

## Circulation & Water Characteristics on Isanosteric Surfaces in the Northern Arabian Sea during February-April

V KESAVA DAS, A D GOUVEIA & K K VARMA

National Institute of Oceanography, Dona Paula, Goa 403 004

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Distribution of water characteristics and circulation were studied on 260, 160, 140, 120 and 80 cl/t surfaces using isanosteric analysis and geostrophic computation. The circulation pattern consisted of several eddies and meanders. The most prominent anticyclonic eddy was located around 24°N and 64°E. Deepest mixed layer occurred in this region. Appreciably deep vertical extension of the eddies was a notable feature. The eddy circulation is proposed to be due to the influence of uneven bottom topography. Persian Gulf water appeared to flow into the Arabian Sea through the northern part of the Gulf of Oman. Distribution of properties was marked by several pockets of high and low values.

The possibility of the presence of eddies in the northern Arabian Sea has been suggested earlier<sup>1</sup>. Adequate information on circulation in this area is lacking except for the data derived from ship's drifts. Present study has been carried out, in view of the above factors. In this connection the works of Wooster *et al.*<sup>2</sup>, Wyrski<sup>3</sup> and Sastry and D'Souza<sup>4</sup> are worth mentioning.

### Materials and Methods

The study is based on data collected on board *INS Darshak* during February-April 1974. Temperature and salinity data were collected using a STD profiler at 72 stations<sup>1</sup> from areas A and A<sub>1</sub>, occupied in February and area B, occupied during March-April (see Fig. 1d). Data were pooled for further analysis in spite of the observational time lag. This was done in the light of justification given in the earlier study<sup>1</sup> and that arose from comparison of the depth of 300 cl/t surface in the northern Arabian Sea between December-February and March-May<sup>2</sup> which has shown no seasonal variation. Oxygen data used were taken from *INS Darshak* data file<sup>5</sup>.

Temperature-salinity curve for each station was drawn on a T-S sheet where isolines of thermosteric anomaly ( $\delta_T$ ) were superimposed. Temperature and oxygen were also plotted on the same sheet against depth. The values of temperature, salinity, oxygen and depth at different isanosteric surfaces (at intervals of 20 cl/t) were read directly from the station curves.

Geostrophic flow on isanosteric surface was deduced following Montgomery and Stroup<sup>6</sup> from the gradient of acceleration potential expressed as

$$\phi_a + P\delta = P_0\delta_0 + \int_{\delta_0}^{\delta} P d\delta$$

where  $\phi_a + P\delta$  is the acceleration potential,  $P$  is pressure,  $\delta$  is steric anomaly and  $P_0$  and  $\delta_0$  are the

pressure and steric anomaly at the reference pressure respectively. In the present study thermosteric anomaly is used in place of steric anomaly.

Numerical integration was done at intervals of 20 cl/t. Reference pressure was chosen as 1000 db arbitrarily. Distribution of acceleration potential, depth, salinity and oxygen for different isanosteric surfaces, viz. 260, 200, 160, 140, 120 and 80 cl/t are presented (Figs 1 to 6).

### Results

**260 cl/t Surface**—Distribution of acceleration potential revealed the presence of several eddies and meanders (Fig. 1a). The trend of contours indicates that spatial extension of the study region would have produced closed isolines. Acceleration potential varied between 12.4 and 14.5 joules/kg. A well pronounced, anticyclonic eddy was present centred around the maximum at 24°N and 64°E. A deep mixed layer was reported earlier in the region<sup>1</sup>. South of this, a cyclonic eddy was present. In this region comparatively shallow mixed layer was noticed<sup>1</sup>. Further west, a large but weak anticyclonic eddy was present between 60.5 and 62.5°E. Between the 2 anticyclonic eddies a small cyclonic eddy existed. The region between 62.5 and 65°E was of strong gradient. Off Okha, a cyclonic eddy was found between southwesterly and easterly flows. Another anticyclonic eddy with weak intensity was observed around 22.5°N and 65.5°E.

Depth contours, in general, were similar to those of acceleration potential except in the western section (Fig. 1b). Depth of this surface varied between 55 and 220 m. Several troughs and ridges were associated with the anticyclonic and cyclonic eddies respectively. In general, in the eastern region, this surface was at a deeper level as compared to the western portion. Wooster *et al.*<sup>3</sup> reported an increase in depth of 300 cl/t

