimum on the 25.7 σ_t surface. The salinity maximum of the Persian Gulf water is identifiable on the 26.6 σ_t surface. The inset shows the station positions.

Persian Gulf water

The observations made by F.S. *Meteor* in the Gulf of Oman in March 1965 (Koske, 1972) give the best indication of the nature of the outflow from the Persian Gulf. At their station 262 (Fig. 10), the salinity maximum had a tempera-

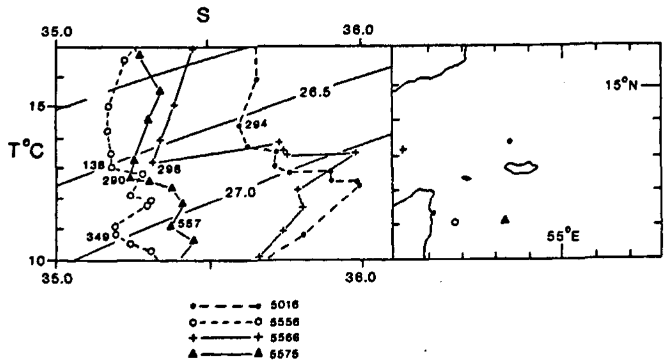


Figure 11

Temperature-salinity relationships in the intermediate and deep salinity minima on the 26.6 and 27.0 σ_t surfaces. The Red Sea salinity maximum at about 27.2 σ_t is also present but rather variable in density at this selection of stations. The inset shows the station positions.

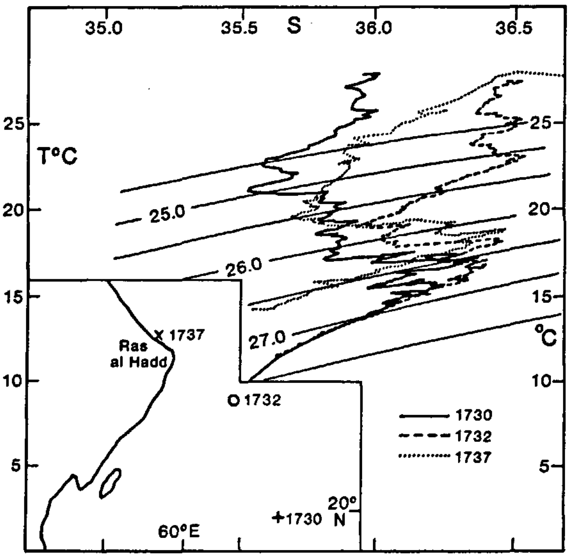


Figure 12

CTD traces from the R.R.V. Charles Darwin stations at the mouth of the Gulf of Oman. They show clearly the salinity maximum of the Persian Gulf water but demonstrate the complexity of the fine structure and the variability of the density at which it occurs.

ture of 20.55°C and salinity of 37.54 at a depth of 300 m. Flowing along the 26.5-26.6 σt surface the water spreads south into the Arabian Sea and is evident on the *Discovery* section V (Fig. 8, station 5 070). Its occurrence in the south Arabian coastal area on the *Discovery 1963* survey is, however, spasmodic and does not form any clear pattern. Defined by the salinity maximum on the 26.5-26.6σt surface, it occurs at most stations on section V, the stations further offshore on section IV, some outer stations on sections III and II and at some stations in the middle of section I.

Rochford (1964) traced the spread of the Persian Gulf water into the Indian Ocean, showing two main directions of flow, one south-westwards and one south-eastwards from the Arabian Sea. With more observations at his disposal, however, Wyrtki (1971) concluded that the main flow of Persian Gulf water into the Arabian Sea is to the south, down the west coast of India.

The Charles Darwin stations in the winter of 1986 (R.R.V. *Charles Darwin* cruise report 86/17) show a much more positive extension of the Persian Gulf water to the west, to 16°N and 57°E, and one is tempted, therefore, to conclude that the westward flow of the Persian Gulf water may be inhibited during the south-west monsoon period and that the *Discovery 1963* sections are showing the remnants of an earlier, more widespread distribution in the area.

