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OCEANOGRAPHIC INVESTIGATIONS ALONG THE SOUTHWEST COAST OF INDIA (1976-78)

A report prepared for
Pelagic Fishery Investigations on the Southwest Coast
Phase II - Project

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
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This is one of a series of reports prepared during the course of the FAO/UNDP project identified on the title page. The conclusions and recommendations given in the report are those considered appropriate at the time of its preparation. They may be modified in the light of further knowledge gained at subsequent stages of the project.

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ABSTRACT

The description of the oceanographic conditions of the shelf waters off the southwest coast of India between Ratnagiri in the north and Tuticorin in the south for the period 1976-78 is based on observations carried out along oceanographic sections located off Ratnagiri, Karwar, Kasaragod, Cochin, Quilon, Cape Comorin and Tuticorin. In accordance with the objectives of Phase II of the Project, more emphasis was given to improving our knowledge of the behavioural characteristics of the oil sardine and mackerel and also to evolving methodologies for fishery forecasting appropriate to Indian conditions. Hydrography/plankton/fishing surveys were conducted during the southwest monsoon to assess the intensity of upwelling and to establish possible correlations between the behaviour of commercially important pelagic fishes and the variations of environmental factors observed in space and time. Data related to the process of upwelling were collected mainly to evaluate the extent and intensity of upwelling and also to verify the variations of certain physical parameters noted during the Phase I.

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1. INTRODUCTION

1.1 TERMS OF REFERENCE

The Government of India, assisted by the United Nations Development Programme and the Food and Agriculture Organization of the United Nations, have been engaged in the Pelagic Fishery Investigations on the Southwest Coast - Phase II - Project (IND/75/038), whose main purpose is estimating the characteristics, size and location of the pelagic fishery resources, determining the most efficient gear and methods for efficient and economic exploitation, and determining for industrial application the most economic ways of processing and marketing pelagic fish.

The project was operational from 1 January 1976 to 30 March 1979.

1.2 BACKGROUND INFORMATION

One of the objectives of Phase I of the Pelagic Fishery Project was to study the relationship between environmental factors and the distribution and migration of pelagic fishes along the southwest coast of India. Accordingly, extensive oceanographic surveys were conducted off the shelf waters between Ratnagiri and Tuticorin between 1971 and 1975. During Phase II (1976-78) more emphasis was given to those areas requiring further study, and in particular to assessing the intensity of upwelling and establishing possible correlations between the occurrence, abundance and migrations of some of the commercially important pelagic fishes and environmental factors. Data relating to the process of upwelling were collected with a view to checking and confirming the findings made during Phase I (see project reports 3, 6 and 16) and also to studying the extent of variations observed in some of the important hydrographic parameters. The present report, while confirming some of the findings made during Phase I, also reports variations, and the possible correlations between the harvestable pelagic fish concentrations and some of the easily observable environmental parameters such as seawater temperature, salinity and dissolved oxygen content. In addition to the published information from the Phase I reports, other oceanographic reports for the same area were published by: Chidambaram and Menon (1945), Panikkar (1949), Bhimachar and George (1950), Ramamirtham and Jayaraman (1960), Ramasastry and Myrland (1960), Pradhan and Reddy (1962), Murthy (1965), Ramamirtham and Patil (1966), Sharma (1966, 1968), Darbyshire (1967), Banse (1968), Lighthill (1969), Noble (1972), Prabhu et al.(1972), Antony Raja (1974), Jhingran (1975), Pillai and Perumal (1975).

2. DATA AND METHODS

The project area and oceanographic sections surveyed during the second phase of the project are shown in Fig. 1 and Table 1 indicates the number of investigations carried out. The coverage of the various sections was limited as the data were collected mainly to confirm the findings of Phase I. Data of both phases are considered here.

During the second phase the oceanographic sections were surveyed using the research vessel RASTRELLIGER. Care was taken to ensure that the various sections were covered within the shortest possible time in order to obtain a synoptic picture of the conditions during each survey. Phase I data enabled the planning of the upwelling cruises in such a way as to collect information pertaining to the process in its various stages at the different sections. Temperature observations at different depths were made using Nansen reversing water bottles and reversing thermometers. Bathythermograph observations were also made at all the stations except the shallowest station located near the coast. Estimates of the top of thermocline were made from the bathythermograms.

3. RESULTS AND DISCUSSION

3.1 SEAWATER TEMPERATURE

In order to minimize the fluctuations in the parameters which are likely to arise out of coastal processes and diurnal influences, it was decided to consider the parameters at the second coastal station at a depth of 10 m as representative of surface layer conditions. Monthly mean sea surface temperatures for 1973-78 showed wide variations in space and time. In general, comparatively low values were observed during January-February and July-October, the lowest being in August (21.13°C) off Cape Comorin. High values were observed during May (the highest being 30.15°C off Karwar) and were evident in summer prior to the onset of the southewest monsoon. A steady increase in the highest monthly mean temperature from south to north (28.73-30.15°C) was noted between Cape Comorin and Karwar.

A comparison of the monthly mean sea surface temperatures (10 m depth) for the period 1972-78 (Figs. 8 and 9) for Cape Comorin and Cochin sections revealed two maxima (April-May and October-November) and two minima (July-August and December-January). Off Ratnagiri (Fig. 10) the maxima occurred in March, June and October and minima in September and December-January.

The mean depths of the top of the thermocline showed large variations from season to season (Table 2). The top of the thermocline was deepest during December-January-February and reached the surface layers south of Cochin during June-September and north of Cochin during October-November. Off Tuticorin the vertical oscillations of the top of thermocline were between 32 m (June-September) and 78 m (December-February).

The vertical time series sections of temperature drawn for the sourthern regions (Cape Comorin and Quilon, Figs. 2A, 2B, 3A, 3C and 3E), the central region (Cochin and Kasaragod, Figs. 4A, 4C, 4E, 5A and 5C) and the northern region (Karwar and Ratnagiri, Figs. 6A, 6C, 6E, 7A and 7B) were used to compare the variations in the vertical movement of the different isotherms in space and time. The net vertical movement was estimated from the oscillations of the 23°C isotherm which exhibited the maximum movement on the vertical plane (Tables 3 and 4). A comparison of the mean upward movement of the isotherm for the period 1973-78 indicated the maximum (110 m) off Quilon and the minimum (79 m) off Cape Comorin. During July 1977 the 23°C isotherm reached the surface off Quilon and Cape Comorin.

3.2 SALINITY

The monthly mean surface salinity at 10 m at the second coastal station for the period 1973-78 (Figs. 8, 9 and 10) indicated two peaks, one during May/June just before the onset of the southwest monsoon and the other during September/October, immediately after the southwest monsoon. The lowest values were associated with the monsoon rain and the river runoff which showed great variation from one section to the other during different years. The monthly mean surface salinity varied between 32.5°/oo and 35.83°/oo. The variations in salinity which are mainly brought about by rainfall, river runoff and prevailing seasonal surface currents are characteristic of the surface layers above the salinity maximum layer. As stated in Phase I reports, the surface salinity maximum was highest in the Karwar and Ratnagiri sections during May/June. Comparatively low salinity waters (33.03°/oo) were observed at the surface off Cape Comorin in December when the equatorial surface stations were advected northward. During the month the salinity values at the surface showed a steady increase from 33.03°/oo off Cape Comorin to 35.08°/oo off Karwar.

The highest values in the southern sections, during April off Ratnagiri and during October off Cape Comorin, were mainly associated with the advection of the high-salinity Arabian Sea water in the southerly flow.

3.3 DISSOLVED OXYGEN

Dissolved oxygen content of the surface layers showed large variations in space and time. The shelf waters were generally well aerated during most of the year except during the southwest monsoon and the associated upwelling. By May, the oxygen-deficient waters slowly started penetrating the shelf. The upward tilting of the isolines of oxygen and the relative position of the oxycline are indicated in the time series sections for the southern region (Quilon, Figs, 3B, 3D and 3F), central region (Cochin and Kasaragod, Figs 4B, 4D, 4F, 5B, 5D and 5E) and the northern region (Karwar Figs. 6B, 6D and 6F). By June/July the oxygen-deficient waters penetrated below the thermocline and covered the entire bottom of the shelf. In August the oxycline became very shallow and in areas of intense upwelling the low oxygen intermediate waters reached the surface. The oxygen-deficient waters remained on the shelf until October, especially in areas where upwelling was intense. By December the shelf waters were again well aerated. The mean surface oxygen values (second coastal station at a depth of 10 m) for the period 1972-78 ranged between 5.35 ml O_2/1 and 1.10 ml O_2/1).

Monthly mean dissolved oxygen values for the period 1972-78 (Figs. 8, 9 and 10) were low during August/September at the southern sections. Off Ratnagiri the minimum occurred in September. The low oxygen values corresponded to the period of peak upwelling when the oxygen-depleted intermediate waters reached the surface. Concentration of dissolved oxygen at the surface during upwelling usually showed an increase toward northern sections corresponding to the decrease in the intensity of upwelling beyond Karwar.

3.4 DENSITY (SIGMA-t)

The monthly mean density at 10 m at the second coastal station (1973-78) varied between sigma-t 20.87 and 24.52. Comparatively high-density waters were characteristic of both northern sections and southern sections where the high-density bottom waters reached the surface layers due to upwelling. The presence of high-density waters at the surface levels near the coast, especially in the central and southern regions during the southwest monsoon, clearly indicated upwelling. Under normal conditions, density in the coastal waters is more dependent on salinity than on temperature but during the southwest monsoon the density in the coastal waters is influenced by the low temperature of the upwelled water.

4. CORRELATIONS BETWEEN SOME OF THE IMPORTANT OCEANOGRAPHIC PARAMETERS

4.1 TEMPERATURE AND OXYGEN

A good correlation between the depth of the top of thermocline and oxycline was observed at almost all the sections. In general, it was found that values between 1 and 2 ml O_2/l were associated with temperatures between 22° and 23°C. A comparative study of the time series sections for temperature and oxygen clearly indicated the above correlation especially during the southwest monsoon when the 23°C isotherm reached the surface in the southern and central sections. Thus the 23°C isotherm could be used as an indicator of the average dissolved oxygen concentrations at a particular depth.

