STUDIES ON OXYGEN MINIMUM LAYER IN THE ARABIAN SEA IN RELATION TO THE OCEANIC CIRCULATION

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"to my beloved husband"

C E R T I F I C A T E

This is to certify that this Thesis is an authentic record of research work carried out by Mrs. A.C. Chandra Prabha, M.Sc., under my supervision and guidance in the School of Marine Sciences for the Ph.D. Degree of the Cochin University of Science and Technology and no part of it has previously formed the basis for the award of any other degree in any University.

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P R E F A C E

"Circulation is responsible for aeration of The Deeps, without which all but the uppermost stratum would be a waste more desert than the Sahara"

H.G. Bigelow

Marine Scientists believed that the deeper parts of the oceans were anoxic because the main source of oxygen for the oceans is the atmosphere and the concentration of dissolved oxygen decreases exponentially with depth in the oceans, thus making life to be non-existent in the deeps. However, in the latter half of the nineteenth centuary, it was realised that life existed even in the deepest parts of the oceans. The presence of high concentrations of oxygen at great depths, caused by the return flow of waters from high to low latitudes in the deeper layers and oxygen minimum layer at intermediate depths were discovered.

The occurrence of oxygen minima at intermediate depths is, probably, the most striking feature of the oxygen distribution in the oceans. The existence of oxygen minima is a permanent feature, which plays a major role in the vertical migration of the biota and in mass mortality, particularly in the tropical and middle latitudes.

The North Indian Ocean is unique in various aspects of the physical processes that take place within it which are, in turn, responsible in controlling the characteristics of the waters. This uniqueness results from the influence of monsoonal winds prevailing over this area; it is a characteristic, especially of the Arabian Sea (western North Indian Ocean), with many unparalleled observations - the highest productivity among the various oceanic areas in the tropical belt; the most intense upwelling resulting in a fall of about fourteen degrees in temperature, a record among those in any tropical ocean; the strongest current observed off the Somalia Coast with record strength; and the shallowest occurrence of the oxygen minimum layer with the lowest concentration of oxygen within it, uncommon in any part of the World Oceans.

Hitherto, a few investigations on the biological and chemical aspects of the oxygen minimum layer were carried out; but no attempts were made to study it in relation to the circulation which is the main factor responsible for the aeration of the oceans, as Bigelow (1931) rightly pointed out. Besides, various diversified explanations are in vogue regarding the formation and variation with depth of the oxygen minimum layer, and the concentration of oxygen within it. Thus, there is an immediate need for a detailed study on the oxygen minimum layer in the Arabian Sea in relation to circulation.

The thesis is divided into six chapters, with further subdivisions.

Chapter one has two sections. Section one deals with a general introduction, and section two, with the material and treatment of data for the present investigation.

The second chapter concerns with the distribution of oxyty in the oxygen minimum layer and its topography during the southwest and northeast monsoons.

The distribution of oxyty at various isanosteric surfaces within which the oxygen minimum layer lies during southwest and northeast monsoons and their topographies form chapter three.

In the fourth chapter the flow pattern and its influence on the oxygen minimum layer are discussed.

The fifth chapter presents the scatter diagrams of oxyty against temperature at the various isanosteric surfaces.

The sixth chapter summarises the results of the investigation and presents the conclusions drawn therefrom.

CHAPTER - I

CHAPTER - I

SECTION - I INTRODUCTION

The oxygen content in the oceans is mainly derived from the atmosphere, apart from the biochemical processes, taking place within the oceans. The ocean surface exchanges the dissolved oxygen with the atmosphere and thus, the concentration of oxygen at the ocean surface maintains an equilibrium with that of the atmosphere. But at subsurface depths, to the extent of the depth of penetration of light, oxygen is added by photosynthesis. In the photic zone the oxygen content may increase appreciably above that found at the surface and in many places reaches supersaturation. Rakestraw (1933) found that 20-40 metre of the Gulf of Maine were invariably "supersaturated" in August 1932. At depths down to the "compensation depth" photosynthetic production of oxygen exceeds its respiratory consumption, by definition, and at the layer below this depth the net change is a loss of oxygen, eventhough photosynthetic production continues. The penetration of light is probably, the most important factor in determining the compensation depth, but temperature, differences in species of plankton and nutrient supply are also important (Richards, 1957).

With the flow of surface waters from low to high latitudes and decrease of temperature towards the poles the oxyty (concentration of dissolved oxygen, Montgomery, 1969) in the surface layers increases poleward as the absorbing capacity of oxygen by the water increases with the decrease of temperature. Thus, the replenishment of oxygen to the deeper parts of the oceans (below the main thermocline) is brought about by advection, in which cold, high oxyty water, formed and sunk in the high latitudes is carried to greater depths and lower latitudes by subsequent vertical and lateral movements. Therefore, the ocean may be subdivided into three layers. The upper layer is well ventilated by its contact with the atmosphere and the oxyty of the water is maintained at high level. The bottom layer is also of high oxygen content due to the effect of deep water circulation from high to low latitudes. The intermediate layer has a depleted oxyty, thus, the minimum oxygen concentration occurs at mid-depths and is represented graphically by the principal point of inflexion of the curve, characterising the vertical distribution of oxygen. In general, this minimum concentration has been observed to occur between depths 200 and 900 m in the

Atlantic and has been traced between 40°S and 50°N (Seiwell, 1937a). But in the high latitudes, no such oxygen minimum layer is formed because, in these regions the vertical variation of oxyty is minimal and its variation is monotonic downward when compared with that in low latitudes.

The oxyty of the aqueous environment is contrasting with that of the atmosphere. In the lower layers of the atmosphere, oxygen constitutes about 200 ml/l with more uniformity, but the maximum in seawater is about 9.0 ml/l and ranges between this value and almost nil. Besides, the distribution of oxygen differs from that of the conservative properties in the ocean, viz, temperature and salinity. The variation of oxygen has important effects on the biota in the environment and various factors are responsible for such variation.

In the early investigations, many scientists believed that the deeper parts of the oceans must be anaerobic and azoic. But in the latter part of the nineteenth century, it was realised that the oxyty was present at greater depths and life existed even in those layers (Thompson, 1874). The widespread occurrence of minimum concentrations of oxygen at intermediate depths is, probably, the most striking feature in the vertical distribution of oxygen. The existence of the oxygen minimum layer, its formation and maintenance in the oceans are fascinating problems to be studied in oceanography.

1.1.2 Factors controlling the oxygen minimum layer

The distribution of oxygen in the oceans depends on the processes which (1) add oxygen to the surface (2) consume oxygen by respiratory, chemical and enzymatic oxidation and (3) distribute it to all depths by various physical processes (Gaarder, 1927; Wattenberg, 1927; Sverdrup, 1929; Bigelow, 1931; Vaughan, 1940). Various explanations were offered for the formation and maintenance of the oxygen minimum layer in the oceans. Jacobsen (1916), Wust (1935) and Dietrich (1936, 1937) remark that the oxygen minimum layer forms because of the circulatory processes, and at the oxygen minimum layer the replenishment of oxygen by mixing and circulatory processes is at minimum, and the same concept was supported by Parr (1939). Bigelow (1931) made a specific remark "circulation is responsible for the aeration of The Deeps, without which all but the uppermost stratum would be a waste more desert than Sahara". Seiwell (1937a) also subscribed to the idea of Wust (1935) and Dietrich (1936, 1937) that circulation was the main factor for the formation of oxygen minimum layer. Besides, he concluded that the vertical variation of an oxygen minimum layer was closely related to the horizontal divergence and convergence. But Seiwell (1937b) and Sverdrup (1938) point out that in the Gulf Stream System, the oxygen minimum zone does not coincide with the minimum in mixing and horizontal replenishment processes, and explains that the oxygen minimum layer is exclusively formed and maintained by the biological processes rather than circulation. Such a concept is further affirmed by Sverdrup and Fleming (1941).

Thompson et al. (1934) puts forth yet another theory that the minimum zone can arise from excessive consumption in the bottom waters which move away and afloat to the upper layers. They postulated that, contact with the bottom itself should result in decreased oxygen concentration as is demonstrated in many parts of the oceans, and the water thus, depleted can move outward and find an equilibrium at intermediate depths. This type of movement appears to have been occurring in the Labrador Sea. Thompson and Barkey (1938) find the evidence that waters deoxygenated at the bottom are found at intermediate levels in certain fjords on the western Canadian Coast.

Redfield (1942) introduces a new concept that the oxygen minimum occurs in that layer of water which bore maximum amount of organic, oxygen-consuming material at the time of its sinking in high latitudes. The density of this water is such that it moves at intermediate depths, and upon oxidation of its organic burden, its oxygen content drops well below that of the waters above and below it. Thus, the concentration of oxygen can be explained by isentropic mixing.

Richards (1957) in a detailed review of oxygen in the oceans, although initially admits that the distribution of oxygen is chiefly a matter of circulation, finally concludes, supporting the opinion of Sverdrup (1938) that the oxygen minimum layer is the consequence of exclusively biological processes rather than circulation. Wyrtki (1962) is very critical of the conclusion of Richards (1957) in support of Sverdrup, ignoring those of Wust (1935) and Dietrich (1936, 1937). He arrives at an opinion that the consumption of oxygen is the first necessary condition for the development of oxygen minimum layer, and the minimum is caused biochemically, but the depth of oxygen minimum layer is determined by circulation, minimum occurring in layers of minimum advection of oxygen which are closely related to the horizontal movements. The oxygen minimum itself lies in the upper part of the layer of smallest advection because the consumption of oxygen decreases almost exponentially with depth. Thus, biochemical processes are responsible for the formation of oxygen minima, but circulation is responsible for its position.

Subsequently, Skopintsev (1965) and Bubnov (1967) postulated that the oxygen minimum of the Atlantic may be formed, entirely, in the eastern regions and the low oxygen water is distributed along the isentropic surfaces, mixing with higher oxygen water to the west, south and north. Menzel and Ryther (1968), based on the concentration of hydrographic observations and applying the dominant controlling factors, contradicts the hypothesis of Sverdrup (1938) and Sverdrup and Fleming (1941) and supports Wyrtki (1962) that the oxygen minimum is caused biochemically and its position is determined by circulation.

Meanwhile, Miyake and Saruhashi (1956) as a result of the study on the vertical distribution of dissolved oxygen in the ocean, arrives at the conclusion that the essential factors determining the vertical variation of dissolved oxygen and the occurrence of the oxygen minimum layer are the local productivity and the vertical density distribution of subsurface waters. By the latter, the depth of oxygen minimum layer is determined and former the extent of oxygen deficit, and the generation of carbon dioxide. In their subsequent paper (Miyake and Saruhashi, 1967), they conclude that the effect of horizontal advection on the distribution of dissolved oxygen is much larger than those of horizontal diffusion and biological consumption, and the former is mainly compensated by vertical diffusion.

1.1.3. Description of the area

The Arabian Sea is the northwestern part of the Indian Ocean covering an area of approximately 7.5 x 10^6 km^2 (Fairbridge, 1966)(exclusive of the Gulf of Aden and Oman) and bounded by the African and Asian continental landmass on three sides with an opening in the south with an oceanic region and the equator as the southern boundary. It is connected with the two marginal seas namely the Red Sea and Persian Gulf through sill depths of about 125 m at the Strait of Bab-el-Mandab through Gulf of Aden and 50 m at Hormuz Strait respectively. These two marginal seas are characterised with extremeties of salinity, nutrients and oxyty due to excessive evaporation over precipitation resulting in the characteristic watermasses of these seas, penetrating into the subsurface depths of the Arabian Sea after the entry through the corresponding sill depths.

Arabian sea is unique in many respects that the record current strength of more than 3.5 ms^{-1} in any part of the world oceans, off the Somalia Coast was measured during the R.R.S. Discovery II cruise in 1964 (Swallow and Bruce, 1966) and it is one of the most productive zones of the tropical oceans of the world. It is another record fall of temperature from 29^{o}C to 14^{o}C due to upwelling that is unobserved in any tropical region of the oceans. Furthermore, a frequent mass mortality is observed as a result of either anoxic condition or extremely low temperature caused by very intense upwelling off the Somalia and Arabia coasts.

The Arabian Sea is dominated by the periodic reversal of the monsoon wind system and the conditions in the upper layers of the sea vary considerably due to the varying winds. During summer, the strong southwesterly winds of the southwest monsoon prevail, while in the winter the northeasterly winds of the northeast monsoon blow. Of these two monsoons, the influence of the southwest monsoon is stronger and steadier for a longer period compared to the weak, less steady and less duration of the northeast monsoon over the Arabian Sea. During the spring (March-April) and autumn (September-October) transition periods, the winds are very weak and unsteady. As a result of the prevailing winds, the surface circulation is anticyclonic during the southwest monsoon when the strong Somalia Current and upwelling along this coast prevail, while cyclonic circulation is present in the northeast monsoon. The peculiarity in the transition of the wind system and the oceanic circulation is that the reversal of the oceanic circulation from the northeast monsoon to the southwest monsoon preceeds the wind reversal whereas both reversals are in phase during the autumn transition. Because of the abnormal features associated with the Arabian Sea, it forms a key region of the world oceans for theoretical as well as synoptic studies and is a natural laboratory to study the time dependent processes for oceanographers, because of its uniqueness with multifarious phenomena taking place in a single region. For the present study, the marginal seas viz. the Red Sea and Persian Gulf are excluded and the southern boundary is the equator.

1.1.4. Oxygen minimum layer in the Pacific and Atlantic

Although certain studies on the oxygen minimum layer were earlier carried out in the world oceans, it is since the time of Challenger Expedition (1872 - 1876), the investigations on the distribution of dissolved oxygen in the oceans gained importance. The important studies which contributed significantly to the knowledge were reviewed under introduction. In the present section the formation of oxygen minimum layer and the variation of oxyty within it and also its vertical migration in the Pacific and Atlantic Oceans are briefly presented.

While reviewing the watermass structure in the oceans, Worthington (1981) made a categorical mention that Tsuchiya's (1968) description of upper waters of the Intertropical Pacific Ocean through isanosteric analysis is the finest use of this method and also remarked that the spreading of the oxygen minimum layer in the Intertropical Pacific Ocean as interpreted by Tsuchiya (1968) can still stand superior to some other studies made even subsequently. Hence, for the present review of the distribution of oxygen minimum layer in the Pacific Ocean, the results of Tsuchiya are mainly considered and they are supplemented with the results of others (Reid, 1965; Judkins, 1980) and the Russian Atlas (Anonymous, 1976).

According to Tsuchiya (1968), the oxygen minimum layer in the Intertropical Pacific Ocean is present everywhere and it lies between the isanosteric surfaces of 80 and 250 cl/t and varies from place to place. In combination with the oxygen distribution on vertical sections and on isanosteric surfaces of 80 and 125 cl/t(Reid, 1965) the distribution of oxygen minimum layer in the whole of the Pacific Ocean can be arrived at.

Tsuchiya (1968) stated that near the coast of Central and South America there is low oxygen in a thick layer below about δ_T = 200 cl/t surface with traces of oxyty, above which an intense vertical gradient develops. To the far southwest, the gradient is weak and the oxygen at the minimum is well above 3.0 ml/l. From a comparison of the topographic charts, it can be noticed that the oxygen minimum layer in the Pacific lies in the depth range of about 50 m in the equatorial region and about 1200 m in the higher latitudes. In general, the oxyty in the oxygen minimum layer in the northern hemisphere is lower than that at the corresponding latitudes in the south, except off the coast of Peru where the lowest values are recorded at the shallower depths. Judkins (1980) also remarked that in the region off Peru the oxygen minimum occurs within 50 to 65 m of the surface. Further, the concentration of oxygen as well as the depth of occurrence decreases from west to east in the Pacific Ocean. Another important feature is the frequent appearance of a double oxygen minimum, one in shallow waters and the other in the deep in the northern hemisphere. Such a double minimum is not so frequent in the southern hemisphere at about similar latitudes of 4^o to 10^oS (Tsuchiya, 1968).

A comparison of the oxyty distribution on different potential thermosteric anomaly surfaces in the northwestern Pacific, worked out by Reid (1973), clearly reveals that the oxygen minimum lies on 80 cl/t and its depth in this region ranges from 500 to 900 m, with an average depth of 600 m. According to the Russian Atlas (Anonymous, 1976) also, the oxyty and the depth of occurrence of the minimum layer increase towards south. The lowest oxyty, observed in the northern hemisphere is 0.1 ml/l while it is 0·45 ml/l in the southern hemisphere.

Compared to the Pacific Ocean, literature on the distribution of oxyty in the oxygen minimum layer is less for the Atlantic Ocean. The lowest oxygen values in the Atlantic, according to Montgomery (1938) and Bubnov (1966), develop along the eastern tropical coast of South Africa. According to the Russian Atlas (Anonymous, 1977), the oxyty in the minimum layer decreases towards the tropics from the north and south. In general, the oxygen minimum layer in the North Atlantic is shallower compared to the corresponding latitudes in the south and the oxyty within it is lower in the north.

In their paper Reid et al. (1977) have discussed the characteristics of dissolved oxygen distribution in the southwestern Atlantic Ocean.

They found the average depth of occurrence in this region to be 1200 m with oxyty as high as 4.3 ml/l which shows that in the southwest Atlantic, oxyty as well as the depth of the minimum layer is greater. The meridional section along $40^{o}W$ ($20^{o}S$ to $66^{o}S$) shows that the oxygen minimum extends across the Circumpolar Current into the Weddel Sea. The minimum layer seen in the Circumpolar Current, is split into two minima north of $50^{o}S$ by the thick maximum layer extending southward from the North Atlantic.

A study of the oxygen-density (σ_t) correlation in the western North Atlantic, particularly in the Gulf Stream was carried out by Richards and Redfield (1955) and according to them the oxygen minimum occurs at σ_t = 27.3 surface. Menzel and Ryther (1968) found in the Southwest Atlantic that the oxygen minimum occurs at the σ_t surfaces between 26.8 and 27.2.

1.1.5. Oxygen minimum layer in the Indian Ocean

It is well known that the oxygen content in the layers within the thermocline is extremely low in the North Indian Ocean, especially in the Arabian Sea. It can be inferred from the Russian Atlas (Anonymous, 1977) that oxyty in the oxygen minimum layer is extremely low in the North Indian Ocean. Values less than 0.56 ml/l (0.05 mg at/l) occur in the tropical region. The oxyty in the minimum layer and its depth of occurrence increases towards south. In the South Indian Ocean, higher oxyty is observed in the minimum layer which is at greater depths. According to Warren (1981), the layer of low oxygen centred at about the 200 m level attenuates southward from the equator to about 25°S in the South Indian Ocean. Taft (1963) remarked that the isanosteric surface on which the oxygen minimum layer forms in the Indian Ocean is very much different from that in the Pacific and Atlantic Oceans.

During the John-Murray Expedition of 1933-34 (Gilson, 1937) a well defined oxygen minimum was observed in the central and northern Arabian Sea. Clowes and Deacon (1935) reported an oxygen minimum between the 100-300 m layer, with oxygen concentrations less than 0.80 ml/l at 8°N and further stated that at 11°S this minimum with increased oxyty of 2.0 ml/l was found at higher depths (1200 m).

The oxygen minimum in the Arabian Sea was observed to be between 125 and 200 m depths by Vinogradov and Voronina (1962). It was also observed that the oxyty was extremely low in this region such that it varied between 0.09 ml/l and 0.15 ml/l. They also stated that the thickness of this layer was upto 1000 m in certain areas.

The occurrence of the oxygen minimum in the upper 500 m of the Arabian Sea was worked out by Rao and Jayaraman (1970), during the pre-monsoon,southwest monsoon, post-monsoon and northeast monsoon. They found that during the pre-monsoon, the topography varied between 120 and 500 m and during the southwest monsoon, between 75 and 400 m. It ranged from 100 to 500 m and 150 to 500 m during post-monsoon and northeast monsoon respectively. Sen Gupta et al. (1975) stated that the shallower oxygen minimum in the Arabian Sea was found between the depths 100 and 400 m. The oxyty observed by them in the northern Arabian Sea ranged from 0.10 ml/l to 0.30 ml/l. In the Arabian Sea, north of 18^{o}N, a double minimum was reported, with the deeper one lying between 1000 and 1500 m (Sen Gupta et al., 1976b). Sharma (1976b) found out the oxyty minimum at about 150 m which protruded as a tongue from the

Arabian Sea towards the equator during the southwest monsoon. According to Swallow (1984), dissolved oxygen concentration is low in the subsurface layers of the Arabian Sea, with concentrations less than 0.20 ml/l between 200 and 1000 m.

SECTION - II: MATERIAL AND TREATMENT OF DATA

Choice of data

Majority of the material used in the present study came from the data collected on board various research vessels during the International Indian Ocean Expedition, conducted during 1960-65. These data were supplemented with those, collected subsequently, in the locations where there is paucity of data. It is noteworthy that the data in certain areas like the western region of the Arabian Sea are so close that a selectivity is to be made. As a result, care has been taken to see that the stations are evenly distributed and preference is given as far as possible to those that were collected during the same cruise and same year so that heterogeniety of the data is minimised. Even with this basis, it became sometimes inevitable to choose the data arbitrarily to have an even coverage. Because of abnormality in the weather as well as in oceanographical conditions in 1963 (Uda and Nakamura, 1973), the data, collected in 1963 have been avoided as far as possible.

The oceanographic conditions in the Arabian Sea are mainly controlled by the semiannual reversal of the monsoon winds that in turn alter not only the surface circulation, but also influence the subsurface physical properties of the seawater in the Arabian Sea. It is, therefore, imperative that clubbing of the data in various months into a single chart leads to complicated pattern and ultimately leads the interpretation of the data to almost meaningless results. Hence, it is decided to bifurcate the data into two groups, one representing the southwest monsoon that were collected, May through early September and November through February, representing the northeast monsoon conditions. As March-April and late September-October form the spring and autumn transitions respectively, the oceanographic conditions in the area under study are more or less unsteady and therefore, the data collected during the transition months are omitted although such data would have filled the gaps where there is scarcity, as it amounts sacrificing the proper interpretation for the steady conditions of the two monsoons.

Before, finally, choosing the data the International Indian Ocean Expedition Atlas (Wyrtki, 1971) has been consulted for the quality of the data and accordingly, some data that are considered as inferior, particularly, in the estimation of oxyty are eliminated, as the main aim of the present study pertains to the oxygen minimum layer in relation to the oceanic circulation in the Arabian Sea.

The details of the oceanographic data used for the southwest and northeast monsoons are presented in Tables 1 and 2, while their geographical positions with different notations of the collecting vessels are shown in Figs. 1 and 2 respectively. From these figures, it is clear that there are wide gaps in the coverage of the data in the northernmost region during the southwest monsoon and in the southcentral region during both the seasons.

1.2.2. Methods of describing the oceans

Worthington (1981) gave a detailed account of describing the oceanic properties. According to him, the simplest and the most universally used method has been the preparation of vertical profiles of temperature, salinity, oxyty or some other variables constructed

TABLE 1 . LIST OF STATIONS USED FOR THE STUDY DURING THE SOUTHWEST MONSOON

Name of the vessel	Symbol used	No. of stations	Period
1. Discovery II	◬	51	1st May 1964 to 19th August 1964
2. Atlantis II	●	73	4th August 1963 to September 23rd 1963
3. Argo	⊙	30	11th July 1962 to 1st September 1962
4. Anton Bruun	⊡	21	August 18th 1963 to 17th May 1964
5. Okean	⛛	36	23rd May 1973 to 8th July 1973
6. Pioneer	◎	6	24th May 1973 to 26th June 1973

TABLE 2. LIST OF STATIONS USED FOR THE STUDY DURING THE NORTHEAST MONSOON

	Name of the vessel	Symbol used	No. of stations	Period
1.	Darshak	◬	20	5th January 1974 to 25th February 1974
2.	Vitiaz	⊙	71	24th January 1960 to 12th December 1960
3.	Meteor	⊡	34	16th December 1964 to 10th March 1965
4.	Anton Bruun	⊕	26	24th February 1963 to 9th February 1964
5.	Academic Korelov	▽ (with dot)	13	31st January 1973 to 5th February 1973
6.	Discovery	▲	8	10th March 1964 to 15th March 1964
7.	Atlantis	●	25	26th February 1965 to 15th March 1965

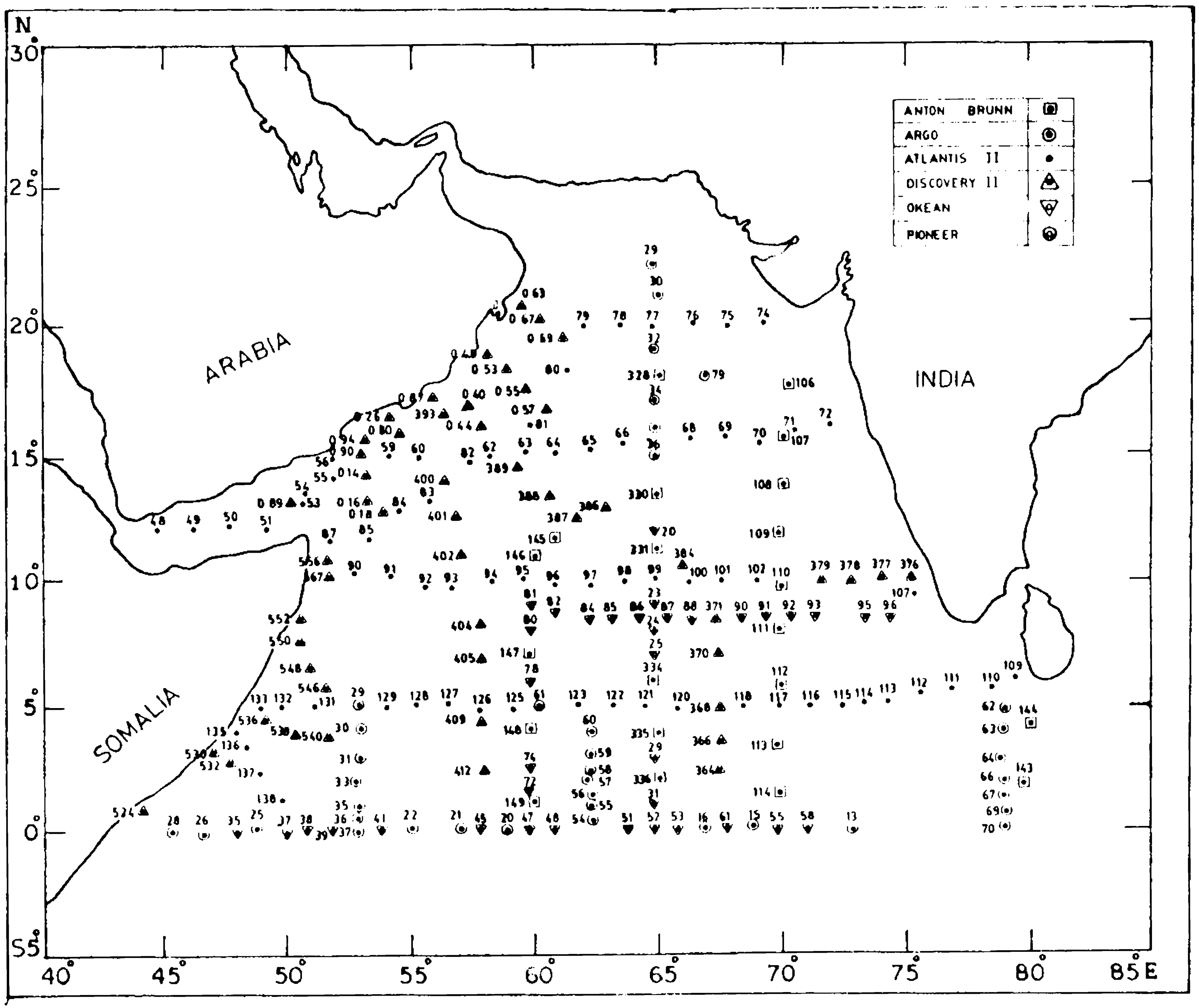


FIG: 1 . STATION POSITIONS DURING THE SOUTHWEST MONSOON

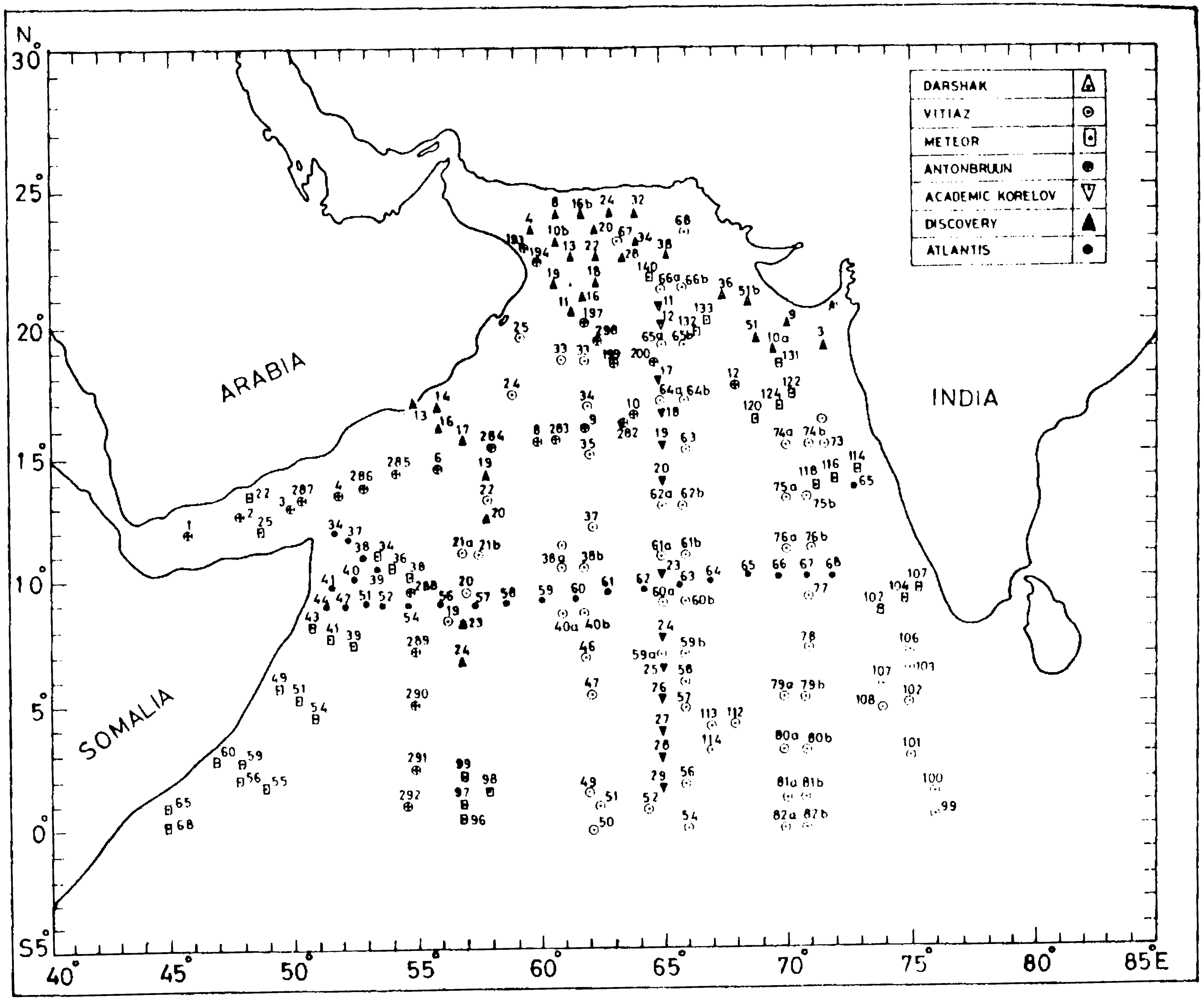


FIG: 2 . STATION POSITIONS DURING THE NORTHEAST MONSOON from oceanographic sections, made across the ocean or part of an ocean, from a single ship or a number of ships. Oceanwide hydrographic profiles have been drawn by oceanographers since Thompson's (1877) treatment of the Challenger sections, but the standard excellence for this kind of presentation was set by Wust and Defant (1936) in their atlas of temperature, salinity and density profiles from the "Atlantic Meteor Expedition" of 1925-27 and Wattenberg (1939) who prepared the dissolved oxygen profiles. Later, many investigators followed this method of describing the oceanic properties and many atlases have been prepared presenting the vertical profiles of properties. According to Worthington (1981), the juxtaposition of the different watermasses can easily be delineated in the vertical profiles.