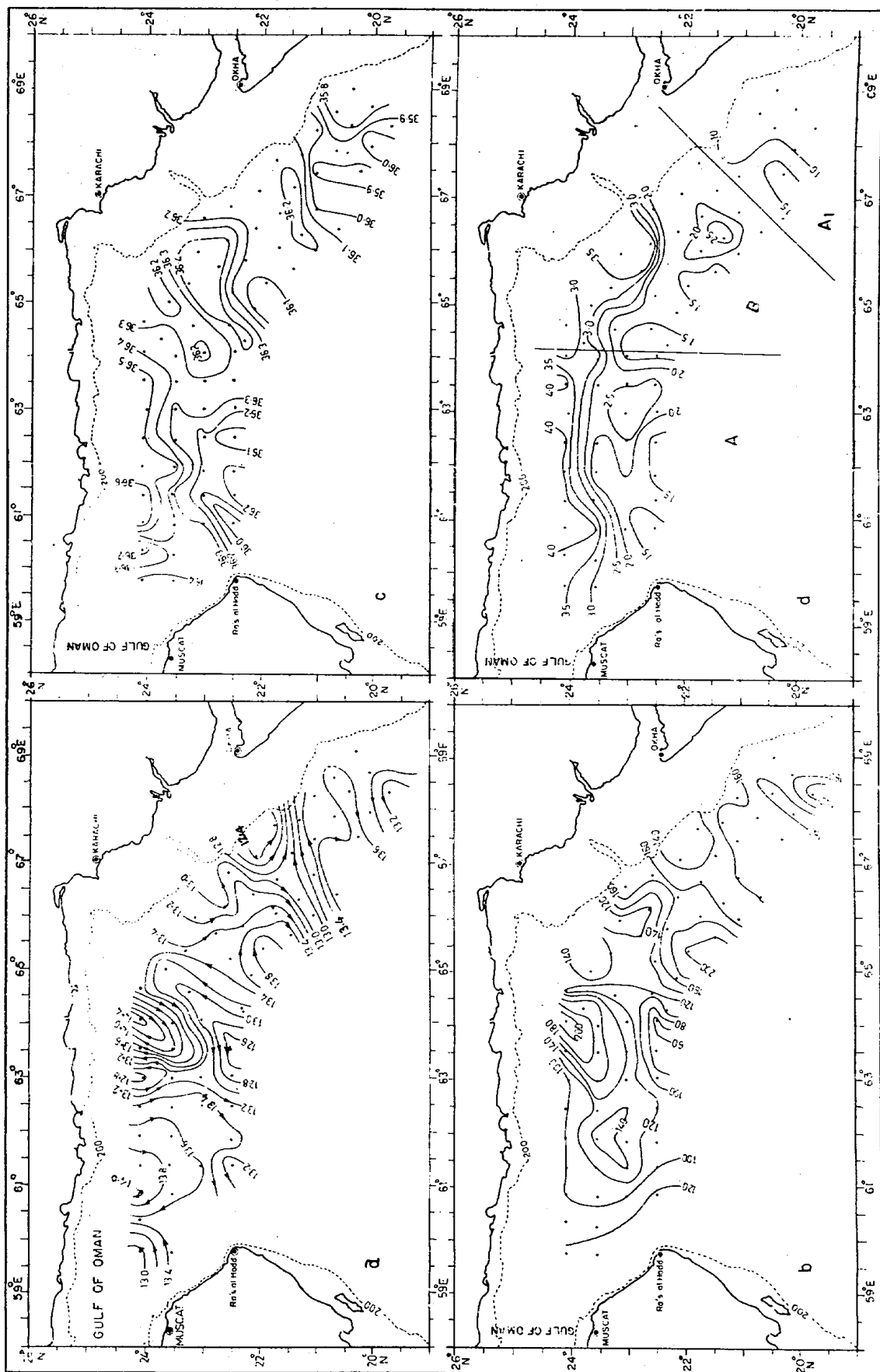


Fig. 1—Distribution of (a) acceleration potential (b) depth (c) salinity and (d) oxygen on 260 cl/t surface

surface from west to east in the northern Arabian Sea.

Salinity varied between 35.7 and 36.7‰ (Fig. 1c). Pockets of low and high salinities were observed. In general, salinity decreased from west to east. The maximum salinity was found around 24°N and 61.5°E and the minimum was observed off the Indian coast.

Oxygen varied between 0.8 and 4 ml/litre (Fig. 1d). The distribution of oxygen showed some similarity to that of salinity. Isolines were generally zonal. However, pockets of high and low oxygen were also observed. Considerable decrease in oxygen was observed off the coast of India from north to south.

**200 cl/t Surface**—Acceleration potential varied between 11.5 and 13 joules/kg (Fig. 2a). The flow pattern, in general, was identical to that of 260 cl/t surface. Eddies located along 64°E were present with less intensity. However, on the eastern side of the large anticyclonic eddy around 64°E, a small cyclonic eddy was present. The weak anticyclonic eddy observed on 260 cl/t surface between 61.5 and 62.5°E appeared to be distorted on this surface. The flow pattern off Okha was almost similar to that of the upper surface but with less intensity.

Depth varied between 125 and 270 m (Fig. 2b). The depth contours were by and large similar to those of the upper surface. However, towards west some difference was observed.