4.2 DENSITY (SIGMA-t) AND DISSOLVED OXYGEN

During the southwest monsoon in areas where upwelling activity was intense, the surface waters were characterized by rather low oxygen concentrations and high density. The correlation may exist for a short period only as the addition of fresh water from rain and river runoff at the surface increase the stability of the water column, thereby resisting any vertical mixing. When the upwelled water remains at the surface, it is aerated by direct contact with the atmosphere.

4.3 DENSITY (SIGMA-t) AND TEMPERATURE

Under normal conditions in the tropical seas, with increasing depth the temperature decreases and density increases, showing an inverse relationship between depth and temperature. During the monsoon at surface levels, the density is dependent on temperature and salinity. Once the process of upwelling begins, high-salinity bottom waters of low temperature are raised toward surface level. The characteristics of this water mass rapidly change when more fresh water is added to the system, thus effecting a fall in density and an increase in temperature brought about by solar radiation, and once again stabilizing the water column.

5. UPWELLING

The upward tilting exhibited by some of the selected isolines (23°C isotherm and 1 ml O_2/l) in the time series sections prepared for Cape Comorin, Quilon, Cochin, Kasaragod, Karwar and Ratnagiri, clearly indicated the occurrence and intensity of the upwelling phenomenon. Vertical velocity of upwelling at the different sections was approximately estimated taking into consideration the net upward movement of the 23°C isotherm (which exhibited maximum oscillations on the vertical plane) and the time taken to complete this motion. The time series sections indicate that the process of upwelling commenced earlier (January/February) in deeper (170-110 m) waters. The intensity of upwelling was higher toward south, especially south of Karwar. Vertical time series sections of both temperature and oxygen were used as indicators of the upwelling process, since both these parameters influence fish distribution. The Kasaragod, Cochin and Quilon sections exhibited the lowest oxygen concentrations on the shelf. The intensity of upwelling was less off Karwar and Ratnagiri than in the southern sections. Figure 11 is a diagram showing the rate of the upward movement (in cm/day) of the 23°C isotherm sectionwise/yearwise (1973-78) and the least depth of occurrence of the isotherm. The rate of ascent of the isotherm has been calculated from the vertical distance travelled and the number of days taken to cover the distance (Table 4). A comparison of the velocity at the different sections in different years indicated wide variations in the onset, intensity and duration of upwelling.

These estimates indicated that upwelling was strongest during 1977, with vertical velocities ranging from 65.4 cm/day to 86.5 cm/day in the area between Kasaragod and Cape Comorin. North of Kasaragod, both off Karwar and Ratnagiri, the intensity was less, the highest being 55.7 cm/day and 56.3 cm/day during 1973 and 1975 respectively. The least depth of occurrence of 23°C isotherm was the minimum associated with the highest velocity showing an inverse relationship between the two parameters. Off Cochin, Quilon and Cape Comorin the isotherm reached depths of 7 m, 0 m and 0 m corresponding to the highest velocities of 73.6 cm, 83.0 cm and 86.5 cm/day respectively. Figure 12 illustrates the depth at which this isotherm started tilting toward the surface each year at the different sections, the approximate duration and also the shallowest depth of the isotherm when upwelling ceased. The figures also indicate the net upward motion for different sections in different years.

The effect of upwelling on the local fishery depends largely on: (1) the depth from which the upwelled water reaches the surface layers; (2) the depth to which the subsurface waters are brought up during upwelling; (3) the nutrient level of the upwelled water and the resultant phytoplankton/zooplankton productivity; (4) the vertical velocity of upwelling; (5) the period during which the upwelled water remains at the surface layers retaining its inherent temperature, dissolved oxygen and nutrient characteristics. Conclusions were drawn taking account of all these factors, with the exception of the nutrient level.

Temperature and dissolved oxygen content are considered to be major indicators of the upwelling process. Temperature is a better indicator of the intensity of the phenomenon since the dissolved oxygen content of the upwelled water is influenced by various factors such as the production and consumption of oxygen in unit time at different depths, dissolution of atmospheric oxygen and resultant transmission due to advective process, etc. It is therefore advisable to select the particular isotherm which exhibits the maximum vertical movement and observe its upward tilting as an indicator of upwelling. The dissolved oxygen values help in confirming the presence of subsurface waters at the surface levels and also in assessing the approximate arrival time of the upwelled water at the surface.

Hydrographic observations carried out during the southwest monsoon in 1976 revealed pronounced upwelling south of Cochin. Observation during 1977 showed strong upwelling as far as Calicut from the south. Comparison of sea surface temperature for the same months for 1974 to 1977 indicated unusually low temperature values south of Kasaragod. A survey conducted in June 1978 revealed the presence of upwelling off Quilon. The increase in the dissolved oxygen content at the surface levels inferred that the water column stabilized in July-August. During October, very low surface temperature (21.70°C) was observed off Mangalore near the coast. Observations off Karwar and Ratnagiri confirmed that the process of upwelling extended only as far as Karwar during 1978. Comparatively low temperature (23.95°C), low oxygen concentration (1.46 ml/1) and high density (sigma-t 23.16) were observed at the surface levels near the coast. A comparison of sea surface temperature during July-August for the period 1973-78 indicated low values off Cape Comorin, Quilon, Calicut and Kasaragod. At most of the coastal stations oxygen concentrations were very low with denser waters at the surface levels. The top of the thermocline was found at the surface at almost all the stations.

Probable Causes of Upwelling

The basic mechanism of upwelling along the southwest coast of India was studied in the past by several experts. According to Banse (1968), the prevailing current system (and not the wind) is the main condition to generate and maintain the upwelling. Even if a uniform current velocity is prevalent all along the coast, the rise of denser, deep water will be stronger farther from the equator. Banse considers that off the southwest coast of India upwelling starts with the onset of the southwest monsoon and reaches maximum intensity during July-August. Darbyshire (1967) concluded that there is no wind-generated upwelling during the southwest monsoon along the west coast of India and she also indicated that the dense bottom waters approach the surface because of the immediate interplay of the current with the tilting of the sea surface and the thermocline. Pillai and Perumal (1975) reported upwelling around Lakshadweep island during November/December and attributed this to the divergent current systems in the vicinity of islands. Ramamirtham and Jayaraman (1960) stated that off Cochin upwelling starts by mid-August, establishes by late September and ends by mid-October. According to Sharma (1966), upwelling along the west coast of India starts in the south slowly extending northward; the process commences at deeper levels during February and reaches the surface by May. The process terminates by July-August when the top of thermocline reaches the surface layers. The influx of the river runoff and rain stratify the surface layers from July onward thereby opposing the process.

Data collected by the project staff revealed that none of the above theories is directly applicable to the project area as a whole. The causative factors which bring up the subsurface water to surface levels vary in space and time. Upwelling starts as early as February at the deeper levels and at different times each year at the various sections. The commencement of the process in February was possibly caused by the northerly winds which transport the surface water away from the coast thereby initiating the vertical ascent. It is possible that the depth at which the motion begins depends largely upon the velocity, direction and duration of the prevailing wind system in a specific area, the bottom topography, the prevailing current system at the surface levels and also on the vertical stability of the water column. Similarly, the speed of the ascending motion would depend on the continuance of the above-mentioned favourable factors. The onset of the southwest monsoon generates the Somali current (Lighthill, 1969) resulting in a general clockwise circulation in the Arabian Sea which in turn develops into a relatively strong southerly current at the surface levels along the west coast of India. The colder low-oxygenated and denser water from subsurface levels rises slowly along the continental shelf, very near the coast. Depending upon the intensity of the various factors which promote upwelling, subsurface waters from greater depths reach surface level, thereby contributing to the productivity of the surface waters. A closer examination of the prevailing wind system during the southwest monsoon revealed the presence of favourable northerly and northwesterly winds in certain localities where the upwelling intensity was also correspondingly higher. It can be presumed that upwelling along the southwest coast of India is brought about by a combination of those factors. In localities where more than one factor becomes dominant, upwelling is also correspondingly stronger.

6. CORRELATION WITH ZOOPLANKTON BIOMASS

Figure 13 shows the correlation between the process of upwelling and zooplankton biomass at the Cochin section (third coastal station) which was surveyed a considerable number of times between 1976 and 1978. Tha maxima for the plankton biomass always coincided with the peak periods of upwelling. Wherever the nutrient-rich subsurface water is raised to the sunlit surface levels by the upwelling process it provides favourable environmental conditions for phytoplankton production followed by a similar bloom in zooplankton production. The nutrient content of the upwelled water depends on the depth from which it originated and the time taken by the water mass to reach the surface level. The plankton biomass curve for the Cochin section showed maximum values during August 1976, July 1977 and July 1978. The minimum values were observed during November-March. With regard to oceanography and biomass correlations, the phytoplankton/zooplankton biomass is a basic element, as many of the commercially important pelagic fishes are plankton-feeders. A careful evaluation of the intensity and duration of upwelling and the physico-chemical charactersitics of the upwelled water will enable the prediction of the phytoplankton/zooplankton biomass and fishing possibilities especially for plankton-feeding pelagic fishes well in advance.

It was generally found that the zooplankton biomass was comparatively high in areas where upwelling was intense, but with some exceptions.

In spite of the high upwelling velocities observed for the Quilon and Cape Comorin sections (especially during the year 1977), supported by the other typical upwelling characteristics of low-temperature, high-density, low-oxygen waters reaching the surface, it was found that the plankton biomass at these sections did not indicate a proportionate increase during the following months. This was in sharp contrast to conditions in the Cochin and Kasaragod sections where a proportionate increase in the plankton biomass was observed during the peak upwelling season. The difference could be due to the comparatively low nutrient level of the upwelled waters which reached the surface levels off both Quilon and Cape Comorin and may be attributable to the rocky bottom of the shallow waters south at Quilon in contrast to the northern area where the bottom is soft or muddy.

7. CORRELATION WITH THE EXISTING PELAGIC FISHERY

7.1 OIL SARDINE AND MACKEREL

Oil sardine and mackerel are among the major pelagic fishes in the project area. The oil sardine fishery starts after the onset of the southwest monsoon and lasts from August to March, reaching a peak in September-December (Jhingran, 1975). Shoals appear first in the south and move gradually northward. The beginning of the fishery is marked by the entry of big-sized fish in an advanced stage of maturity. The major fishery is constituted by the medium-sized fish with the peak generally ranging from September to January and terminating by April/May. Along the southwest coasts (south of Calicut) the mackerel fishery starts in August and lasts until February. The area between Calicut and Ratnagiri is very important for the mackerel fishery. Between Calicut and Mangalore the fishery starts in August/September and lasts until March/April. North of Mangalore the fishery starts late in October/November and lasts until February/March. Both the oil sardine and the mackerel make large-scale migrations from offshore to inshore areas and from south to north, immediately following the southwest monsoon rainfall (August). Panikkar (1949) observed that delays in the onset of monsoon are often followed by delays in the fishing seasons for mackerel and oil sardine. Chidambaram and Menon (1945) found correlation between the landings of mackerel and environmental factors such as rainfall, surface temperature, salinity, specific gravity of the water and planktonic abundance. Bhimachar and George (1952) observed that peak mackerel landings coincide with or follow the abundance of plankton.