Although, presentation of physical and chemical properties of the oceans is the simplest and best in the vertical sections, the main drawback in this method is to understand the spatial variation of these properties. Further, unless the sections are along straight lines they are likely to give scope for misinterpretation in spatial variation and their utility has a limited scope when the purpose is to describe the oceanographic properties in space, which is possible by clubbing a number of sections taken in straight lines and cutting across each other that is not only cumbersome, but also very expensive to spend the shiptime. Worthington (1981) remarks "Composite vertical profiles are often drawn from data provided by a number of ships from different years or even different decades. Such sections are, of course, less useful for dynamic studies but sometimes provide an excellent description of the water. I find such profiles difficult to read, but that may be idiosynchratic".

Alternatively, the use of "core layer" method to describe ocean waters is almost wholly due to Wust (1935), his students, and to a lesser extent, Defant (1936). In ~~this~~ his classic description of the Atlantic, Wust (1935) identified seven such core layers, characterized by maxima or minima in oxygen, salinity and temperature. Worthington (1981), while remarking the unquestionable value of this method in the study of spreading of these layers points out the criticism of Montgomery (1938) that these layers are few in number whereas the number of potential density surfaces (which Montgomery prefers) is infinite. The core method had its initial application in a wide variety of studies, particularly, in spreading of the watermasses from different sources either with salinity maxima or minima like that of the Mediterranean Sea, Caspian Sea, Red Sea, Persian Gulf etc. But another drawback in the core method is that core layers are often uncertainly assumed to be main paths of ocean circulation (Worthington, 1976). With the measurements of currents associated with the hydrographic observations, made by Steele, Barrett and Worthington (1962), Worthington and Volkman (1965) and Swallow and Worthington (1969), they come to the conclusion that the core method unambiguously leads to misleading results.

Rochford (1964), Varadachari et al. (1968) and Wyrtki (1971) worked out the spreading of the Red Sea, Persian Gulf and Arabian Sea waters to the south of the equator and even into the Bay of Bengal based on the core method. Warren et al. (1966) remarks that the core method, although, gives some interesting results in the Atlantic, it leads to complicated conclusions in the Indian Ocean because of the complexity of the spreading of various watermasses in the Arabian Sea from various sources. Sharma (1976a) has been very critical of the results arrived by Rochford (1964), Varadachari et al. (1968) and arrived at the conclusion based on the volumetric analysis (Montgomery, 1958) that the watermasses originating in the Red Sea and Persian Gulf do not cross the equator. Hence, it is concluded that the core method in the North Indian Ocean arrives at misleading interpretation.

The concept that the buoyancy forces in a stratified fluid may influence flow and mixing to conserve density more than any other characteristics has been a topic of interest for long time. Examination of characteristics along surfaces, defined by various density related parameters began in the 1930s, both for the atmosphere and oceans. Various quantities (σ_t, σ_θ, δ_T, δ_θ and σ_1, σ_2, σ_3 ... referring the density to 1000, 2000, 3000 db.....) have been employed and the method has been called "isentropic", "isosteric", "isanosteric", "isopycnic" and "isopycnal" analysis (Reid 1981). According to Reid, none of these quantities is entirely satisfactory because surfaces so defined can represent mixing or spreading surfaces only in various approximations. The problem, of course, is that while such spreading may take place predominantly along such definable surfaces, it need not and cannot exactly preserve any chosen density parameter. Density is also altered by mixing processes, as an examination of characteristics along such isopycnal or steric surfaces makes obvious. The assumption of maximum mixing and flow along such surfaces remains an assumption, but it has been accepted as one of the useful concepts in studying the oceans (Reid, 1981). Worthington (1981) also made a critical review of this technique and finally concludes that it has been a useful qualitative tool for describing the oceans, since, waters of different origin on the same steric surface usually contain widely different concentrations of variables, such as salinity,dissolved oxygen and nutrients.

The initial major studies, using the method of isentropic analysis, were those of Montgomery (1938) and Parr (1938). Both of these dealt with the upper levels of the ocean, where a simple density parameter such as σ_t could be used. At greater depths, the choice becomes more difficult. In such cases σ_1 , σ_2 are more useful (Reid, 1981). Prominent studies, carried out, incorporating the method are those of Taft (1963), Reid (1965), Tsuchiya (1968), Buscaglia(1971)

Callahan (1972), Sharma (1972) and Sharma et al. (1978) in the three major oceans. Of course, there are many more papers published adopting the "isentropic" "isopycnic", "isosteric", "isanosteric" or σ_t , σ_2 .... surfaces.

Montgomery and Wooster (1954) arrives at a conclusion that for the purpose of describing the upper layers of the oceans, steric anomaly can be replaced by thermosteric anomaly, as the contribution to the steric anomaly due to pressure effect is insignificant, particularly, in the tropical oceans. In the Arabian Sea, the oxygen minimum layer is mainly confined to the upper layers although a secondary minimum at deeper layers is also reported at some places (Sen Gupta et al., 1976a). As the present study aims at the identification of the upper oxygen minimum, its formation and maintenance, it is preferred to incorporate the isanosteric analysis.

1.2.3. Procedure

For each station, graph was constructed with temperature as a common property on the abscissa against depth, salinity and oxyty on the ordinate with overprinted isopleths of thermosteric anomaly. Smooth curves were drawn through plotted points. Station curves were drawn for 217 and 197 stations that were occupied during May to early September and November to February that represent the southwest monsoon and northeast monsoon respectively. An overall general scrutiny of the station graphs reveals that the oxygen minimum layer lies between 180 - and 220 -cl/t surfaces during the southwest monsoon and 200 - and 240 - cl/t surfaces during the northeast monsoon. It is, therefore, preferred to workout the distribution of oxyty and acceleration potential on 180 -, 200 - and 220 - cl/t surfaces and 200 -, 220 - and 240-cl/t surfaces for the southwest and northeast monsoons respectively, besides presenting the topographies of these surfaces and also the distribution of oxyty in the oxygen minimum layer and its topography for both the seasons.

The values of depth and oxyty at each chosen isanosteric surface were read directly from the station curves with the help of the overprinted isopleths of thermosteric anomaly.

Station values so obtained were plotted on each map and smooth isopleths were drawn. If a station value was incompatable with the neighbouring stations, the stationcurves were revised, without violating the observed values in such a way that, the station values better fit with the nearby stations. The isopleths on the maps were drawn strictly following the station values and some points that showed very much deviation for a smooth contouring were rejected. This is particularly true in the distribution of oxyty that were collected on board the Russian research vessels.

Geostrophic flow along the isanosteric surfaces was deduced from the gradient of acceleration potential (Montgomery, 1937; Montgomery and Spilhaus, 1941; Montgomery and Stroup, 1962) or Montgomery function as it has often been termed Reid (1965). The expression of acceleration potential used for numerical computation is

$$\int_{\delta_{T_0}}^{\delta_T} P \, d\delta_T + P_0 \, \delta_{T_0}$$

Where 'P' is the pressure (db) 'δ_T' is the thermosteric anomaly (cl/t) and the subscript '0' denotes the values at reference pressure.

The level of no motion in the Arabian Sea was selected differently by different investigators. But majority of the investigators who made a critical assessment of the level of no motion for working out the circulation in the upper layers chose it as 1000 db (Swallow and Bruce, 1966; Duing, 1970; Wyrtki, 1971). Hence, in the present investigation of the computation of geostrophic flow, the reference level, selected was 1000 db. The numerical integration was carried out at varying intervals of σ_T of 10 to 40 cl/t. The value of oxyty in the oxygen minimum layer was taken as where the inflection of oxygen in the vertical takes place and its depth was chosen as the one where this oxygen low value either commences with depth or occurs.

Temperature - oxyty characteristics on different steric levels offer a useful view of the qualitative description of the oxyty distribution. An attempt was made to present the scatter diagrams of temperature - oxyty for different representative areas shown in Fig. 3. In order to maintain a uniform number of points for each representative area, exactly ten stations which are uniformly distributed within the representative area were selected, except for areas 7, 6 and 2 during

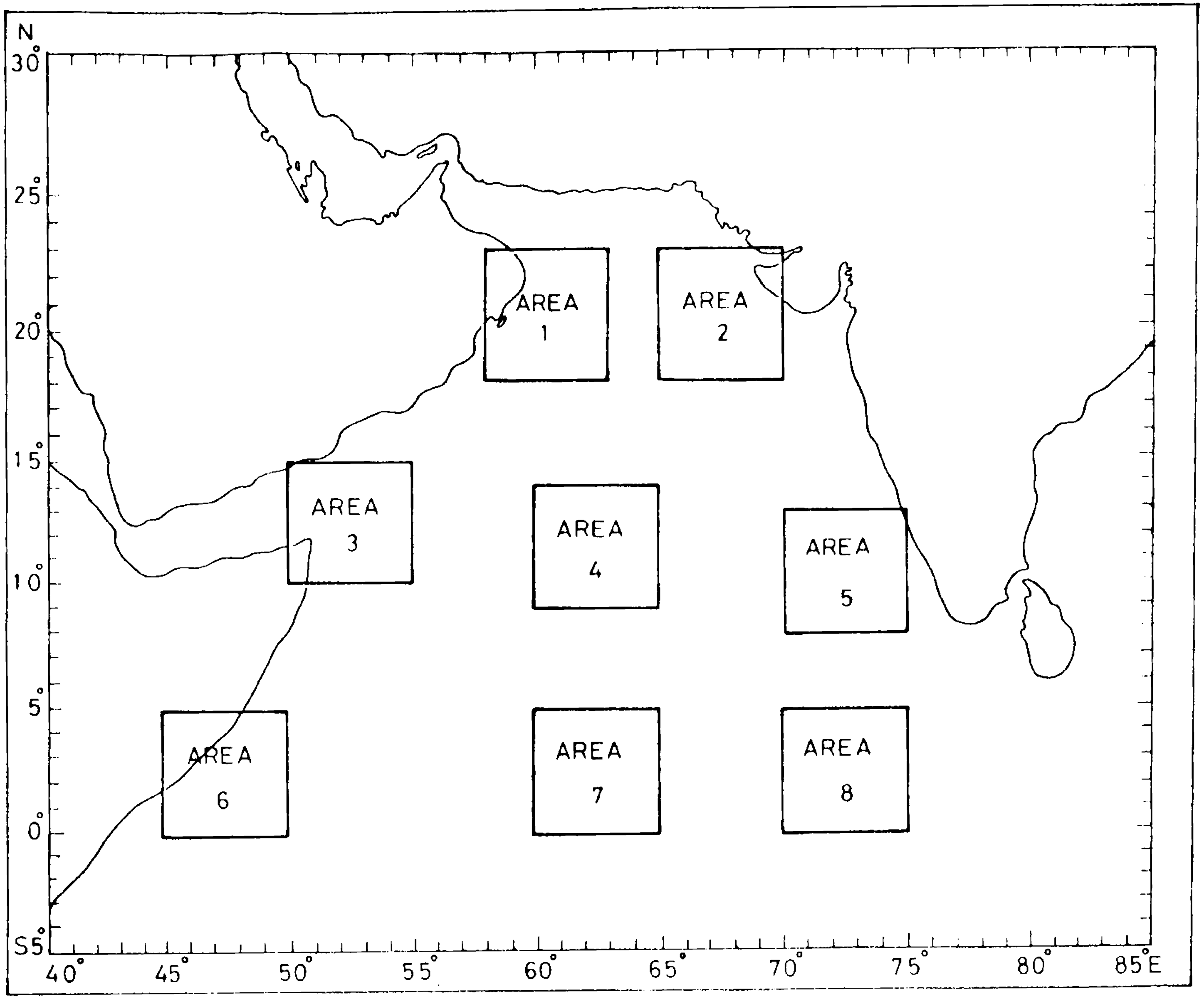


FIG: 3. REPRESENTATIVE AREAS OF THE SCATTER DIAGRAM.

the northeast monsoon where there are data available only for eight stations. Further, to make the comparison more effective and representative, the oxyty values against the temperature were read from station curves at intervals of 20 cl/t commencing with the isanosteric surface 40 cl/t upto 600 cl/t and also at the surface.

1.2.4. Limitations

As stated earlier and shown in the Tables 1 and 2 the observations used in this study were made in various months in different years. Although, some precautions were taken to avoid the heterogeneity by working out the distributions for the two conspicuous seasons of the southwest and northeast monsoons, certain amount of heterogeneity due to different years of observations and different techniques adopted,are bound to be crept in. Whenever such deviations make the interpretation difficult, attempts are made to spell out the causative factors. The discussion in the present thesis does not incorporate the results in the shelf regions because of the fact that the uppermost isanosteric surface 240 cl/t lies below the shelf, besides that the data selected from the NODC do not cover the shelf regions particularly off the west coast of India.

C H A P T E R - II

CHAPTER - II

OXYTY AND TOPOGRAPHY OF THE OXYGEN MINIMUM LAYER

In this chapter the dissolved oxygen content (oxyty) in the oxygen minimum layer and its topography are presented incorporating the values from the T - S diagrams on which the distribution of temperature against depth, salinity and oxyty are plotted. At certain stations eventhough the minimum oxygen content is almost constant with depth, the lowest value of the dissolved oxygen is taken as the oxyty in the oxygen minimum layer and the depth at which the lower value begins is taken as the depth of the oxygen minimum layer. As this chapter pertains with the two different aspects, namely, the distribution of oxyty within the oxygen minimum layer and the topography of the oxygen minimum layer, it has been divided into two sections presenting the results of these aspects. Section I deals with the distribution of oxyty (Figs. 4 and 5) while in section II the topography of the oxygen minimum layer is presented (Figs.6 and 7).

SECTION-I

2.1. Distribution of oxyty in the oxygen minimum layer

As the concentration of oxygen in the oxygen minimum layer varies with season in the Arabian Sea because of the control of the atmospheric circulation which is monsoonal in nature and in turn controls the oceanic circulation, it is proposed to present the distribution of oxyty in the oxygen minimum layer for the two seasons namely the southwest and northeast monsoons. Hence, each section is again subdivided pertaining to the results of each season.

2.1.1. Oxyty in the oxygen minimum layer during the southwest monsoon

While describing the distribution, initially, some general statements are made, the details of which are explained subsequently. In general, the orientation of the oxypleths is parallel to the coast, although they touch the coasts at different points (Fig.4). In the open sea, alternate cells of high and low oxyty are conspicuous. It is interesting to note that while in the southern region the oxypleths have a zonal orientation (south of 5^{o}N), they have, mostly, a meridional orientation in the north. Obviously, such an orientation indicates that the zonal distribution north of 5^{o}N has alternate increase and decrease of oxyty at any particular latitude. Normally, oxyty in the open sea decreases southward and increases, zonally, on eitherside of the central

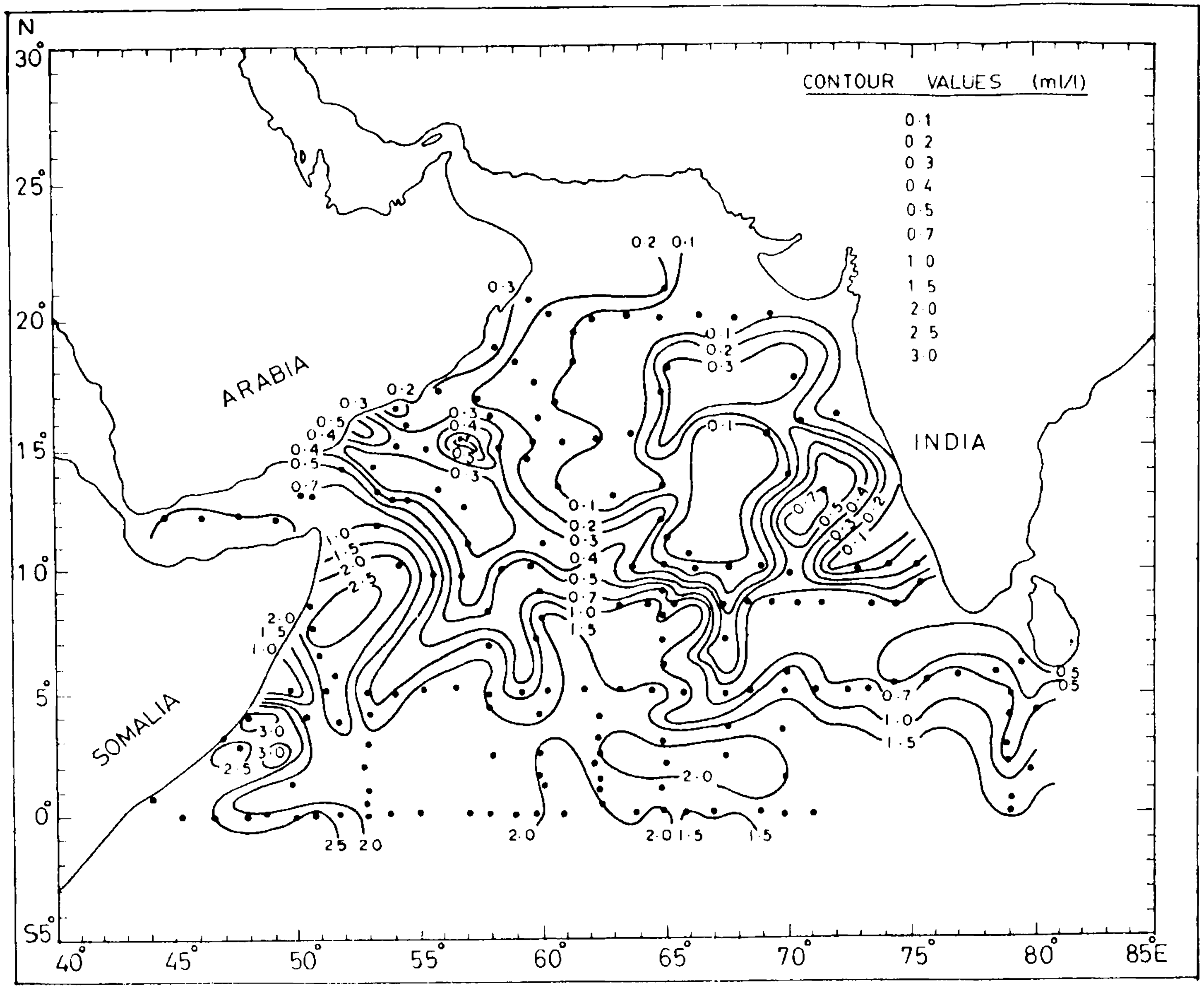


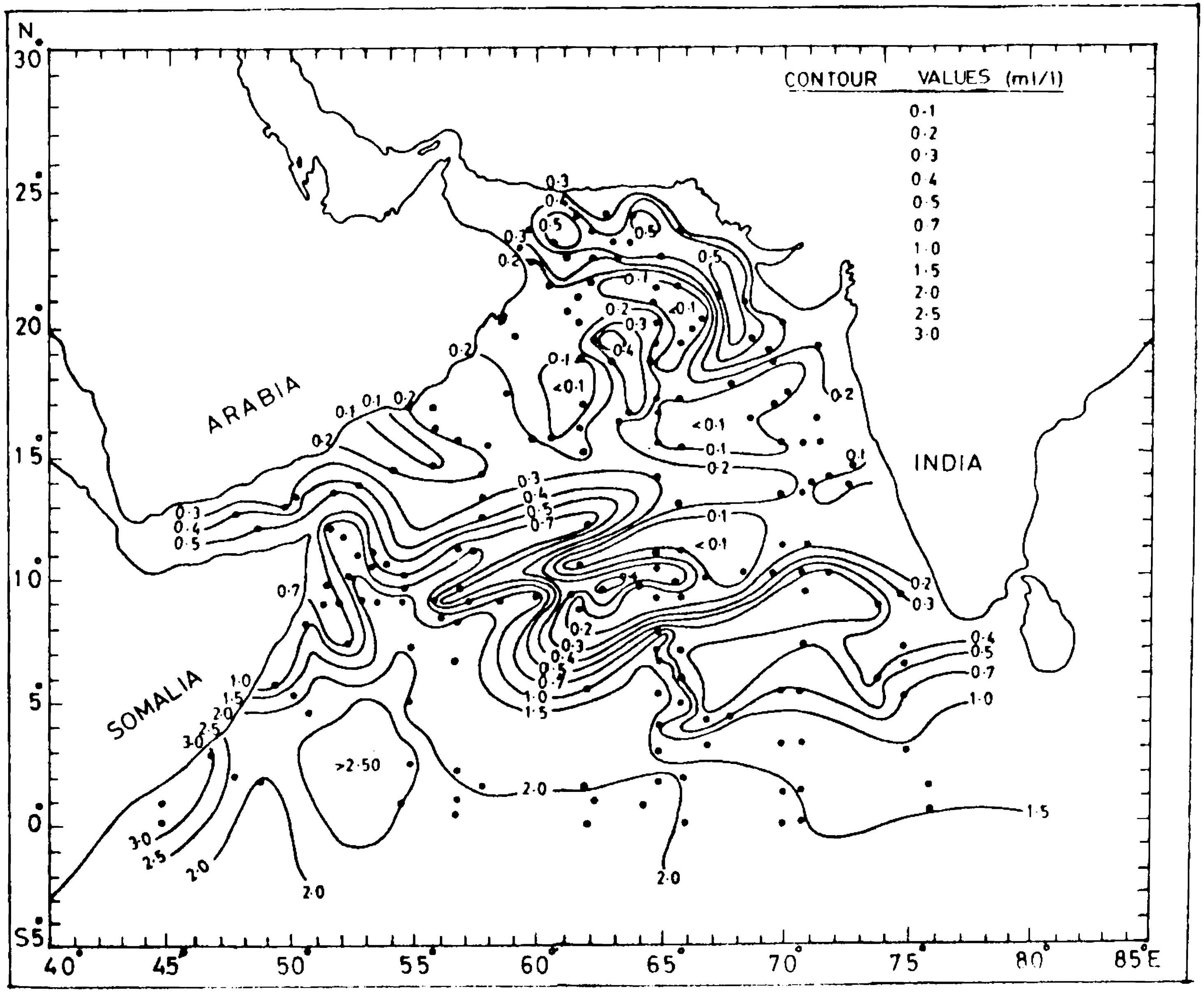
FIG: 4. DISTRIBUTION OF OXYTY IN THE OXYGEN MINIMUM LAYER DURING THE SOUTHWEST MONSOON region north of 12^{o}N where the lowest values occur. However, there is an exception to this general statement, as a closed cell of high oxyty with values greater than 0.30 ml/l is centred around 17^{o}N, 67^{o}E. The alternate cells of high and low depict the presence of cyclonic and anticyclonic circulation with hyperbolic points in between them. In coherence with such a presentation, it is noticed that the high and low oxyty cells are separated by oxypleths having same values.

Off the Arabia Coast, the oxyty is in general higher with offshore decrease, nevertheless, off the southwest coast of Arabia, higher oxyty (with values greater than 0.50 ml/l)is found around 15^{o}N, 57^{o}E. In contrast, off the west coast of India the oxyty increases offshore, particularly north of 8^{o}N. Off the Somalia Coast, the distribution of oxyty shows entirely a different picture; it is not possible to make a general statement of either offshore increase or decrease because there are alternate high and low oxyty values off the coast. The gradient of the oxypleths is zonally stronger between 8^{o}N and15^{o}N west of 57^{o}E and east of 68^{o}E.

The lowest values of oxyty are recorded in the central Arabian Sea with less than 0.10 ml/l and also off the northwest coast of India. In fact, the concentration in the northcentral Arabian Sea is even much less than 0.05 ml/l or sometimes only traces of oxyty are noticed. As the lowest oxypleth that is drawn here is only 0.10 ml/l the details of the values less than 0.1 ml/l cannot be depicted, although they are very well represented in the station curves. South of 10°N, the oxyty increases southward, almost all along the longitudes except in the coastal regions. But between 62°E and 70°E, a zonally oriented high oxyty cell is located between 3°N and 1°N.

2.1.2. Oxyty in the oxygen minimum layer during the northeast monsoon

In contrast to that during the southwest monsoon, the orientation of the oxypleths is zonal in nature in a more extended area (south of 15°N upto the equator) in this season (Fig. 5). But it is mostly meridional north of 15°N. In the open sea, high and low values occur alternately. However, the frequency is relatively less, compared to that of the southwest monsoon. Just as in the southwest monsoon, the central part of the northern Arabian Sea


CONTOUR VALUES (ml/l)
0·1
0·2
0·3
0·4
0·5
0·7
1·0
1·5
2·0
2·5
3·0
ARABIA
INDIA
SOMALIA
>2·50
N
30
25
20
15
10
5
0
S5
40
45
50
55
60
65
70
75
80
85°E

records the lowest oxyty, except a high oxyty cell centred around 18^{O}N, 64^{O}E. Another main deviation is, that the oxyty increases northward from around 20^{O}N and also towards the northeastern coast of India and Pakistan. Off the Arabia Coast, the oxygen content is much lower and increases southward. Similarly, off the Somalia Coast oxyty increases offshore. Off the southwest coast of India the oxyty during the northeast monsoon is relatively much less and also extends offshore. One of the main contrasting features is the presence of too many alternate cells of high and low oxyty during the southwest monsoon and less during the northeast monsoon. Parallel to 10^{O} N, there is a zonally extended region of low oxyty with higher values on eitherside in the north and south. In general, the distribution of oxyty in the oxygen minimum layer indicates lower values in almost all the regions, except the northcentral Arabian Sea. In the area, covered by 12^{O}N to 4^{O}N and 54^{O}E to 75^{O}E the meridional gradients are extremely strong. Another common feature is that south of 8^{O}N, oxyty increases southward. In the equatorial region, the orientation of the oxypleths is in general similar to that in the southwest monsoon, running almost parallel to the latitudes. Generally, it can be stated that the highest oxyty occurs in the southwestern Arabian Sea with values greater than 3.0 ml/l, and the central and northcentral Arabian Sea records the lowest oxyty, with values as low as 0.10 ml/l.

SECTION - II

2.2. Topography of the oxygen minimum layer

A study of the topography of the oxygen minimum layer is essential in understanding the physical processes that are taking place within this layer. Similar to the variation in the distribution of oxyty, the topography also has a seasonal variation, not only because of the reversal of the circulation, but also due to the winter cooling, particularly in the northern part of the Arabian Sea where convective mixing takes place. The depth of the oxygen minimum layer has been found out as explained in the beginning of this chapter.

2.2.1. Topography of the oxygen minimum layer during the southwest monsoon

The orientation of the isobaths are in alignment with the coasts off Arabia and to a certain extent, off Somalia (Fig.6). But off the west coast of India there is no similar alignment of the isobaths with reference to the coast. There are alternate troughs

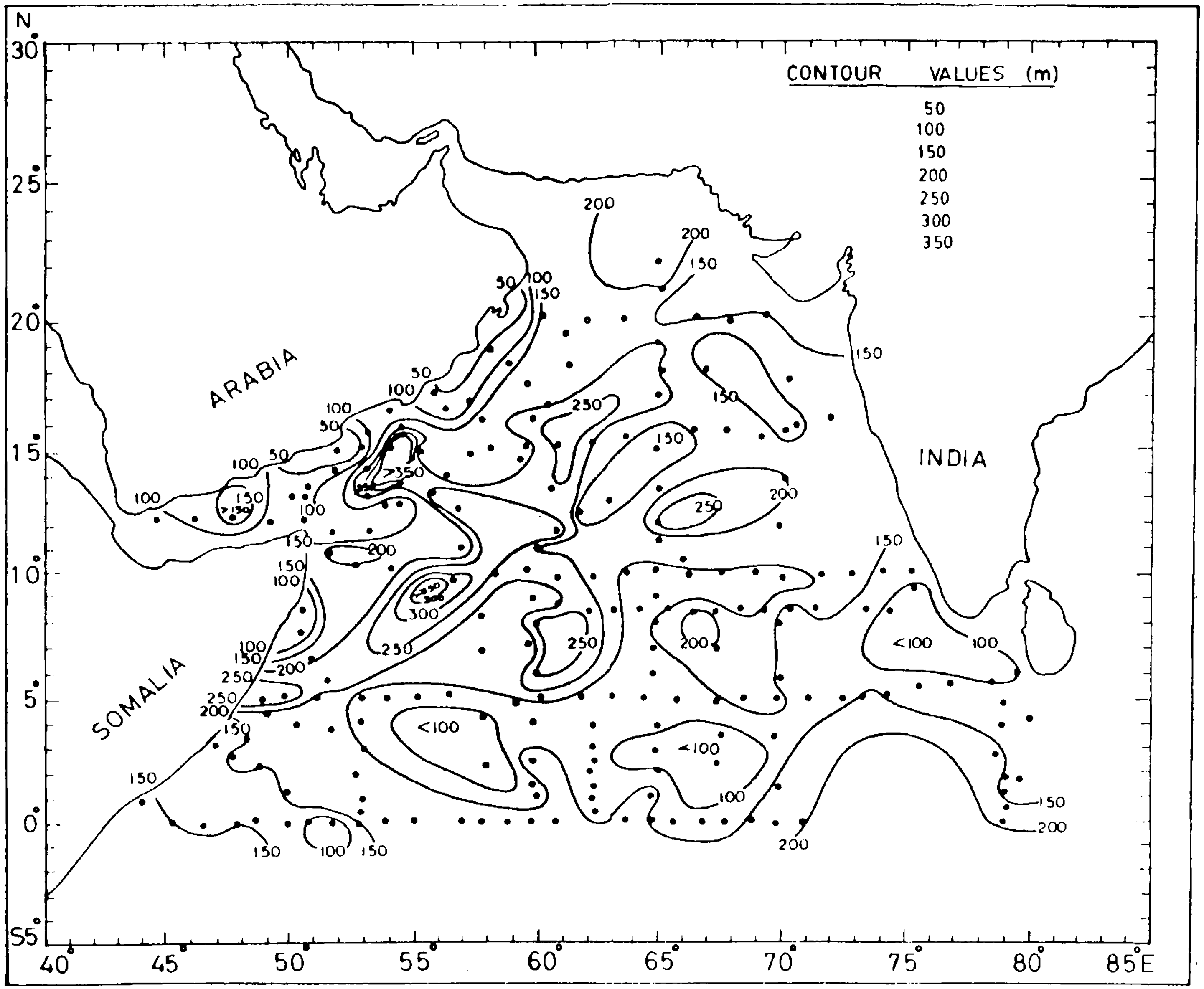


FIG: 6. TOPOGRAPHY OF THE OXYGEN MINIMUM LAYER DURING THE SOUTHWEST MONSOON.

and ridges present in the topography of the oxygen minimum layer and the topography varies from less than 50 m off the South Arabia to the deepest troughs (greater than 350 m) around 14^{o}N, 53^{o}E and 9^{o}N, 55^{o}E. The maximum variation is observed off the southeast coast of Arabia. But in other regions and open sea the variations are less, more so in the eastern Arabian Sea where it ranges from slightly less than 100 m to about 150 m. Similar to the orientation of the oxypleths, the isobaths also run almost parallel to the latitudes south of 5^{o}N whereas in the northern region they have, mostly, a meridional orientation. Troughs are located around 16^{o}N, 61^{o}E; 12^{o}N, 67^{o}E and 7^{o}N, 61^{o}E, besides one off the Somalia Coast with depth greater than 250 m. The prominent ridges are centred at about 8^{o}N, 76^{o}E; 4^{o}N, 57^{o}E; and 3^{o}N, 67^{o}E in addition to the shallowest topography off the Arabia Coast and northern part of Somalia. It is interesting to note that in general the troughs are associated with low oxyty waters while ridges are related with high oxyty.