Salinity varied from 35.8 to 36.2‰ (Fig. 2c). Off the coast of India a decrease in salinity towards south was observed. A high salinity pocket was observed at the southern end of the section along 64°E. In the area between 60 and 65°E salinity generally decreased towards south. Oxygen decreased considerably as compared to the 260 cl/t surface and the values on this surface varied from 0.3 to 1.5 ml/litre (Fig. 2d).

**160 cl/t Surface**—The flow speeds, in general, were considerably reduced (Fig. 3a). The anticyclonic eddy around 64°E was present with weaker intensity. But the anticyclonic eddy observed on the 260 and 200 cl/t surfaces between 61.5 and 62.5°E appeared to be broken. However, the flow in the opposing directions persisted. Near to the Gulf of Oman, the flow was northerly and east of that up to 63°E the flow was southerly. In general, the flow pattern off the coast of India was similar to that of the upper surfaces.

Depth of this surface varied between 210 and 300 m (Fig. 3b). The deepest trough was observed around 24°N and 64°E. There were ridges and troughs associated with the cyclonic and anticyclonic flows.

Salinity on this surface, generally, was greater than that of the 200 cl/t surface (Fig. 3c). This was presumably due to the presence of the Persian Gulf water (PGW) which was found to be maintaining steric levels between 140 and 160 cl/t (ref. 1). Salinity varied between 35.8 and 36.6‰. An interesting feature was

the very low salinity observed at st 12 (24°N, 61.5°E) in spite of the higher values in the neighbourhood. This was caused by the bifurcation of the salinity maximum of PGW that produced 2 maxima<sup>1</sup> resulting in a minimum at about 160 cl/t surface. Some pockets of high and low salinity were also observed.

Oxygen values were less than that of 200 cl/t surface and varied between 0.35 and 1.1 ml/litre (Fig. 3d). High values were encountered in the region of the anticyclonic eddy around 64°E. Few pockets of low and high oxygen were present.

**140 cl/t Surface**—Acceleration potential varied between 10.1 and 11.3 joules/kg (Fig. 4a). The flow pattern more or less showed similar features as on 160 cl/t surface, though the intensity was comparatively less. Depth contours (Fig. 4b) also showed almost identical features as on 160 cl/t surface. Depth varied between 260 and 385 m. The range of salinity was almost the same as on the upper surface (Fig. 4c) indicating the presence of PGW on this surface too. Oxygen varied between 0.3 and 0.9 ml/litre (Fig. 4d). The distribution was marked by pockets of high and low values as observed on 160 cl/t surface.

**120 cl/t Surface**—Acceleration potential varied between 9.5 and 10.5 joules/kg (Fig. 5a). The intensity of the flow was considerably reduced. Anticyclonic eddy around 64°E was also present. A conspicuous difference as compared to the upper surfaces was that the southerly meandering observed in the middle of the study region was not present. Depth varied between 320 and 465 m (Fig. 5b). This surface was more uneven as compared to the upper surfaces. Salinity was comparatively less than that on 160 and 140 cl/t surfaces (Fig. 5c). It varied between 35.6 and 36.2‰. Oxygen values varied from 0.15 to 1 ml/litre (Fig. 5d) showing an increase compared to 140 cl/t surface.

**80 cl/t Surface**—Flow on this surface was very sluggish (Fig. 6a). Acceleration potential range was considerably less than that of other surfaces (7.5 to 7.9 joules/kg). No definite flow pattern could be observed. Depth contours (Fig. 6b) showed that this was the most uneven surface. Range of depth was greater than the other surfaces (650 to 870 m). Variation in salinity was less (35.5 to 35.8‰) than that of the other surfaces (Fig. 6c). Oxygen values were, in general, greater than that on 120 cl/t surface and varied between 0.3 and 1 ml/litre (Fig. 6d).

The sea surface circulation pattern is not presented because of observational time lag between areas A and B and the consequent seasonal variation in temperature and salinity noticed in the surface layers<sup>1</sup>. In spite of this seasonal variation, distribution of acceleration potential on the sea surface (available with the authors) showed almost similar direction of flow as on 260 cl/t surface. However, there was a reduction in