A characteristic of the flow, which is very evident in the *Charles Darwin* CTD records and also in the *Meteor* observations, is the extremely complex layering and fine vertical structure (Fig. 12), not resolved by the *Discovery* water bottle observations. It does, however, go some way towards explaining the occurrence of salinity maxima on a range of density surfaces.

Red Sea water

The highly saline outflow from the Red Sea through the straits of Bab-el-Mandeb is identifiable as a salinity maximum on the 27.2 σt density surface, extending eastwards through the Gulf of Aden. The initial water type, defined by a temperature of 22.0°C and a salinity of 40.6 (Van Aken and Otto, 1974), becomes progressively modified by mixing but the maximum shows well at a number of stations on section I. Further east, however, on *Discovery* section III it lies at about 12.0°C and 35.65, becoming progressively more and more obscured.

The distribution of salinity in this maximum (Fig. 13) gives an indication of the spread of the Red Sea water into the Arabian Sea at a depth of about 500 m. Its eastward flow along the Arabian coast seems to be coherent to about 58°E but east of that only a few isolated maxima were recorded, mainly close to the continental slope. A marked easterly flow also seemed to occur north of Socotra and its spread southwards across the Indian Ocean has been the subject of numerous studies (Rochford, 1964; Wyrtki, 1971).

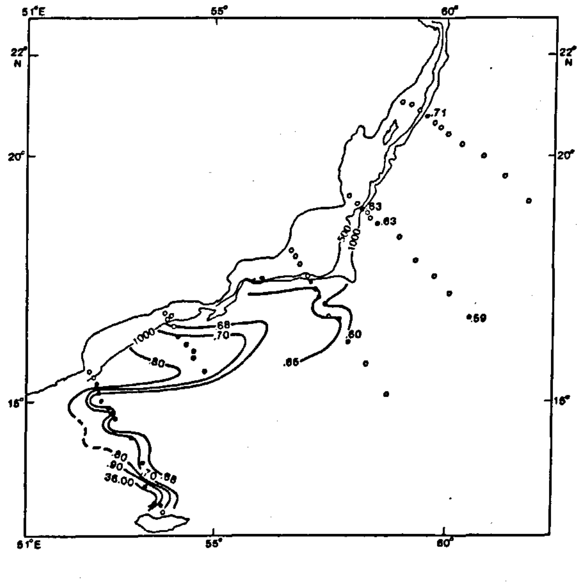
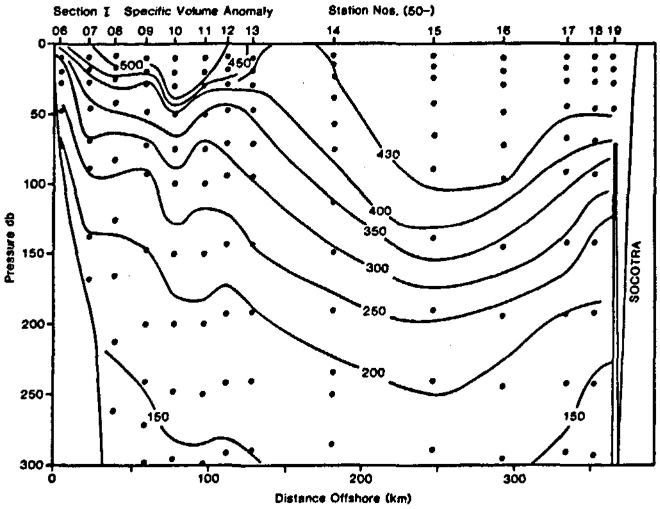
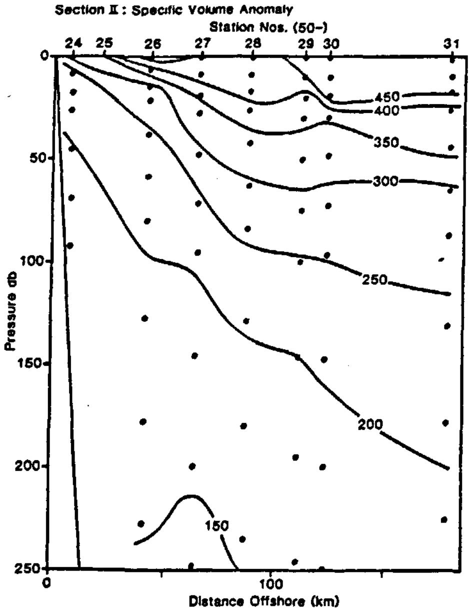


