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Current Structure in the Upper Layers of the Arabian Sea during Southwest Monsoon

A SATYANARAYANA MURTHY*, M G SESHAGIRI RAO & G S SHARMA

Department of Marine Sciences, University of Cochin, Cochin 682016

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Circulation pattern in the Arabian Sea is derived from computation of acceleration potential at 2 isanosteric surfaces (400 and 200 cl/t) using oceanographic data obtained during the International Indian Ocean Expedition. As the current structure in the upper layers of the Arabian Sea varies from season to season, the study is limited to the southwest monsoon, when the surface circulation in the North Indian Ocean differs very much from the other 2 major oceans. Maps showing the distribution of acceleration potential at 400 and 200 cl/t surfaces are presented. Distribution of the thickness of the layer between 10 cl/t above and 10 cl/t below each surface is also presented in order to gain quantitative information about the water volume, water flux and stability according to characteristics.

Atmospheric circulation over the North Indian Ocean reverses semi-annually which in turn affects the oceanic circulation and water characteristics of this region. The variation of winds which causes the surface circulation is reflected in the distribution of water properties and current structure in the upper 200 m up to which the monsoon wind-driven circulation is influenced. The northeast monsoon which is less effective and prevails over a shorter period of time has got lesser influence in the Arabian Sea than that of the powerful and longer prevailing southwest monsoon. As such the space as well as time variations of circulation and water characteristics in the Arabian Sea are more conspicuous during the southwest monsoon than during the northeast monsoon.

The atmospheric circulation over the North Indian Ocean is similar to that over the Atlantic and Pacific where the western boundary currents, viz. the Gulf Stream and the Kuroshio, respectively are present throughout the year. But in the North Indian Ocean the northward flowing western boundary current namely, the Somali Current, is present only during the southwest monsoon when the atmospheric circulation over the North Indian Ocean is dissimilar to that over the other 2 major oceans. In view of these peculiarities in its western region, it is desirable to study the current structure in the upper layers of the Arabian Sea during southwest monsoon.

Düing[1] derived the surface circulation of the North Indian Ocean by dynamic computations. Bruce[2] compared the near surface circulations in the western Indian Ocean for the northeast and southwest monsoons using dynamic computations and the current measurement data. Swallow and Bruce[3] presented the currents measured and the geostrophic flow for the southwest monsoon of 1964.

The flow of water takes place along the steric surfaces rather than along the geometric level surfaces. Distribution of acceleration potential on the isanosteric surfaces gives a better representation of the circulation pattern than the dynamic topographic charts. Sharma[4] arrived at the flow pattern for the intertropical Indian Ocean using the isanosteric analysis at 200 cl/t surface for the southwest monsoon. Hence the current structure in the upper layers of the Arabian Sea is studied by presenting the distribution of acceleration potential on the surfaces of 400 and 200 cl/t for the southwest monsoon.

In order to give an insight to the quantitative assessment of water volume, water flux and stability, distribution of the thickness of the layer 10 cl/t above and 10 cl/t below each surface is also presented.

A special reference is made in this paper to the Somali Current which prevails only during the southwest monsoon as a strong western boundary current flowing northward and also crossing the equator unlike any other western boundary current in any of the major oceans, because of 2 reasons. In the first place, it is the major contributing current for the circulation off the Somali Coast producing the most intense upwelling resulting in a decrease of surface temperature by about 14°C in a span of 2 weeks which is unknown in any other part of the tropical ocean. Secondly, this current identified its path in the subsurface layers indicating a decrease in the strength of the current with depth[5,6].

Materials and Methods

The oceanographic data used are those collected at 250 stations during the International Indian Ocean

*Present address: Department of Marine Sciences, University of Berhampur, Berhampur 760007.

Expedition by various vessels. Station position and the sources of the data are presented in Fig.1.

For each station a graph was drawn with depth and salinity as ordinates against the common abscissa of temperature with overprinted isopleths of thermosteric anomaly. The curves were finally modified and smoothened through the plotted points in consultation with the graphs of neighbouring stations.