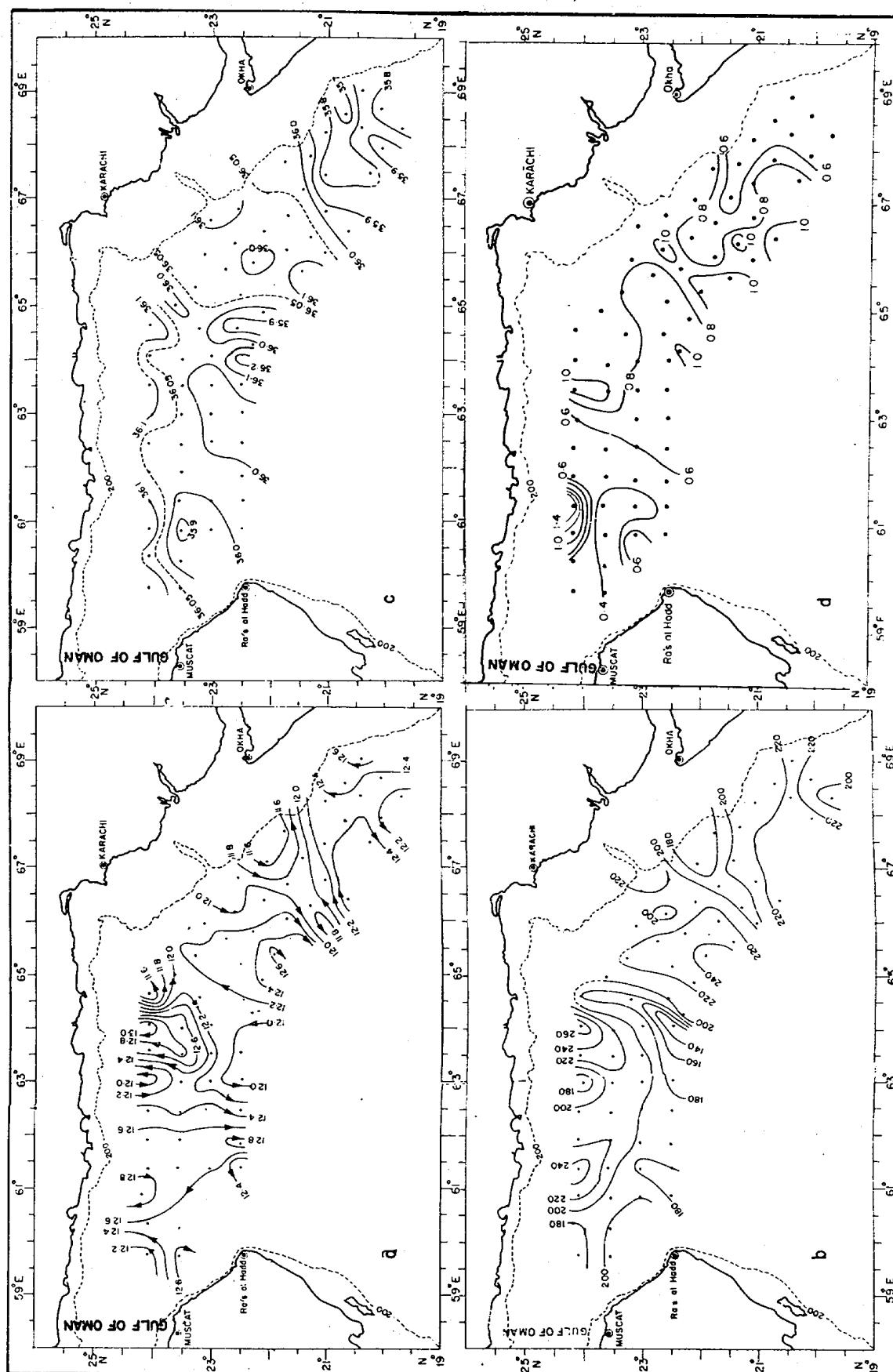


Fig. 2—Distribution on 200 c/t surface (a to d as in Fig. 1)