It was found that the annual migrations of oil sardine and mackerel were related to:

- The process of upwelling which commences first in the south and slowly proceeds northward. The low oxygen concentrations of the upwelled water compel the fishes to avoid areas of intense upwelling and hence their vertical distribution during this season is limited to a narrow column above the top of the thermocline. The plankton bloom following the upwellingattracts the plankton-feeders to move behind the northward spreading of upwelling to take advantage of the plankton bloom.

- The spatial and year-to-year fluctuations in the onset, intensity and duration of the monsoon and associated upwelling; the fisheries for oil sardine and mackerel exhibiting similar fluctuations in space and time.

During June-July 1976 some of the densest concentrations of breeding oil sardines were located off Mt.Delli where the temperature range was comparatively small (26^{o}-27^{o}C). Concentrations of breeding oil sardines were also found between Calicut and Kasaragod, within 10-15 n mi from the coast in less than 50 m depth. The oil sardine may prefer areas with less vertical temperature gradients for breeding purposes and they normally move away from the coast in search of suitable environment once they attain maturity.

During July 1977, most of the pelagic fish population avoided areas of upwelling intensity with low oxygen concentrations and less spawning activity was noted in the coastal waters during this season (see project report 6). The survey conducted between Mangalore and Ratnagiri in September 1977 showed that, except for the first few metres of the water columns, the entire shelf was occupied by low-oxygen water. It was noted that even demersal fishes, with rare exceptions, were absent from areas with oxygen concentrations less than 2 ml/1. The survey during July-August 1978 indicated that the average quantity of spawn products was high between Alleppey and Kasaragod and intense fish spawning activity, with the peak off Kasaragod, was observed. This surface temperature in this area was comparatively low (22.61^{o}-26.32^{o}C) with less vertical gradients. Oxygen concentrations, which were below 20 m, slowly increased toward offshore waters (0.16-2.76 ml O_2/1).

7.2 WHITEBAIT

Whitebait exhibited large-scale seasonal migrations. The observed seasonal fluctuations in space and time and areas of maximum abundance are shown in Table 5. Table 5 also shows that whitebait is distributed on the shelf between Ratnagiri and Quilon from October to May, but during the southwest monsoon, between June and September, it migrates southward and later southeastward to the Cape Comorin/Tuticorin area. The southward migration seems to be closely related to the southerly flow at the surface levels during the southwest monsoon.

It is possible that whitebait makes the southerly migration during June-July mainly to avoid the high temperature (above 28^{o}C) prevailing in the Ratnagiri-Karwar region. Further south, the effect of the low temperature (less than 23^{o}C) and less aerated upwelled water (2 ml O_2/1), to which the fish has less tolerance, drives it further south and later south-east where favourable temperature (between 24^{o}C and 27^{o}C) and oxygen (more than 2 ml O_2/1) conditions prevail. During June-October the fish remains in the area between Cape Comorin and Tuticorin in dense concentrations extending from the surface to the bottom exhibiting the typical diurnal vertical migrations. Jhingran (1975) observed that the spawning of Indian anchovies takes place from November to March. The observations made by project personnel indicated that the northward migrations of the fish begins early November. The onset of the northerly current with the post-monsoon conditions prevailing along the southwest coast, viz., higher oxygen concentration, the plankton bloom which followed the upwelling and the gradual rise in sea water temperature resulting from the recession of the upwelling process, provide the fish with favourable environmental conditions. By December the distribution of fish spreads almost throughout the project area. During both southward and northward migration the prevailing surface currents also favour passive floating and drifting.

8. CONCLUSIONS

The upwelling phenomenon recurs annually in the project area but with variations in its characteristics and associated processes both in space and time. The meteorological and other oceanographic parameters which influence the fishery also exhibit wide variations in space and time.

The most important aspect of the oceanographic features of the area is the prevailing current systems at the surface levels which change their direction from one season to another. The southerly current which develops in May continues until November when the current reverses and the northerly current continues until April. The southerly current brings comparatively high saline Arabian Sea waters southward and the northerly current transports the less saline equatorial waters northward. The effect of the spreading of the high saline Arabian Sea water toward south is largely neutralized by the southwest monsoon rain and the river runoff. Hence the annual salinity cycle at the surface levels is dependent on the onset of southwest monsoon and the direction, velocity and duration of the above-mentioned two current systems.

The seawater temperature shows very wide seasonal and spatial fluctuations. During the southwest monsoon, when the northern sections exhibit relatively high temperatures, the situation prevailing in the central and southern sections, especially in areas where upwelling is very active, is entirely different. In areas where the upwelled water reaches the surface, the temperature falls considerably below what could otherwise be expected for the season. The shelf waters were well aerated during most of the year except for the southwest monsoon and the associated upwelling. In August the oxycline became very shallow and in areas of intense upwelling the low oxygen intermediate waters reach the surface and remained there until October, especially in areas where upwelling was intense. By December the shelf waters were once again well aerated.

The upwelling process is very strong in parts of the project area between Karwar and Cape Comorin. No regularity in the occurrence of upwelling could be observed for any specific locality. For example, intense upwelling noted off Quilon during July 1977 was not repeated in the proceding or subsequent years with the same intensity or duration. This also applies to the upwelling observed off Cochin and Kasaragod. The occurrence, intensity and duration of upwelling are found to be dependent on the prevailing wind system, current system and bottom topography.

The process of upwelling which commences in February at deeper levels continues during the southwest monsoon and the upwelled water reaches the surface levels during June-October, depending upon the vertical velocity of upwelling. The vertical velocity at different sections averaged between 7 m and 26 m/month. The immediate effect of the upwelled water, which is highly oxygen-deficient, reaching the surface, is the expulsion of all animals, including fishes, from the vicinity. Dissolved oxygen concentration of these water masses slowly increases due to dissolution of atmospheric oxygen. Increased phytoplankton production leading to a zooplankton bloom commences in areas where, as a result of upwelling, highly productive water from the bottom levels, rich in unutilized nutrients, is brought to the surface. The oil sardine and mackerel fisheries commence immediately after the southwest monsoon when the zooplankton biomass at the surface layers reaches the peak. The upwelling process is initiated by the prevailing northeast wind system which displaces the surface waters offshore resulting in shallower layers of surface waters. Once the southwest monsoon sets in the southerly flow continues the induction process and the subsurface waters slowly rise to the surface, in spite of the southwesterly winds which are not favourable for the process to intensify. The velocity of the southerly current is moderately high in areas where the prevailing winds are northerly or northwesterly. A stronger northerly/northwesterly wind is favourable for the upwelling because of the effect of Ekman's spiral. Even when the velocity of the southerly current is strong, the upward extent of the upwelling is governed by the stability characteristics of the water column. The southwest monsoon rain and the associated river runoff increase the stability of the water column and thus oppose the tendency for the upwelled water to reach the surface. The vertical time series sections were found to be good indicators of the commencement, intensity and duration of the upwelling process. The zooplankton biomass in space and time proved a good indicator of the effect of upwelling on the productivity of the surface waters and the productivity an indicator of the prospects of the ensuing pelagic fishery. Hence, a prediction system for the major pelagic fisheries in the project area - oil sardine, mackerel and whitebait - could be evolved from observation of the oceanographic characteristics of the waters leading to/resulting from the phenomenon of upwelling, and the effect of upwelling on productivity from a study of the zooplankton biomass characteristics. A direct correlation has been observed (at the Cochin section) for different years between the period of intense upwelling and the zooplankton bloom. A study of the behavioural pattern of oil sardine, mackerel and whitebait and the environmental parameters indicated that the seawater temperature and dissolved oxygen at the surface levels influenced the seasonal migration of these species which avoided areas of intense upwelling activity mainly because of the low oxygen concentration and very low temperature conditions. Whitebait was found to move with the changing surface currents and remain within optimum temperature range avoiding oxygen-deficient upwelled water and taking advantage of the prevailing surface currents.

9. RECOMMENDATIONS

In view of the wide variations observed in the meteorological and oceanographical parameters leading to and resulting from the upwelling process and its effect on the productivity of the sea surface layers, the following recommendations are made:

1. The following sections with stations spaced at a maximum distance of 10 mi apart be monitored for the relevant meteorological and oceanographic data:

Existing	Additional
1. Ratnagiri	1. Vengurla
2. Karwar	2. Coondapur
3. Kasaragod	3. Calicut
4. Cochin	
5. Quilon	
6. Cape Comorin	
7. Tuticorin	

2. The major meteorological parameters, such as surface wind (direction and velocity), atmospheric pressure, cloud (type and amount), be monitored at the oceanographic stations.

3. Two additional sections be monitored every month, one 10 n mi north and another 10 n mi south of the existing Cochin section with stations at 10 n mi apart, to study the effect of tidal currents on hydrographic parameters.

4. Variations in space and time of important plant nutrients (phosphates, nitrates, silicates) be studied.

5. Plankton sampling and hydrographic observation be carried out at all the stations simultaneously.

6. Sea surface current measurements be made at fixed stations along the standard sections at regular intervals to investigate the seasonal reversal of the prevailing surface currents.