The geostrophic flow at an isanosteric surface can be deducted from the gradient of an acceleration potential also known as Montgomery function[7,8]. The expression used for the numerical computation of acceleration potential is

$$\int_{\delta_0}^{\delta} p\, d\delta + p_0\delta_0$$

where p is pressure, δ is steric anomaly and the subscript 0 denotes the value at the reference level. The steric anomaly in the expression above has been replaced with thermosteric anomaly, because the contribution of the pressure terms in steric anomaly to the gradient of acceleration potential is negligible in the region of present study[9], as the maximum depth of the deeper isanosteric surface chosen here (200 cl/t) extends only to 250 m. The modified expression used here for the computation of acceleration potential with thermosteric anomaly is

$$\int_{\delta_{T_0}}^{\delta} p\, d\delta_T + p_0\delta_{T_0}$$

where δ_{T_0} and δ_T are thermosteric anomalies at the reference and required levels of pressure respectively. The reference pressure chosen for the present study is 1000 db. The unit of acceleration potential chosen is Joules per kilogram.

The acceleration potential, for all the 250 stations, was computed using the above expression and plotted on each map. The values of acceleration potential on the 2 surfaces vary from 970 to 1640 J/kg. While plotting the values of acceleration potential the thousand's digit was omitted in order to make the presentation clearer. Smooth isopleths were drawn at an interval of 50 J/kg. The isopleths range from 1150 to 1650 J/kg and 1000 to 1250 J/kg on the surfaces of 400 and 200 cl/t respectively. The isopleths in Figs 2A and B that show the distribution of acceleration potential on 400 and 200 cl/t surfaces respectively, were labelled after dividing the values by 100. Thus they are identified as 10.0, 10.5, 11.0 .... J/kg. The direction of the flow has been marked such that the