2.2.2. Topography of the oxygen minimum layer during the northeast monsoon

Contrary to the conditions during the southwest monsoon, the topography shallows offshore off the

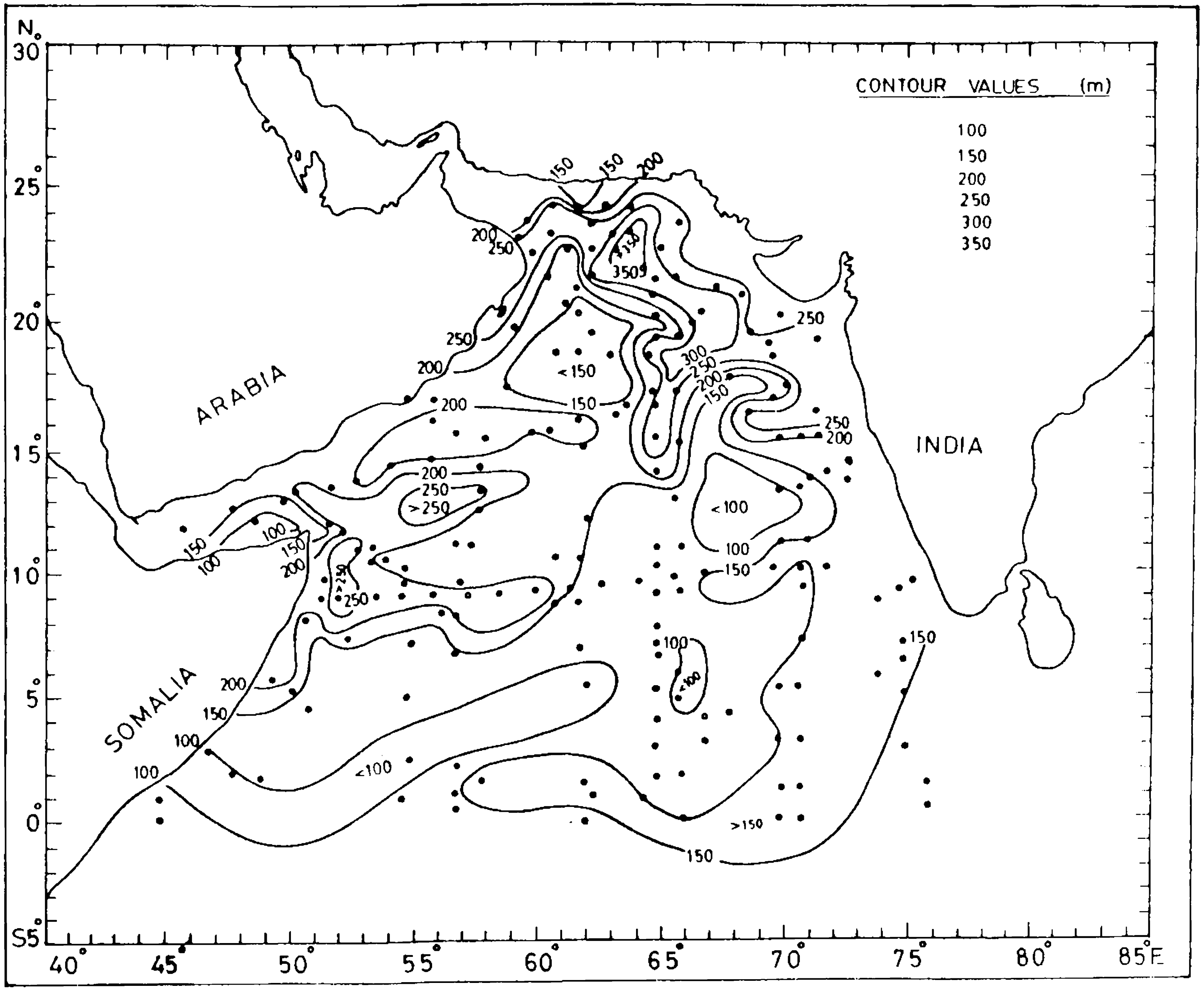


FIG: 7. TOPOGRAPHY OF THE OXYGEN MINIMUM LAYER DURING THE NORTHEAST MONSOON

Arabia Coast (Fig.7). Furthermore, the gradients are also relatively weaker off the Arabia Coast, while they are strong in the easternpart of the Arabian Sea. The topography ranges from values less than 100 m to greater than 350 m, indicating that the variation of topography is less during the northeast monsoon compared to that of the southwest monsoon. Similar to the orientation of oxypleths as well as the isobaths during the southwest monsoon, north of 15^{o}N the isobaths during this period run almost parallel to the meridians, south of which they have either zonal or slightly inclined orientation. Another interesting feature is that the number of troughs and ridges are small during the northeast monsoon. The predominant trough with a depth greater than 350 m is stationed around 24^{o}N, 63^{o}E; while other less prominent troughs are situated at 13^{o}N, 56^{o}E; 8^{o}N, 51^{o}E and 16^{o}N, 58^{o}E. With regard to the ridges which are less conspicuous in nature, are placed at about 18^{o}N, 63^{o}E; 12^{o}N, 69^{o}E and 4^{o}N, 67^{o}E apart from the elongated one extending from the southern coast of Somalia.

DISCUSSION

In general, the troughs and ridges in the topographic maps of the oxygen minimum layer are associated with low oxyty and high oxyty waters respectively, mainly because the oxyty decreases with depth. However, such a general statement does not hold good in the coastal regions where advective processes play a major role in determining the oxyty distribution. For example, off the west coast of India during the northeast monsoon while the oxyty is very low, the topography is not very deep, particularly, in the central region. Perhaps, this is due to higher consumption of oxygen by the biota. In the regions of upwelling, understandably, the topography is very shallow as the upwelled water brings the oxygen minimum layer to within 50 to 65 m of the surface. Judkins (1980) observed the same phenomena in the region off Peru. But,normally, such regions are expected to be associated with low oxyty subsurface waters that are brought upwards. Instead, off the Arabia and Somalia Coasts, relatively higher concentration of oxygen is noticed during the south-west monsoon, probably, because of the higher absorbing capacity of oxygen by the cold upwelled waters. Warren et al. (1966) have noticed the presence of cold surface waters with temperatures as low as 14^{o}C near the Somalia Coast during periods of upwelling. Such low temperatures increase the oxygen absorbing capacity of the surface waters. In contrast, during the northeast monsoon these two regions are associated with deeper topography and lower oxyty as a result of downwelling as well as winter convectional mixing. The central region of the northern Arabian Sea, where low oxyty prevails throughout the year, records deeper topography. The higher oxyty values during both the seasons in the equatorial region may be the result of mixing with relatively high oxyty Equatorial Indian Ocean Water. The prominence of vertical advection is not immediately clear from the oxyty distribution in the oxygen minimum layer and its topography, and it will be discussed in relation to the distribution of oxyty on different isanosteric surfaces.

One of the conspicuous inferences that can be drawn from the oxyty distribution is the trapping of high oxyty waters off the west coast of India during the southwest monsoon, especially off the central west coast of India. A close comparison of the oxyty distribution with the topography cannot explain such a situation; it may, probably, be associated with some eddies entrapped in the circulation. Even in the open sea, there are certain deviations from the general statement that the ridges are associated with high oxyty waters. The prominent exceptions are seen off the Central Arabia Coast where a ridge (with depth less than 150 m) is associated with oxyty less than 0.10 ml/l during the northeast monsoon and along 8^{o}N where low oxyty water with concentrations less than 0.10 ml/lis located in a ridge region where the depth is less than 100 m. Similarly, a slight general deviation is also noticed with a trough located at about 11^{o}N, 56^{o}E during the northeast monsoon. However, such deviations appear to be relatively weak resulting in some of these features, which can be better explained by studying the distribution of oxyty at different isanosteric surfaces, where horizontal and vertical advection processes can easily be delineated. The presence of weaker gradients during the northeast monsoon, both in oxyty and topography compared to those during southwest monsoon, may be an indication of stronger horizontal advection associated with weaker vertical advection, while the reverse processes are likely to take place during the southwest monsoon. The strong gradients are, especially, conspicuous in the central Arabian Sea where anticyclonic circulation during the southwest monsoon is prominent. The alignment of the isolines with the coasts appears to be due to the predominance of the coastal processes or the boundary conditions.

The Indian Ocean is landlocked in the north, and does not extend into the cold climatic regions of the northern hemisphere. This causes an asymmetrical development of its structure and circulation, which are most obvious in the development of the huge layers of extremely low oxygen content in the Arabian Sea (Wyrtki, 1973). He also remarked that the isolation and stagnation of the North Indian Ocean Intermediate Water and the lack of substantial horizontal advection, together with the high productivity of the northern Indian Ocean, cause the development of this oxygen minimum layer. The lower oxyty in the North Indian Ocean in general, and in the Arabian Sea in particular, is a consequence of the existence of the Asian landmass, forming the northern boundary, preventing a quick renewal of subsurface layers that results into reverse depletion of oxygen below the thermocline (Dietrich, 1973). In the present study also, all these facts are proved and the explanation emphasises the argument of Wyrtki (1962) that the position and maintenance of the oxygen minimum layer in the oceans are determined mainly by circulation. Wust (1935) and Dietrich (1936, 1937) were also of the same opinion.

It is not only the formation of oxygen minimum in the Arabian Sea at shallow depths, with extremely low values that is interesting,that the thickness of the low oxyty layer which varies from about 50 m to more than 800 m. As a result of such large thickness, it becomes, sometimes, difficult to specify the depth of the oxygen minimum layer. Sen Gupta et al. (1976a)identified two oxygen minima in the Arabian Sea, one at shallow depths of less than 300 m and another between 1000 and 1500 m. But they stated that the deeper minimum is observed only in some parts of the Arabian Sea. A close examination of the station curves based on which the present study has been carried out, does not indicate any continuity of the deeper minimum. Hence, it is doubtful if there is really a secondary minimum similar to the one in the equatorial Pacific as reported by Tsuchiya (1968) or only an isolated and localised phenomenon at certain places due to abnormal biochemical processes.

C H A P T E R - III

CHAPTER - III

DISTRIBUTION OF OXYTY ON THE ISANOSTERIC SURFACES AND THEIR TOPOGRAPHY

In the introductory chapter, an attempt is made to explain that, normally, the flow in the oceans takes place along the steric surfaces, as the isosteric surfaces almost coincide with isentropic surfaces. The distribution of water properties on isopycnic surfaces was attempted for the first time by Montgomery (1938). Where the distribution of physical properties in the upper layers are concerned, Montgomery and Wooster (1954) introduced the term "thermosteric anomaly" in place of "steric anomaly" or "specific volume anomaly", as the contribution due to pressure terms to the specific volume anomaly is insignificant. As the depth of the oxygen minimum layer in the Arabian Sea is confined to the upper 300 m, the distribution of oxyty at different isanosteric surfaces, instead of steric surfaces is presented here. Further, such a distribution on isanosteric surfaces reveals the influence of horizontal as well as vertical advection when the distribution of properties at one surface is compared with those on the other. The troughs and ridges in the topography of the isanosteric surfaces are, generally, associated with the boundaries in the circulation pattern. As already explained, the circulation in the Arabian Sea varies semiannually. The boundaries of the cyclonic and anticyclonic circulation can easily be delineated from the topographic charts of isanosteric surfaces. Furthermore, they are important zones of variations in vertical as well as horizontal advective processes. It is, therefore, imperative that the topography of the isanosteric surfaces within which the oxygen minimum layer lies gives an understanding of the physical processes involved in the observed variation of oxygen concentration. At the boundaries, the horizontal and vertical advections vary considerably and influence the distribution of oxyty. Of these, the vertical advection plays a major role in the variation of oxyty because the vertical variation of oxyty is higher by three orders of magnitude than that of the horizontal. Hence, it is expected that the distribution of oxyty on various isanosteric surfaces within which the oxygen minimum layer lies, along with their topography, gives better scope to explain the advective processes involved in altering the depth of the oxygen minimum layer and the concentration of oxygen within it.

3.1. Distribution of oxyty on the isanosteric surfaces

Because of the monsoonal influence in the Arabian Sea, the depth of the oxygen minimum layer varies with season. During the southwest monsoon, mostly, the oxygen minimum layer lies between 220 - and 180 - cl/t isanosteric surfaces, while it lies between 240 - and 200 - cl/t surfaces during the northeast monsoon. Hence the distribution of oxyty on the 220-, 200- and 180- cl/t surfaces for the southwest monsoon and the 240-, 220- and 200- cl/t surfaces for the northeast monsoon are worked out and presented in Figs. 8 to 10 and 11 to 13 respectively. While making a comparison of the distribution of oxyty at one surface with another, it may be noted that the contour intervals are not the same; the contour values have been presented in the corresponding diagrams.

3.1.1. Distribution of oxyty on isanosteric surfaces during the southwest monsoon

In general, south of 12°N, the oxyty increases southward on all the surfaces except the 180- cl/t surface on which a relatively low oxyty water is noticed between 66°E and 69°E near to the equator. The oxyty gradient decreases from the 220- to 180- cl/t surface. However, there is a slight deviation from this general statement; in the southwestern region under study, the gradients are equally strong on the 200- and 180- cl/t surfaces. The oxypleths show coastline orientation in the western region, whereas off the west coast of India, they do not show such a tendency. Just as in the distribution of oxyty in the oxygen minimum layer, alternate highs and lows are prominent on all the surfaces. The oxypleths, mostly, run parallel to the latitudes east of 60^{o}E and south of 10^{o}N on the 180- cl/t surface while there is no such regularity in the alignment of the oxypleths on the 220- and 200- cl/t surfaces. Two elongated tongues of low oxyty, separated by a high in between and protruding westward away from the west coast of India are present on the 220- and 200- cl/t surfaces although the low oxyty water is not so prominent on the 180- cl/t surface.

Comparing the distribution of oxyty in the oxygen minimum layer, with that on the isanosteric surfaces it can be realised that there is a similarity in the general pattern, except that the location of the highs and lows are slightly shifted.

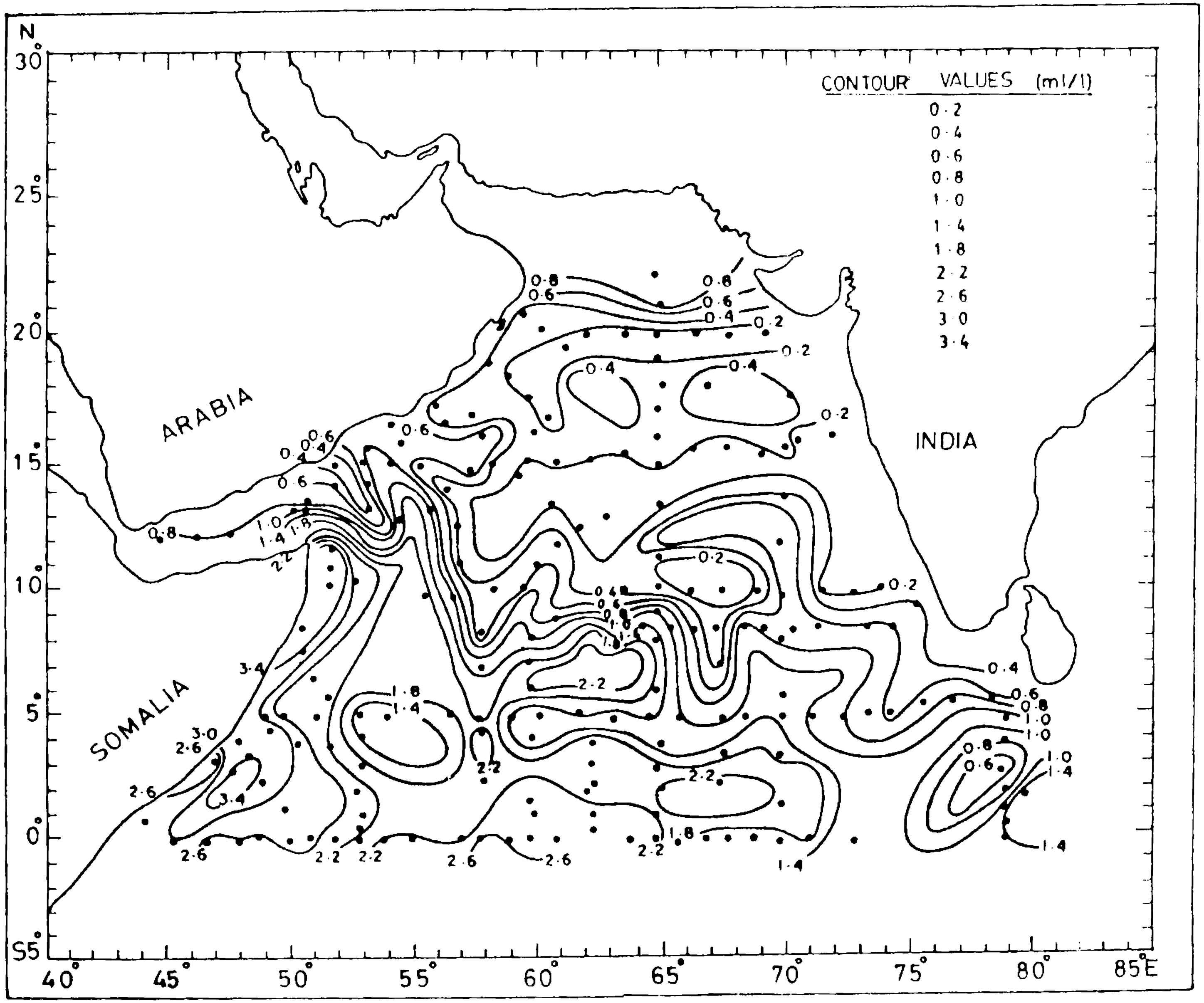


FIG: 8. DISTRIBUTION OF OXYTY ON THE 220 - cl/t ISANOSTERIC SURFACE DURING THE SOUTHWEST MONSOON

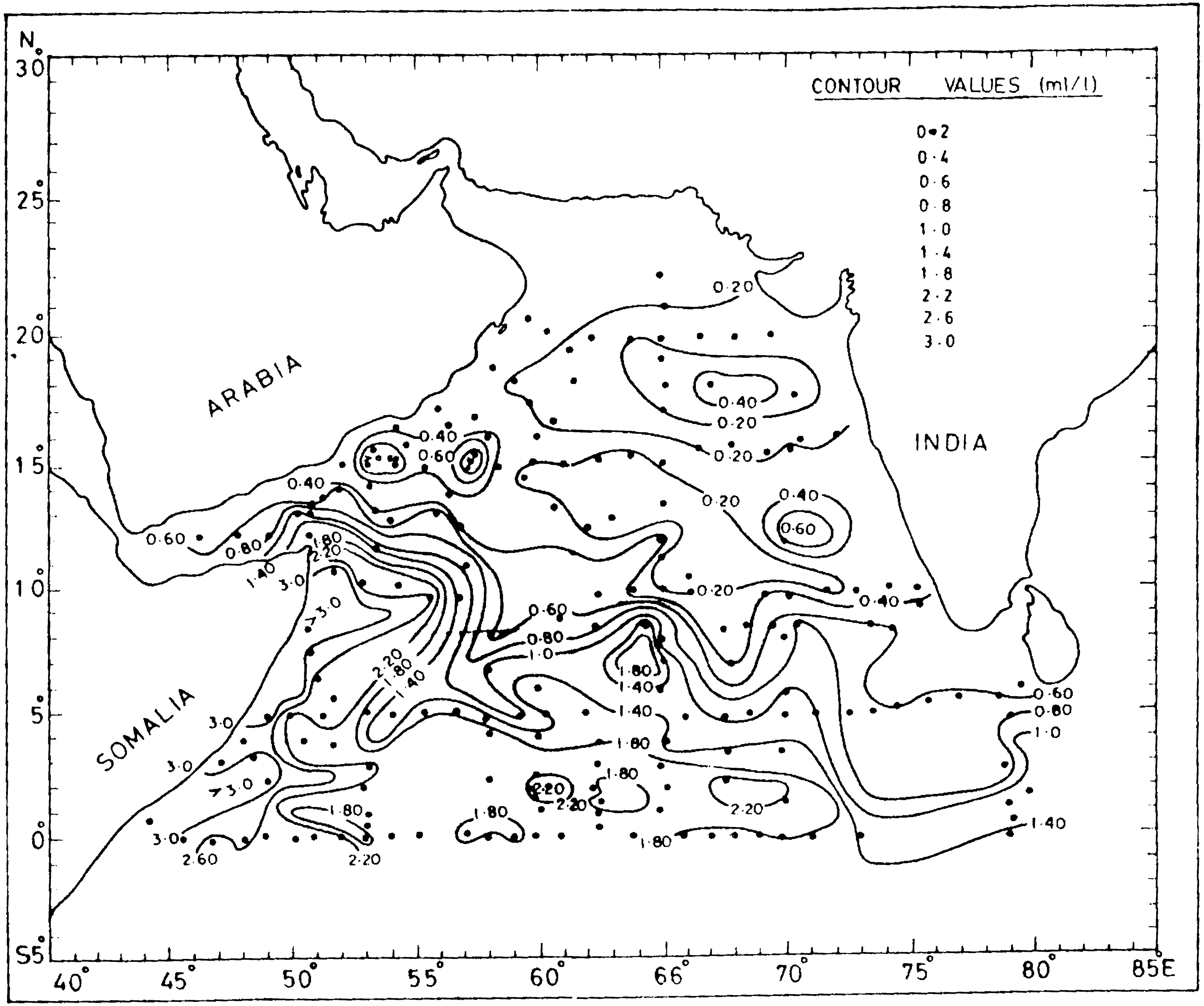


FIG: 9. DISTRIBUTION OF OXYTY ON THE 200 - cl/t ISANOSTERIC

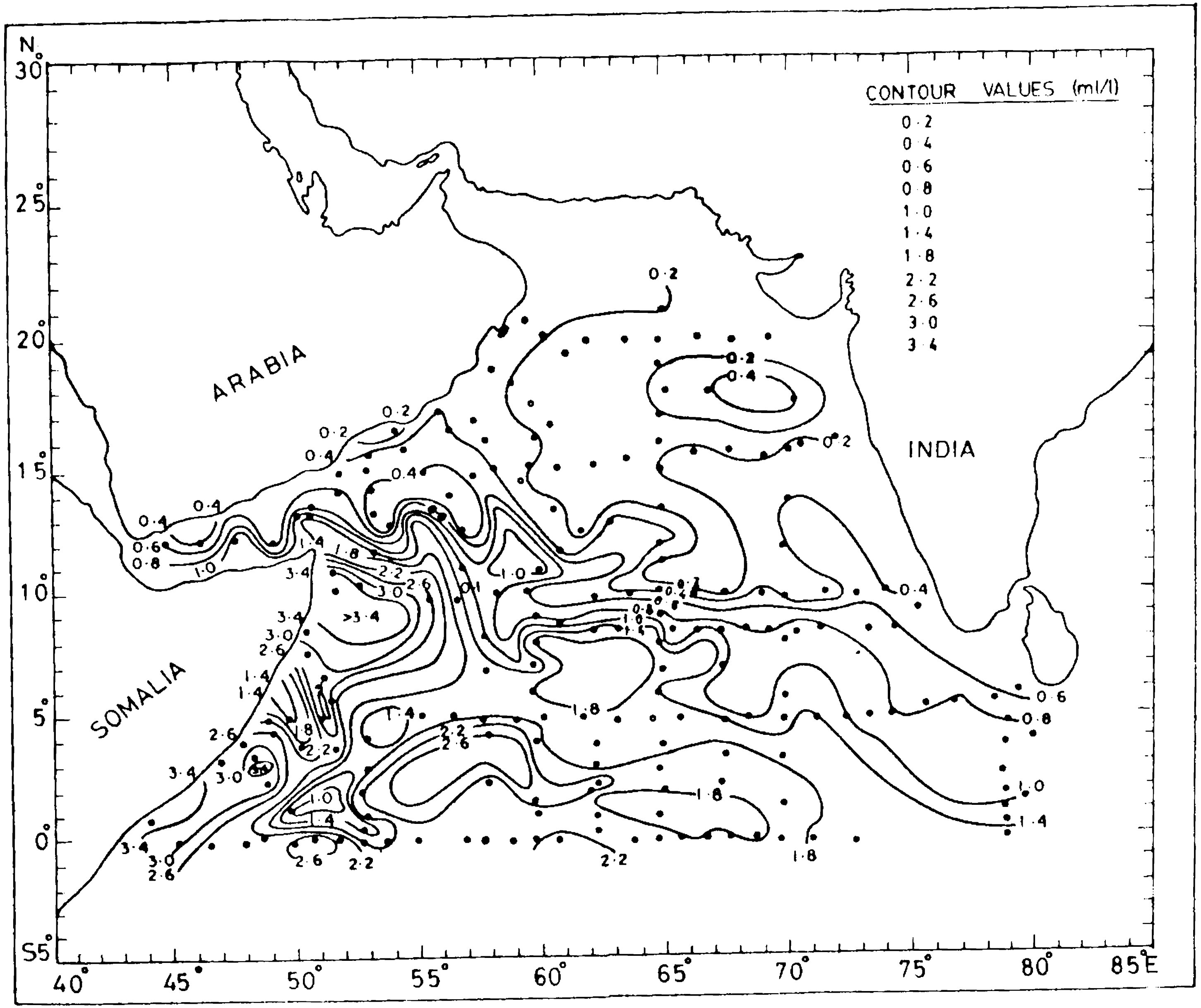


FIG: 10. DISTRIBUTION OF OXYTY ON THE 180 - cl/t ISANOSTERIC SURFACE DURING THE SOUTHWEST MONSOON.

There is a small variation in the oxygen concentration from one surface to the other. In most of the area, oxygen minimum layer coincides with the 200- cl/t surface. As a result, the lowest values are conspicuous on this surface. But in certain regions, the oxygen minimum layer coincides either with the 220- cl/t or 180- cl/t surface.

It is interesting to note that while the oxyty on the 220- cl/t surface is around 0.80 ml/l in the northernmost region, it is around 0.20 ml/l or sometimes even less on the 200- and 180- cl/t surfaces (Figs 8, 9 and 10). Such a condition implies a strong vertical gradient of oxyty between the 220- and 200- cl/t surfaces (Figs. 8 and 9) while the oxyty is vertically homogenous between the surfaces of 200- and 180- cl/t. Similarly, off the Arabia Coast, there is not much variation in the distribution of oxyty on the 220- and 200- cl/t surfaces (Figs. 8 and 9); on the contrary, it is very small on the 180- cl/t surface.

In the north, off Somalia, the oxyty is exactly the same (greater than 3.4 ml/l) on the 220- and 180- cl/t surfaces while it is around

3.0 ml/l on the 200- cl/t surface, which gives an implication that the oxygen minimum layer coincides with the 200- cl/t surface in this region. But in comparing the topography of the oxygen minimum layer with that of the 200- cl/t there is no such indication. On the other hand, the minimum layer is very deep. It can, therefore, be inferred that the lower value of 3.0 ml/l at the 200- cl/t is not the minimum. In the central part, off the Somalia Coast, there is an abrupt decrease of oxyty on the 180- cl/t surface from 3.4 ml/l to less than 1.4 ml/l (Fig. 10), which again increases southward to greater than 3.4 ml/l. On the other hand, on the 220- and 200- cl/t surfaces (Figs. 8 and 9) the variation is marginal. Another conspicuous feature on the 180- cl/t surface is the very low oxyty between 5^{o}N and the equator, along 51^{o}E. This low oxyty cell, present on the 180- cl/t appears to have shifted northeastward on 220- cl/t surface, lying around 5^{o}N, 55^{o}E. A common feature on all the surfaces is the presence of low oxyty water surrounded by high oxyty water, in the northern part of the region under study. The lower values appear on the 200- cl/t surface whereas they are relatively higher on the 220- and 180- cl/t surfaces, indicating that the oxygen minimum layer lies at the

200- cl/t surface. A comparison of the oxyty on the 220- and 180- cl/t surfaces in this region shows that the oxyty is higher at the former.