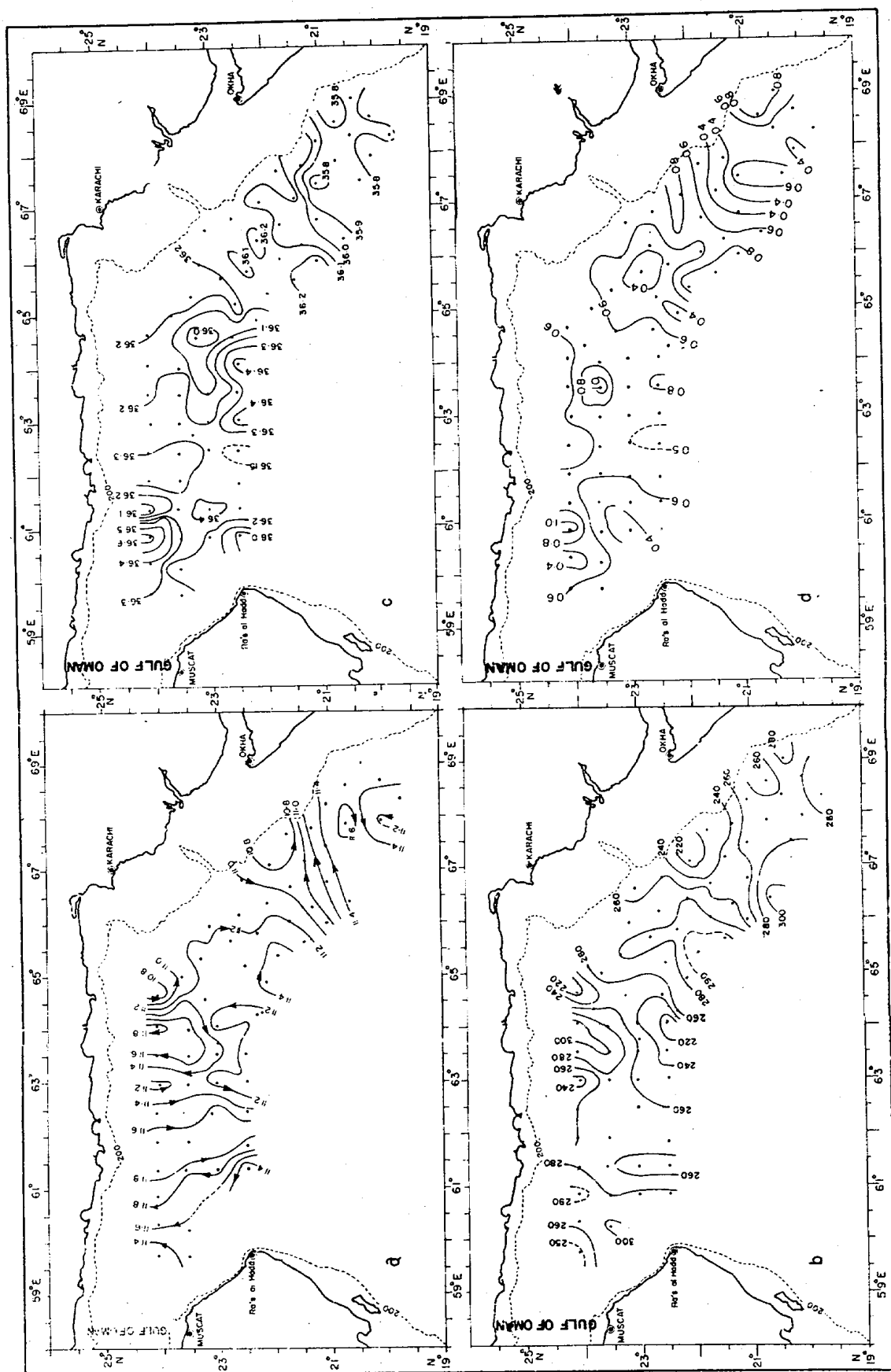


fig. 3—Distribution on 160 cl/t surface (a to d as in Fig. 1)