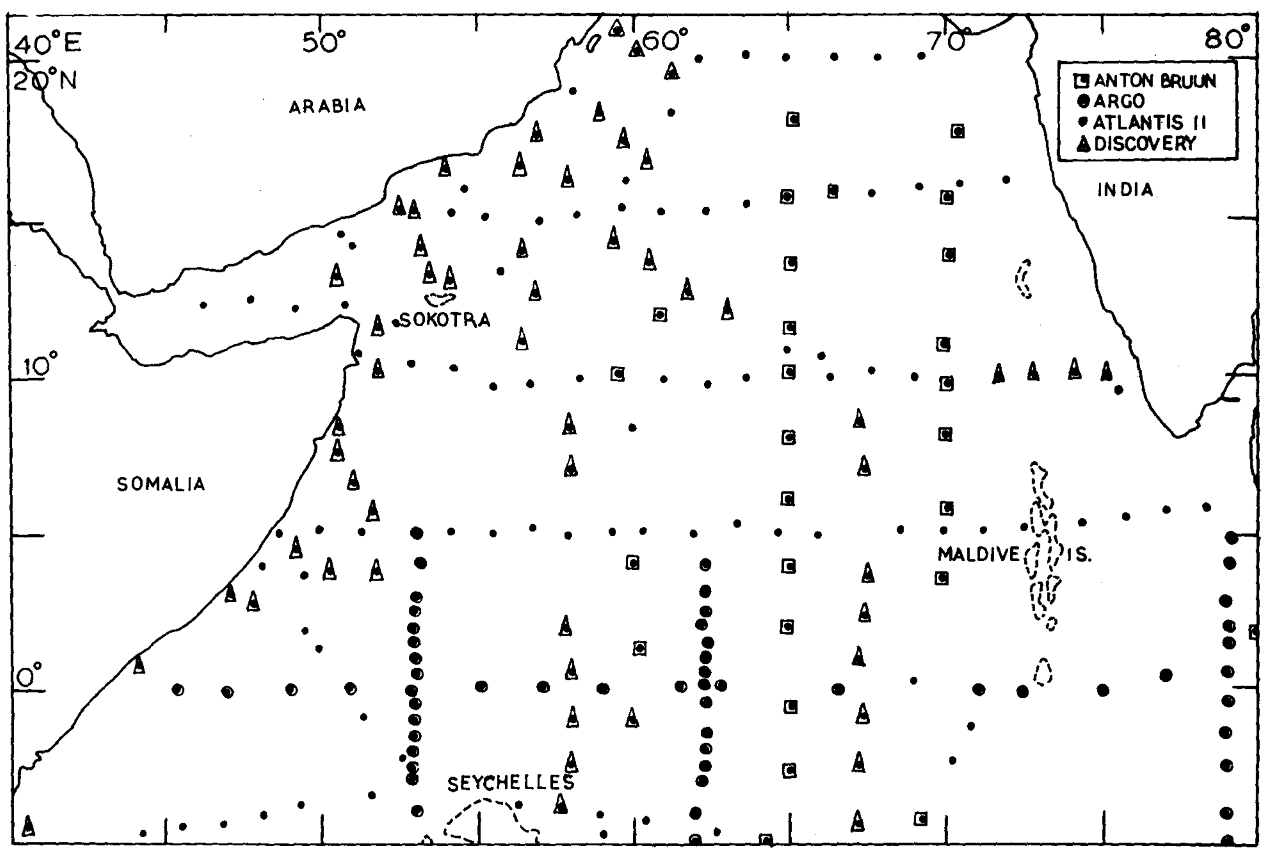

Fig. 1—Station locations and data sources

low values of acceleration potential are on the left hand side in the northern hemisphere and marked reverse in the case of southern hemisphere. The thickness of the layer between 10 cl/t above and 10 cl/t below each surface was read from the station curves and the distribution of the same for 400 and 200 cl/t surfaces are shown in Figs 3A and B respectively.

Results

Geostrophic flow—The geostrophic flow along the isanosteric surface of 400 cl/t relative to the 1000 db surface is given by the gradient of the acceleration potential (Fig.2A). The circulation suggested by the acceleration potential at this surface represents a strong and narrow northerly flow off the Somali Coast, identified by the intense gradient of the acceleration potential. The branching of the Somali Current at about 10°N and 53°E is obvious from the orientation of the contours of the acceleration potential. The general circulation in the central Arabian Sea is found to be clock-wise with a southerly flow off the west coast of India. The westward flowing South Equatorial Current, south of the Monsoon Current, at the southeastern periphery of the chart (Fig.2A) is less indicated. Nevertheless, the cellular structure in between 0° and 5°S appears to be an indication of the boundary between the east flowing Southwest Monsoon Current and the South Equatorial Current. The Southwest Monsoon Current is indicated quite clearly around the equator and also north of it. In the eastern area south of 10°N, the data are sparse, but the eastward flow is a fairly well documented feature on the surface of 400 cl/t. North of the anticyclonic cell there is a hyperbolic point, north of which again there is an anticyclonic tendency. North of 20°N due to lack of data, the complete circulation pattern could not be arrived at.

In the western region of the Arabian Sea the acceleration potential at the 200 cl/t surface with respect to 1000 db surface (Fig.2B) indicates a circulation similar to that seen at 400 cl/t surface, with an exception that the strength of the current is relatively weak on 200 cl/t surface; the horizontal pressure gradients are correspondingly less. The weakening of the current in the eastern Arabian Sea is more conspicuous. But a closer examination of the actual values of the acceleration potential on these 2 charts clearly reveals that the decrease in the strength of the current in the western region is much more than in the eastern region. The broader clock-wise circulation in the central Arabian Sea present on 400 cl/t surface is not noticed on the 200 cl/t surface. Nevertheless, from the magnitude of the acceleration potential on 200 cl/t surface one can infer the presence of the anticyclonic circulation with a relatively higher value centred around 12°N and 68°E. The Southwest Monsoon Current appears to shift southward on the surface of 200 cl/t and so is the South Equatorial Current.

Thickness—Distribution of the thickness of layer of 10 cl/t above and 10 cl/t below the surface of 400 cl/t is presented in Fig.3A. It varies from 1 to 82 m. The contours on this surface were drawn at an interval of 10 m. In order to avoid overcrowding thickness contours were drawn only up to 40 m. However, a letter 'H' is marked in the areas where the contour values exceed 40 m.