Figure 13

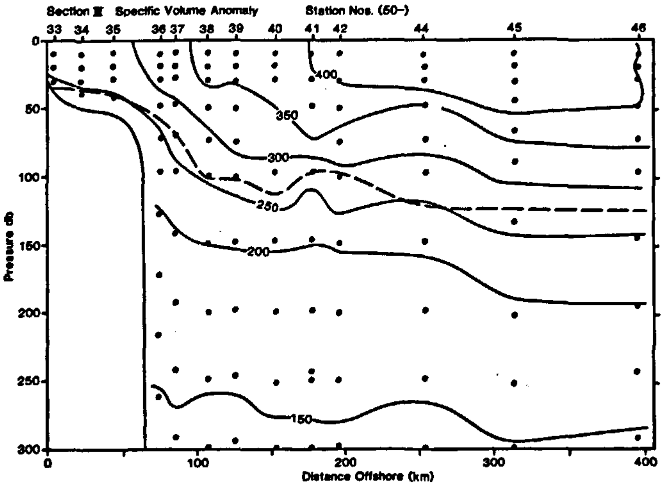
Horizontal distribution of salinity in the salinity maximum of the Red Sea water; this lies at a depth of about 500 m, values decreasing from 36.00 in the west to a minimum observed of 35.59 in the east of the area.



a: Section I.

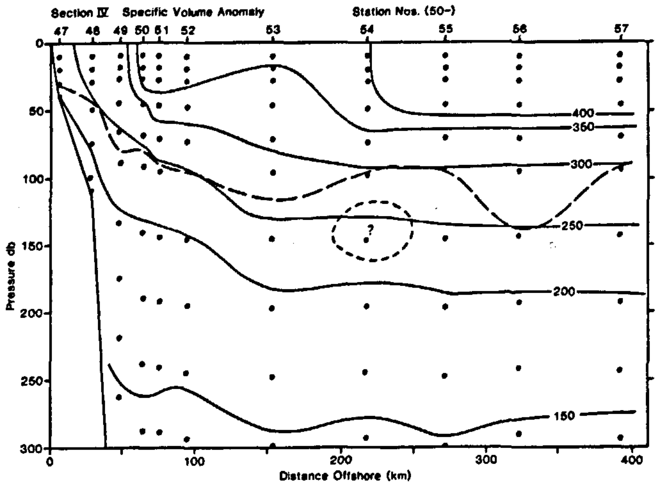


b: Section II.

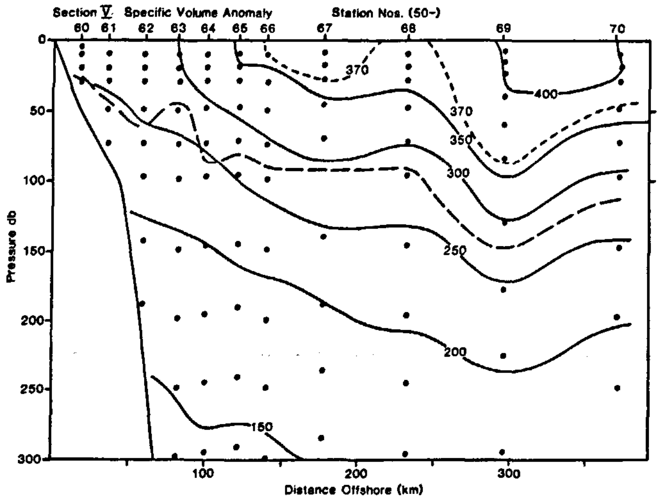


c: Section III.