3.1.2. Distribution of oxyty on isanosteric surfaces during the northeast monsoon

Comparing the distribution of oxyty during the two seasons, the most predominant feature observed, particularly, in the upper layers is the offshore decrease of oxyty at the west coast of India. The oxypleths on the 200- and 240 cl/t surfaces (Figs. 11 and 13) are oriented parallel to the coast in the eastern region, whereas there is no such indication in the west. Another conspicuous feature is the spreading of low oxyty water on all the surfaces in the central eastern Arabian Sea. In general, on all the surfaces the oxyty decreases from north to south upto 18^{o}N, south of which it increases southward. The oxyty in the whole of the Arabian Sea decreases with the thermosteric anomaly except south of 5^{o}N, where it shows almost no change. On the 200- cl/t surface, the orientation of the oxypleths are more meridional than zonal, particularly, west of 65^{o}E. But on the other surfaces, they show a zonal orientation south of 10^{o}N and meridional

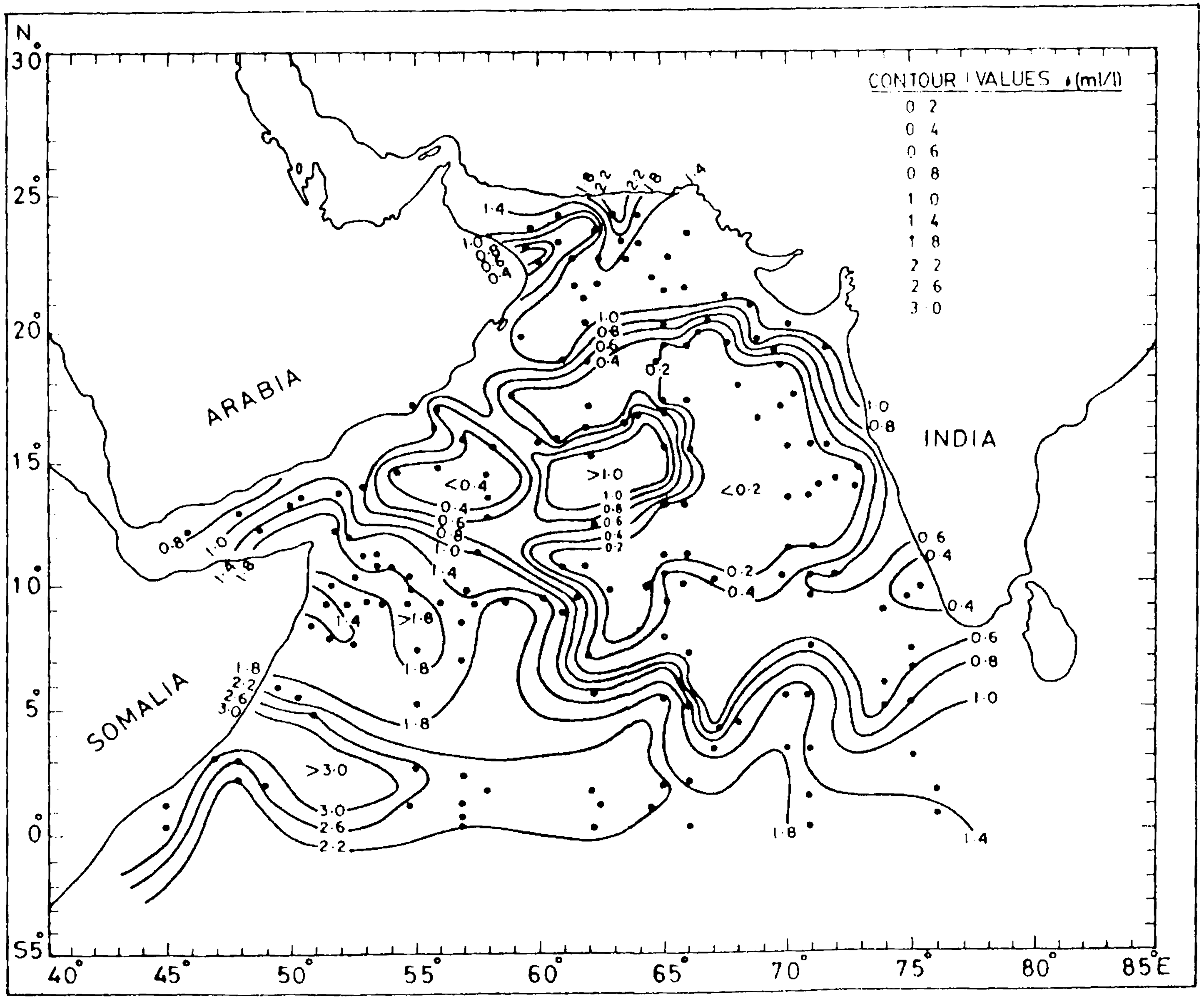


FIG. 11 DISTRIBUTION OF OXYTY ON THE 240 - cl/t ISANOSTERIC SURFACE

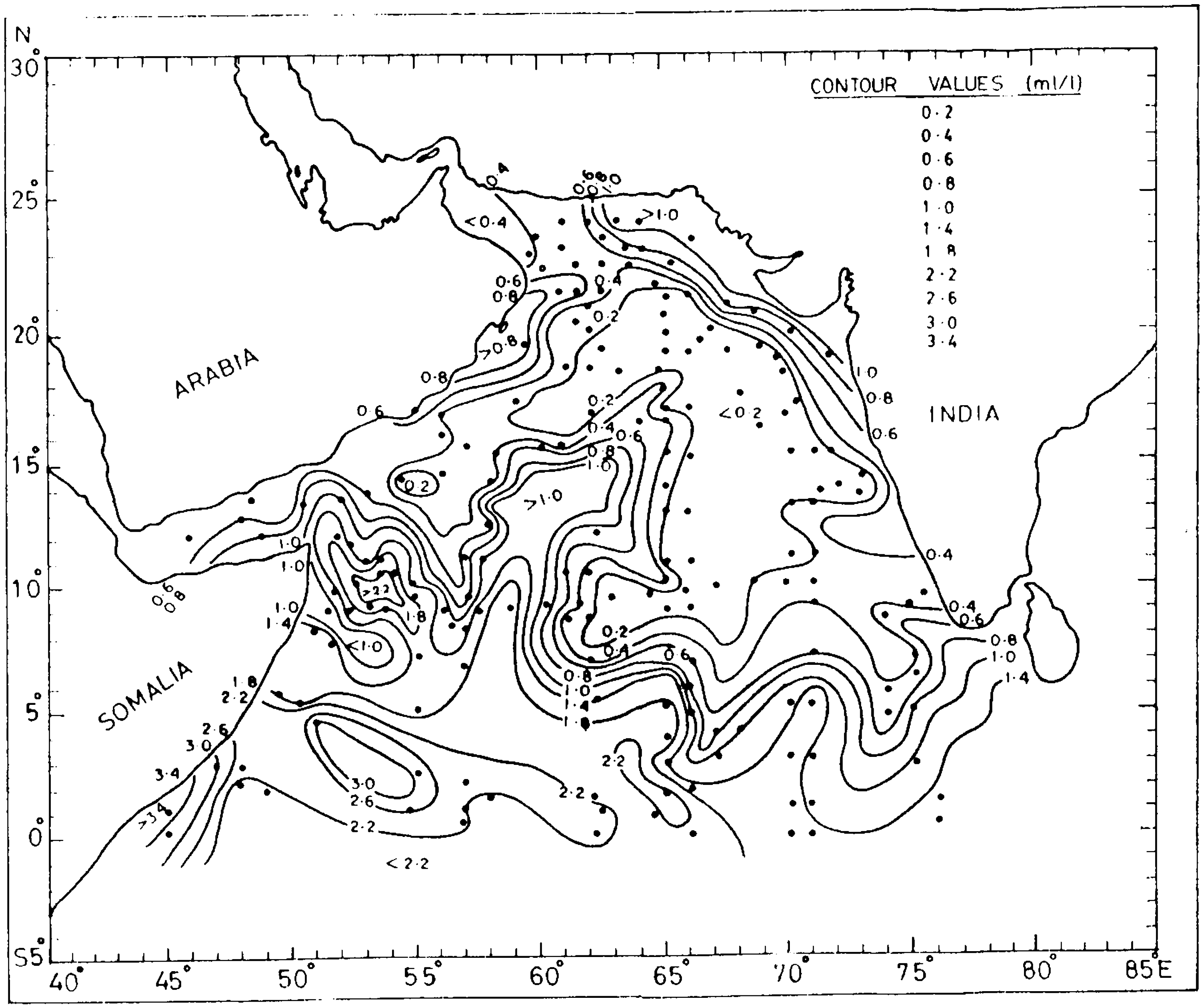
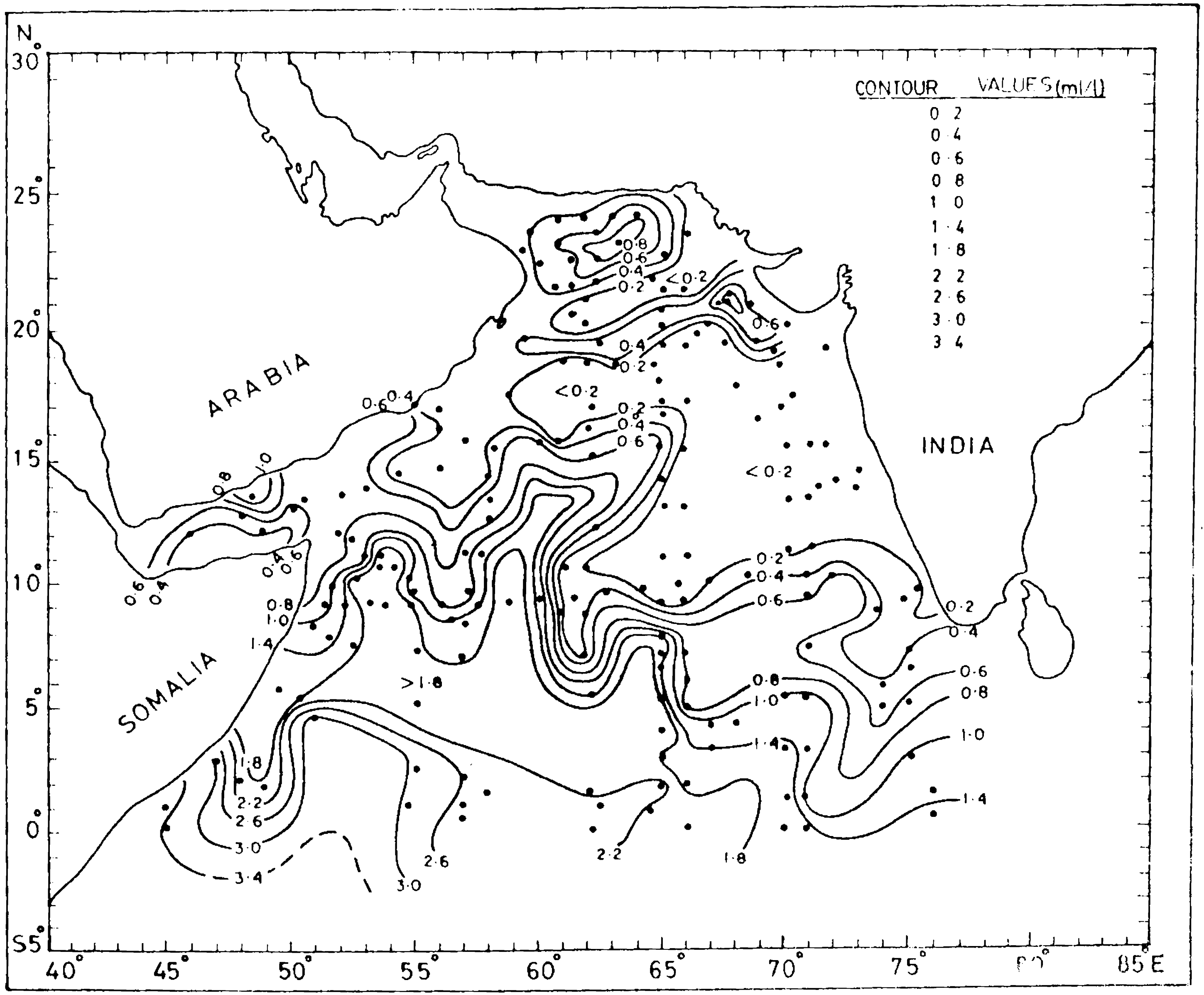


FIG: 12. DISTRIBUTION OF OXYTY ON THE 220 - cl/t ISANOSTERIC SURFACE



CONTOUR VALUES (ml/l)
0·2
0·4
0·6
0·8
1·0
1·4
1·8
2·2
2·6
3·0
3·4
ARABIA
INDIA
SOMALIA
<0·2
>1·8
N
30°
25°
20°
15°
10°
5°
0°
S5°
40°
45°
50°
55°
60°
65°
70°
75°
85 E

orientation in the north, except between 19^{o}N and 22^{o}N (Figs. 11, 12 and 13). By comparing the distribution of oxyty in the oxygen minimum layer (Fig.5) with that on 200- cl/t surface (Fig.13), it can be construed that the oxygen minimum layer in most of the region under study coincides with the 200- cl/t surface as the oxyty values are almost similar, except in the southernmost region, where the oxygen minimum layer appears to have been uplifted to higher isanosteric surfaces, as the oxyties on the 200- cl/t surface are relatively greater than those at the 240 and 220 cl/t (Figs. 11, 12 and 13).

Compared to the distribution of oxyty during the southwest monsoon, the cells of high and low oxyty are relatively fewer and they are almost absent on the 200-cl/t surface except in the northernmost region (Figs. 9 and 13). A noticeable feature at the 240- and 220- cl/t surfaces is a tongue-like structure of low oxyty water from the central Somalia Coast, separated by high oxyty waters on either side (Figs. 11 and 12). Such a feature is absent in the 200 cl/t. On the contrary, oxyty increases continuously from north to south off the Somalia Coast. Off the Arabian Coast, while oxyty increases offshore in the northern region it decreases offshore of the southwest Arabian Coast.

3.2. Topography of the isanosteric surfaces

The topography of the isanosteric surfaces of 220 , 200 and 180 cl/t during the southwest monsoon and 240-, 220- and 200-cl/t surfaces for the northeast monsoon are shown in Figs. 14 to 16 and 17 to 19 respectively. It may be borne in mind that the contour intervals of the topographic charts and the topography of the oxygen minimum are not the same. However, the contour values are clearly presented in the corresponding diagrams.

3.2.1. Topography of the isanosteric surfaces during the southwest monsoon

Similar to the oxypleths, the isobaths also run parallel to the coast in the western Arabian Sea. But in the eastern region, although oriented meridionally, they do not give clear indication of an orientation parallel to the coast. Whereas the zonal gradients are relatively stronger in the western region, they are weaker in the east (Figs. 14, 15 and 16). The number of troughs and ridges increases with lower steric surfaces, which gives an indication that the

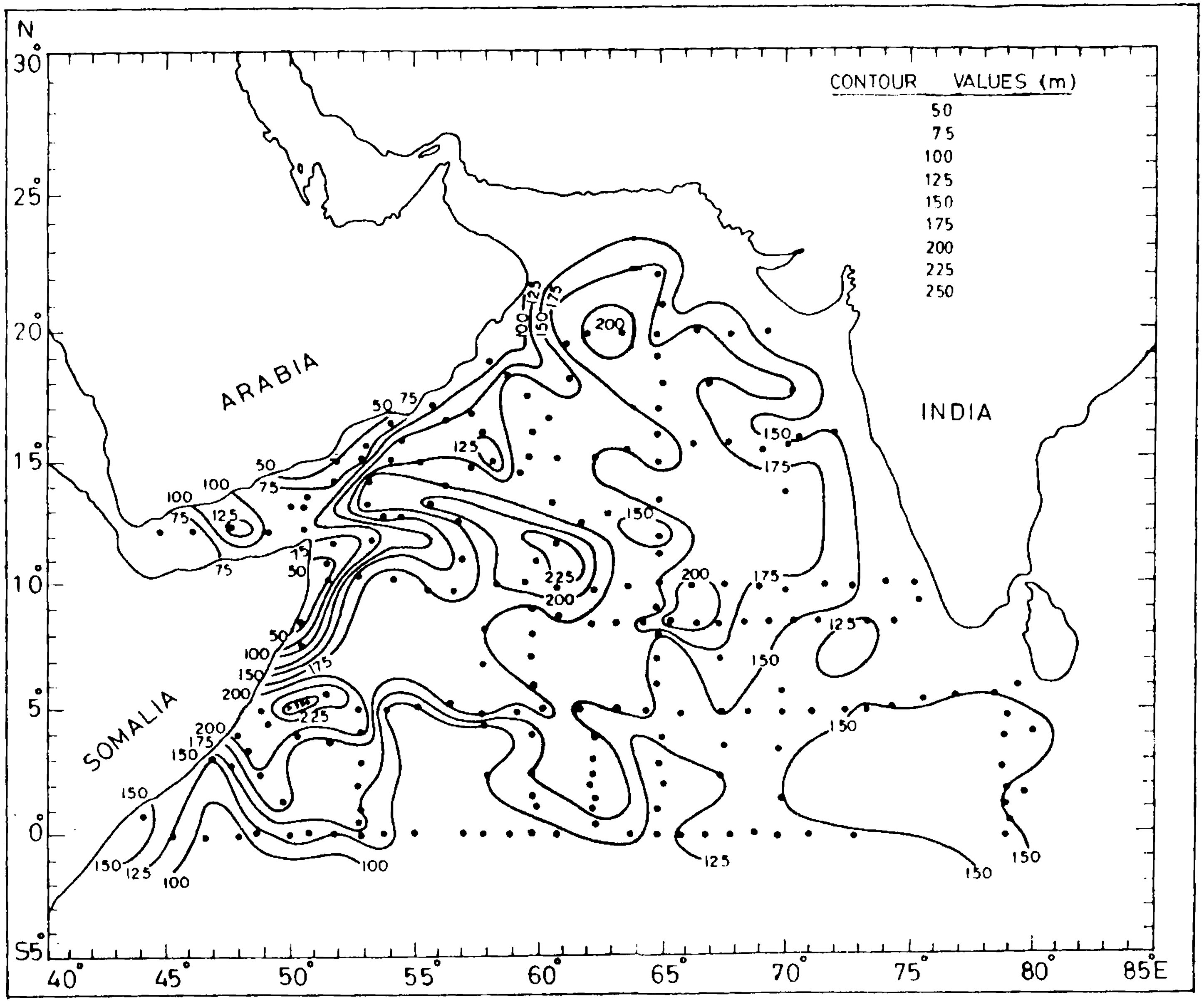


FIG: 14. TOPOGRAPHY OF THE 220 - cl/t ISANOSTERIC SURFACE

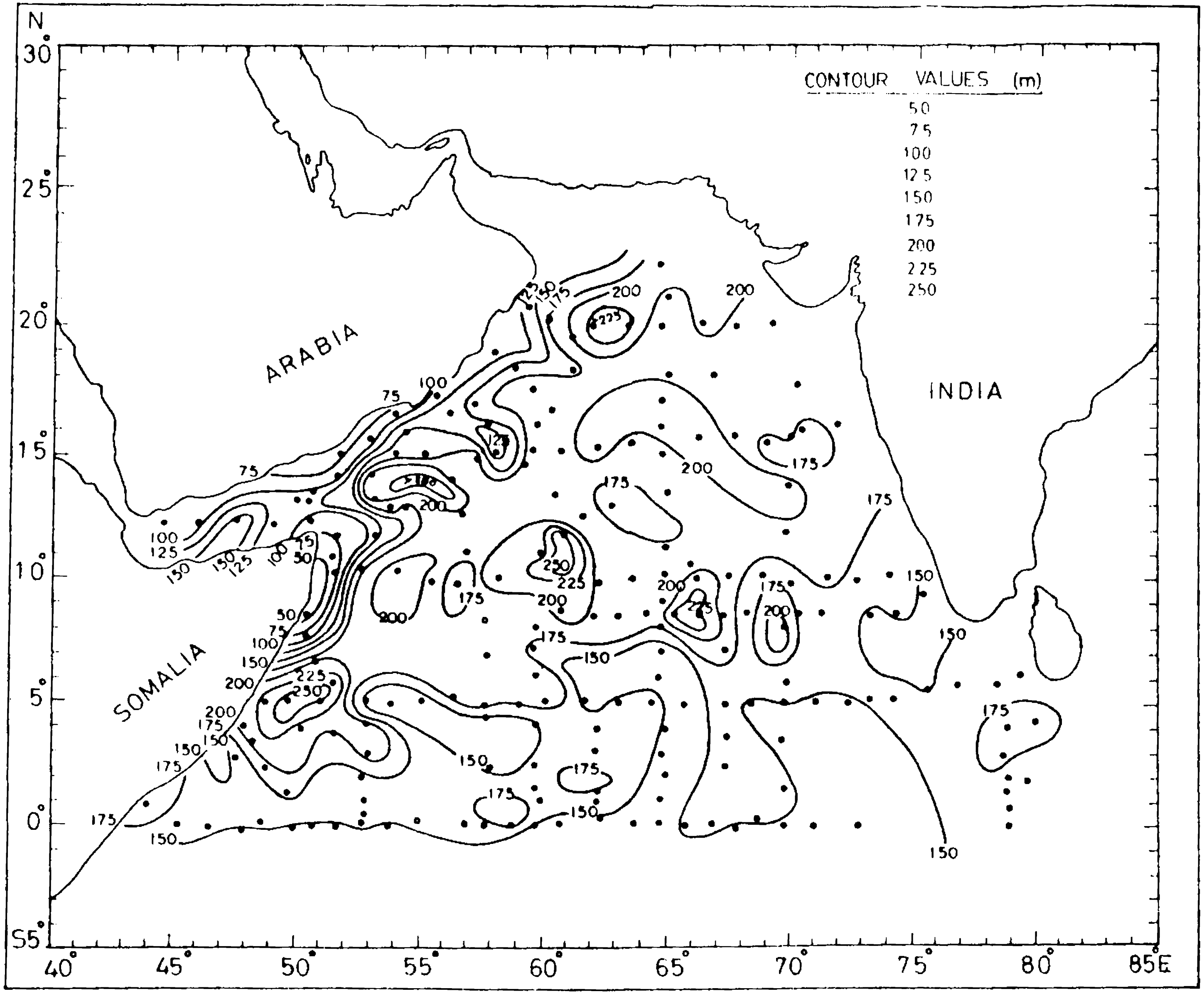


FIG: 15. TOPOGRAPHY OF THE 200 - cl/t ISANOSTERIC SURFACE

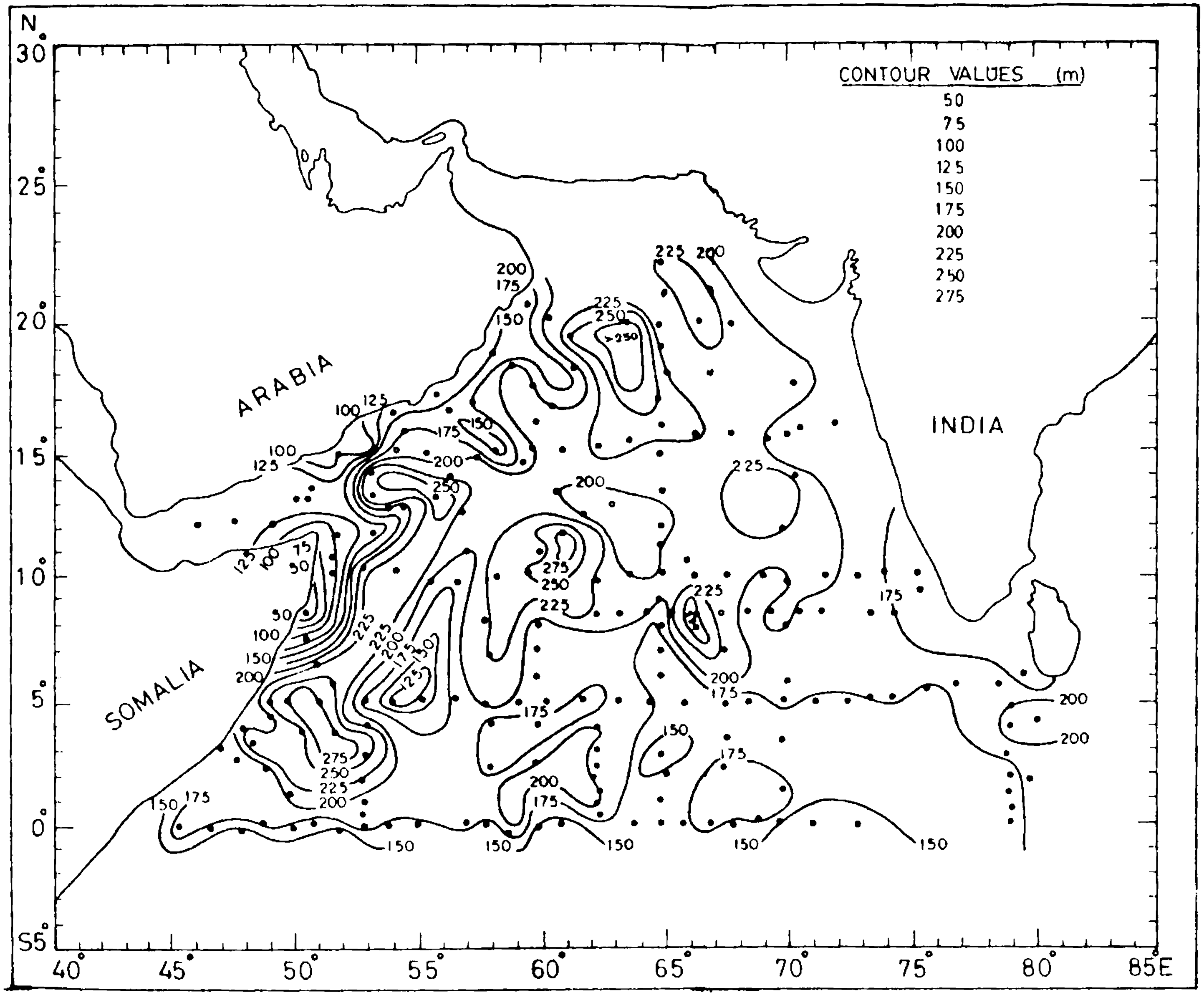


FIG: 16. TOPOGRAPHY OF THE 180 - cl/t ISANOSTERIC SURFACE DURING gradients also increase with increase of depth. While the topography of the 220- cl/t surface ranges from depths much less than 50 to about 250 m, it ranges from less than 50 to more than 250 m for the 200- cl/t and from around 50 to more than 275 m for the 180- cl/t surfaces (Figs. 14, 15 and 16). As the lowest contour drawn was for 50 m, the topographies could not be depicted when the surfaces were shallower. But, as the actual values can be understood from the station curves, a distinction is made as much less, less and around 50 m for 220-, 200- and 180- cl/t surfaces respectively. The most predominant and consistent feature in the topography of all the surfaces is that it is shallowest off the north Somalia Coast and the zonal gradients are also very strong. A similar feature is seen off the Arabia Coast, but, the depth increases with decrease of the steric surfaces, from which it can be construed that there are strong vertical density gradients off the Somalia and Arabia Coasts, resulting in strong gradients of topography also. The isanosteric surfaces slope up towards the coast, north of 5°N in the western region. The troughs and ridges on the topographic charts reveal the boundaries of the cyclonic and anticyclonic cells.

A comparison of the topography of the oxygen minimum layer (Fig.6) with the topographies of 220-, 200- and 180- cl/t surfaces (Figs. 14, 15 and 16) indicates that the oxygen minimum layer is much below even the 180- cl/t surface, very near to the coasts of Somalia and Arabia. But in the offshore regions, it lies between 220- and 180- cl/t surfaces. In the northcentral region, the topography of the oxygen minimum layer coincides with that of 200 cl/t confirming the inference drawn from the distribution of oxyty in the oxygen minimum layer and the isanosteric surfaces. Off the west coast of India and in the southeastern region, the topography of the oxygen minimum layer coincides with the topography of 220- cl/t surface. This is in confirmity with the distribution of oxyty. In the southcentral region, the topography of the oxygen minimum coincides with the 180- cl/t surface.

The thickness of the layer between 220- and 200- cl/t surfaces is lowest off the Somalia Coast and highest in the northern region. The thickness, in general, decreases towards the central Arabian Sea. The thickness between 180- and 200- cl/t surfaces is lowest off the Somalia Coast and highest in the northern region, with lower values in the central region (Figs. 14, 15 and 16).

3.2.2. Topography of the isanosteric surfaces during the northeast monsoon

The depths of the 240-, 220- and 200- cl/t surfaces range from values less than 100 m to slightly greater than 200 m, less than 100 m to greater than 200 m and around 125 m to slightly higher than 225 m respectively (Figs. 17, 18 and 19). Comparing these values with those of the southwest monsoon, the depth ranges over a variation of 40 cl/t thermosteric anomaly is much smaller during the northeast monsoon. Although during the northeast monsoon the oxygen minimum layer lies between 200- and 240- cl/t surfaces, it occurs between 180- and 200- cl/t surfaces during the southwest monsoon, the lowest values of the topography for the common surfaces of 220, and 200- cl/t are relatively higher and the highest values are lower compared to the depths of the corresponding surfaces during the southwest monsoon. It implies that the vertical gradients of density are higher during the northeast monsoon than during the southwest monsoon. As a result, vertical advection must be much less during the northeast monsoon compared to that during the southwest monsoon. Further, it can also be