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Table 1

OCEANOGRAPHIC SURVEYS CONDUCTED IN PROJECT AREA DURING PHASE II OPERATIONS
(January 1976-October 1978)

Section	No. of surveys		
	1976	1977	1978
Ratnagiri	1	3	2
Karwar	5	3	3
Kasaragod	5	2	2
Cochin	6	5	5
Quilon	6	1	1
Cape Comorin	4	2	2
Tuticorin	2	1	1

Table 2

MEAN DEPTHS OF TOP OF THERMOCLINE (1973-1978)

Section	Shallowest (m)	Period	Deepest (m)	Period
Ratnagiri	11	Oct./Nov.	39	Dec./Jan./Feb.
Karwar	10	"	61	"
Kasaragod	13	"	56	"
Cochin	10	Jun./July Aug./Sept.	61	"
Quilon	16	"	66	"
Cape Comorin	20	"	63	"
Tuticorin	32	"	78	"

Table 3

POSITION OF 23°C ISOTHERM (sectionwise/yearwise)

Section	1973		1974		1975		1976		1977		1978	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
Cape Comorin	Mar.	Jul.	Feb.	Oct.	Feb.	Jul.	Feb.	Jul.	Feb.	Jul.	Feb.	Jul.
Depth (m)	110	57	140	43	120	45	115	42	115	0	115	53
Quilon	Jan.	Jul.	Feb.	Oct.	Feb.	Sept.	Feb.	Aug.	Feb.	Jul.	Feb.	Jul.
Depth (m)	115	20	140	23	132	15	127	15	127	0	127	32
Cochin	Jan.	Aug.	Jan.	Aug.	Feb.	Sept.	Feb.	Aug.	Mar.	Jul.	Jan.	Jul.
Depth (m)	110	17	130	16	113	17	124	16	110	7	112	24
Kasaragod	Feb.	Aug.	Jan.	Aug.	Mar.	Aug.	Jan.	Aug.	Jan.	Jul.	Jan.	Aug.
Depth (m)	128	27	110	32	122	30	144	17	144	27	144	27
Karwar	Feb.	Sept.	Jan.	Nov.	Mar.	Oct.	Jan.	Aug.	Jan.	Sept.	Jan.	Oct.
Depth (m)	128	16	120	34	138	35	134	48	134	22	134	15
Ratnagiri	Feb.	Nov.	Jan.	Nov.	Feb.	Oct.	--	--	Feb.	Sept.	Feb.	Oct.
Depth (m)	125	50	122	56	170	45	--	--	170	70	170	70

Table 4

UPWELLING INTENSITY IN THE PROJECT AREA
(Based on the vertical movement of 23°C isotherm)

Section	Year	No. of days taken	Upward movement (m)	Speed cm/day	Least depth (m) for 23°C isotherm
Cape Comorin	1973	109	53	48.6	57
	1974	239	97	40.6	43
	1975	155	75	48.4	45
	1976	159	73	45.9	42
	1977	133	115	86.5	0
	1978	157	62	39.5	53
Quilon	1973	170	95	55.9	20
	1974	238	117	49.2	23
	1975	194	117	60.3	23
	1976	164	112	68.3	15
	1977	153	127	83.0	0
	1978	160	95	59.4	32
Cochin	1973	211	93	44.1	17
	1974	212	114	53.8	16
	1975	195	96	49.2	17
	1976	167	108	64.7	16
	1977	140	103	73.6	7
	1978	201	88	43.8	24
Kasaragod	1973	173	101	58.4	27
	1974	217	78	35.9	32
	1975	155	92	59.4	30
	1976	205	127	62.0	17
	1977	179	117	65.4	27
	1978	186	117	62.9	27
Karwar	1973	201	112	55.7	16
	1974	290	86	29.7	34
	1975	239	103	43.1	35
	1976	209	86	41.1	48
	1977	240	112	46.7	22
	1978	249	119	47.8	15
Ratnagiri	1973	262	75	28.6	50
	1974	290	66	22.8	50
	1975	240	125	56.3	45
	1976	--	--	--	--
	1977	202	100	49.5	70
	1978	220	100	45.5	70

Table 5

OBSERVED DISTRIBUTION OF WHITEBAIT IN SPACE AND TIME WITHIN THE PROJECT AREA

Year	Period	Distribution of whitebait	Area of maximum abundance
1973	Jan.-Mar.	Ratnagiri-Quilon	Vengurla-Quilon
	May -Jun.	Vengurla-Quilon	
	Jun.-Jul.	Mangalore-Tuticorin	C.Comorin-Tuticorin
	Jul.-Aug.	C.Comorin-Tuticorin	C.Comorin-Tuticorin
	Oct.-Nov.	Tuticorin-Ratnagiri	C.Comorin-Tuticorin
1974	Mar.-Apr.	Quilon-Ratnagiri	Quilon-Calicut
	Apr.-May	Quilon-Ratnagiri	Cochin-Kasaragod
	Jun.-July	Quilon-Kasaragod	Cochin
	Aug.	C.Comorin-Tuticorin	C.Comorin-Tuticorin
	Sept.-Oct.	C.Comorin-Tuticorin	C.Comorin-Tuticorin
	Nov.	Tuticorin-Cochin	Quilon-Cochin
	Dec.	Quilon-Kasaragod	Calicut
1975	Feb.-March	Quilon-Ratnagiri	
	Apr.-May	Ratnagiri-Tuticorin	Quilon-Tuticorin
	May-Jun.	Ratnagiri-Tuticorin	Quilon-Tuticorin
	Aug.-Sept.	C.Comorin-Tuticorin	C.Comorin-Tuticorin
1976	Jan.-Feb.	Ratnagiri-Quilon	Karwar
1978	Jun.-Jul.	C.Comorin-Tuticorin	C.Comorin-Tuticorin