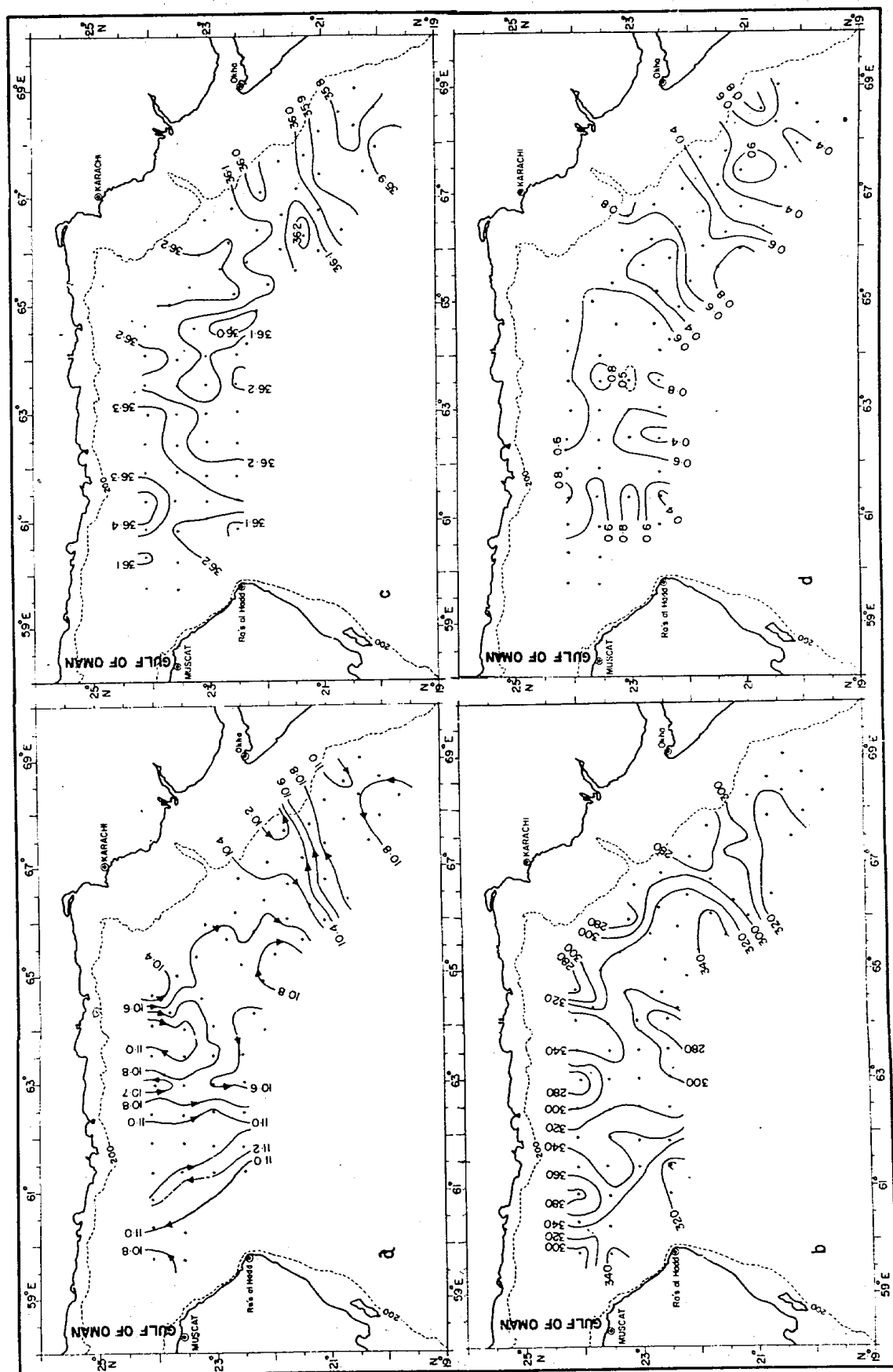


Fig. 4—Distribution on 140 c/t surface (a to d as in Fig. 1)

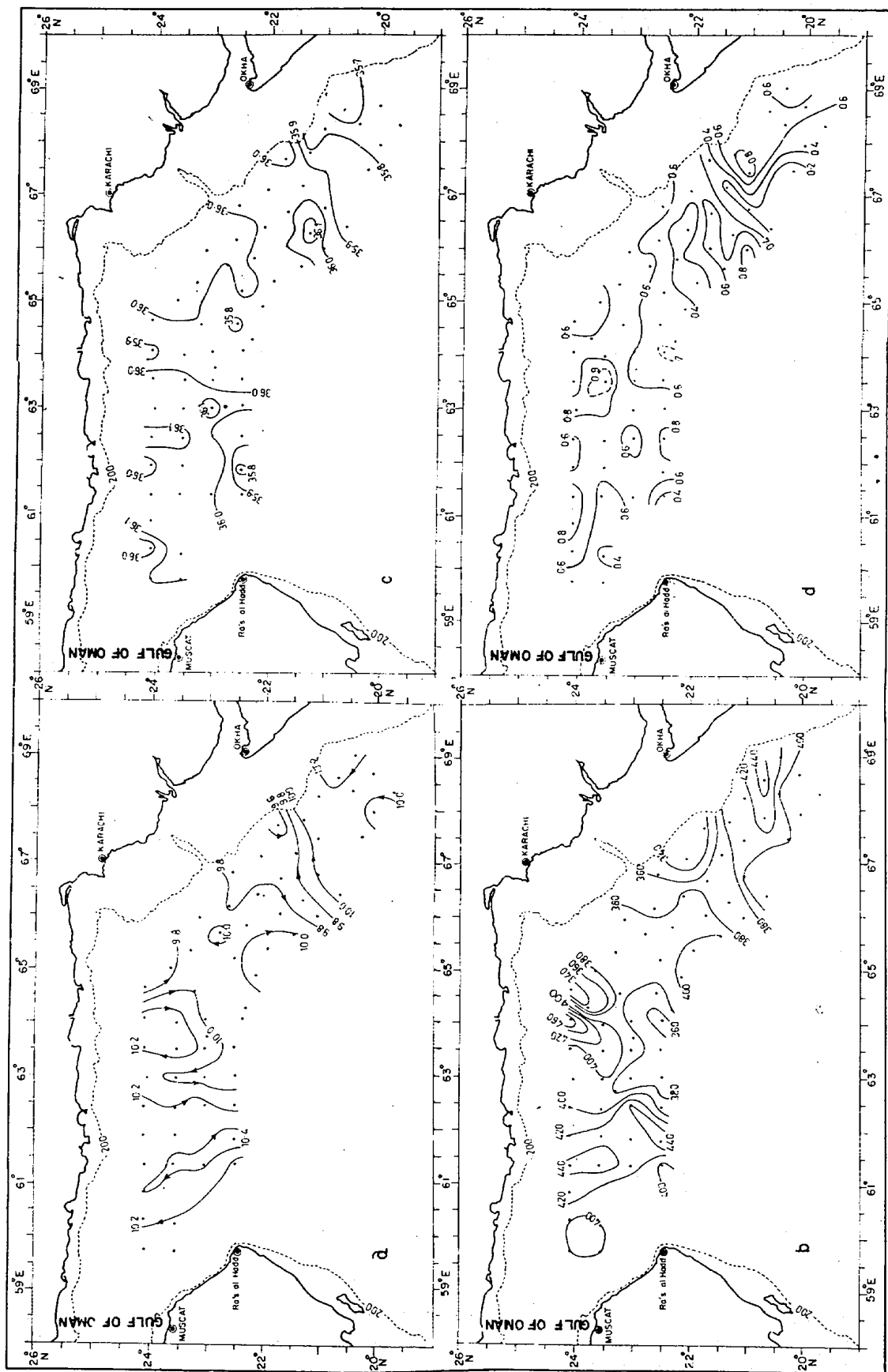


Fig. 5—Distribution on 120 cl/t surface (a to d as in Fig. 1)