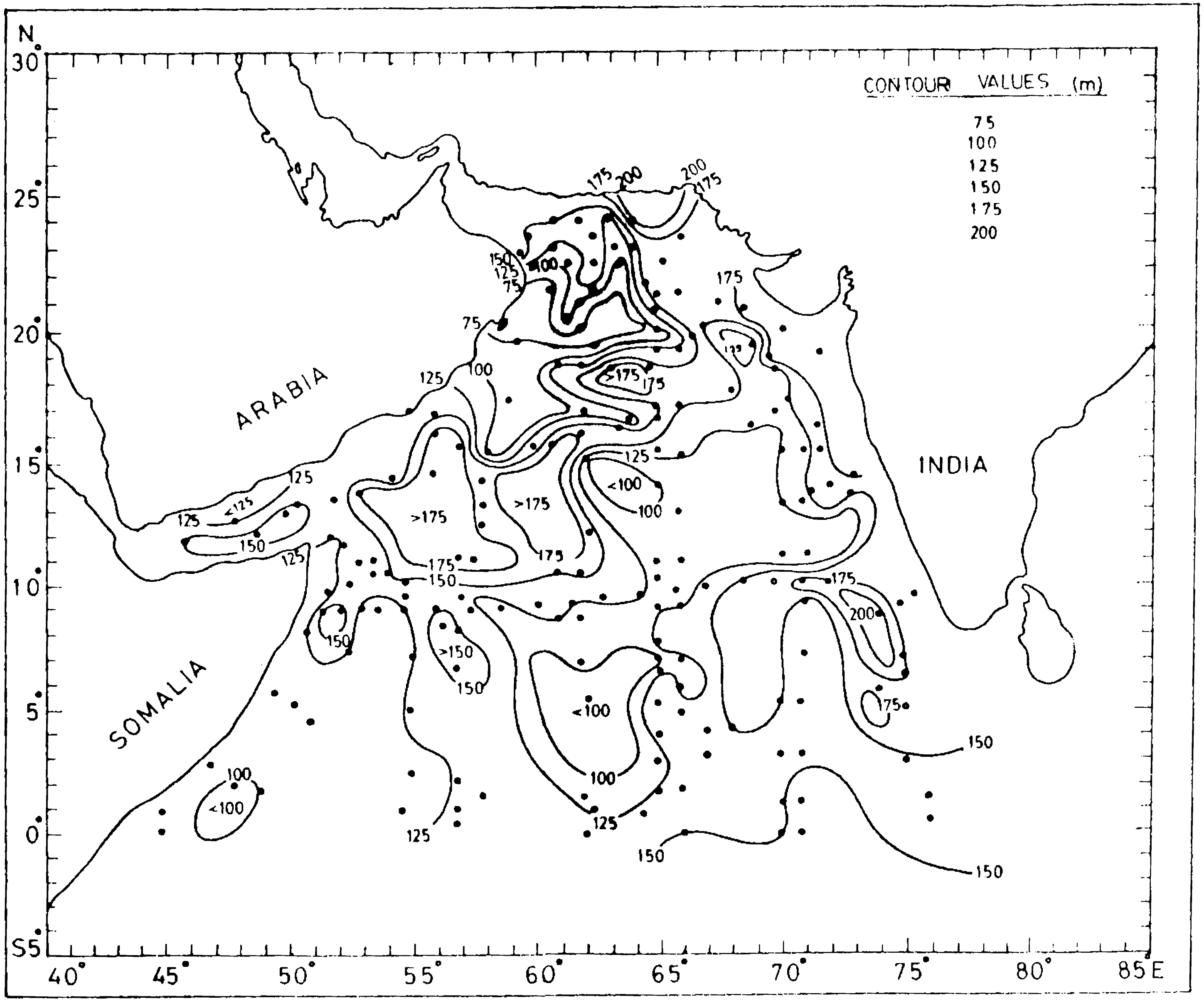


FIG: 17. TOPOGRAPHY OF THE 240 cl/t ISANOSTERIC SURFACE

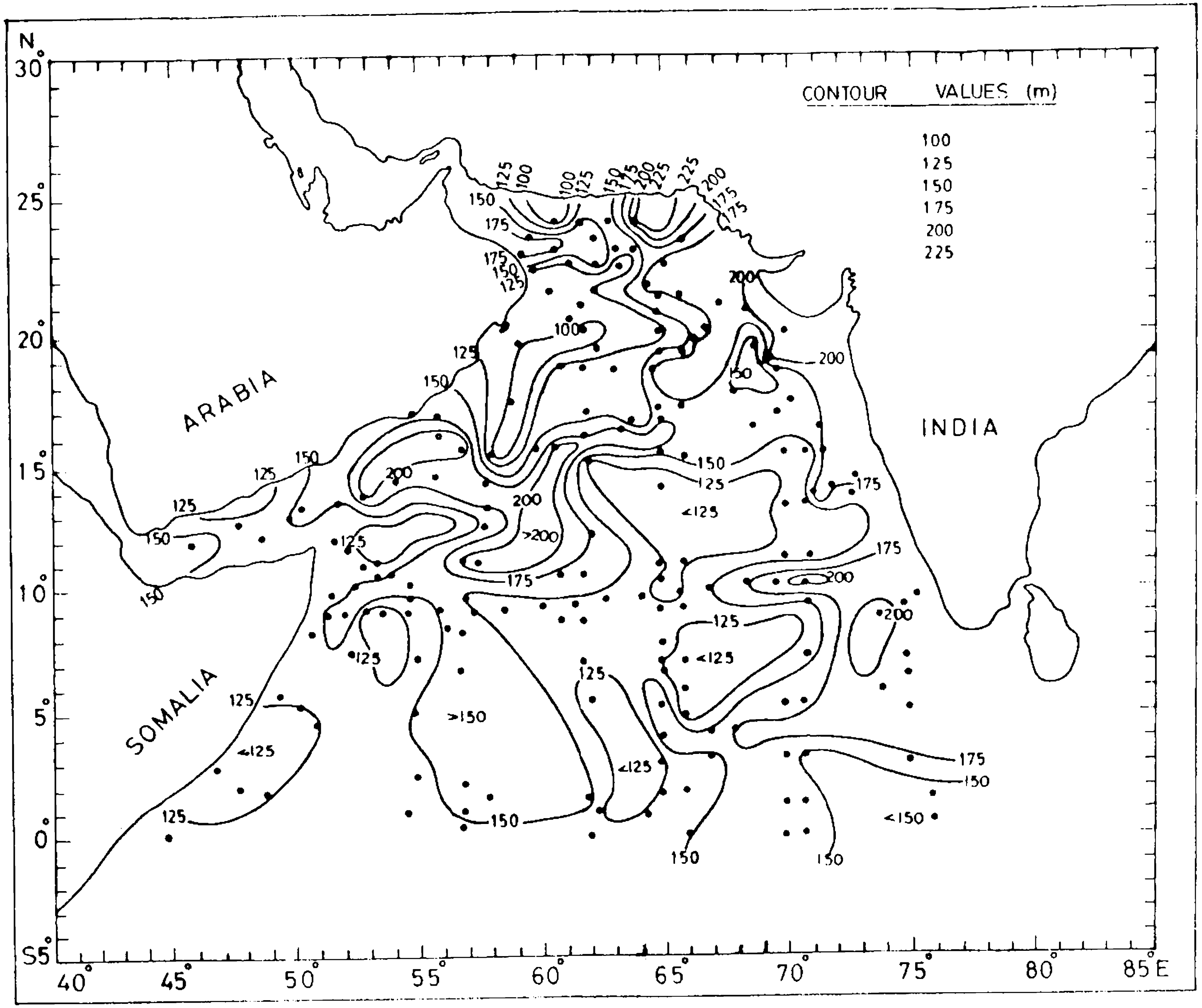


FIG: 18. TOPOGRAPHY OF THE 220 - cl/t ISANOSTERIC SURFACE DURING

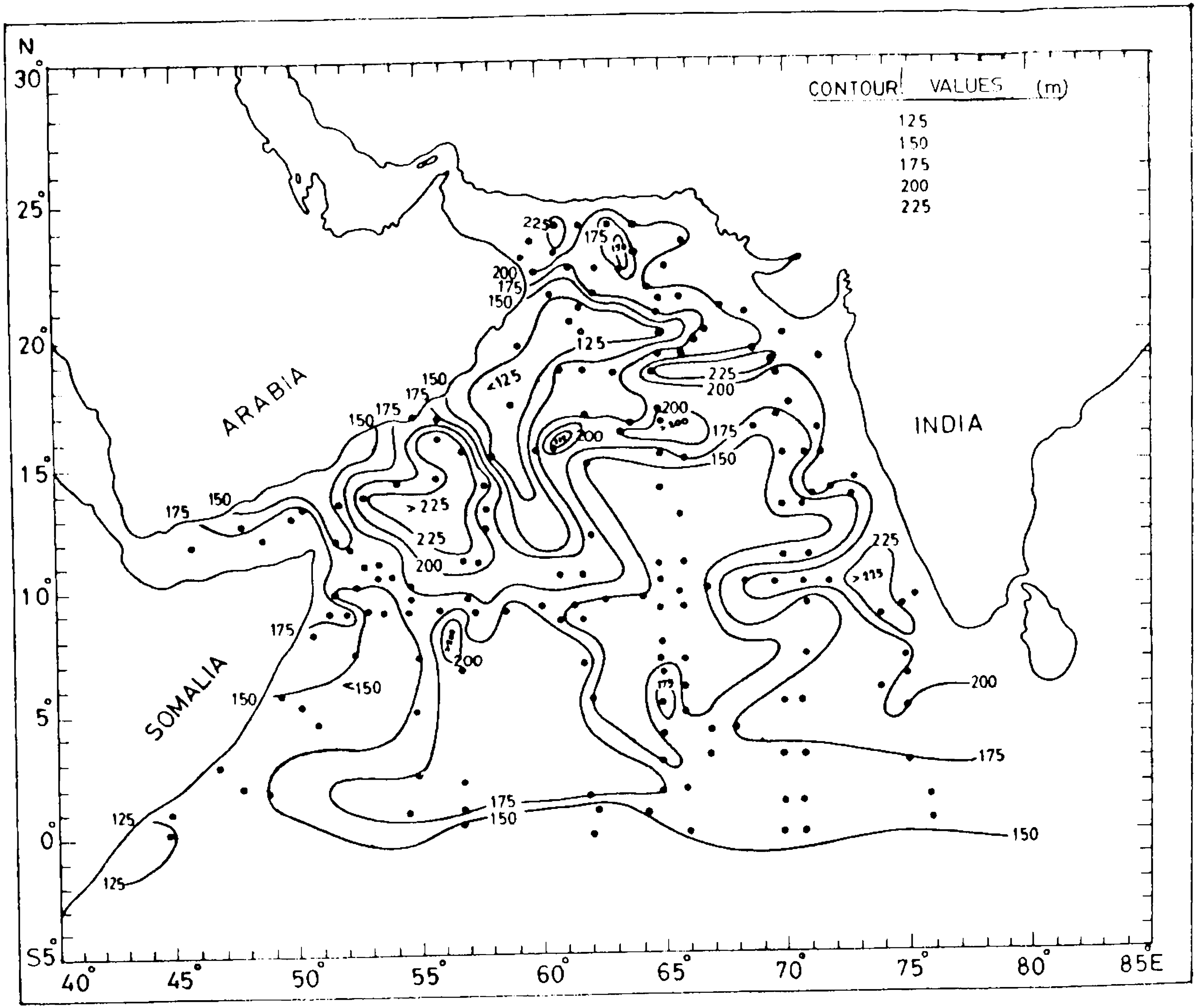


FIG: 19. TOPOGRAPHY OF THE 200 - cl/t ISANOSTERIC SURFACE DURING THE NORTHEAST MONSOON.

inferred that the horizontal advection plays a major role in the distribution of oxygen in the minimum layer during the northeast monsoon while it is the vertical advection during the southwest monsoon.

The depth of the isanosteric surfaces increases towards the west coast of India on all the three surfaces and the isobaths run almost parallel to the coast during the northeast monsoon (Figs. 17, 18 and 19). On the otherhand, the depth of the steric surfaces decreases towards the coast in the western Arabian Sea with few exceptions on 200- cl/t surface. Another important feature to be borne in mind is that the number of ridges and troughs are relatively less during the northeast monsoon, which is comparable with the number of highs and lows in oxyty distribution for the corresponding seasons. The general pattern of the topography of the different steric surfaces are almost similar, except that there is a slight deviation at the 200- cl/t surface, particularly in the northwestern region of the Arabian Sea, where the topography deepens shoreward. Unlike during the southwest monsoon, the number of troughs and ridges on the different surfaces are almost the same. Because of the complicated pattern, it is not possible to discuss about the meridional and zonal variation of the topography in the central and northern region of the Arabian Sea.

Comparing the topographies (Figs. 17, 18 and 19)of these surfaces with that of the oxygen minimum layer (Fig.7), it can be noticed that the oxygen minimum layer in most of the area coincides with the 200- cl/t surface and it can further be confirmed by comparison of the distribution of oxyty on the 200- cl/t surface and oxygen minimum layer (Figs. 13 and 5). The regions where there are deviations are off the southern coast of Somalia where the minimum layer coincides with the 240- cl/t surface and off the southwest coast of India where it coincides with 220- cl/t surface. On the topography of the oxygen minimum layer there is a deep trough with depths greater than 350 m which does not coincide with any of the depth values of these steric surfaces. Probably, the trough depicted in the oxygen minimum layer is based on a couple of abnormal values; otherwise,the general topography of the oxygen minimum layer in this region coincides with 200- cl/t surface. Such a conclusion is confirmed by comparing the oxyty distribution in the minimum layer with that on the 200- cl/t surface.

The thickness of the layer between 240- and 220- cl/t surfaces and 200- and 220- cl/t surfaces is the least off the Somalia Coast and it is the highest in the northern Arabian Sea. In general, it decreases towards the central region (Figs. 17, 18 and 19).

DISCUSSION

On comparing the topographies of the isanosteric surfaces and the oxyty distribution on these surfaces, it can be inferred that, in general, the oxygen minimum layer lies on the 200- cl/t surface in the Arabian Sea, during the southwest and northeast monsoons.

As pointed out earlier, the northern Arabian Sea exhibits stronger vertical gradients of oxyty between the 220- and 200 - cl/t surfaces compared to those between the 200- and 180- cl/t surfaces, during the southwest monsoon. Similar is the feature during the northeast monsoon except that the absolute values of the corresponding isanosteric surfaces are 240-, 220- and 200- cl/t surfaces respectively. The low oxyty on the 180- cl/t surface off the Arabia Coast during the southwest monsoon leads to the conclusion that the oxygen minimum layer either coincides with this surface or is further down. Although the minimum layer coincides with the 200- cl/t surface off Somalia, the oxyty within this layer is relatively higher during the southwest monsoon compared to that during the northeast monsoon. Compared to the regions mentioned above, relatively smaller variations in oxyty are observed at the different isanosteric surfaces in the rest of the Arabian Sea. The two elongated tongues of low oxyty, separated by high oxyty, at the west coast of India, suggests horizontal advection from east to west during the southwest monsoon.

Relatively deeper topography is observed in the northern and central Arabian Sea. The variation in topography for all the isanosteric surfaces are less during the northeast monsoon, which clearly indicates the relatively weaker vertical advections that take place during this season compared to those during the southwest monsoon. The topographies indicate the presence of anticyclonic and cyclonic eddies in the subsurface layers. The distribution of oxyty on these surfaces also suggests such a characteristic. During the northeast monsoon, the topographies show relatively smaller number of such features suggesting a decreased eddy circulation at these surfaces. Eddy type of circulation appears to be more dominant at lower steric surfaces, as evidenced by the stronger gradients in topography.

It is interesting to note that the distribution of oxyty on any two isanosteric surfaces has a close association with the thickness of the layer between them. The thickness of such a layer gives an indication of the stability of the waters in that layer and also reveals the relative intensity of vertical advection. Whereas lower stratification and greater mixing are characteristic of regions with greater thickness between the surfaces, smaller thickness indicates stronger vertical density gradients (greater stratification) allowing lesser vertical mixing. In the latter case, horizontal advection plays the major role in bringing about spatial variations. Specific cases, which illustrate the above mentioned correlation, may be found out from a comparison of the charts depicting the oxyty distribution (Figs. 8, 9 and 10) and topography (Figs. 14, 15 and 16)of isanosteric surfaces. For example, in the northern region of the Arabian Sea, during the southwest monsoon, the thickness of the layer between the 200- and 180- cl/t surfaces is more than that between the 220- and 200- cl/t surfaces (Figs. 14, 15 and 16). It is also noticed that the oxyty maintains approximate homogeneity between the lower surfaces, whereas significant gradients are present between the 220- and 200- cl/t surfaces (Figs. 8, 9 and 10). Other areas particularly in support of this characteristic are the south central and southeastern Arabian Sea during this season. In the northern Arabian Sea, during the northeast monsoon also a similar characteristic is observed.

C H A P T E R - IV

CHAPTER - IV

CIRCULATION AND ITS INFLUENCE ON THE OXYGEN MINIMUM LAYER

It is well known that the atmospheric circulation over the Arabian Sea reverses semi-annually, which in turn influences the circulation of the Arabian Sea. Compared to the northeast monsoon, the southwest monsoon is more powerful and it prevails over a longer period over the Arabian Sea. During the southwest monsoon, the southwest winds develop an anticyclonic current system in the Arabian Sea and during the northeast monsoon the northeast trade winds cause a cyclonic flow. The flow patterns at the 220-, 200- and 180- cl/t isanosteric surfaces and 240-, 220- and 200- cl/t surfaces representing the southwest and northeast monsoons, are presented in Figs. 20 to 22 and 23 to 25 respectively, since the oxygen minimum layer is found to lie within these surfaces during the corresponding seasons. The acceleration potentials used in the preparation of the charts were computed with reference to the 1000 db surface.

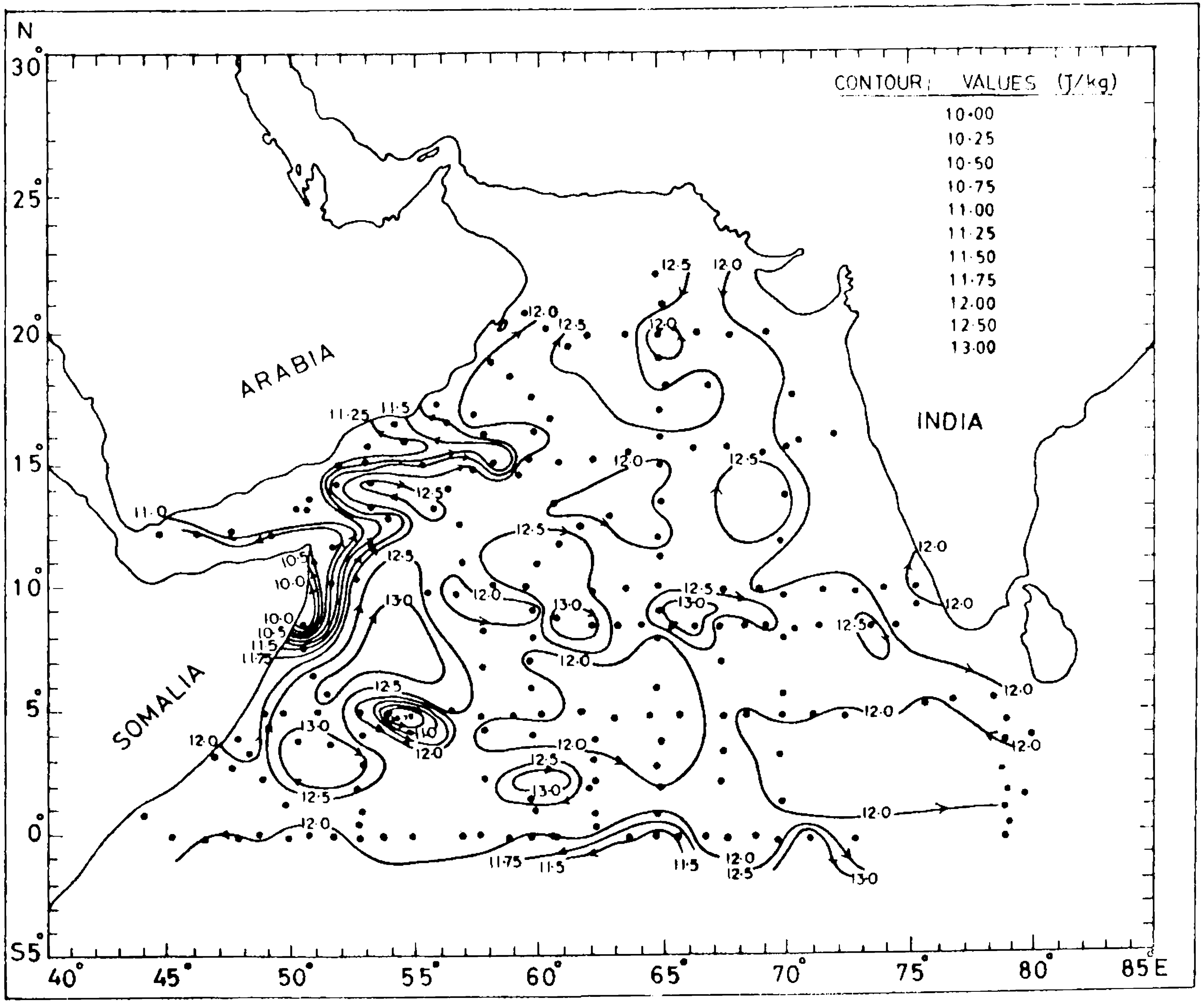


FIG: 20. FLOW PATTERN AT THE 220 - cl/t ISANOSTERIC SURFACE DURING

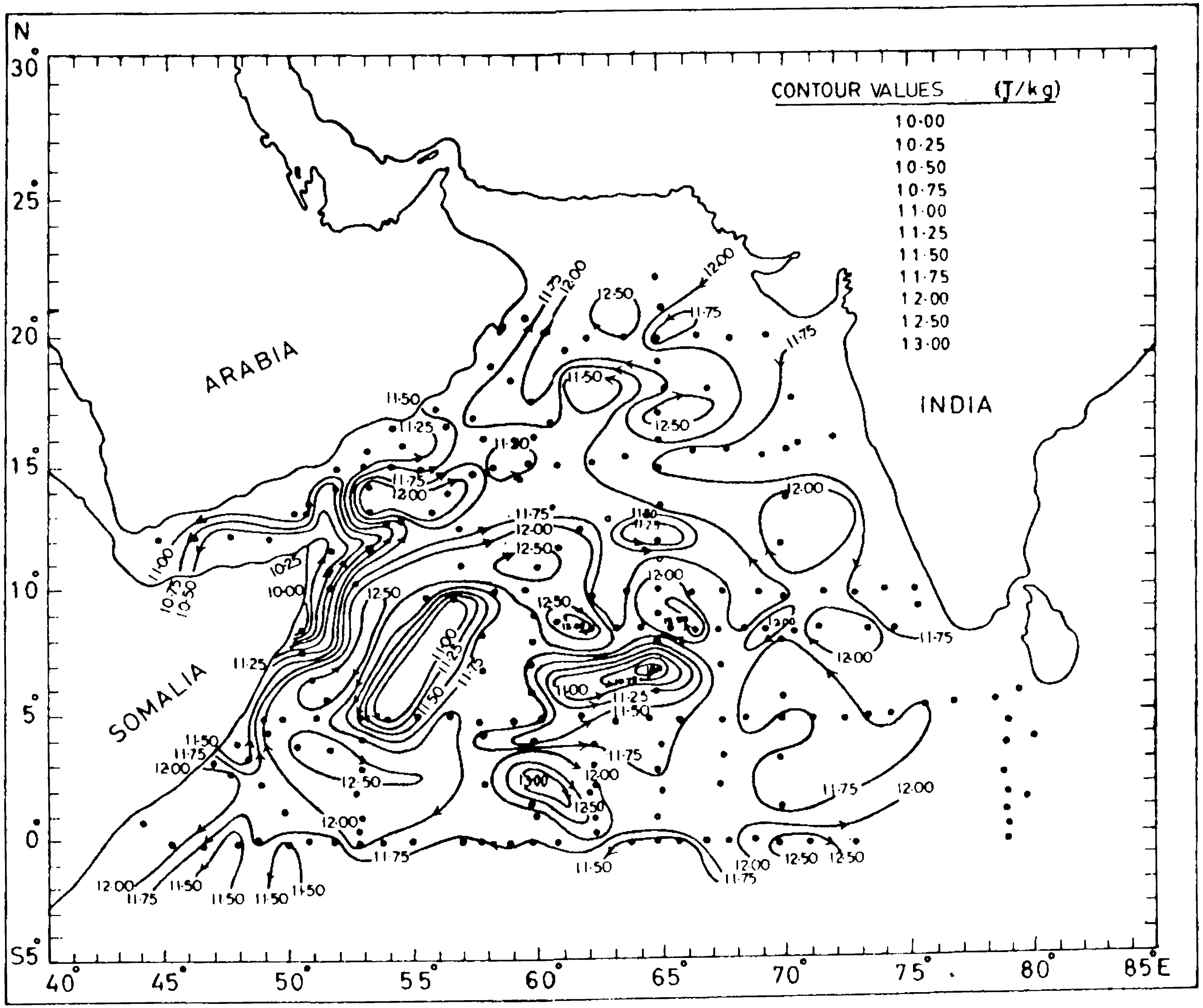


FIG: 21. FLOW PATTERN AT THE 200 - cl/t ISANOSTERIC SURFACE DURING THE SOUTHWEST MONSOON.

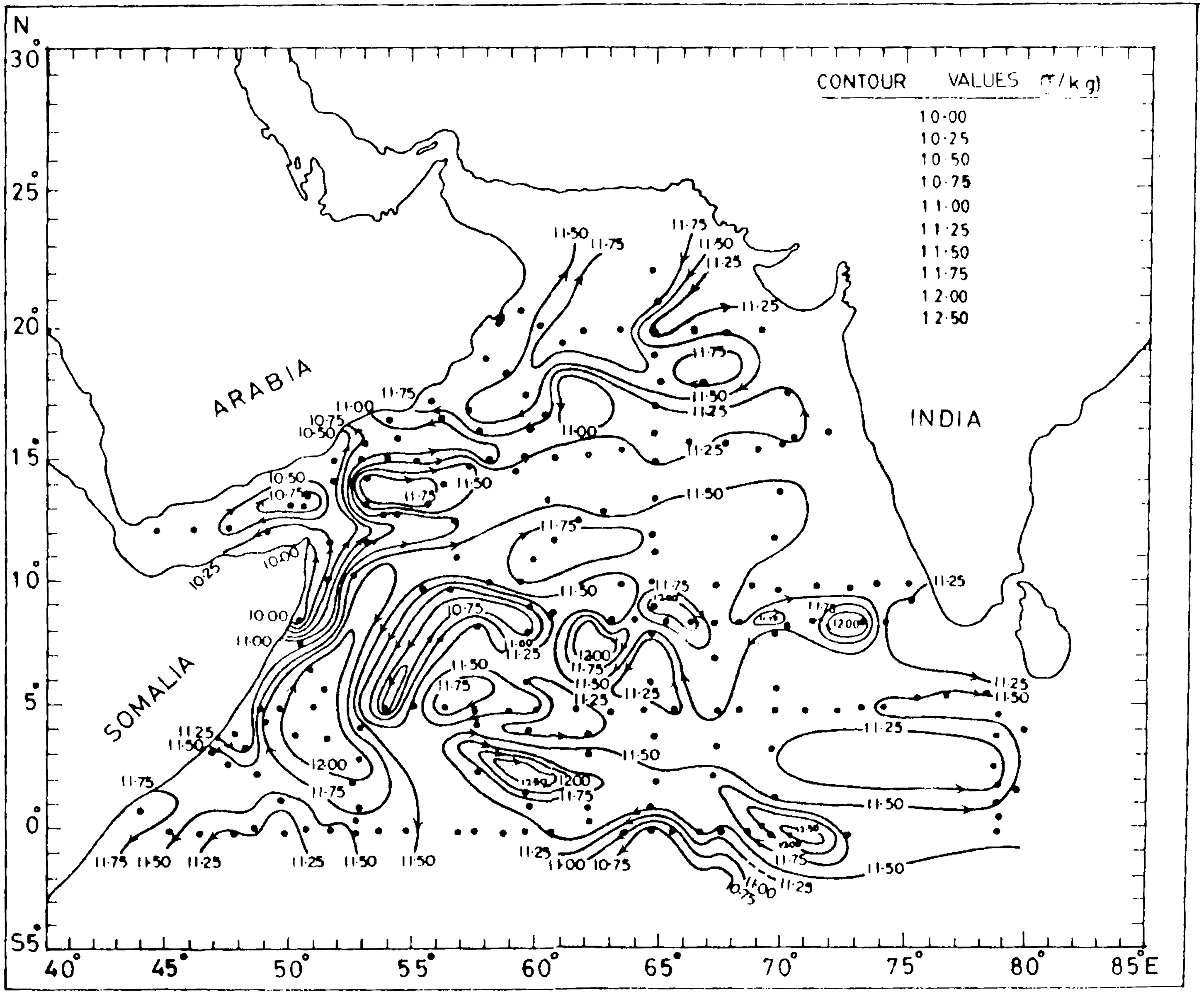


FIG: 22. FLOW PATTERN AT THE 180 - cl/t ISANUSTERIC SURFACE DURING THE SOUTHWEST MONSOON.

4.1. Results

4.1.1. Flow pattern at the isanosteric surfaces during the southwest monsoon

Many common features are observed in the flow patterns at the three isanosteric surfaces. The northerly flow off the Somalia Coast is strong and narrow north of $7^{o}N$ (Figs. 20, 21 and 22). It is identified clearly from the flow patterns that a part of this Somalia Current flows northward, while the other branch flows eastward. A single clockwise gyre is noticed in the Somalia Current System, as the data for this region were collected during August. A part of the anticyclonic circulation in the northern Arabian Sea flows southward along the west coast of India, especially in the upper layers. It is observed that alternate cyclonic and anti-cyclonic eddies are present in the central Arabian Sea. The flow is westerly near the equator, which is a permanent feature in both the seasons. All the three surfaces show the presence of an anticyclonic cell around $14^{o}N$, $55^{o}E$, but it is prominent at the 200- and 180- cl/t surfaces. There is a prominent cyclonic gyre between $5-10^{o}N$ and $53-60^{o}E$ at the 200-

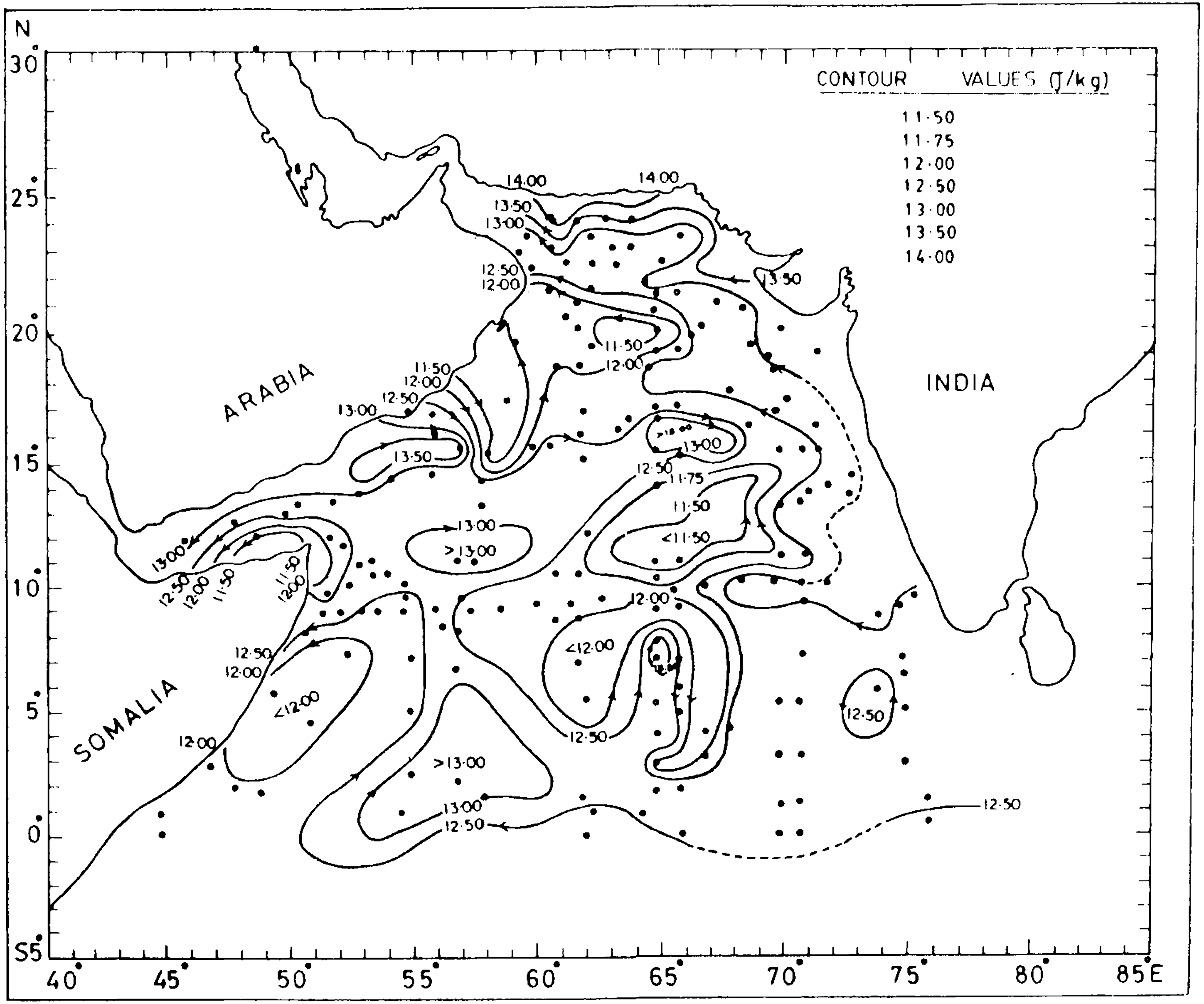


FIG: 23. FLOW PATTERN AT THE 240 - cl/t ISANOSTERIC SURFACE DURING THE NORTHEAST MONSOON.

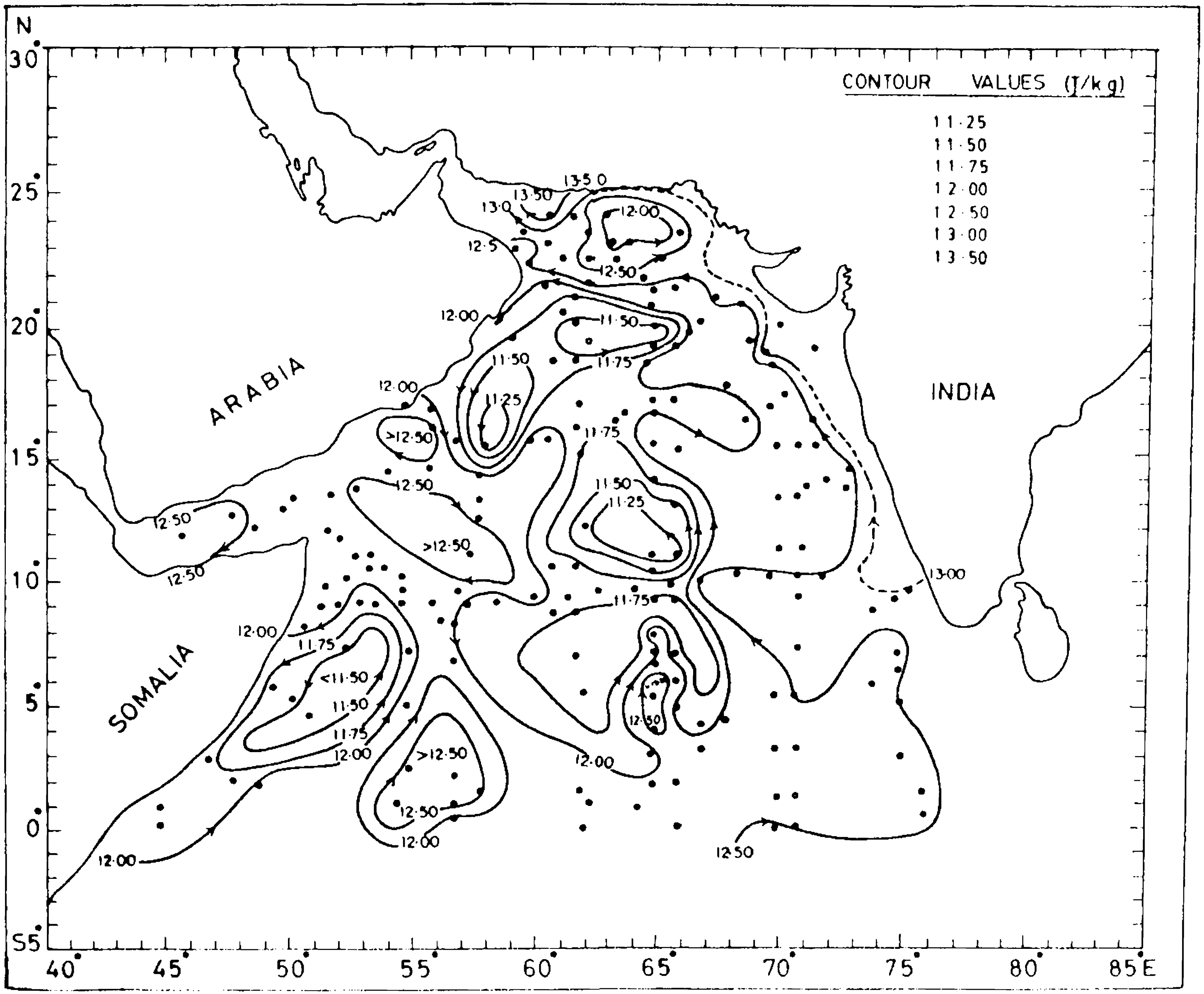


FIG: 24. FLOW PATTERN AT THE 220 - cl/t ISANOSTERIC SURFACE DURING THE NORTHEAST MONSOON.