The heavy broken line in this and the following two figures is the upper limit of the Oxygen Minimum Zone, defined by the 1.0 ml/l isoline.



d: Section V.



e: Section V.

Figure 14

Specific volume anomalies: Discovery 1963.

UPWELLING

Smith (1968) gives the most comprehensive review of the physical process of upwelling, covering various theoretical models, giving a summary of the geographical occurrence of the phenomenon and its resultant effect on the distribution of properties, biology, climate, etc. of the regions involved.

The process of upwelling, which features a combination of vertical and horizontal advection and mixing, does not lend itself readily to study by a conventional geostrophic approach. It seems unlikely that a "steady state" exists more than transiently and in most upwelling regions one is dealing with an interaction between changes in the density field associated with the geostrophic transport of the currents and a superimposed wind-induced Ekman transport generating offshore movement of the surface layers and a vertical replacement motion.

Such a situation becomes difficult to study with direct current velocity measurements but Smith and Bottero (1977), using the *Discovery 1963* data and a method described by Wyrtki (1963), determined the absolute dynamic topography of the sea surface and calculated the horizontal and vertical mass transports between a number of defined and closed contiguous cells. To maintain continuity, the mass of water entering each cell was taken to be equal to the mass leaving. They did not use stations on the continental shelf and inner slope and thus the shoreward boundary of their cells was some 50 km from the coastline and they emphasise that "The vertical velocities shown in (their) figure 5 are not for coastal upwelling per se by which we mean the upwelling induced by the coastal boundary causing a divergence in the Ekman flow". Their computations relate to what they call "open ocean" upwelling, which others have described as "large scale upwelling" because of its association with the large scale wind systems.

A different approach has been adopted here, namely of examining the distribution of mass, expressed as the specific volume anomaly (δ cl t^{-1}) on the different sections and these are reproduced in Figures 14 *a-e*. As in earlier figures of temperature and salinity, the coastline has been drawn on the left so that one is looking through the sections towards the north-east. Since South-East Arabia lies in the northern hemisphere, an upward slope of the isosteres may not only be indicative of uplift of water, but it follows, on geostrophic considerations, from the distribution of mass that an upward slope to the left is synonymous with a relative current towards the north-east and an upward slope to the right, with a flow to the South-West.

It will be immediately obvious that all five sections have certain features in common but also some significant differences. On all sections the heavier water lies closest to the coast and there are clear indications of vertical motion affecting depths to more than 300 m and an overall transport to the north-east. In fact Smith and Bottero's (1977) computations indicate that vertical motion is perceptible at 700 m depth. The general slope of the isosteres up towards the coast is similar on all five sections and would be compatible with a broad and comparatively uniform geostrophic current in the main body of water.

The water in the euphotic zone close to the coast appears consistently to be continuous with water at 100-150 m depth offshore.

On sections III, IV and V, however, there are strong indications of offshore transport in the upper layers where the isosteres run almost vertically by comparison with the upper layer isosteres at the coastal ends of sections I and II. This suggests that wind induced coastal upwelling may only have been taking place on sections III, IV and V, and that it was superimposed on the general north-easterly geostrophic flow. This would be consistent with the greater wind stress encountered on sections III, IV and V (*see* Fig. 3) and with its direction being more effective in generating offshore transport of the surface layers (Fig. 15).

Section I is more complicated in that there is clearly a marked south-westerly flow below 50 m depth north of Socotra. There is also indication of divergence some 100-150 km from the Arabian coast associated with what could be a strong westerly flow between stations 5 010 and 5 013 but this is probably brought about by flow around the contour of the tongue of the easterly flow of Gulf of Aden surface water.

Distribution of the upwelling

Reference has already been made to Bobzin's analysis of sea-surface temperatures which indicated broadly the areas of greatest negative sea-surface temperature anomaly (Bobzin, 1922; Tafel 2), which is probably the best indication of the location of the centres of upwelling. The present results confirm his conclusions but add somewhat more detail since it is possible to consider the sea-surface temperature distribution in relation to the water column and factors which may bring about or influence that distribution; for instance, the direction of the wind stress on the sea surface, the orientation of the coastline and the sea bed topography.