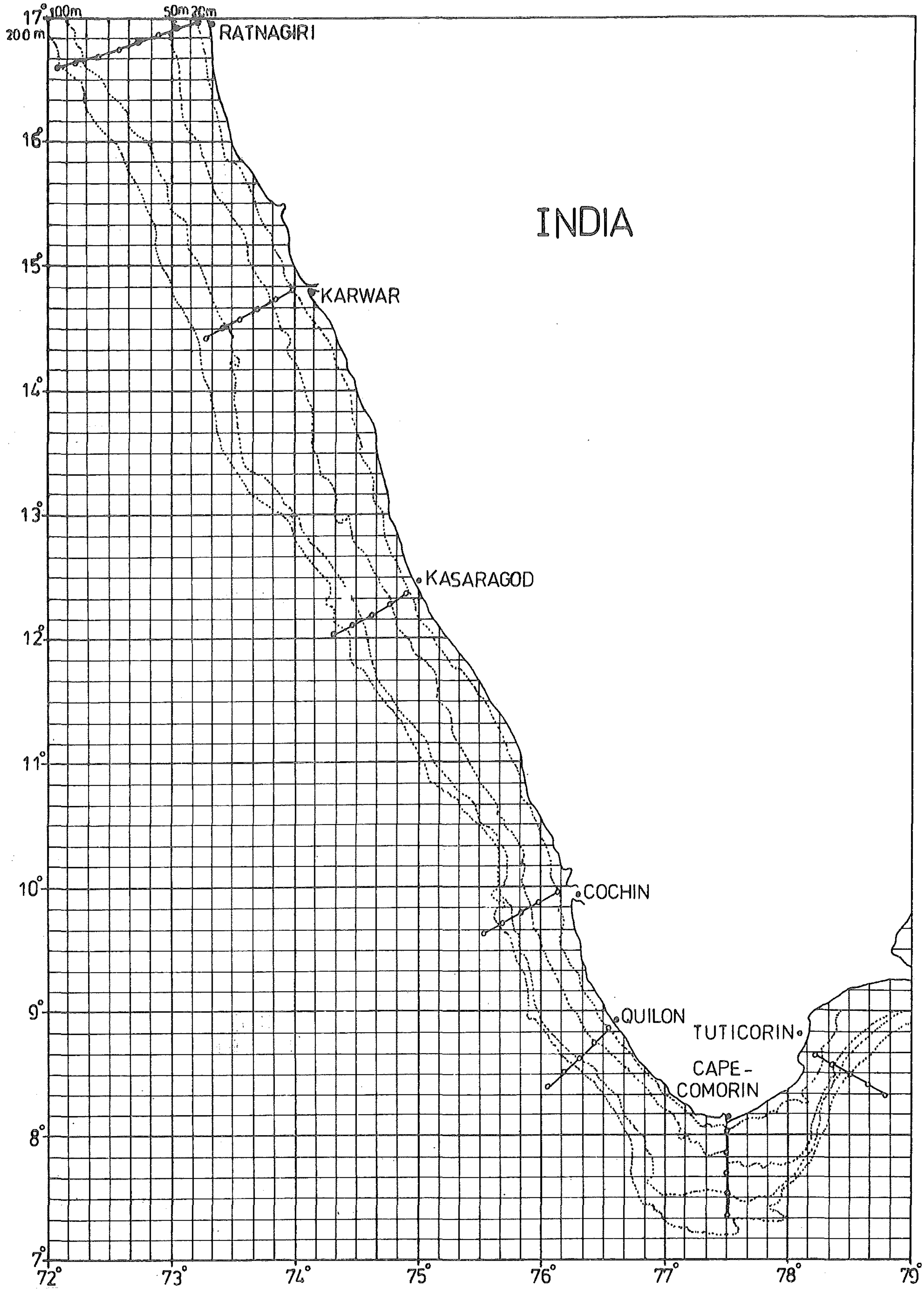

Fig. 1 - Map showing the location of oceanographic sections/stations

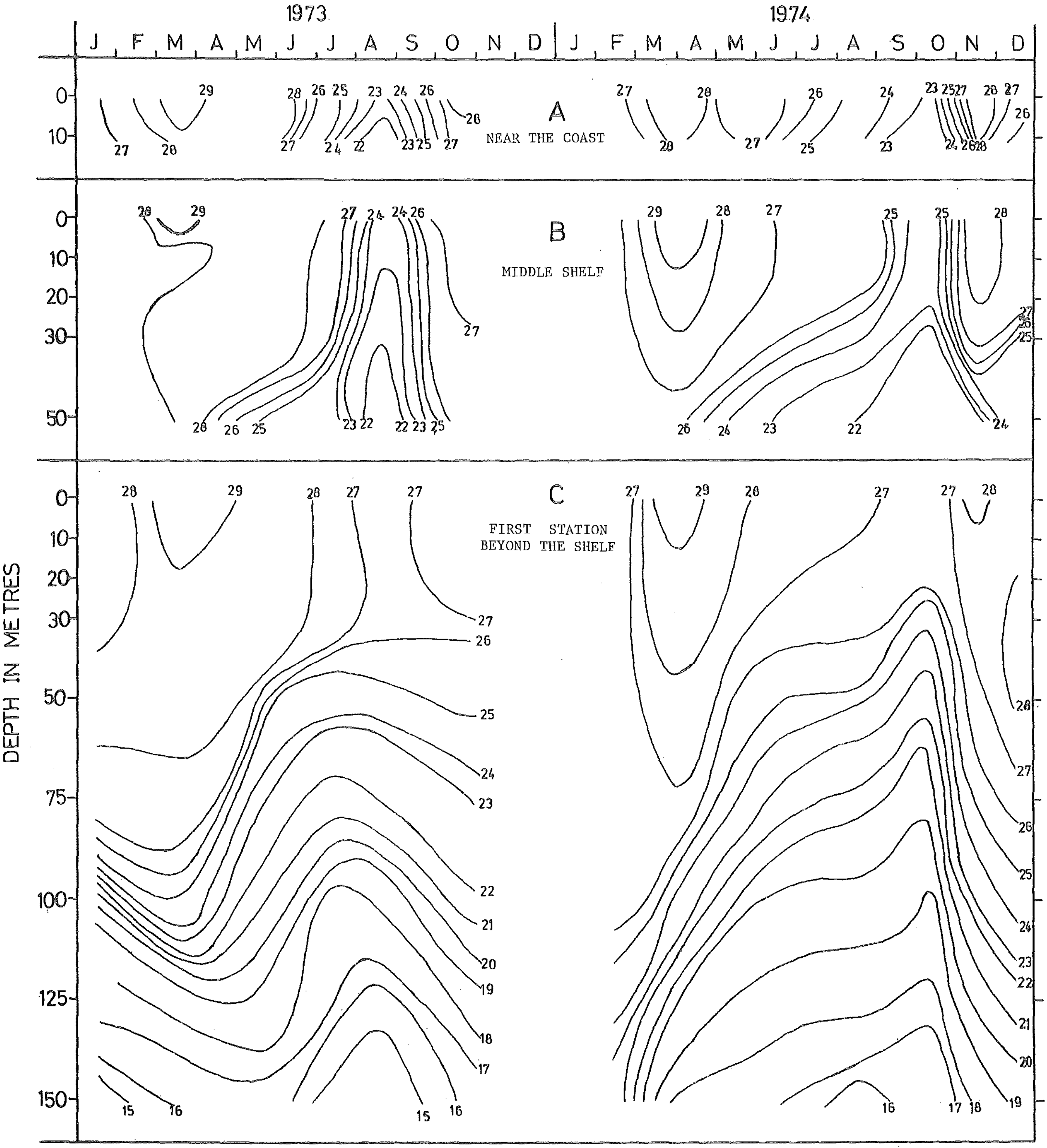

Fig. 2A - Vertical time series section for temperature off Cape Comorin (1973,1974)

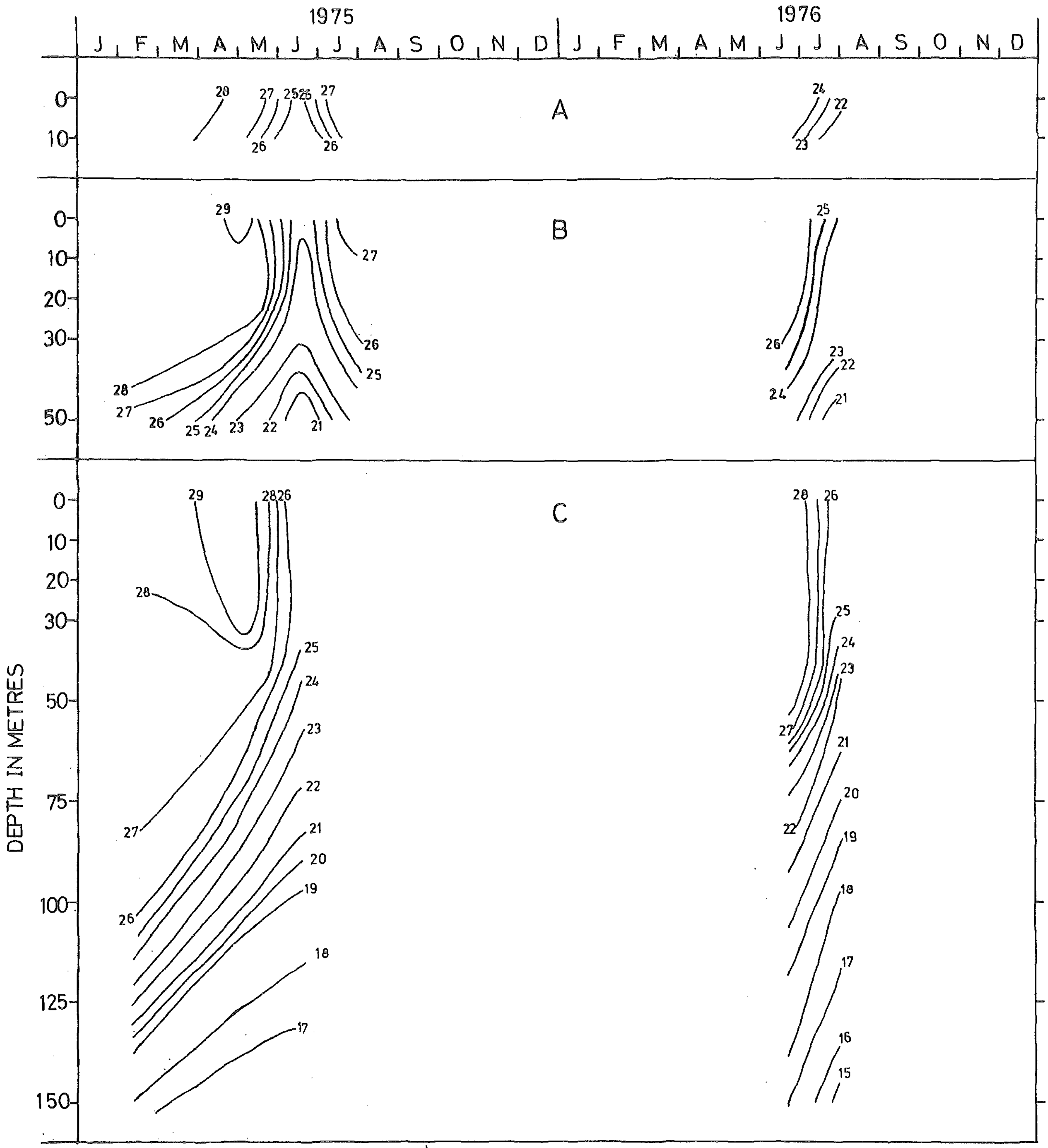

Fig. 2B - Vertical time series section for temperature off Cape Comorin (1975, 1976)

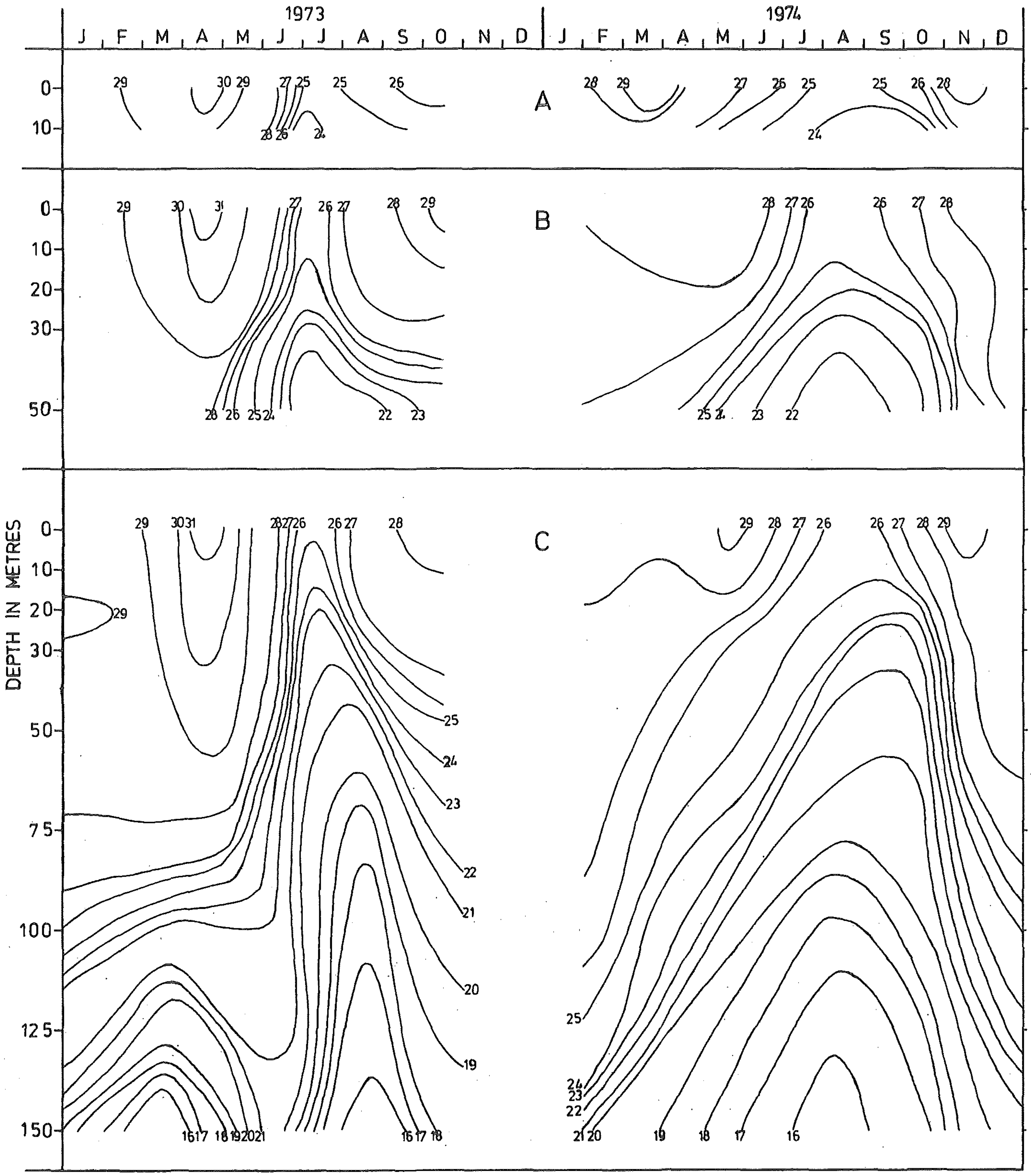

Fig. 3A - Vertical time series section for temperature off Quilon (1973, 1974)