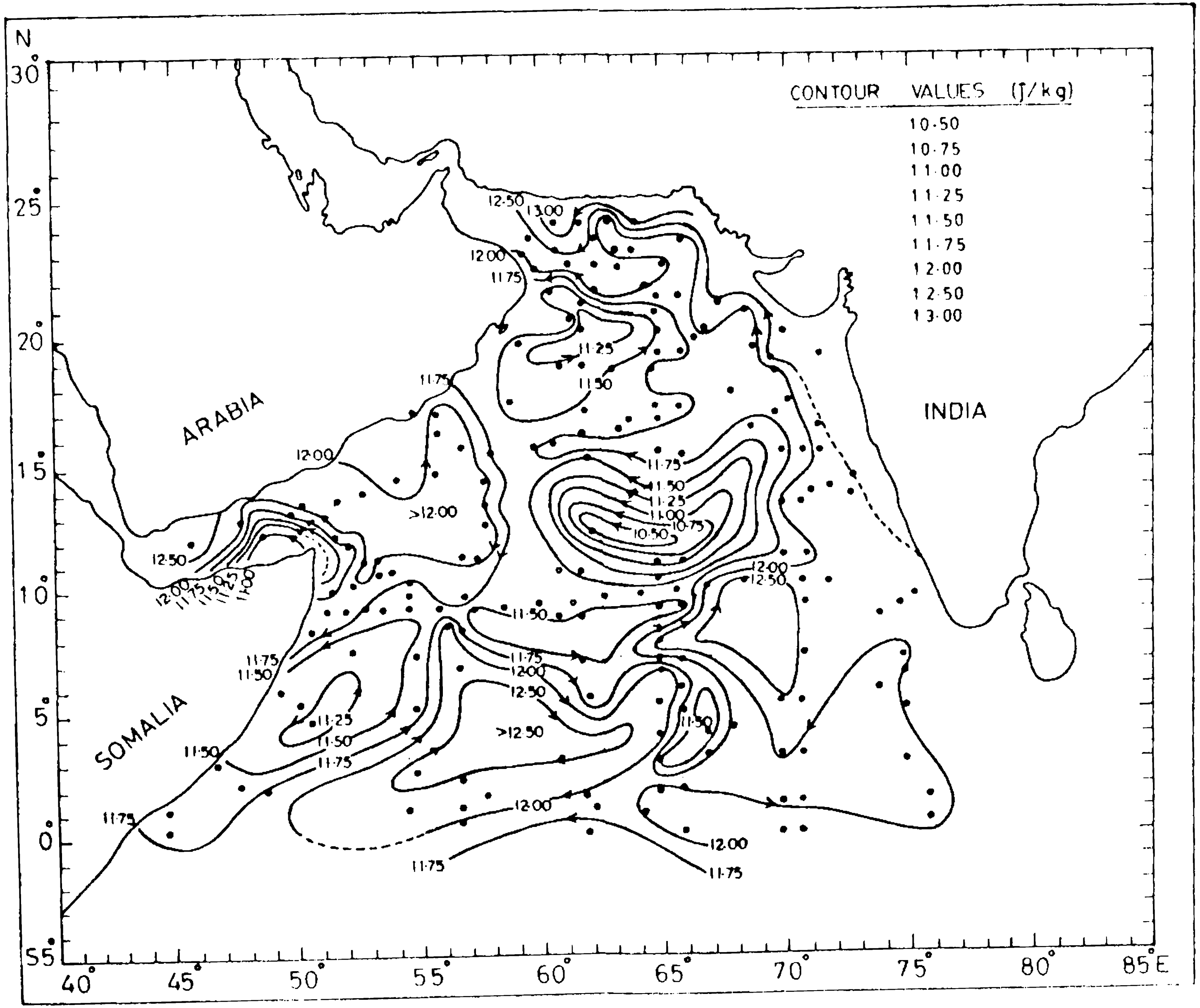


FIG: 25. FLOW PATTERN AT THE 200 - cl/t ISANOSTERIC SURFACE DURING THE NORTHEAST MONSOON.

and 180- cl/t surfaces, which weakens towards the 220- cl/t surface. The current strengths are more in the western, than the eastern Arabian Sea.

4.1.2. Flow pattern at the isanosteric surfaces during the northeast monsoon

During the northeast monsoon, the flow is cyclonic in the Arabian Sea (Figs. 23, 24 and 25). The flow pattern does not appear to be as complex as it is during the southwest monsoon.

Off the Somalia and Arabia coasts, a southerly flow is well indicated on 220- and 200- cl/t surfaces (Figs 24 and 25). At all the three levels, a northerly flow is observed off the west coast of India which transports waters of the equatorial Indian Ocean and Bay of Bengal into the northern Arabian Sea. A number of cyclonic and anticyclonic cells are seen in the central and southern Arabian Sea. A prominent cyclonic eddy circulation is noticed between 10-17°N and 60-70°E at the three surfaces. Another notable feature is the presence of an anticyclonic eddy within the latitudinal belt of 1° to 7°N, which can be traced on all the three surfaces. It is located between 55°E and 68°E at the 200- cl/t surface(Fig.25) and between 53^{o}E and 60^{o}E at the 220- and 240- cl/t surfaces (Figs. 23 and 24). In general, the circulation is less intense and devoid of specially noticeable features during this period.

4.2. Oxygen minimum in relation to circulation

As indicated earlier, the flow is anti-cyclonic during the southwest monsoon and cyclonic during the northeast monsoon in the Arabian Sea; it is embedded with smaller cyclonic and anticyclonic cells. The division of the Somalia Current into northerly and easterly branches was clearly established during INDEX (Leetma et al., 1982). According to Schott (1983), the Somalia Current exhibits a two-gyre nature during the early part of the southwest monsoon. The presence of eddies are more during the southwest monsoon, especially in the central Arabian Sea, because of the shear produced by the Somalia Current. Similar features were reported earlier (Satyanarayana Murthy et al., 1982). The flow charts during both seasons suggest the presence of alternate cyclonic and anticyclonic vortices in the Arabian Sea (Figs. 20-25) which appears to have been present even at the surface also (Duing, 1970).

The complex pattern of the highs and lows of the acceleration potential is the most predominant feature,observed. A similar complex pattern of highs and lows of the oxypleths in the distribution map of oxyty in the oxygen minimum layer (Figs. 4 and 5) appears to be a result of the above characteristic. During the southwest monsoon, and in the upper layers, the Somalia Current carries waters having higher oxyty towards north from the southwestern Arabian Sea. Intense upwelling is known to occur off the Somalia Coast during this period (Warren et al., 1966), which tends to increase the oxygen carrying capacity of the surface waters by lowering the temperature. Mixing of these two waters keep the oxygen content in the oxygen minimum layer to be relatively high in this region (Fig.4). Near the Somalia Coast, upwelling brings the oxygen minimum layer to shallower depths during the southwest monsoon (Fig.6). On the contrary, during the northeast monsoon, the replenishment of water in the western side of the Arabian Sea, by the Somalia Current, is not taking place. Upwelling is also absent during this season. As a result, the oxygen minimum layer is deeper and poorer in oxygen (Figs.5&7) off the Somalia Coast than they are during the southwest monsoon. These results clearly show that the depth of occurrence of the oxygen minimum layer and its maintenance are controlled only by circulation, whatever may be the cause of formation of the minimum layer. The oxyty in the oxygen minimum layer in the southwestern Arabian Sea is higher during both the seasons (Figs. 4 and 5). In addition, farther from the Somalia Coast, the oxyty is higher during the southwest monsoon due to the convergence associated with the anticyclonic gyre (Fig.4), although there is an offshore decrease. As a consequence of the effect of convergence, the oxygen minimum layer is pushed downwards, to greater depths. This observation strongly supports the earlier statement that the position of the minimum layer is determined by the circulation and the associated advective processes. The western Arabian Sea exhibits higher oxyty in the minimum layer compared to the eastern, in both the seasons(Figs. 4 and 5). On comparison of the circulation pattern at different isanosteric surfaces (Figs. 20-22)with oxygen distribution at these surfaces (Figs 8, 9 and 10) as well as that in the oxygen minimum layer (Fig. 4) during the southwest monsoon, it can be inferred that the oxyty in the western Arabian Sea increases due to the horizontal advection of the high oxyty waters transported from the south, apart from the increased capacity to absorb more oxygen due to cooling of the waters by upwelling. It is, therefore, further confirmed that it is the circulation which plays a major role in the maintenance of the oxygen minimum layer and variation of oxyty within it. The southerly flow of low oxyty water from the northern Arabian Sea, along the west coast of India, causes the oxyty in the minimum layer in this region to drop to values around 0.10 ml/l (Fig.4) during the southwest monsoon. Due to the paucity of data during the southwest monsoon, no clear cut comment can be made in the region north of 20°N during the southwest monsoon.

In the central Arabian Sea, eddy circulations observed during both the seasons result in the alternate highs and lows in the concentration of oxygen in the minimum layer (Figs. 4 and 5). When there are anticyclonic and cyclonic eddies, they give rise to zones of sinking and upwelling resulting in highs and lows in the oxygen distribution. The topography of the oxygen minimum layer (Figs. 6 and 7) in this region also supports these features.

The flow in the equatorial region is mainly zonal (Figs. 20-25). During both the seasons, higher oxyty is a characteristic of the minimum layer in this region (Figs. 4 and 5). This results from the exchanges taking place with the high oxyty waters of the southern hemisphere. At intermediate depths, the equatorial waters are nearly isohaline (Quadfasel and Schott, 1982). The topography of the oxygen minimum layer in this region during both the seasons are comparatively shallow (Figs. 6 and 7). The Red Sea, Persian Gulf, Banda and Timor Sea waters present in the equatorial region contain very low oxyty (Swallow, 1984). But, it is to be noted that the oxygen minimum layer is situated much above the core layer of all these watermasses so that these low oxyty waters do not affect the oxyty in the minimum layer.

In general, the thickness of the layer between 220- and 200- cl/t surfaces for the southwest monsoon (Figs. 14 and 15) and that between 240- and 220- cl/t surfaces for the northeast monsoon (Figs. 17 and 18) is minimum off the Somalia, implying high stratification. Hence, in this region, horizontal advection is important especially during the northeast monsoon. This could be the reason for the relatively higher oxyty in the minimum layer observed in this region (Figs. 4 and 5), compared to the other parts of the Arabian Sea. On the other hand, the thickness between 220- and 200- cl/t surfaces for the southwest monsoon and that between 240- and 220-cl/t surfaces for the northeast monsoon are relatively higher in the northern Arabian Sea suggesting less stratification, as a consequence of which vertical advection predominates rather than horizontal mixing resulting in very low oxyty values in the minimum layer (Figs. 4 and 5). From the topographic charts, it is clear that strong vertical density gradients exist off the Somalia and Arabia Coasts (Figs.6 and 7).

The result of the present study is in consonance with those of the earlier studies on the equatorial Indian Ocean circulation, including direct current measurements that the flow, below the thermocline and at the level of the oxygen minimum layer is nearly zonal. There is little evidence of exchange of waters between the southern hemisphere and Arabian Sea at the level of the oxygen minimum. The absence of transequatorial flow in the depth range of 100 to 1000 m is confirmed by Sharma (1976a) through volumetric analysis that gives a quantitative estimation rather than a qualitative one. Such a conclusion can also be derived from the IIOE Atlas (Wyrtki, 1971) although it gives a mean picture over larger grids. Thus, the lack of any significant renewal of waters at the intermediate depths is the reason for the anomalously low oxyty in the oxygen minimum layer in the Arabian Sea.

The larger bodies of water, with extremely low oxygen content, are found on the eastern sides of the subtropical oceans, where, at intermediate levels, horizontal circulation is very weak but vertical ascending movements prevail. These centres of formation of low oxyty waters are connected across the equator by a shallower minimum layer resulting from equatorial upwelling. From these water bodies of lowest oxygen content, oxygen minima spread by mixing into their surroundings (Wyrtki, 1962). In the present study, the conditions under which an oxygen minimum layer develops in the oceans can be summarized as follows. Consumption of oxygen is the primary condition for the development of an oxygen minimum layer; and the minimum results from biochemical processes. Its position and the oxyty within it are determined by circulation. The minimum occurs in the layers of minimal advection of oxygen, which are closely related to the layers of minimum horizontal movements. The oxygen minimum itself lies in the upper part of the layer of smallest advection, because the consumption of oxygen decreases almost exponentially with depth. Thus, biochemical processes are responsible for the existence of oxygen minima, but circulation is responsible for their position and the variation of oxyty within them.

CHAPTER - V

CHAPTER - V

SCATTER DIAGRAMS

The properties of watermasses or air masses can be well detected on characteristic diagrams. Such a diagram was first introduced in oceanography by Helland - Hansen (1916) as T-S diagram. Subsequently, many more characteristic diagrams have been introduced, both in oceanography and meteorology, to identify water and air masses. In the present chapter, in order to characterise the oxyty relationship with temperature and thermosteric anomaly, scatter diagrams have been drawn for eight representative areas; the details of the method adopted are given in chapter I under Material and Treatment of Data.

Figs. 26 to 33 and 34 to 41 represent the temperature-oxyty-thermosteric anomaly relationship for the eight representative areas for the southwest monsoon and northeast monsoon respectively.

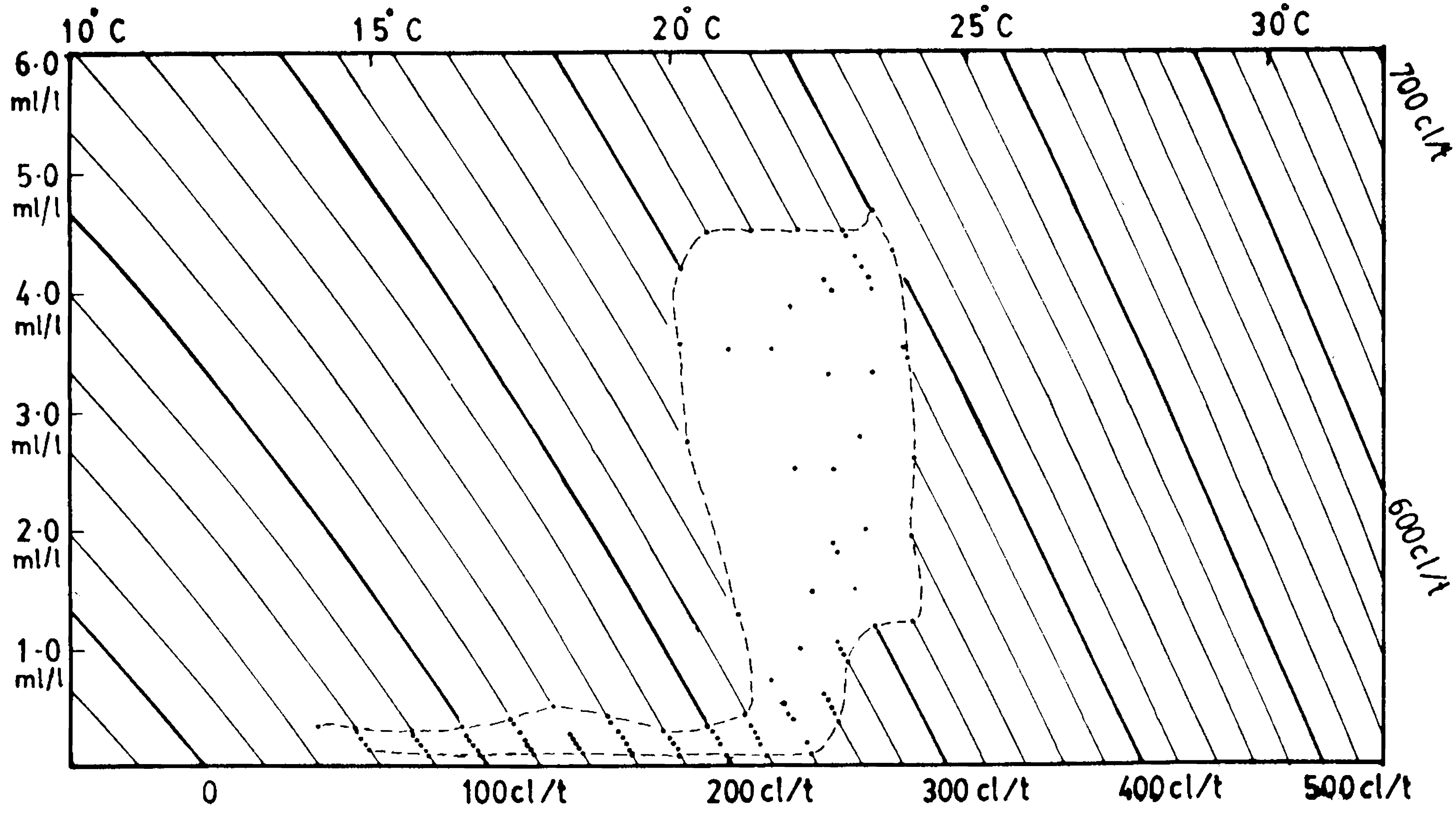


FIG: 26. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE SOUTHWEST MONSOON - AREA - 1.

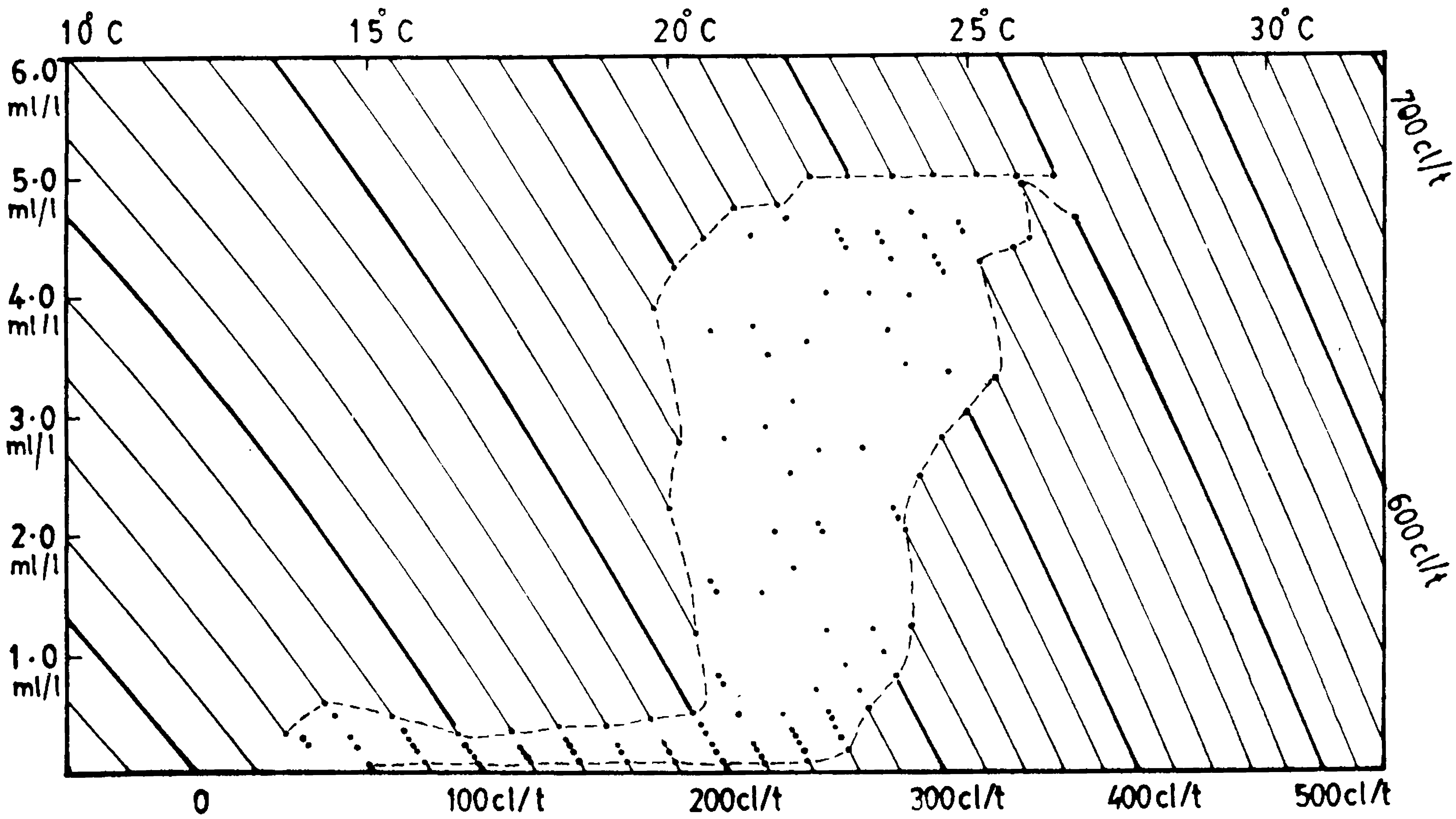


FIG: 27. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE SOUTHWEST MONSOON - AREA - 2.

5.1. Scatter diagrams for the southwest monsoon

5.1.1. Area 1. (18^{0}N to 23^{0}N and 58^{0}E to 63^{0}E)

The distribution of oxyty against temperature at various isanosteric surfaces exhibits less scatter at intermediate layers in this region. Oxyty is extremely low on surfaces of 220 , 200 and 180 cl/t, and there is not much variation upto 60- cl/t surface, indicating that the thickness of the oxygen minimum layer is high in this area (Fig.26). The lowest oxyty observed in this area is less than 0.10 ml/l. The oxypleths in the distribution map of oxyty also show the same characteristic feature.

5.2.2. Area. 2 (18^{0}N to 23^{0}N and 65^{0}E to 70^{0}E)

The scatter is almost similar to that in area 1, in the intermediate layers (Fig. 27). From the diagram it is understood that eventhough the minimum layer starts at the 220- cl/t surface it extends upto 40- cl/t surface. Oxyty is almost constant below the 220- cl/t surface and the lowest value is less than 0.10 ml/l. This is an agreement with the distribution of o"yty in the minimum layer. Thus, the thickness of the low oxyty layer in area 2 is greater than that in area 1.

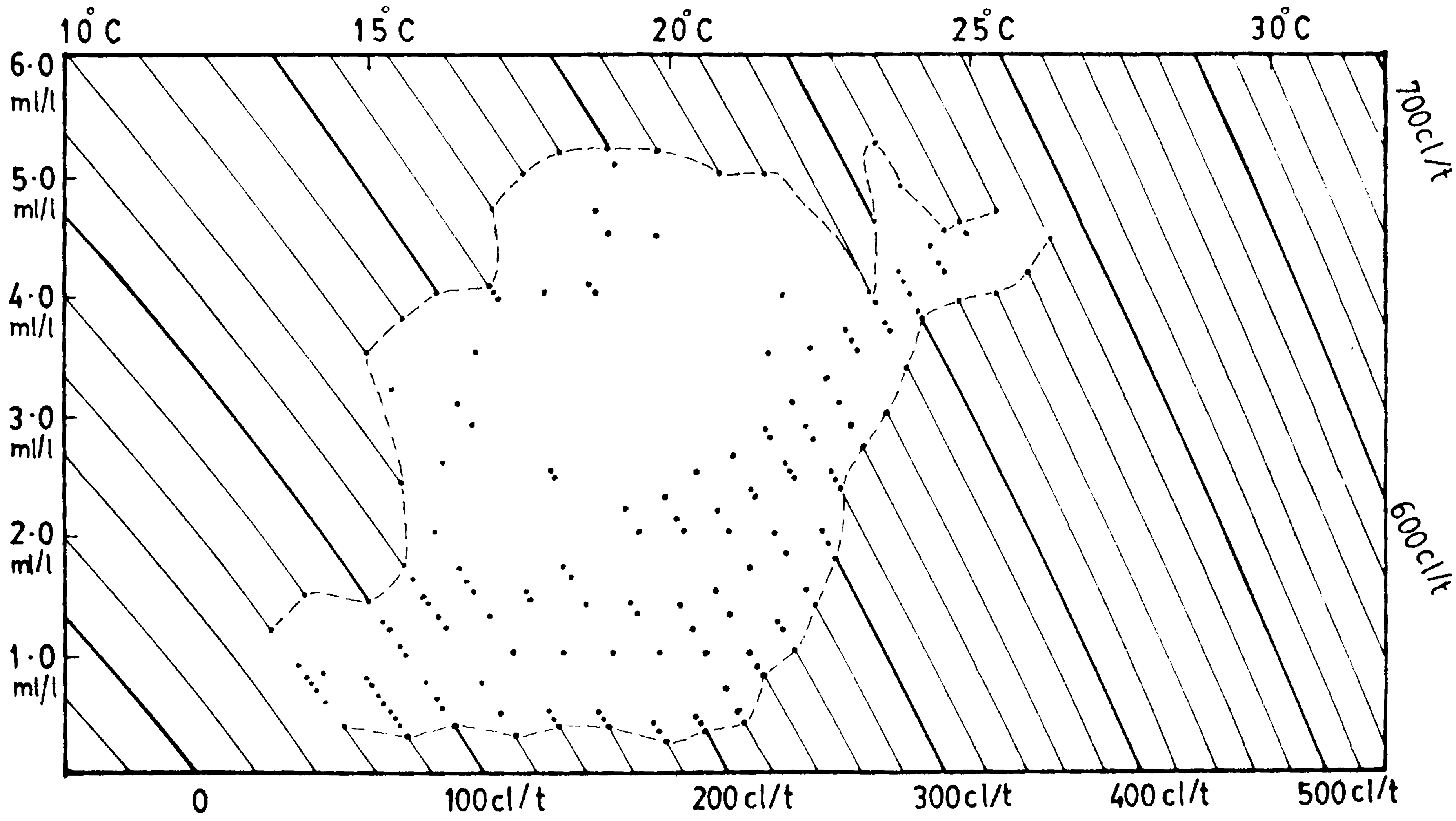


FIG: 28. SCATTER DIAGRAM FOR OXYIY-TEMPERATURE DURING THE SOUTHWEST MONSOON - AREA - 3.

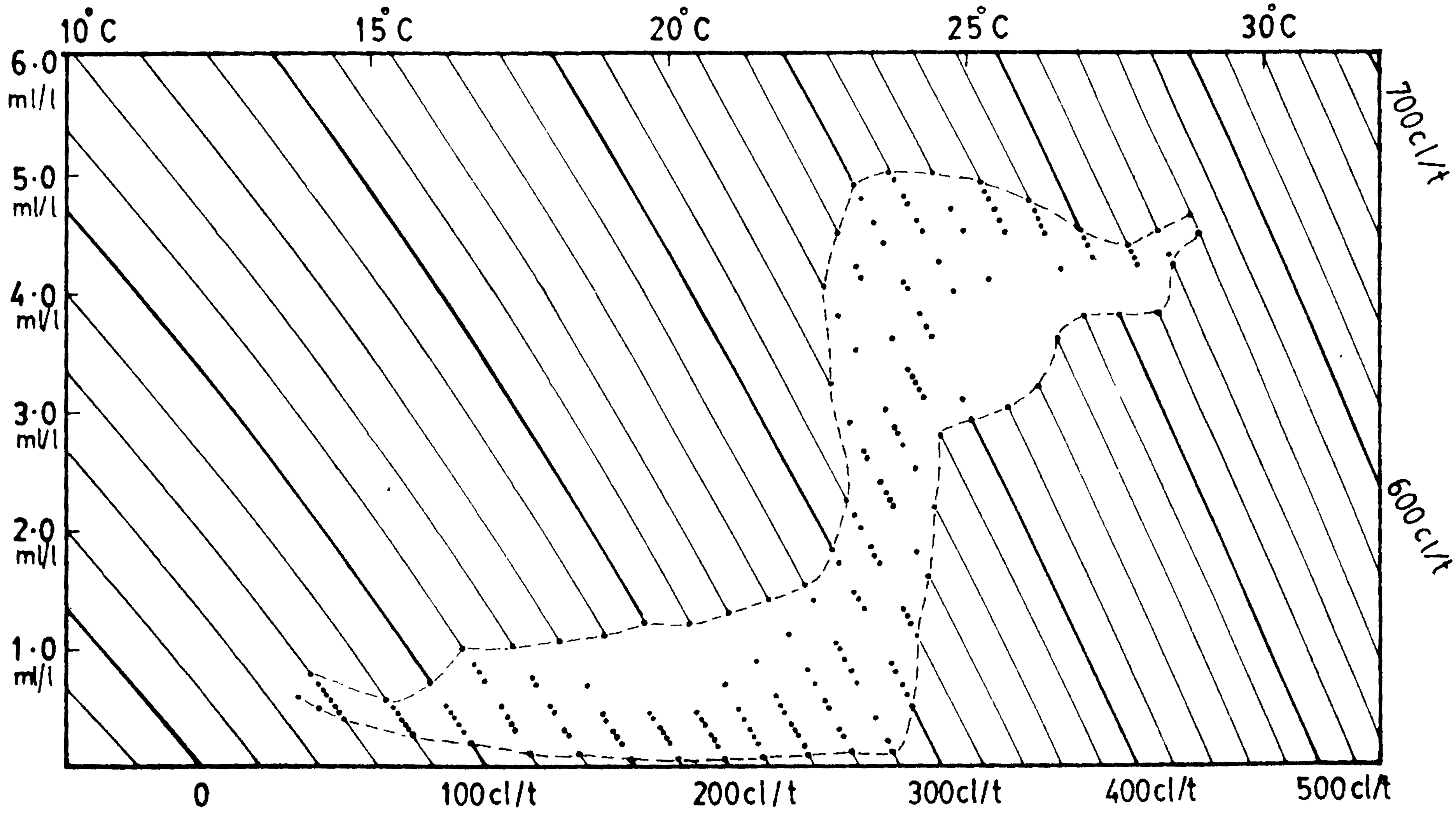


FIG: 29. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THL SOUTHWEST MONSOON - AREA - 4.

5.2.3. Area. 3 (10^{o}N to 15^{o}N and 50^{o}E to 55^{o}E)

The scatter in the intermediate layers is wider than that in the earlier two areas (Fig. 28) which implies that there is much variation with depth. The figure shows that the oxygen minimum layer lies between the 220-, and 180- cl/t surfaces, although, low values occur upto 60- cl/t surface. The lowest oxyty is 0.20 ml/l, at the 180- cl/t surface.