The main development of the coastal upwelling thus occurs to the east of Merbat (55°E), in, and to the east and north of Kuria Muria bay (*see* Fig. 4 *a*). Merbat is the point east of which the general orientation of the coastline becomes more northerly (p. 47). To the west of Merbat the winds on the *Discovery 1963* survey, in the coastal zone, had a significant onshore component (*see* Fig. 3) and were rather weak, whereas east of Merbat the winds were very much stronger and had a consistent longshore component. The offshore component of the Ekman drift would therefore have been negligible west of Merbat, but pronounced east of Merbat, which would be compatible with the development of the wind-induced upwelling (Fig. 15).

The area to the east of Kuria Muria bay is also marked by a distinctive promontory of the continental shelf (*see* Fig. 2) giving a wider expanse of shallower water which continues north to Ras Madraka and on this shelf some of the lowest

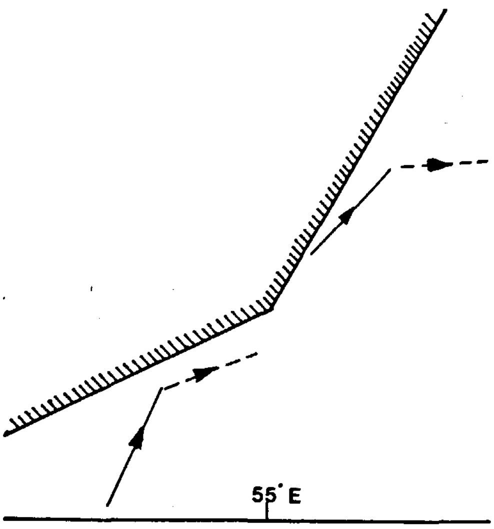


Figure 15

Schematic diagram of the surface wind direction near the coast (solid lines and the theoretical surface Ekman drift (broken lines) showing the pronounced offshore component in the latter, east ofMerbat in 55°E.

sea-surface temperatures were recorded. It is not possible to say if this promontory influences the generation of upwelling, but certainly the wide shelf acts as a pool for upwelled water.

The sequence of upwelling

Bobzin's charts for the months of May to October show the development and decline of the upwelling during the course of the south-west monsoon. It is possible, however, to follow the phases of this development in more detail from data collected by several ships during the IIOE. Repetitions of the *Discovery 1963*, section III, were made by the R.V. *Anton Bruun* in September (1963), by the R.R.S. *Discovery* in March and May (1964) and the section was in the same position as one made by the R.V. *Vladimir Vorob'yev* in December (1961). These sections were sufficiently close geographically to allow reasonable comparison.

The December section showed a south-westerly flow along the South-East Arabian coast which together with the measurements of non-conservative properties confirm the absence of upwelling in that month (Seryi and Khimitsa, 1963). The March section, by contrast (Fig. 16 *a*) shows a well developed geostrophic current flowing to the north-east in the upper 150 m, extending about 180 km offshore but below this the relative current is still to the South-West. Again, the nutrient levels in the upper layers at the coast show no signs of enrichment (Currie *et al.*, 1973).

In May, however, there is a marked steepening of the isosteres close to the coast in the upper 100 m (Fig. 16 *b*) accompanied by a significant increase in nutrient levels indicating a strengthening of the North East Coastal Current and the development of a wind induced upwelling within the local Rosby radius of deformation. Below 100 m depth, however, the south-westerly flow persisted. By July (Fig. 14 *c*) this had disappeared and the upwelling in the upper 150 m was well developed.

In October, the stations (175-180) worked by the R.V. *Anton Bruun* show no indication of upwelling and a warm surface layer extended in to the coast.

DISCUSSION AND SUMMARY

The dominance of the South-West monsoon in driving the summer circulation of the Arabian Sea is well documented and reflected in the *Discovery 1963* observations. In the upper 200 m or so, the main water mass occupying the Arabian Sea is evidently a northward extension of comparatively low salinity sub-tropical surface and sub-surface water, overlain in the Gulf of Aden and also in the North-East Arabian Sea, by warmer high salinity layers, and overlying the more saline waters originating from the Persian Gulf and the Red Sea.