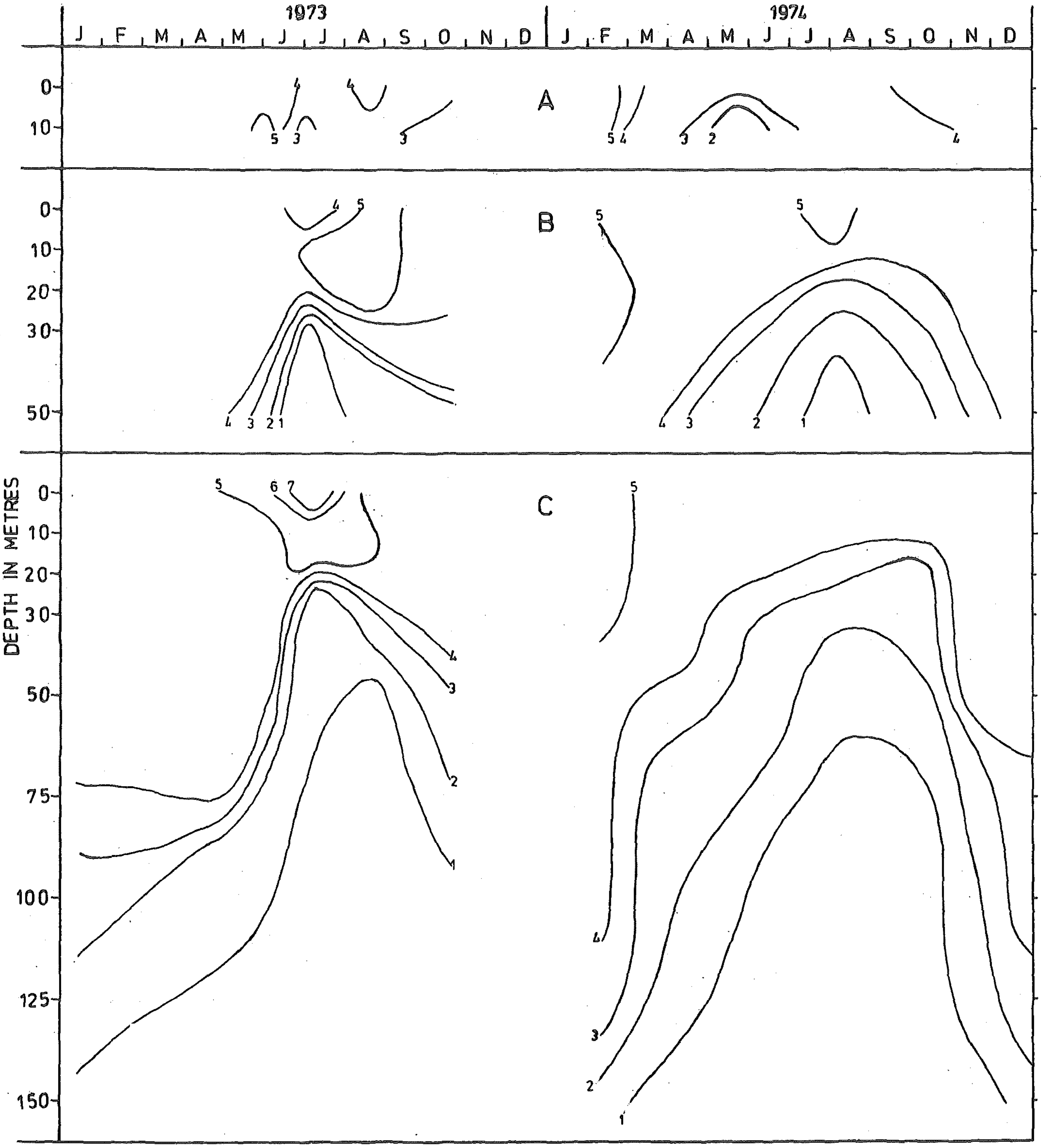

Fig. 3B - Vertical time series section for dissolved oxygen off Quilon (1973, 1974)

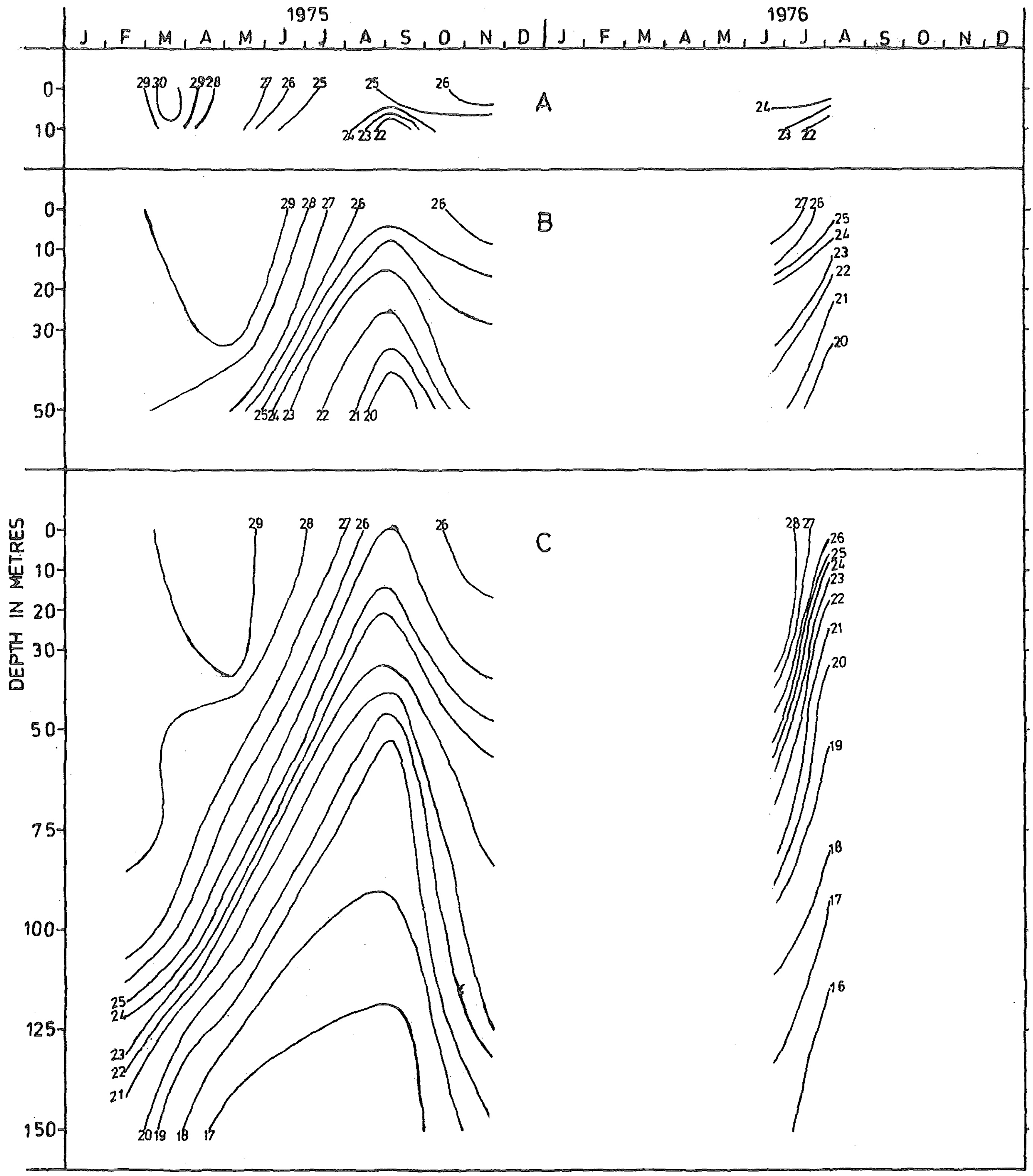

Fig. 3C - Vertical time series section for temperature off Quilon (1975, 1976)

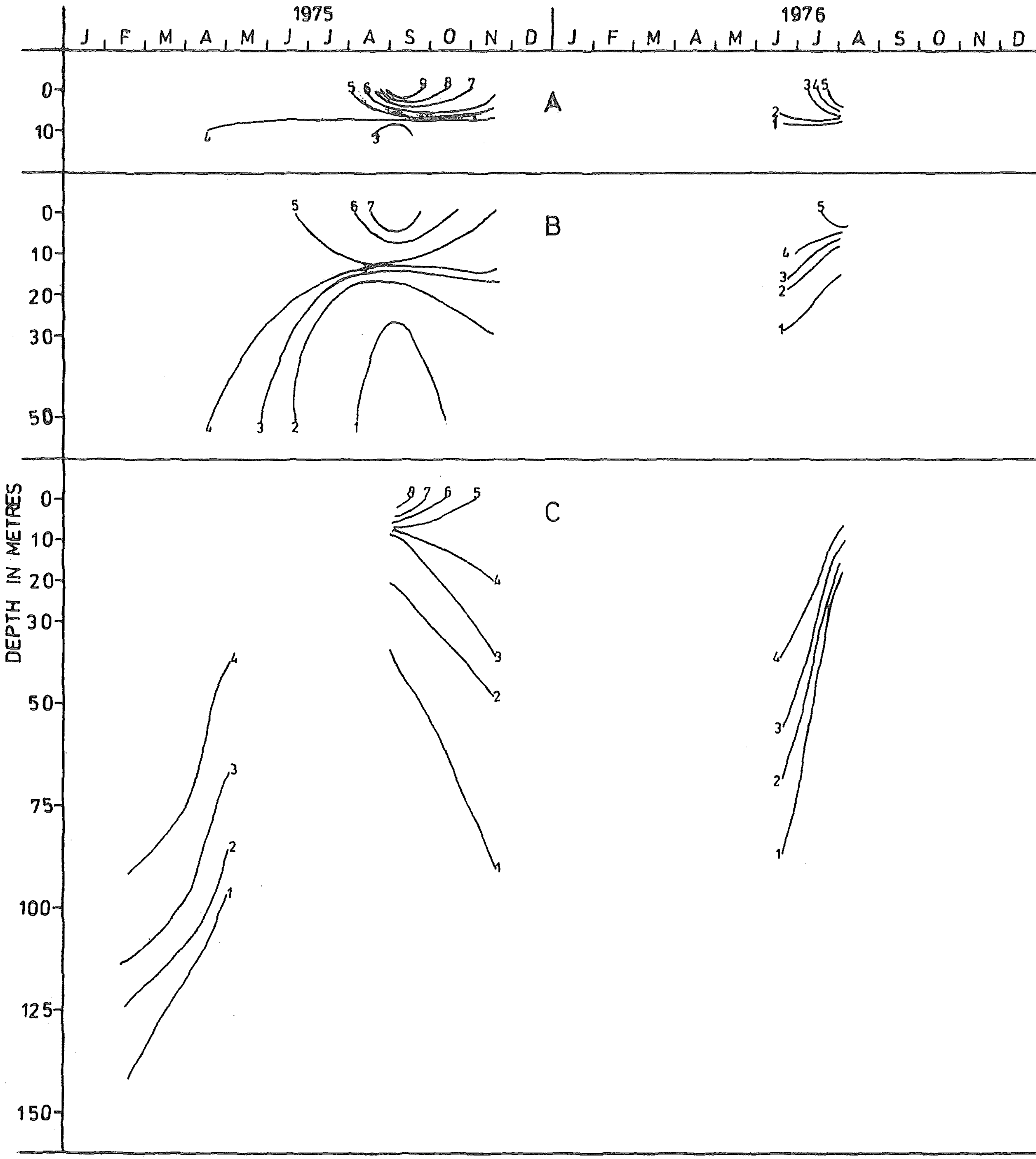

Fig. 3D - Vertical time series section for dissolved oxygen off Quilon (1975, 1976)