5.2.4. Area. 4 (9^{o}N to 14^{o}N and 60^{o}E to 65^{o}E)

In this area, low oxyty occurs below 300- cl/t surface upto the 60- cl/t surface (Fig.29). Lowest oxyty (0.05 ml/l) is observed between the 220- and 180- cl/t surfaces, indicating the oxygen minimum layer to be between these two surfaces. It is clear from this characteristic that in this area, the thickness of the minimum layer is greater than those in the areas already discussed. The scatter between 300- and 340- cl/t surfaces is relatively less.

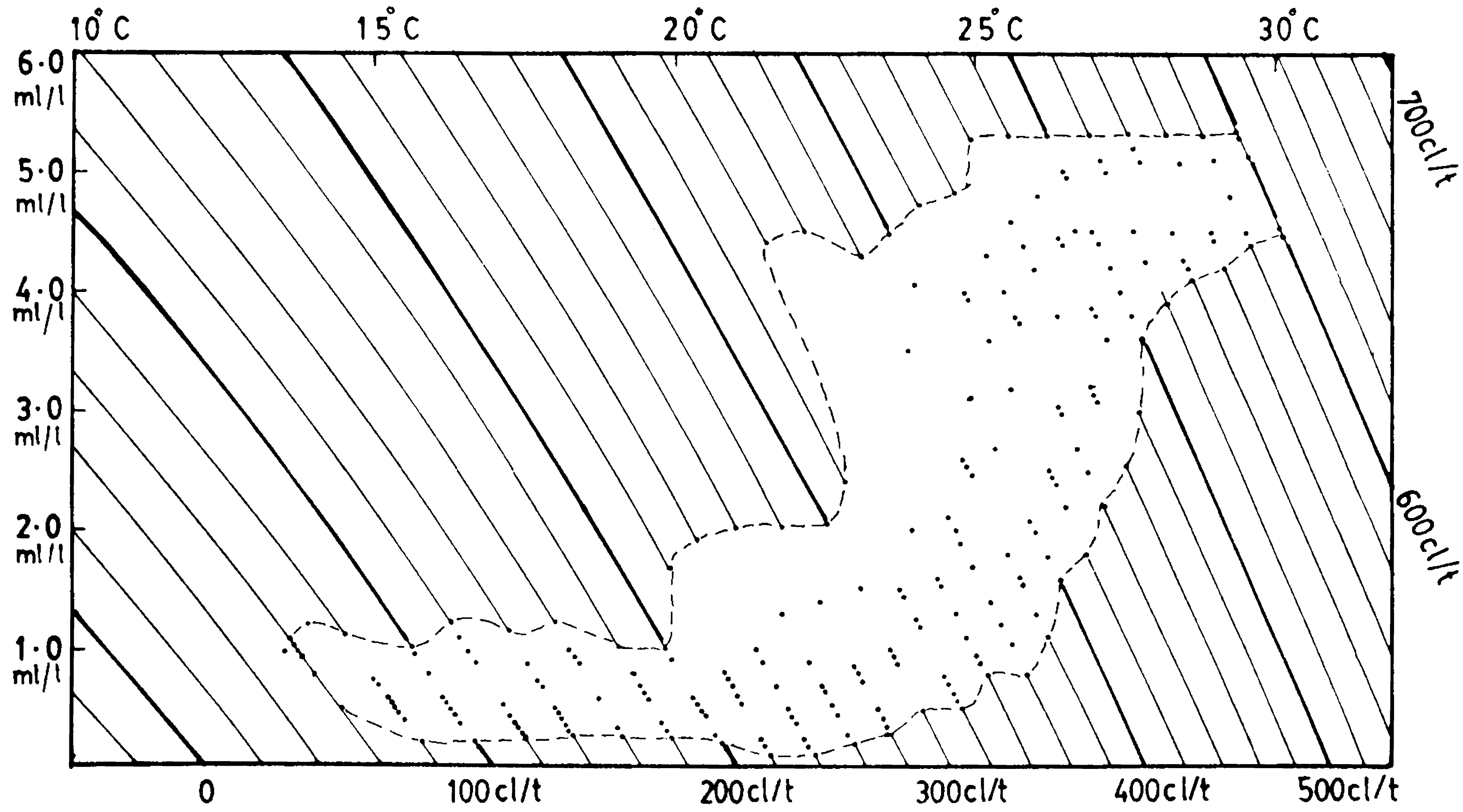


FIG: 30. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE SOUTHWEST MONSOON - AREA - 5.

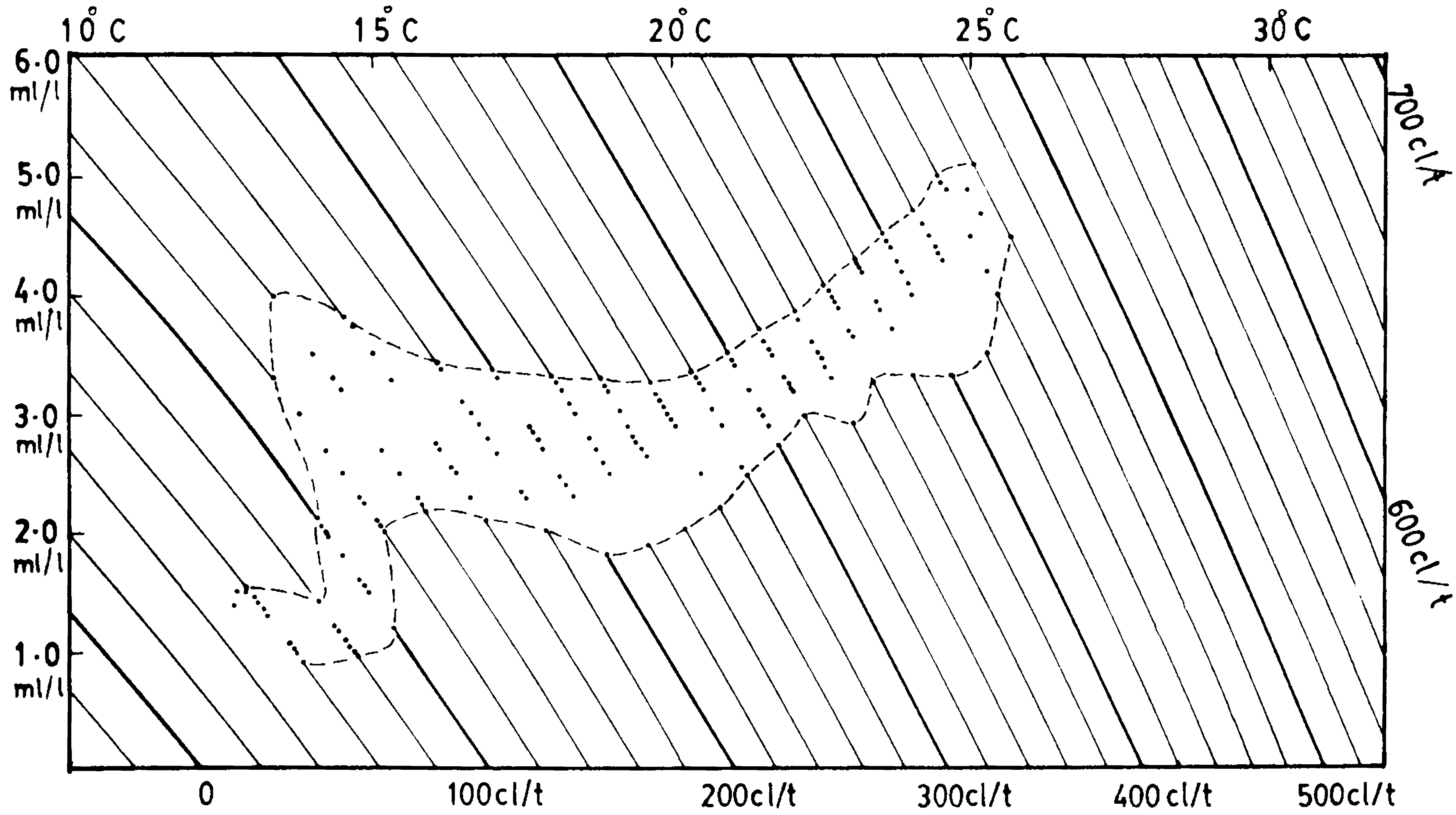


FIG: 31. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE SOUTHWEST MONSOON - AREA - 6.

5.2.5. Area. 5 (8^{o}N to 13^{o}N and 70^{o}E to 75^{o}E)

From the diagram, it is seen that the oxygen minimum layer lies between the 220- and 180- cl/t surfaces, although low oxyty values begin to occur from the 280- cl/t surface onwards (Fig. 30). The lowest value observed is 0.10 ml/l, the same as that observed in the distribution diagrams. Another prominent feature observed is the greater thickness of the minimum layer which reaches upto the 80- cl/t surface.

5.2.6. Area. 6 (0^{o} to 5^{o}N and 45^{o}E to 50^{o}E)

The first noticeable difference in this scatter diagram (Fig. 31) when comparing it with the previous ones is the high oxyty that occurs in the minimum layer. The minimum layer is between the 220- and 180- cl/t surfaces, with the lowest oxyty of 1.8 ml/l occurring on the 200-cl/t surface. The same conclusion can be drawn from diagrams showing distribution of the oxyty. A secondary minimum is observed in this region, with oxyty less than 1.0 ml/l below the 100- cl/t surface.

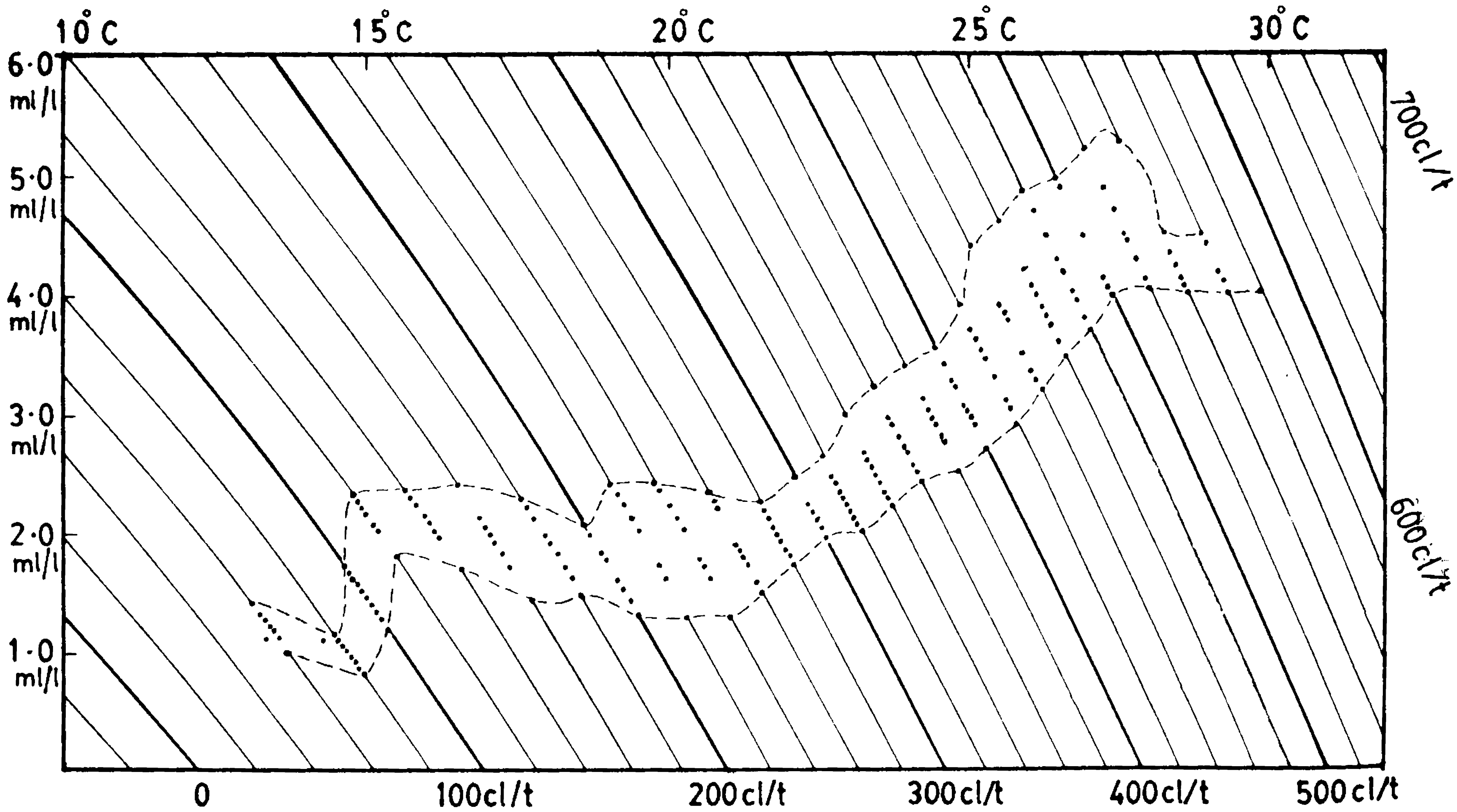


FIG: 32. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE SOUTHWEST MONSOON - AREA - 7.

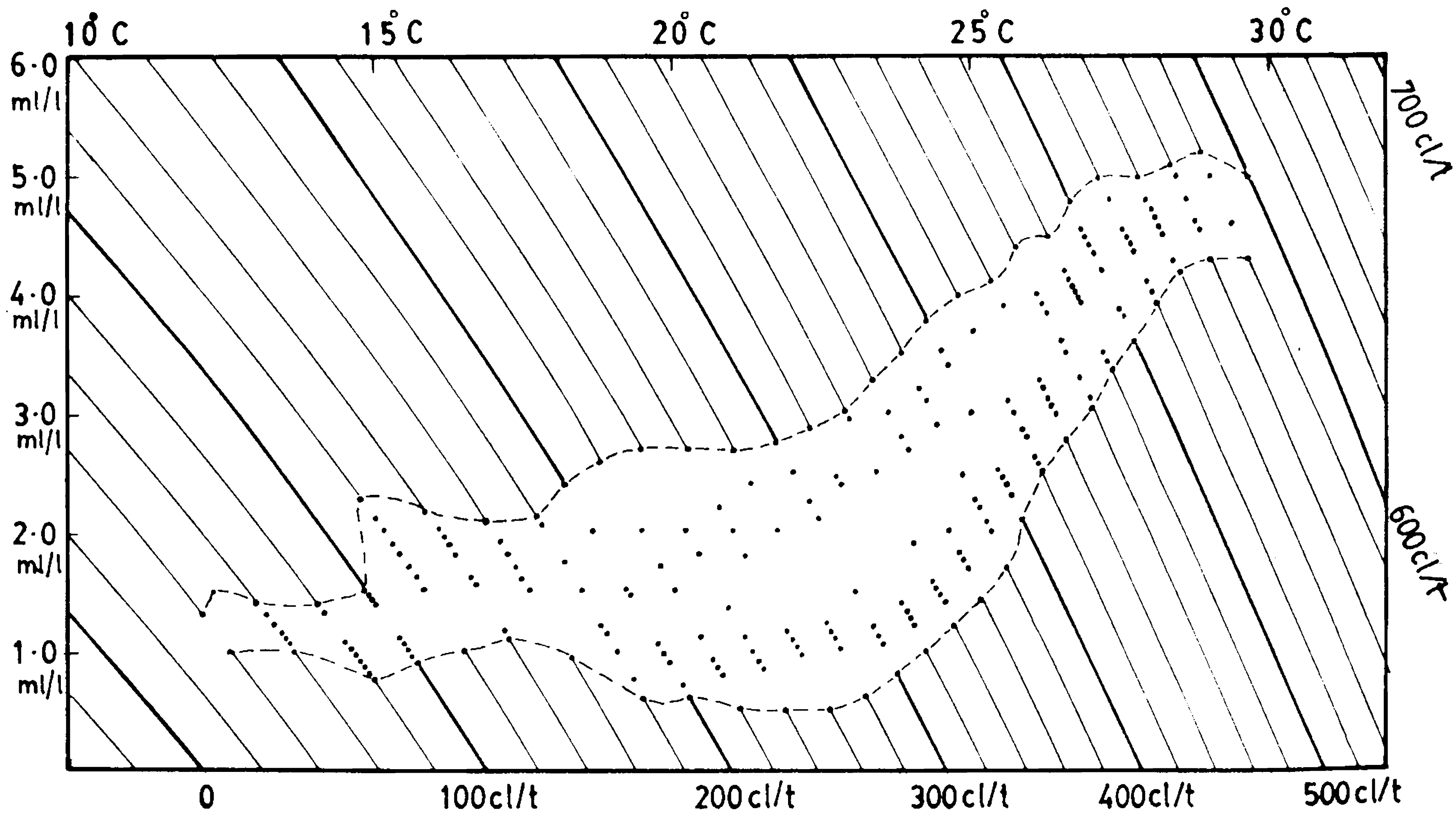


FIG: 33. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE SOUTHWEST MONSOON - AREA- 8.

5.1.7. Area. 7 (0^o to 5^oN and 60^oE to 65^oE)

From the diagram (Fig. 32), it is seen that the oxygen minimum layer lies between the surfaces of 220- and 180- cl/t. As far as the oxyty in the minimum layer is concerned, this area is almost similar to the area 6. The lowest value that is observed is 1.30 ml/l. Oxyty increases from 160- to 120- cl/t surface. Then it decreases rapidly upto the 80- cl/t surface to 0.8 ml/l, the least concentration shown in the diagram.

5.1.8. Area. 8 (0^oN to 5^oN and 70^oE to 75^oE)

The scatter is greater at the intermediate layers as shown by the diagram (Fig. 33). From the 260- cl/t surface upto the 180- cl/t surface, lower oxyty values are observed, from which it can be stated that the thickness of the minimum layer is not small. The minimum layer has lowest oxyty between the 260- and 220- cl/t surfaces.

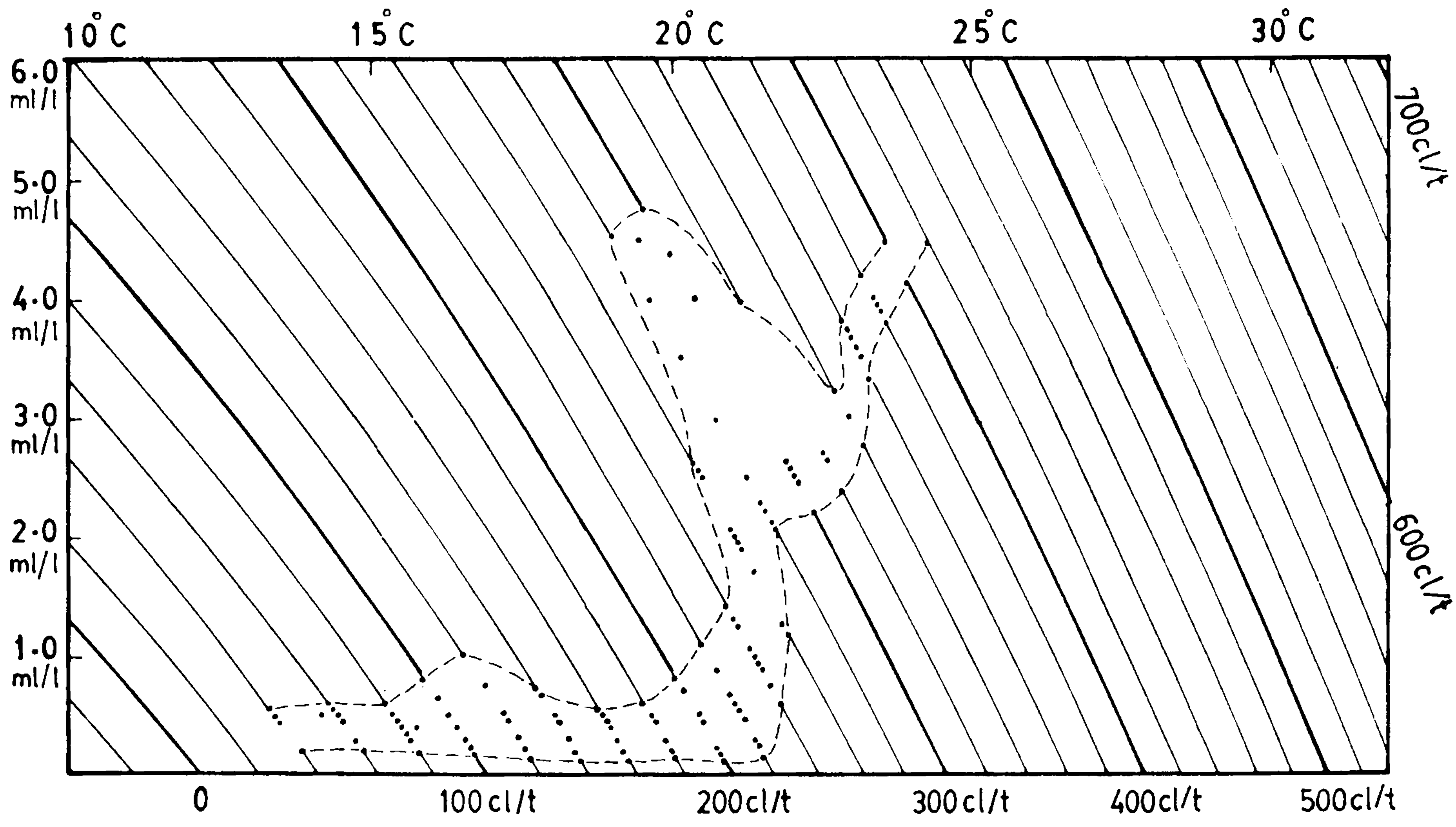


FIG: 34. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE NORTHEAST MONSOON - AREA - 1.

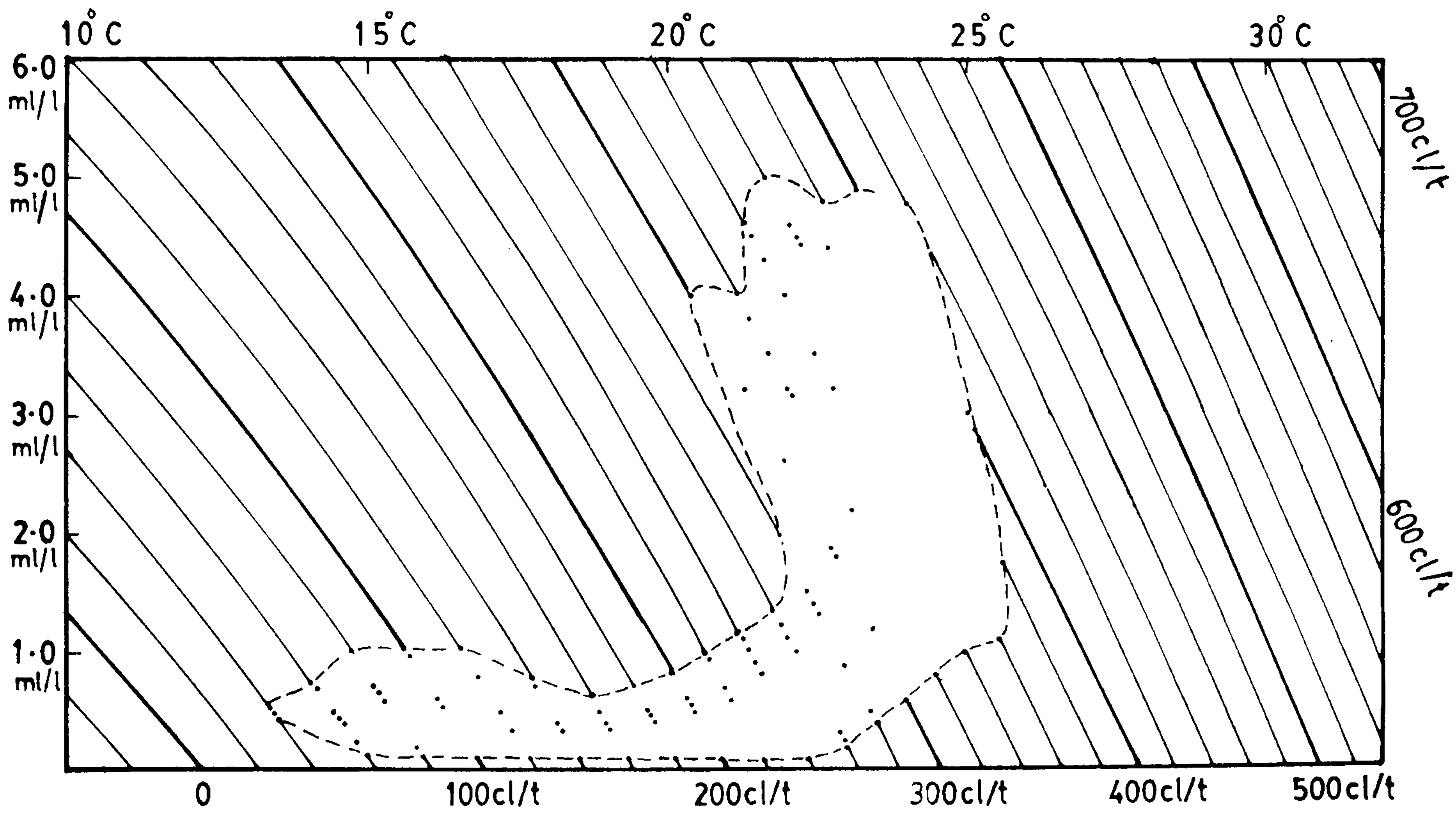


FIG: 35. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE NORTHEAST MONSOON - AREA - 2.

5.2. Scatter diagrams during the northeast monsoon

5.2.1. Area 1. (18°N to 23°N and 58°E to 63°E

The scatter is small in the intermediate layers in this region (Fig. 34). The oxygen minimum layer is found to begin from the 220- cl/t isanosteric surface. The diagram indicates that the thickness of the layer is large, extending upto the 40- cl/t surface. The lowest oxyty in this area is 0.10 ml/l.

5.2.2. Area 2. (18°N to 23°N and 65°E to 70°E)

In this scatter diagram also (Fig. 35) lesser scatter is noticed in the intermediate layers. Low oxyty values are found to occur below the 250- cl/t surface. The minimum layer starts from the 240- cl/t surface and extends upto the 60- cl/t surface. The lowest oxyty observed in this part of the Arabian Sea is less than 0.10 ml/l. This is one of the regions where the oxyty in the minimum layer is very small, which agrees with the result of the distribution diagrams.

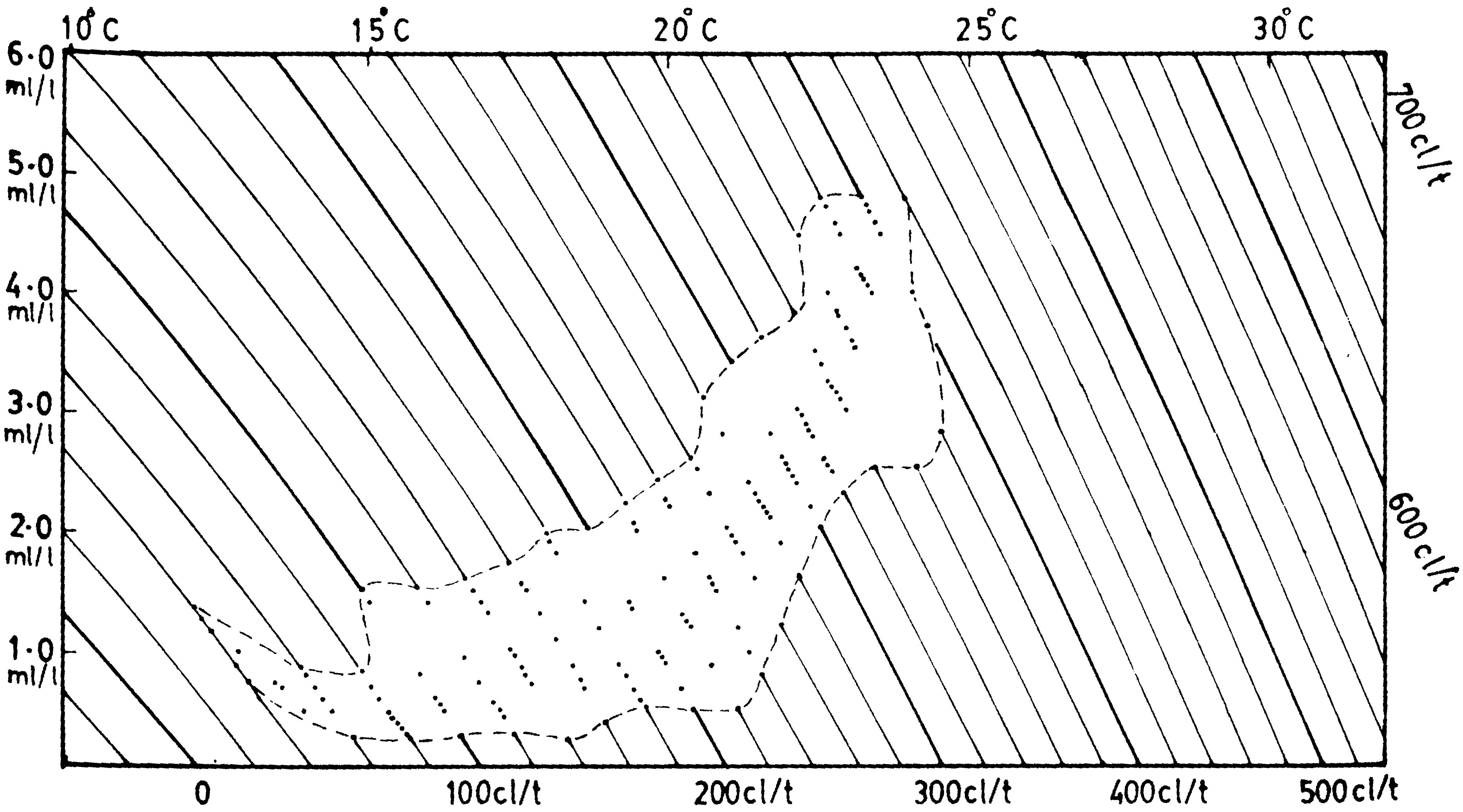


FIG: 36: SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE NORTHEAST MONSOON - AREA - 3.