The gross features of the thickness distribution of 400 cl/t surface are that the thickness is higher at the regions of boundaries of opposing currents and also in the regions of anticyclonic flow. Thin layers are prominent in the zones of cyclonic flow and where the layer lies within the thermocline.

The thickness of 200 cl/t surface varies from 3 to 53 m (Fig.3B). The isolines on this surface also were drawn at the same interval of 10 m along with the marking of 'H' for the layer thickness exceeding 40 m. It is conspicuous on this surface that the thicker layers are centred near the gyral circulations. It is also interesting to note that where the thickness is higher on 400 cl/t surface, it is less on 200 cl/t surface and vice-versa.

The regions of higher thickness indicate less stability while those of minimum thicknesses reveal highly stable conditions. In the former regions the flux of the water will be more whereas in the latter it will be less.

Discussion

The conspicuous feature common on both the surface is the occurrence of a complex pattern of highs and lows in the distribution of acceleration potential. These alternate cells of highs and lows are indicative of cyclonic and anticyclonic vortices. Such a complex nature is observed even on the dynamic topographic charts at the sea surface by Düing[1]. Although Düing[1] initially attributed the complex pattern to the heterogeneous quality of the data, he could subsequently be convinced that this pattern is inherent in this region by considering the data of a single cruise and also of a particular year. The complex cellular pattern may be due to the strong shear of the Somali Current, and the same shear appears to be responsible for a reverse southerly flow off the coast of Somalia. Furthermore, from a comparison of the distribution of the acceleration potential at the surfaces of 400 and 200 cl/t, it is obvious that apart from the horizontal shear there is a very strong vertical shear present particularly off the Somali Coast. Undoubtedly the vertical shear should have contributed for an intense upwelling off the coast of Somalia and also off the