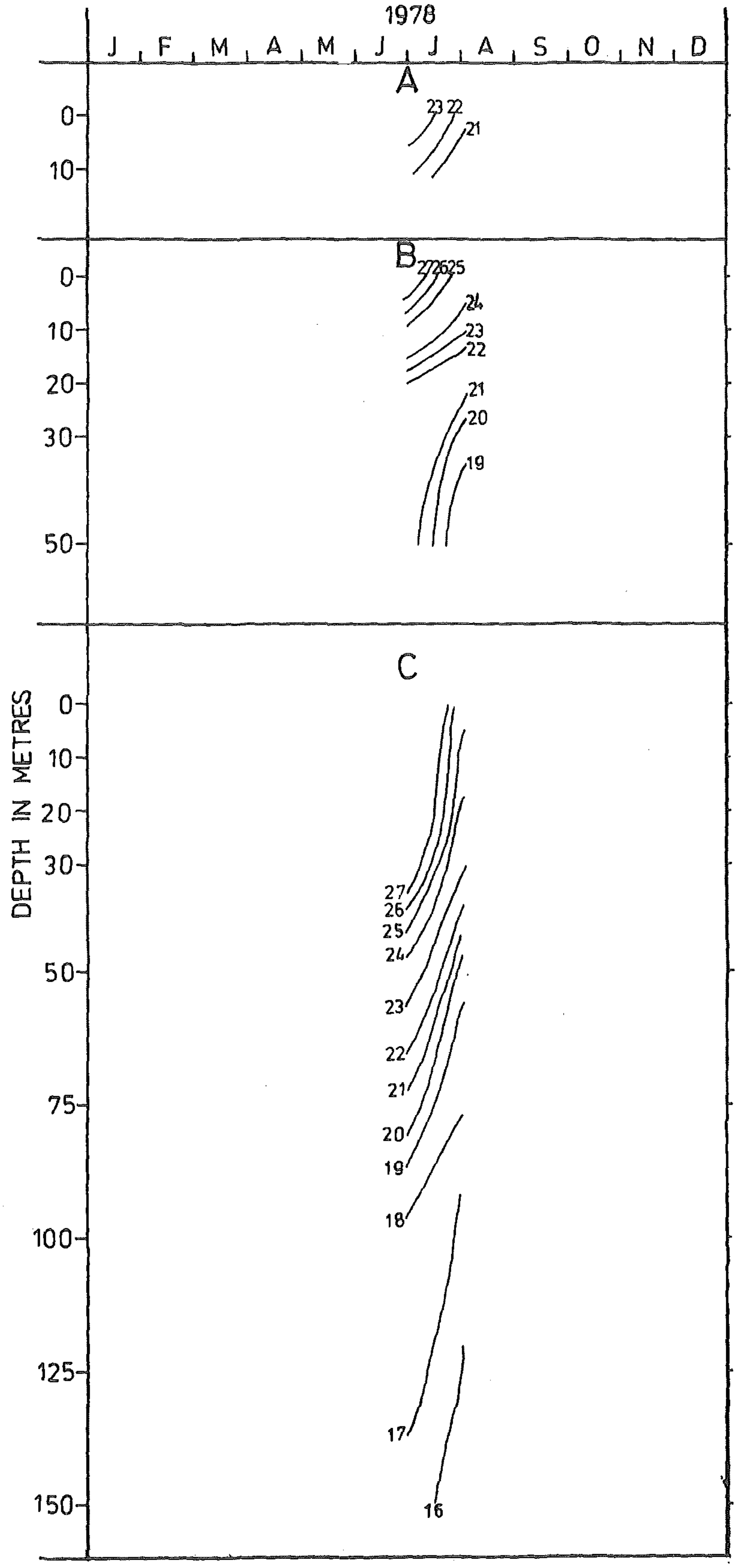

Fig. 3E - Vertical time series section for temperature off Quilon (1978)

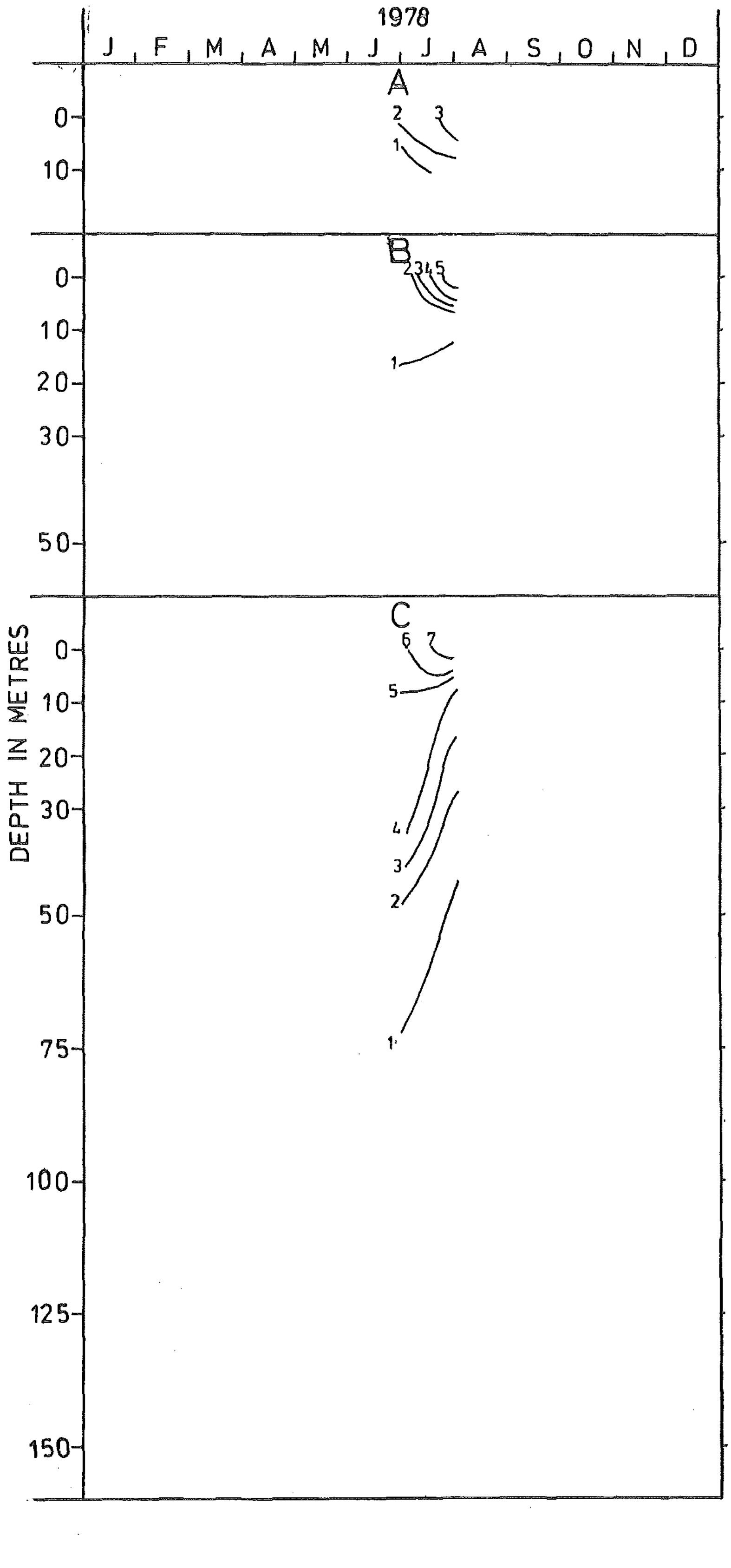

Fig. 3F .- Vertical time series section for dissolved oxygen off Quilon (1978)