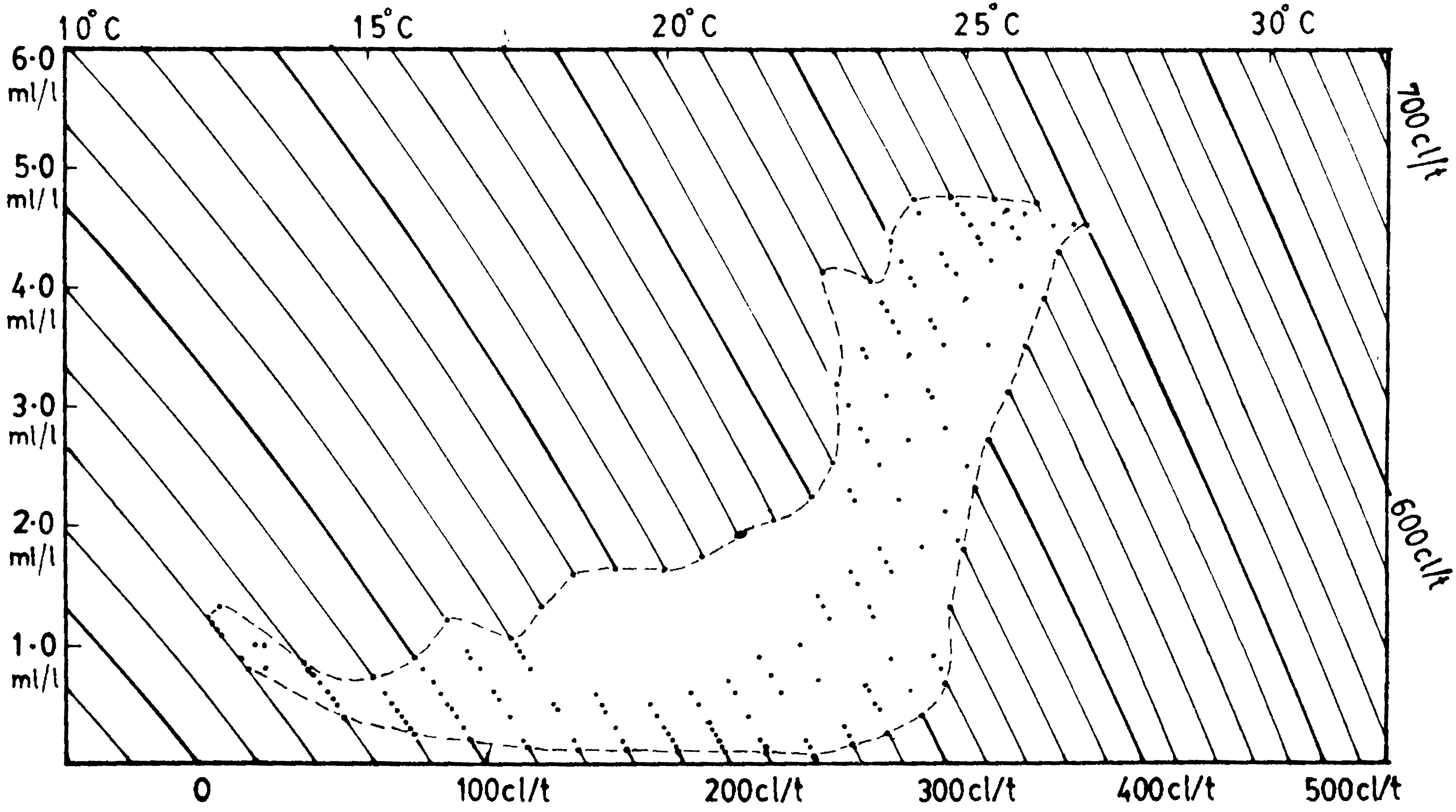


FIG: 37. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE NORTHEAST MONSOON - AREA-4.

5.2.3. Area 3. (10^{0}N to 15^{0}N and 50^{0}E to 55^{0}E)

In contrast to the diagrams for areas 1 and 2, wide scatter is noticed here, in the intermediate layers (Fig. 36). The scatter diagram shows that the oxygen minimum layer begins from the isanosteric surface of 220- cl/t and extends upto the 60- cl/t surface. The lowest oxyty observed is 0.25 ml/l.

5.2.4. Area 4. (9^{0}N to 14^{0}N and 60^{0}E to 65^{0}E)

Scatter diagram for this area (Fig. 37) indicates greater scatter at intermediate depths than at other levels (Fig. 37). Another prominent feature is the extremely low values of oxyty encountered in the minimum. It is as low as 0.05 ml/l. There is a sudden decrease of oxyty from the surface to about 300- cl/t surface, below which the decrease is less and the lowest value is present from about 240 cl/t to 140 cl/t, which indicates that the oxygen minimum layer is extremely thick. Such a possibility occurs when there is strong vertical mixing.

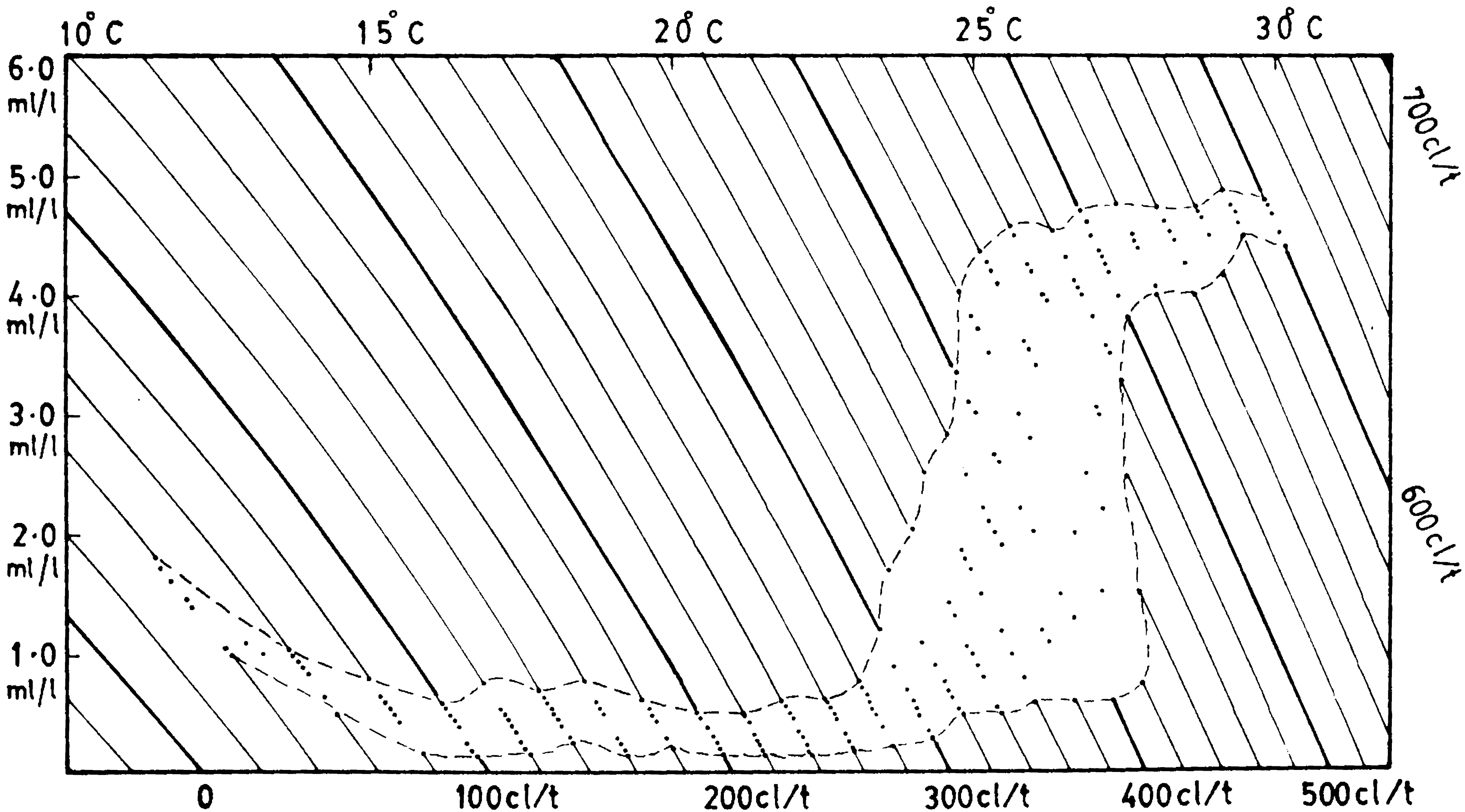


FIG: 38. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE NORTHEAST MONSOON - AREA-5.

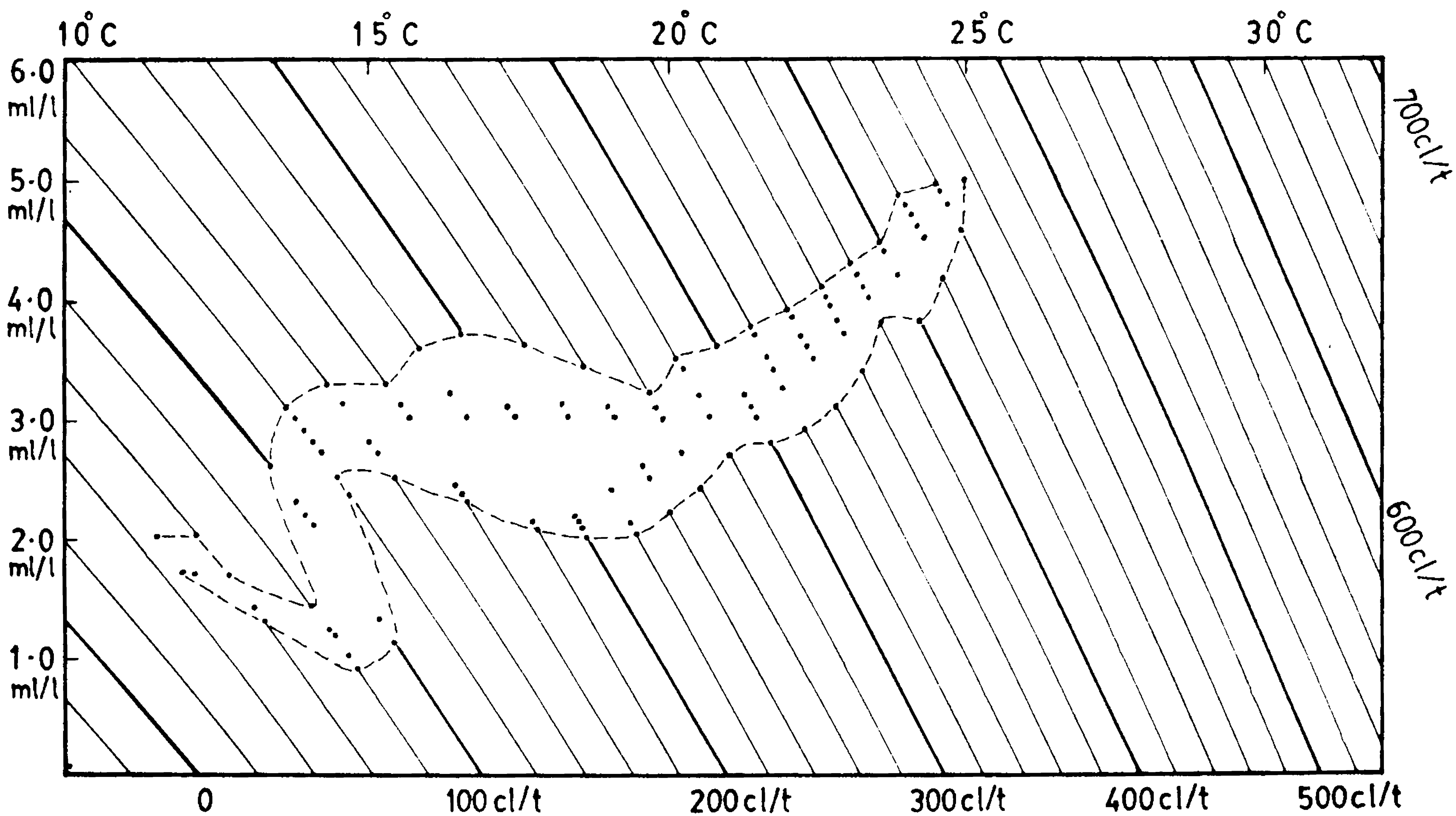


FIG: 39. SCATTER DIAGRAM FOR UXYTY-TEMPERATURE DURING THE NORTHEAST MONSOON - AREA G.

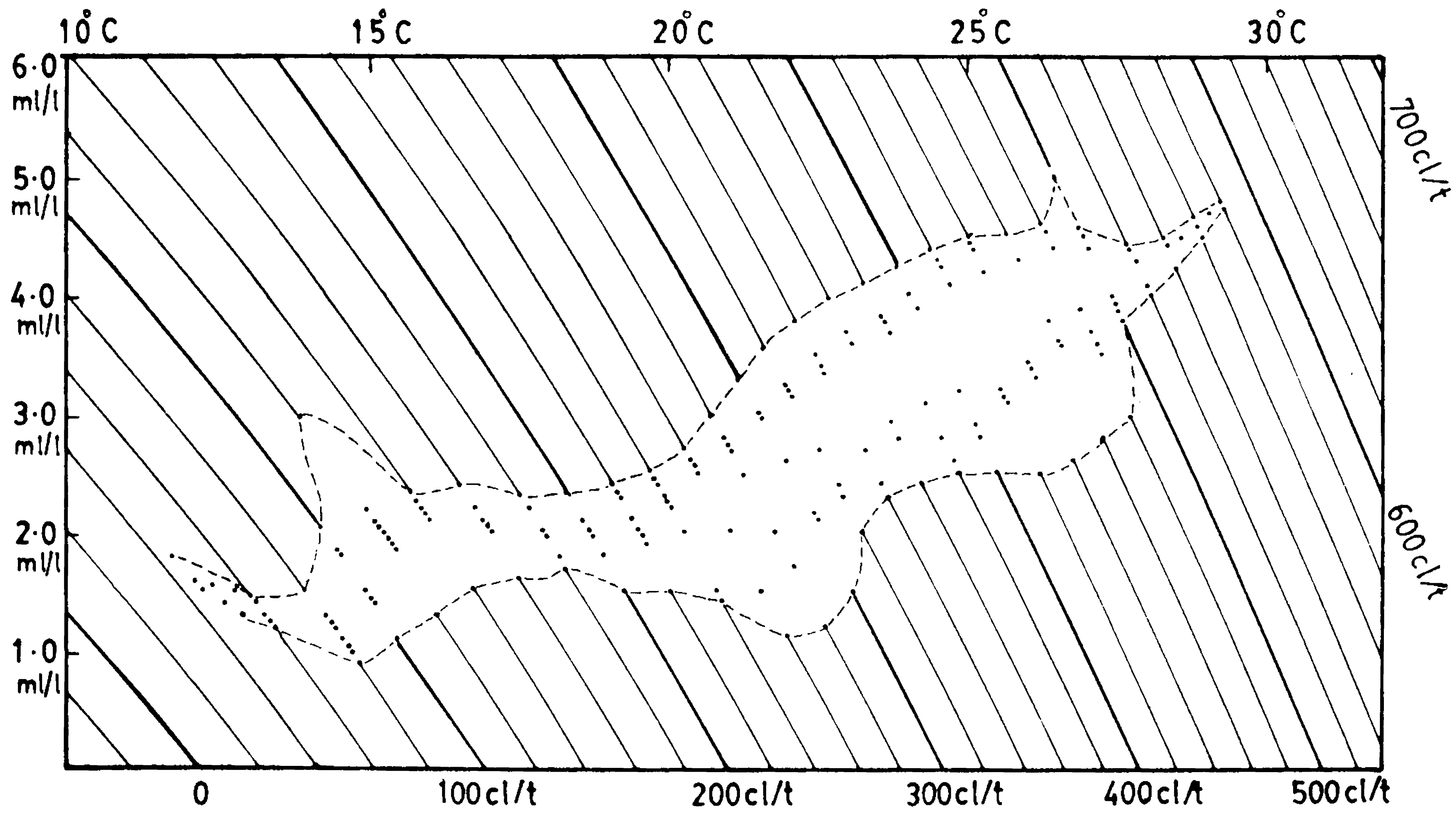


FIG: 40. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE NORTHEAST MONSOON - AREA - 7.

5.2.5. Area 5. (8°N to 13°N and 70°E to 75°E)

In this area, very small scatter is observed in the intermediate layers (Fig. 38). The diagram indicates that the oxygen minimum layer in this area lies between the surfaces of 240- and 200- cl/t. But, low oxyty continues upto the 80- cl/t surface. The lowest oxyty that occurs here is 0.15 ml/l.

5.2.6. Area 6. (0° to 5°N and 45°E to 50°E)

The lowest oxyty in this region is seen to be 0.90 ml/l. The minimum layer is found to lie between 240- and 180- cl/t surfaces. The spreading is relatively more in the intermediate layers (Fig.39).

5.2.7. Area 7. (0° to 5°N and 60°E to 65°E)

The lowest oxyty observed from this diagram is 0.80 ml/l (Fig.40). Wide scatter is observed in the intermediate layers. The oxygen minimum layer lies between 260- and 280- cl/t surfaces in this area. Another interesting feature in this area is the occurrence of a double minimum, the deeper one being located at 80- cl/t surface. The high oxyty water

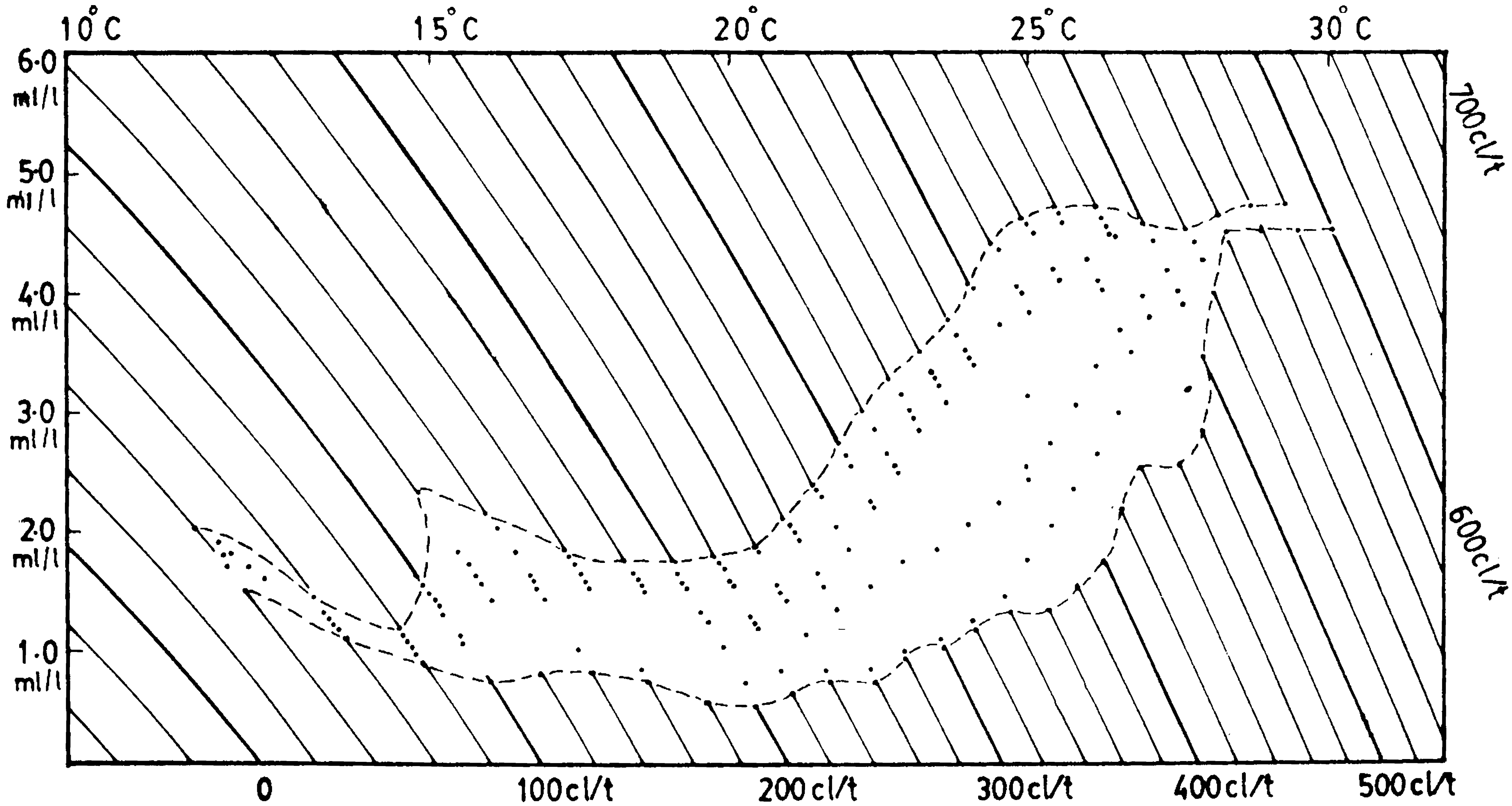


FIG: 41. SCATTER DIAGRAM FOR OXYTY-TEMPERATURE DURING THE NORTHEAST MONSOON AREA → 8.

in between these two minima must be a consequence of the incrusion of oxygen-rich water from either south or east. Such an explanation confirms the secondary maximum at about the 120- cl/t surface where the scatter in the subsurface depths is very wide. This area is south of area 4 (9^o to 14^oN and 60^oE to 65^oE) where the oxyty decreases abruptly to the 300- cl/t surface. Because the flow is southerly during this period, influence of that water where there is strong vertical mixing might have been horizontally advected with the relatively higher oxyty water below 300- cl/t surface, resulting in the formation of the oxygen minimum layer between the 260- cl/t and 280- cl/t surfaces. On comparison with the distribution of oxyty on 240 cl/t there is an indication of horizontal advection with strong gradients of oxyty (Fig. 11).

5.2.8. Area 8. (0^o to 5^oN and 70^oE to 75^oE)

The scatter is lesser in the intermediate layers in this region. The oxygen minimum layer lies between the 240- and 200- cl/t surfaces. The lowest oxyty of 0.50 ml/l is observed on the 200- cl/t surface (Fig. 41).

DISCUSSION

From the scatter diagrams it is confirmed that the oxygen minimum layer lies between the 220- and 180- cl/t surfaces during the southwest monsoon and between the 240- and 200- cl/t surfaces during the northeast monsoon. A small scatter in the diagram implies relative homogeneity in the waters at their corresponding depths in the ocean. A feature that may be observed from these diagrams is the decrease of oxyty in the oxygen minimum layer towards north. Extremely low oxyties occur in the central and northern Arabian Sea, and higher oxyties in the equatorial region, during both the seasons.

It is observed that the oxyty values in the minimum layer are the highest in area 6 (Fig. 31), during the southwest monsoon. On comparing the scatter diagrams from the southern region, area 8 (Fig. 33) has the lowest oxyty in the minimum layer, during the above season. It is noticed that the highest oxyty in the minimum layer during the northeast monsoon occurs in area 6 (Fig. 39), similar to that during the southwest monsoon. Area 7 (Fig. 40) also records higher oxyty during the northeast monsoon.

From the scatter diagrams, it is clear that the thickness of the oxygen minimum layer is the largest in the northern and central Arabian Sea.

Dietrich (1973) and Swallow (1984) pointed out the greater thickness of the oxygen minimum layer in the Arabian Sea, than in other oceans. In chapter three, it was observed that stratification is high and mixing is small in this region. Thus, lack of renewal of oxygen-rich waters is the main reason for the existence of the extremely low values of oxyty in the oxygen minimum layer in this part.

A double minimum with high oxyty in between is observed in the southwestern region during both the monsoons. This is a result of the high oxyty water at intermediate depths from either east or south. Although Sen Gupta et al. (1976b) reported a double minimum north of 18°N in the Arabian Sea, the scatter diagrams prepared for the purpose of this study do not reveal such a feature. But, the oxygen minimum layer shows relatively greater thickness in that area than in the rest of the Arabian Sea. According to Fig.7 of Sen Gupta et al. (1976b), it is noticed that the secondary oxygen minimum occurs only south of 8°N which is contradictory to their statement.

C H A P T E R - VI

CHAPTER - VI

SUMMARY AND CONCLUSIONS

The present investigation is an attempt, made for the first time by any researcher to carry out a detailed study of the unique and peculiar characteristic features of the oxygen minimum layer occurring at the shallowest depths and also with lowest concentration in the Arabian Sea compared to any of the oceanic region in the world, in relation to the oceanic circulation. Such an attempt is made, mainly, because of the various debatable opinions expressed by earlier investigators about the formation of the oxygen minimum layer in the oceans and its maintenance with reference to its variation of depth as well as the concentration of dissolved oxygen in it which is termed as oxyty in this thesis following the terminology of Montgomery (1969).

The aim of the study is achieved by working out the topography of the oxygen minimum layer and also the oxyty within it. In order to study the horizontal and vertical advective processes at play in changing the oxyty and the depth of oxygen minimum layer, the distribution of oxyty on various isanosteric surfaces and also their topography are presented. The flow pattern at the selected isanosteric surfaces is also worked out so as to study the influence of the advective processes on the oxygen minimum layer. Temperature-oxyty characteristics on different isanosteric levels offer a useful view of the qualitative description of the oxyty distribution. An attempt was made to present the scatter diagrams of temperature-oxyty at various isanosteric surfaces for different representative areas.

As the oceanic characteristics in the Arabian Sea are controlled by the monsoonal wind system prevailing over the North Indian Ocean, it is thought preferable to map the above mentioned distributions for the southwest and northeast monsoons separately.

The data for the present study mainly come from those collected on board different research vessels during the International Indian Ocean Expedition (1960-65) and they are supplemented with those that are collected subsequently, with a principal aim of covering the area under study with an even distribution of station positions. Ultimately, 217 and 197 stations are selected for the southwest and northeast monsoon respectively.

Station curves with temperature as common abscissa against depth, salinity and oxyty are drawn. From a general examination of the station curves, it is realised that the oxygen minimum layer in the Arabian Sea mostly lies within the isanosteric surfaces of 180 to 220 cl/t and 200 to 240 cl/t during the southwest and northeast monsoons respectively, except very near the coasts particularly off Somalia and Arabia.

In the present study, no serious attempt is made to look into the causative factors of the formation of oxygen minimum, which are mainly determined by the biochemical processes taking place within the sea (Wyrtki, 1962). The area covered by the marginal seas connected with the Arabian Sea, namely the Red Sea and Persian Gulf are omitted. The southern boundary of the area under study is the equator. Further, the limitations involved in the interpretation of the assemblage of heterogeneous data are clearly spelled out in the introduction.

In the Arabian Sea, oxyty in the oxygen minimum layer shows southward increase during the southwest and northeast monsoons. Low oxyty with values less than 0.10 ml/l occurs in the northern and northern central Arabian Sea, while, maximum oxyty occurs in the southwestern Arabian Sea (3.0 ml/l) during both the seasons. Western Arabian Sea records higher oxyty compared to the eastern Arabian Sea. Off the Somalia Coast, higher oxyty is observed in the minimum layer because of mixing with the high oxyty waters of the Somalia Current and also because of the high oxygen absorbing capacity of the cold upwelled waters, during the southwest monsoon. But, during the northeast monsoon, oxyty in this region is comparatively less. In the open sea, alternate cells of high and low oxyty are conspicuous especially during the southwest monsoon, as a consequence of cyclonic and anticyclonic circulation with hyperbolic points in between them.

The depth of the minimum layer decreases towards south. The topography varies from 50 m to greater than 350 m during the southwest monsoon and it ranges between 100 m and more than 350 m during the northeast monsoon. This indicates that the variation of topography is less during the northeast monsoon compared to that in the southwest monsoon. Alternate troughs and ridges are present in the topography of the oxygen minimum layer. The number of troughs and ridges are less during the northeast monsoon. In general, the troughs are associated with low oxyty waters while ridges are related with high oxyty waters. Another conspicuous inference that can be drawn is the trapping of high oxyty water off the west coast of India during the southwest monsoon. The Indian Ocean is landlocked in the north, and does not extend into the cold climatic regions of the northern hemisphere. This causes an asymmetrical development of its structure and circulation, which is most obvious in the development of the huge layers of extremely low oxygen content in the Arabian Sea (Wyrtki, 1973). It is also interesting to note that the thickness of the oxygen minimum layer is also greater in the Arabian Sea; at some times, it is more than 800 m.

The oxyty on the isanosteric surfaces increases southward, while the isanosteric surfaces slope up southward. Oxyty on these surfaces ranges between less than 0.10 ml/l and more than 3.0 ml/l during both the seasons. The topography of 220- cl/t surface ranges from much less than 50 to around 250 m; of the 200- cl/t surface, from less than 50 to more than 250 m and of the 180- cl/t surface, from around 50 to more than 275 m during the southwest monsoon.

During northeast monsoon, the depths of 240-, 220- and 200- cl/t surfaces range from values less than 100 m to slightly greater than 200 m, less than 100 m to greater than 200 m, and around 125 m to slightly greater than 225 m respectively. An important feature observed during the southwest monsoon is the shallowest topography and high oxyty on all the surfaces, off Somalia. Off the Arabia Coast also a similar character is observed. Upward motion during this season in those areas is the cause of occurrence of these phenomena. Compared to the southwest monsoon, the oxyty on the isanosteric surfaces is lower and the topography is deeper off Somalia during the northeast monsoon, because of the sinking that takes place near the coasts. Normally, in the regions of upwelling oxyty decreases at the surface layers,but the oxyty in the oxygen minimum layer increases because of its shallow depth associated with upward movement of cold water for which absorbing capacity for oxygen is high. Alternate highs and lows are prominent, both in the oxyty distribution on the isanosteric surfaces, and troughs *and ridges on their topography. These ridges and troughs in the topographic charts reveal the* boundaries of the anticyclonic and cyclonic cells, which are associated with convergences and divergences. They indicate downward and upward vertical advections. The large number of troughs and ridges on lower steric surfaces indicate the presence of eddy type of circulation at subsurface depths, which is comparatively less during the northeast monsoon. The vertical gradients of density are higher during the northeast monsoon than during the southwest monsoon. This implies that vertical advection is much less and it is the horizontal advection that mainly controls the minimum layer during the northeast monsoon compared to that during the southwest monsoon. The thicknesses of the layers between the isanosteric surfaces are least off the Somalia Coast and they are the highest in the northern Arabian Sea. In general, the thickness decreases towards the central Arabian Sea. The thickness between the surfaces gives an indication of stability of the waters and also indicates the intensity of the vertical advection; greater thickness indicates lower stratification and more vertical mixing, while reverse is the case in regions with smaller thickness.

During the southwest monsoon, an anticyclonic current system is observed in the Arabian Sea, while it is cyclonic during the northeast monsoon. Off Somalia, during the southwest monsoon, the northerly flow is strong and narrow, which indicates intense horizontal advection. But during the northeast monsoon, the flow is weaker, broad and opposite in direction. During the southwest monsoon, high oxyty waters from the south are transported towards north along the westernside of the Arabian Sea. In the western Arabian Sea, replenishment is more compared to that in the northeast monsoon, as concluded from the flow patterns. As a result, the oxyty in the minimum layer is higher in the southwestern Arabian Sea and also off the Somalia Coast during the southwest monsoon. Farther from the coast, the minimum layer is pushed downwards as a result of convergence, and hence the topography of the minimum layer is deeper in this region, during the southwest monsoon. Alternate cyclonic and anticyclonic gyres are present in the central Arabian Sea, which in turn produce alternate highs and lows of oxyty in the oxygen minimum layer. This eddy type circulation is more intense during the southwest monsoon. During this season, low oxyty water from the north is transported towards south along the west coast of India where low oxyty is observed in the minimum layer. Zonal flow is observed in the equatorial region during both the seasons. High oxyty in the minimum layer, observed in this region is explained by this flow pattern.

The scatter diagrams clearly support the fact that the oxygen minimum layer lies between the 220- and 180- cl/t surfaces during the southwest monsoon and it lies between 240- and 200- cl/t surfaces during the northeast monsoon. Lower oxyty is observed in the northern Arabian Sea, and it increases southward. High oxyties in the oxygen minimum layer occur in the southwestern Arabian Sea. Less scatter is observed, mostly, in the subsurface layers. The greater thickness of the oxygen minimum layer in the Arabian Sea is also revealed from the scatter diagrams. Although the formation of oxygen minimum layer is attributed to the biochemical processes in the oceans, from the foregoing, one can realise that irrespective of the causative factors of the formation of the oxygen minimum layer, variation of the depth of the oxygen minimum layer and the oxyty within it are mainly controlled by the advective processes as Wyrtki (1962) pointed out. Thus, the present thesis confirms the hypothesis of Wyrtki (1962) and is against the opinion expressed by Sverdrup (1938) and Sverdrup et al. (1941) that the biochemical processes control the oxygen minimum layer. But, to arrive at such a conclusion for coastal regions, one should be cautious to look for the biodegradation that normally takes place on the continental shelf.

R E F E R E N C E S

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