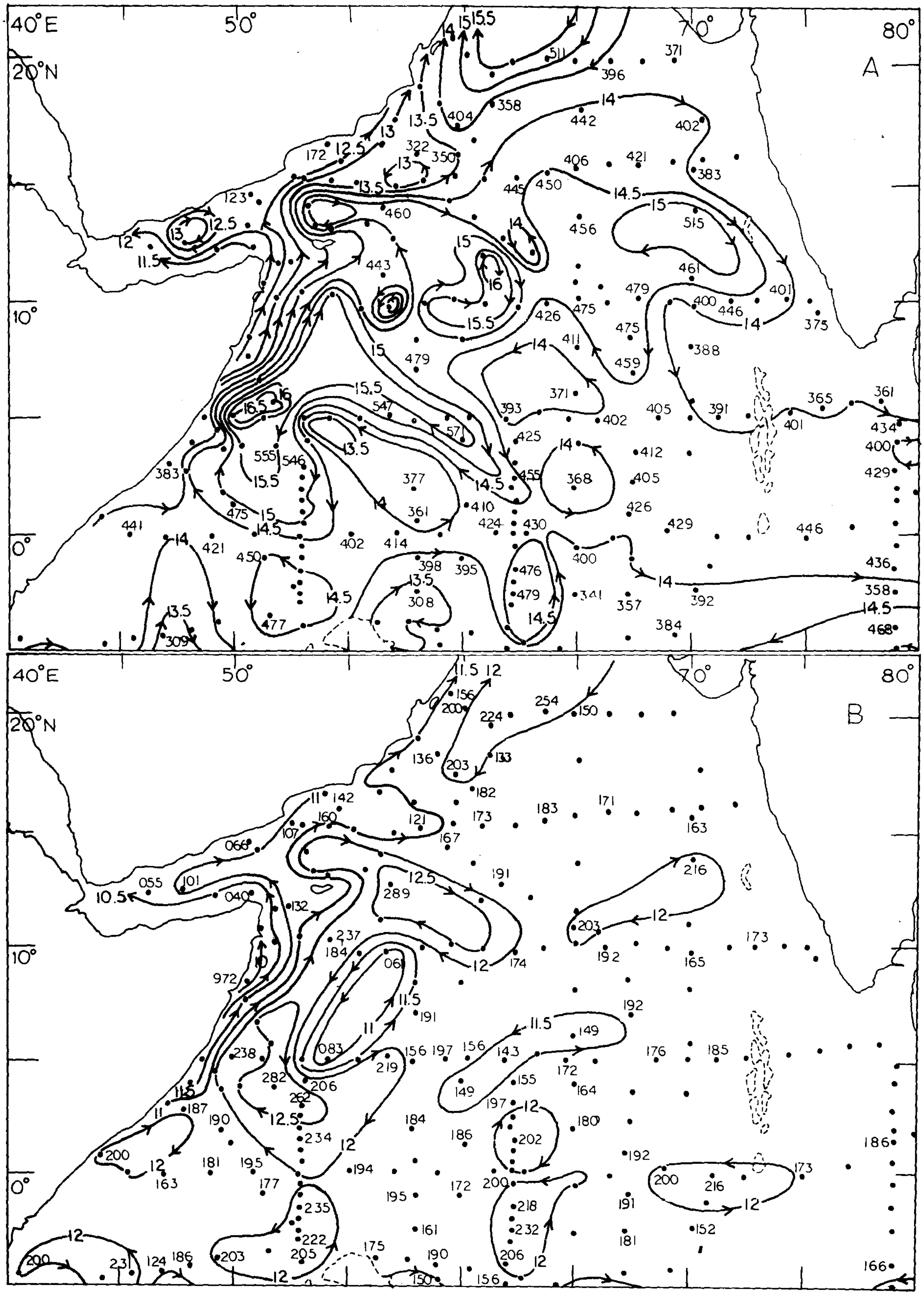

Fig. 2—Distribution of acceleration potential at 400 cl/t (A) and 200 cl/t (B) surfaces