The shallow salinity minimum (25.7 σt) which in the east of the region overlies the Persian Gulf water, evidently originates from the equatorial surface waters of the eastern Indian Ocean and its main northward transport towards the Arabian coast appears to be to the east of Socotra since it can be seen at *Atlantis* station 61 but is not evident at the *Anton Bruun* stations in 60°E. It seems probable that its northward movement is associated with the anticyclonic circulation identified by Düing (1970) east of Socotra and possibly the anticyclonic circulation north of the Somali current, identified by Warren *et al.* (1966). The salinity in the minimum, which increases progressively to the north and east, is accompanied by a corresponding reduction in dissolved oxygen content.

The lower salinity minima (26.7-27.0 σt) appear to arise from Sub-Tropical Sub-Surface Water formed at the Sub-Tropical Convergence in 40°S. In the east it appears to be more dense, and underlies the Persian Gulf water but in the west it seems to replace the Persian Gulf water on the 26.5-26.7 σt surface and directly overlies the Red Sea water.

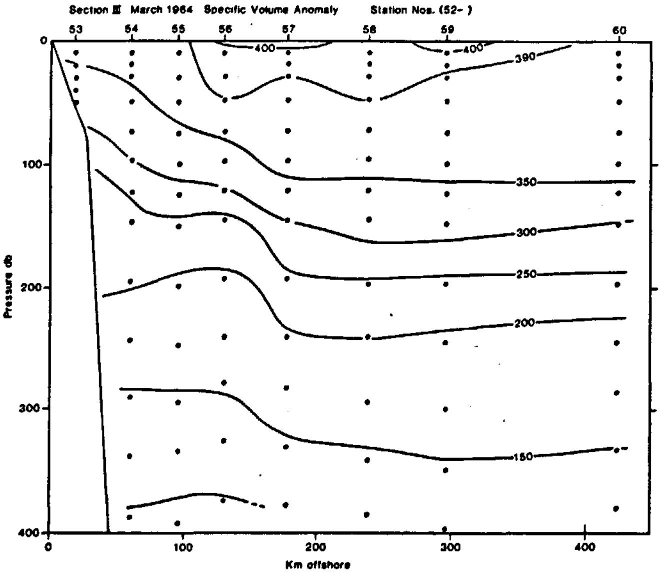


Figure 16 *a*

Specific volume anomalies (cl t^{1}): Discovery, *March, 1964.*

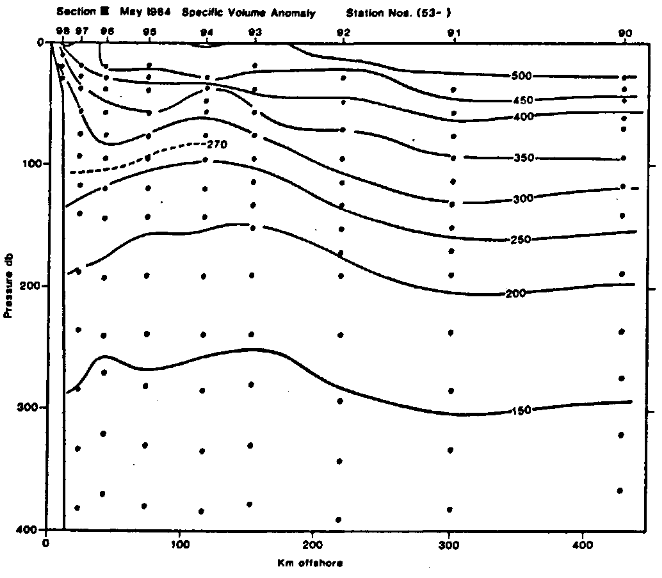


Figure 16 *b*

Specific volume anomalies (cl t^{1}): Discovery, *May, 1964.*

The general north-easterly drift along the South-East Arabian coast appears to be associated with a fairly uniform geostrophic current flowing in a band some 200-300 km wide. This seems to dominate the flow, since the measurements of surface drift, particularly in the coastal belt, follow the contours of the sea-surface topography reasonably closely. There is also evidence, however, of departure from the geostrophic flow in that both the direct current measurements and the temperature-salinity structure indicate easterly and offshore movement which can be ascribed to drift induced by the surface wind stress. The small number of deeper current measurements available (p.13) suggest the presence of a compensatory coastwards flow at a depth of about 100 m.