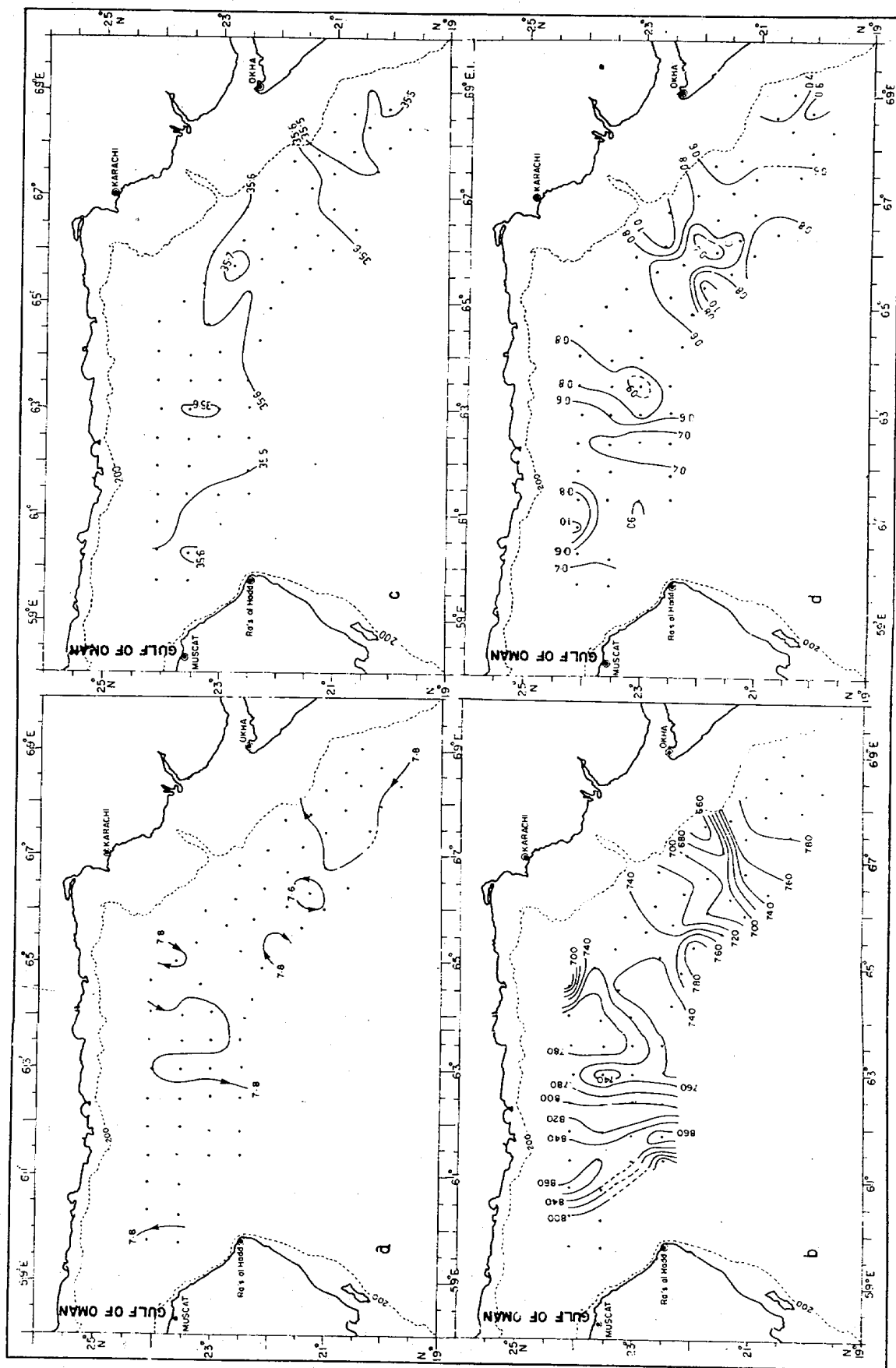


Fig. 6—Distribution on 80 cl/t surface (a to d as in Fig. 1)



the intensity of flow at the regions where stations covered in different months were joined together. This may, perhaps, be indicating that the seasonal variation of properties in the surface layers between areas A and B was not sufficient to alter the direction of flow albeit the intensity was affected.