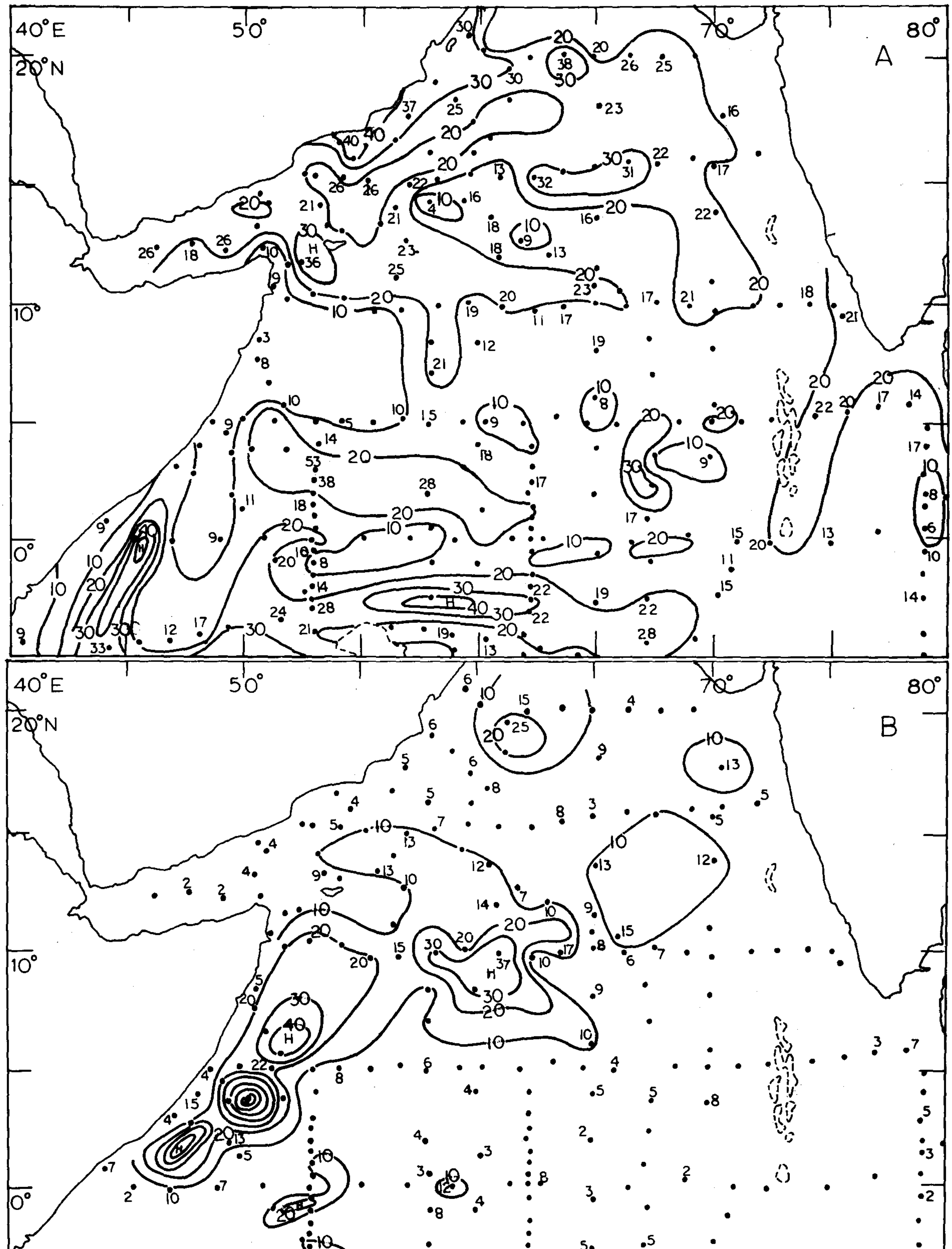

Fig. 3—Thickness in meters of 400 cl/t (A) and 200 cl/t (B) surfaces

Arabian Coast during the southwest monsoon. The eddies present south of the equator on both the surfaces are the consequence of the boundary between the Southwest Monsoon Current and the South Equatorial Current.

Relatively greater thickness between 0° and 5°S and 400 cl/t surface is related to the boundary of the Southwest Monsoon and the South Equatorial currents where the vertical mixing predominates resulting in a homogeneous layer. The flux within such a layer is significantly large. A narrow strip with a thickness greater than 30 m near Socotra on this surface represents a relatively less homogeneous and less stable layer associated with the anticyclonic cell in which the thermocline spreads. The minimum thickness of the Somali Coast roughly coincides with the core of the Somali Current deduced from the field of acceleration potential (Fig.2A). This small thickness represents the water within the thermocline which rises nearer to the surface because of strong upwelling off the Somali Coast during the southwest monsoon. A similar minimum, though less pronounced in the southcentral Arabian Sea is associated with the cyclonic cell around 7°N and 65°E. This great stability comes from the lower part of the sharp thermocline which ascends nearer to the surface because of diverging flow in the anticyclonic cell (Fig.2A).

The greater thickness off the Somali Coast on 200 cl/t surface is evidently due to the presence of this surface at the bottom of the thermocline where homogeneous characteristics water prevails vertically. It is because of a similar reason alone another thicker layer occurs in the central Arabian Sea with its centre around 10°N and 60°E. In the rest of the region under study the narrow thickness, may probably be because of this layer lying within the thermocline where the stability is very high and also there is less possibility for any vertical mixing.

As stated in the introduction none of the earlier studies on circulation in this part of the India pertains to the flow along the isanosteric surfaces, but only along the geometric surfaces and so a close comparison of those with the present is not feasible. Nevertheless, the general features can be discussed. The occurrence of alternate lows and highs representing the cyclonic and anticyclonic vortices are common in the earlier works[1-3,10] as in the present study. One interesting feature that is observed on the dynamic topography of the surface in the Arabian Sea for the summer of 1963 presented by Düing[1] differs much from the rest of the charts. This difference is attributed mainly to the abnormal conditions of the atmospheric circulation during the summer of 1963 compared to other years[11,12]. During this particular year alternate cells in the Arabian Sea showed more meridional orientation than zonal. The horizontal and vertical current shear off the Somali Coast that can be inferred from the acceleration potential gradient on the surfaces of 400 and 200 cl/t could also be noticed in the vertical sections of others[2,3,10]. Northward shift of the South Equatorial Current to the northernmost latitude during southwest monsoon is also obvious from the dynamic topographic charts of Bruce[10].

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