The picture is, however, complicated by a considerable degree of variability which it appears is associated with eddies, not fully resolved by the observations and the anticyclonic flow around the high salinity surface water masses of the Gulf of Aden and the North-East Arabian Sea.

Associated with the north-easterly geostrophic flow, upwelling occurs to some degree all along the coast but the main area of wind induced coastal upwelling evidently lies to the east of Merbat (55°E). Water is upwelled on to the continental shelf from depths of about 150 m and the greatest extent of upwelled water lies over the broadest expanse of the continental shelf north-east of the Kuria Muria islands, in Suqara bay and in the Gulf of Masira. The upwelled water comes from the shallow salinity minimum.

In the 1963 *Discovery* observations Smith and Bottero (1977) estimated the vertical velocity on the shelf at > 3 x 10-3 cm s^{-1} and offshore at 1 to 2 x 10^{-3} cm s^{-1} giving a vertical transport through the 50 m level of 8 x 10^6 m^3 s^{-1} over the area of 1 000 by 400 km.

The *Discovery 1964* observations indicate that the geostrophic current development was detectable in March but that wind induced upwelling does not become evident until May. The *Discovery 1963* observations probably show its fullest development in July-August and the *Anton Bruun* observations, its rapid decline in September. This agrees with Bobzin's interpretation of events. The latter was, of course, based on the sequence of events over a number of years and it suggests, therefore, that events in 1963-1964 were fairly typical of the usual pattern. By contrast, there is reason to suppose that in 1964, at least on the northern boundary of the Somali current, the extent of the upwelling there was rather greater than average (Currie *et al.*, 1973) but it is impossible to say how far that may have extended to the Oman coast.

There are a number of features of the South-East Arabian coastal upwelling which depart from the general pattern in the eastern boundary current upwelling systems but in the main there is close similarity. For instance, the broad and deep divergence in the geostrophic current, the oceanic upwelling (Smith and Bottero, 1977; Swallow, 1984), can be compared with the similar divergence in the eastern boundary currents of the Atlantic and Pacific Oceans. Also, the coastal upwelling, particularly east of Merbat, has features closely similar to the Peru, Benguela, Californian, and Canary current systems (Smith, 1968), with a well mixed coastal water column, high nutrient levels, and high productivity.

Off the Oman coast, however, there is no indication, in the specific volume sections III to V, of the localised offshore divergence or front between the coastal and oceanic water such as is characteristic of all the major eastern boundary current upwelling systems (Smith, 1968). Although a local offshore divergence is evident on section I, it is probably associated with the eastward flow of the Gulf of Aden surface water.

Likewise, there is little to suggest in the present observations the existence of an undercurrent flowing counter to the surface water movement which is also a characteristic of the eastern boundary current upwelling regions where there is a distinct poleward flow beneath the surface. The reason for this may lie in the strength of the geostrophic current and that it adequately compensates for the offshore flow at the surface.

Another particularly interesting aspect is that the alternation between the North-East and South-West monsoon circulations generates a strong seasonal signal, which is generally lacking in the sub-tropical eastern boundary upwelling regions where upwelling takes place to a greater or lesser degree through the year. This seasonality is unusual in sub-tropical environments and has a profound effect on the biota of the shore and coastal waters (Hiscock, 1985).

In other respects, the South-East Arabian upwelling is associated with phenomena common to other upwelling regions: depressed sea-surface temperature, cloudy, humid conditions, poor visibility, low coastal rainfall and adjacent desert.

Acknowledgements

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