### Discussion

Distribution of acceleration potential, depth, salinity and oxygen on different isanosteric surfaces clearly revealed the presence of eddies and meanders. The general circulation on the sea surface<sup>7</sup> (averaged over 2° square) in the region of present study in February-March also showed flow of opposing directions. Some of the eddies were of appreciable vertical extent. While studying the circulation on isanosteric surfaces, Sastry and D'Souza<sup>4</sup> observed several eddies in the Arabian Sea, south of 20°N, during southwest monsoon and reported considerable vertical extension of these eddies. Wooster *et al.*<sup>2</sup> studied distribution of depth, salinity and oxygen on 3 steric surfaces (300, 150 and 100 cl/t) in the Arabian Sea for different seasons. The depth of 150 cl/t surface shown by them for March-May in the northern Arabian Sea is comparable with those in the present study. Wyrski<sup>3</sup> also presented distribution maps for various  $\sigma\theta$  surfaces (25, 25.8, 26.6, 27.2 and 27.4) for the entire Indian Ocean. He has shown the depth of 26.6  $\sigma\theta$  (~146 cl/t) surface as around 300 m in the northern Arabian Sea which is somewhat in agreement with our finding. Also, the closed isobath of 300 m on this surface<sup>3</sup> vaguely indicates the presence of a clockwise eddy. The oxygen values presented by Wooster *et al.*<sup>2</sup> on 150 cl/t surface in the northern Arabian Sea (<0.25 ml/litre) are comparatively less than that in the present study. Wyrski<sup>3</sup> also showed the oxygen values to be around 0.2 ml/litre on 26.6  $\sigma\theta$  (~146 cl/t) surface. These comparisons were made with the values on data sheets. The 140 and 160 cl/t surfaces in the present study appeared to be within the oxygen minimum layer.

In the present study region, Wooster *et al.*<sup>2</sup>, for March-May on 150 cl/t surface and Wyrski<sup>3</sup> on 26.6  $\sigma\theta$  (~146 cl/t) surface reported salinity between 36 and 36.5‰. This is in agreement with our findings. While their<sup>2,3</sup> studies showed a gradual decrease in salinity from the mouth of the Gulf of Oman, our study revealed pockets of high and low salinities.

A very close comparison either with Wooster *et al.*<sup>2</sup> or Wyrski<sup>3</sup> is not possible because of the difference in the nature of data. While Wooster *et al.*<sup>2</sup> used sparse data in the northern Arabian Sea, Wyrski<sup>3</sup> used spatially averaged data regardless of seasons; the data used in this study were from continuous profiles of very closely spaced stations worked out in only 3 months.

This is the reason for encountering small scale features which were not reported earlier.

PGW flows into the Arabian Sea through the Gulf of Oman and maintains steric levels between 140 and 160 cl/t (ref. 1). Because of the variation in the steric levels, no definite flow path of PGW could be inferred from the distribution of salinity on either 160 or 140 cl/t surfaces. Nevertheless, average values of salinity on and 160 cl/t surfaces plotted on a station map (available with the authors) indicated that the flow of PGW was towards south in the western part of the study region. Further, from the distribution of acceleration potential, depth and salinity on 160 and 140 cl/t surfaces (Figs. 2 and 3) it could be inferred, though vaguely, that the high saline PGW flows out in to the Arabian Sea from the Gulf of Oman through its northern portion.

The regions where anticyclonic eddies were encountered correspond to the locations of deep mixed layer reported earlier<sup>1</sup>. The most prominent feature was along 64°E where 2 eddies of opposing directions were observed at either end of the section which correlates well with the earlier findings<sup>1</sup>.

The eddy circulation inferred in the present study can, perhaps, be due to the influence of bottom topography. Bottom topography as one of the causative factors of eddy generation was studied by several authors<sup>8-11</sup>. Conservation of potential vorticity would imply that flow lines tend to be clockwise over depressions in the bottom and counter-clockwise over mounts, in the northern hemisphere<sup>8</sup>. Beckerle<sup>8</sup> correlated the eddies found in the Sargasso Sea with the bathymetry of that region. The bottom topography of the region of present study revealed several depressions and rises (ref. 12, p 25). Major part of the study region lies over the Murray ridge<sup>12</sup> and it appears that this ridge influences the circulation in the Arabian Sea. The large well pronounced anticyclonic eddy around 24°N and 64°E and the cyclonic eddy further south in the same longitudinal section correlate well with the topographic features of the region. While the anticyclonic eddy was observed over the deeper region, the cyclonic eddy was encountered above a sill depth of about 500 m. However, some of the eddies observed did not correlate directly with bottom shape. There may be ambiguity in the coupling of all eddies and meanders to the bottom shape because lateral displacements of eddies from the places of generation are possible, even if they are generated by the bottom topography<sup>11</sup>. Deep vertical extension of the eddies observed in present study also suggests that the topography is influencing the circulation. In view of the correlation of the flow pattern with sea bottom, some features of flow pattern are expected to persist for long periods of time as suggested by Beckerle<sup>8</sup>. A detailed

study over longer period and larger area would be essential to understand fully the eddy circulation, its generation and persistence in the northern Arabian Sea.

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