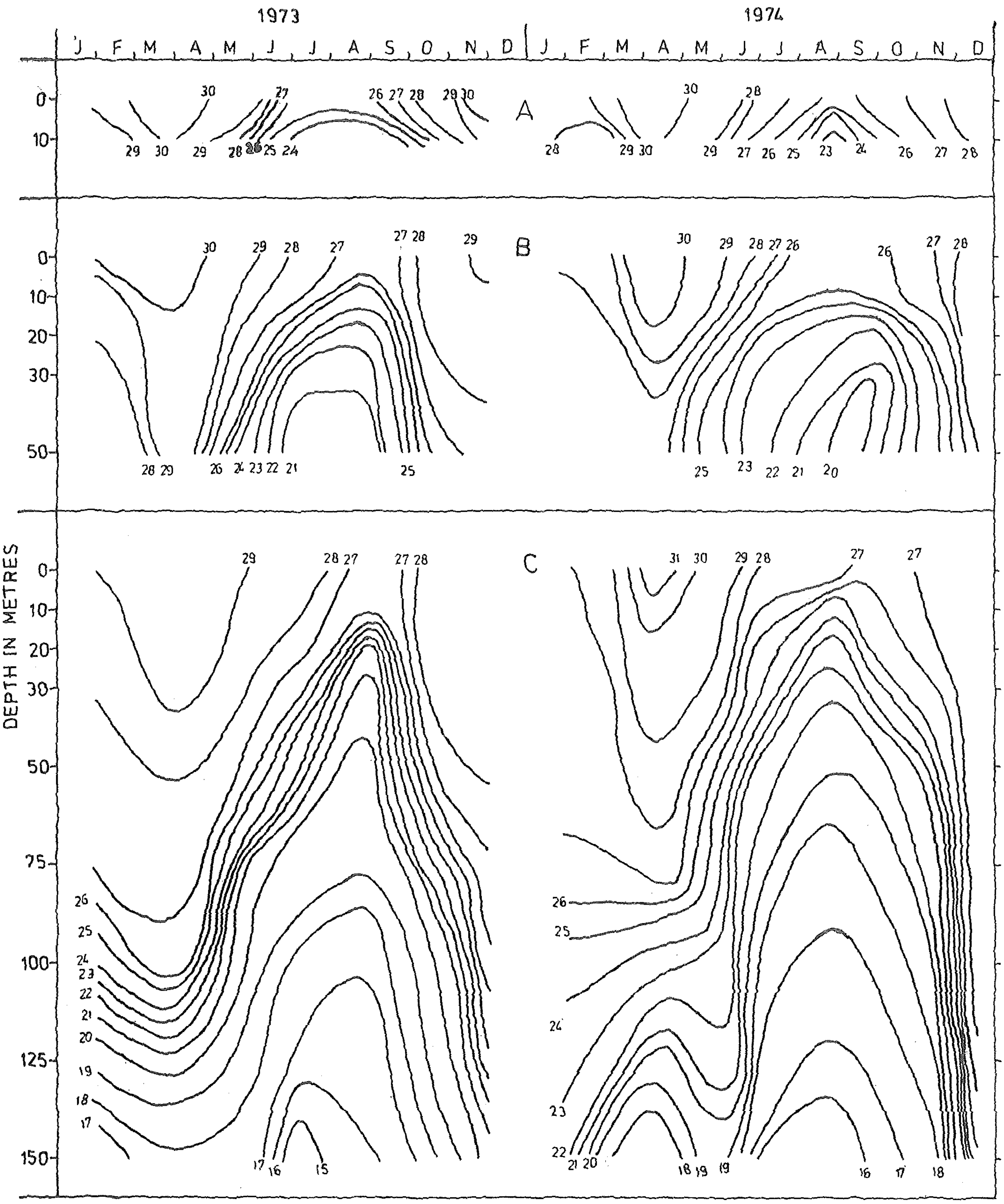

Fig. 4A - Vertical time series section for temperature off Cochin (1973, 1974)

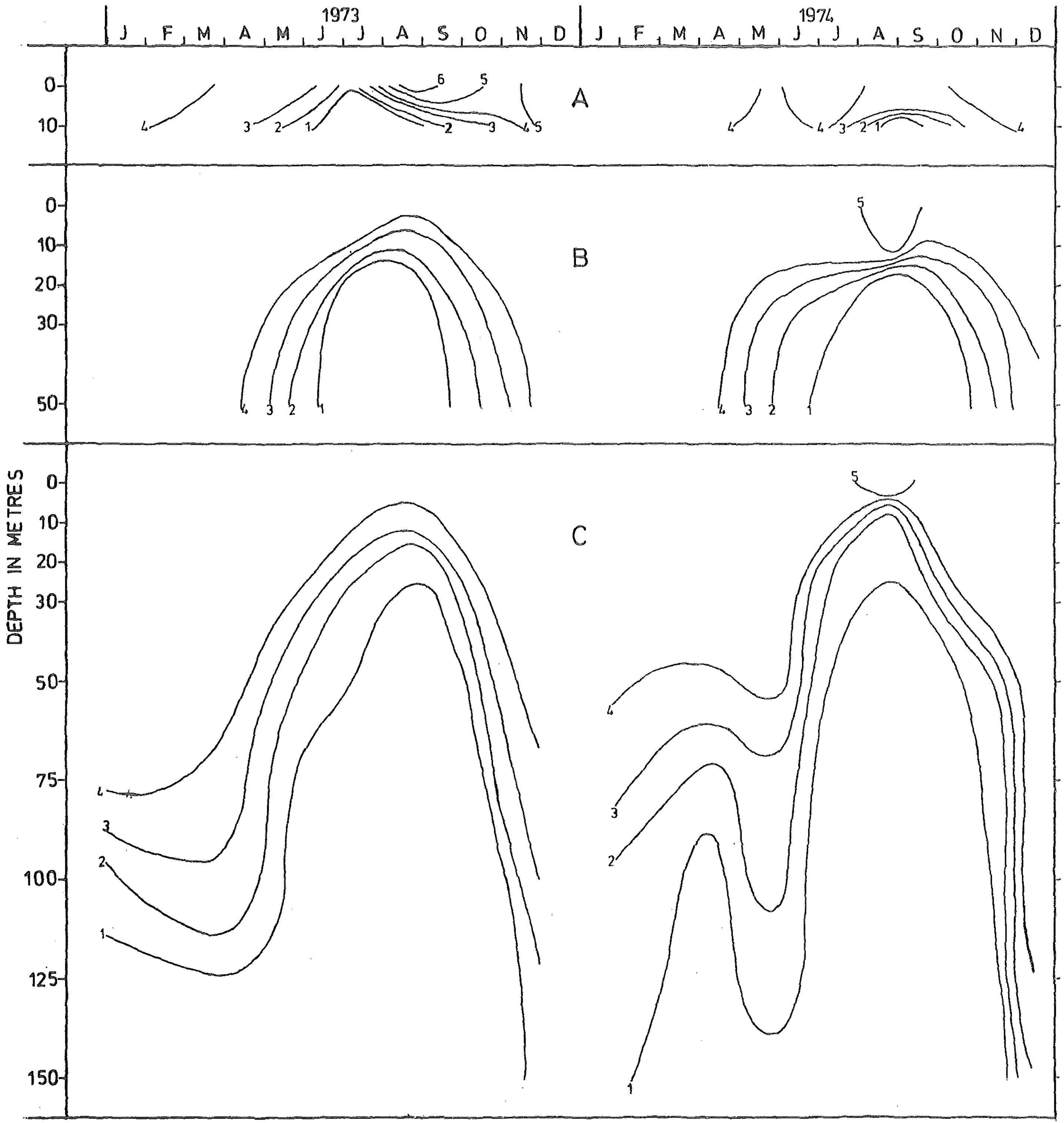

Fig. 4B - Vertical time series section for dissolved oxygen off Cochin (1973, 1974)

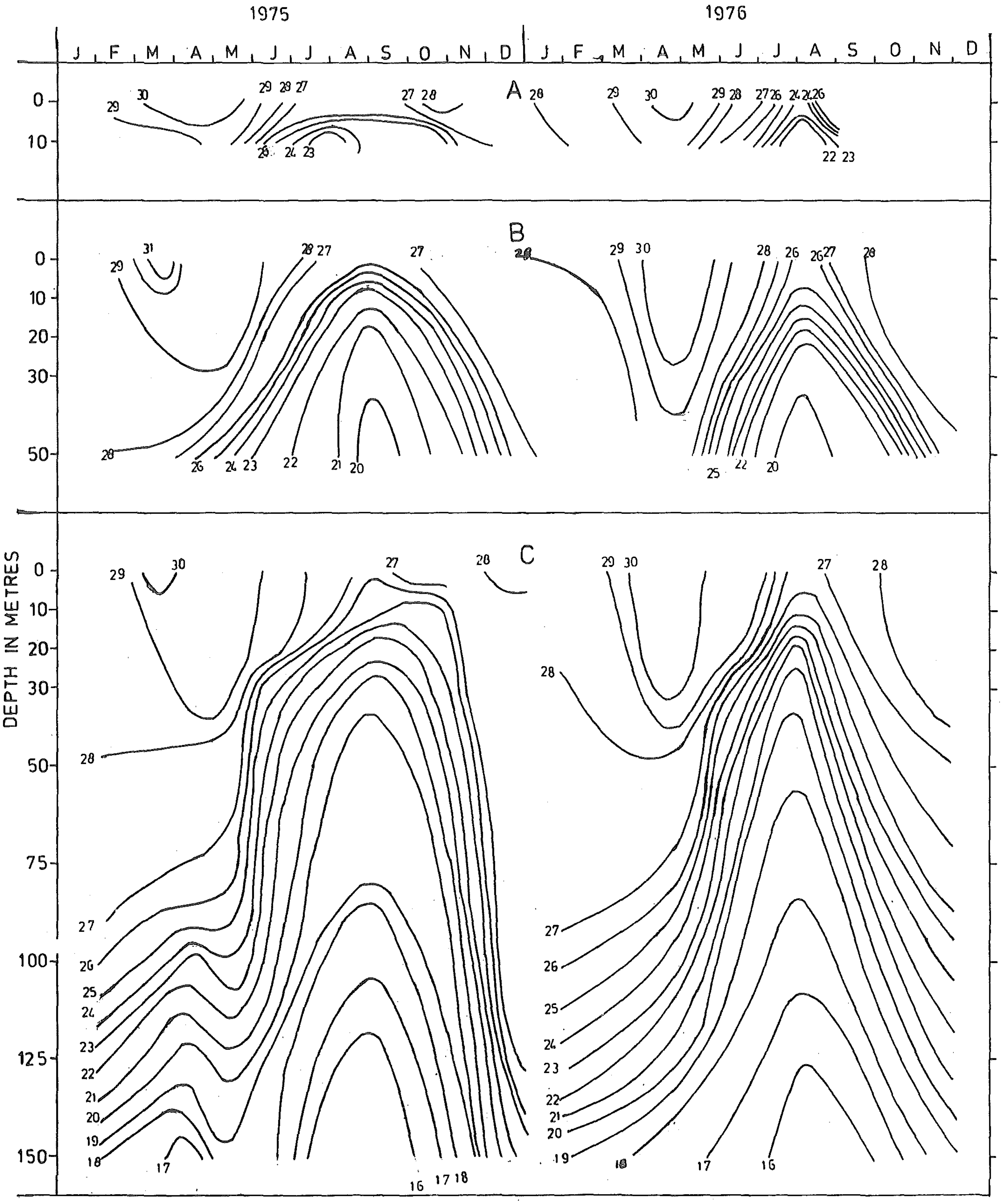

Fig. 4C - Vertical time series section for temperature off Cochin (1975, 1976)

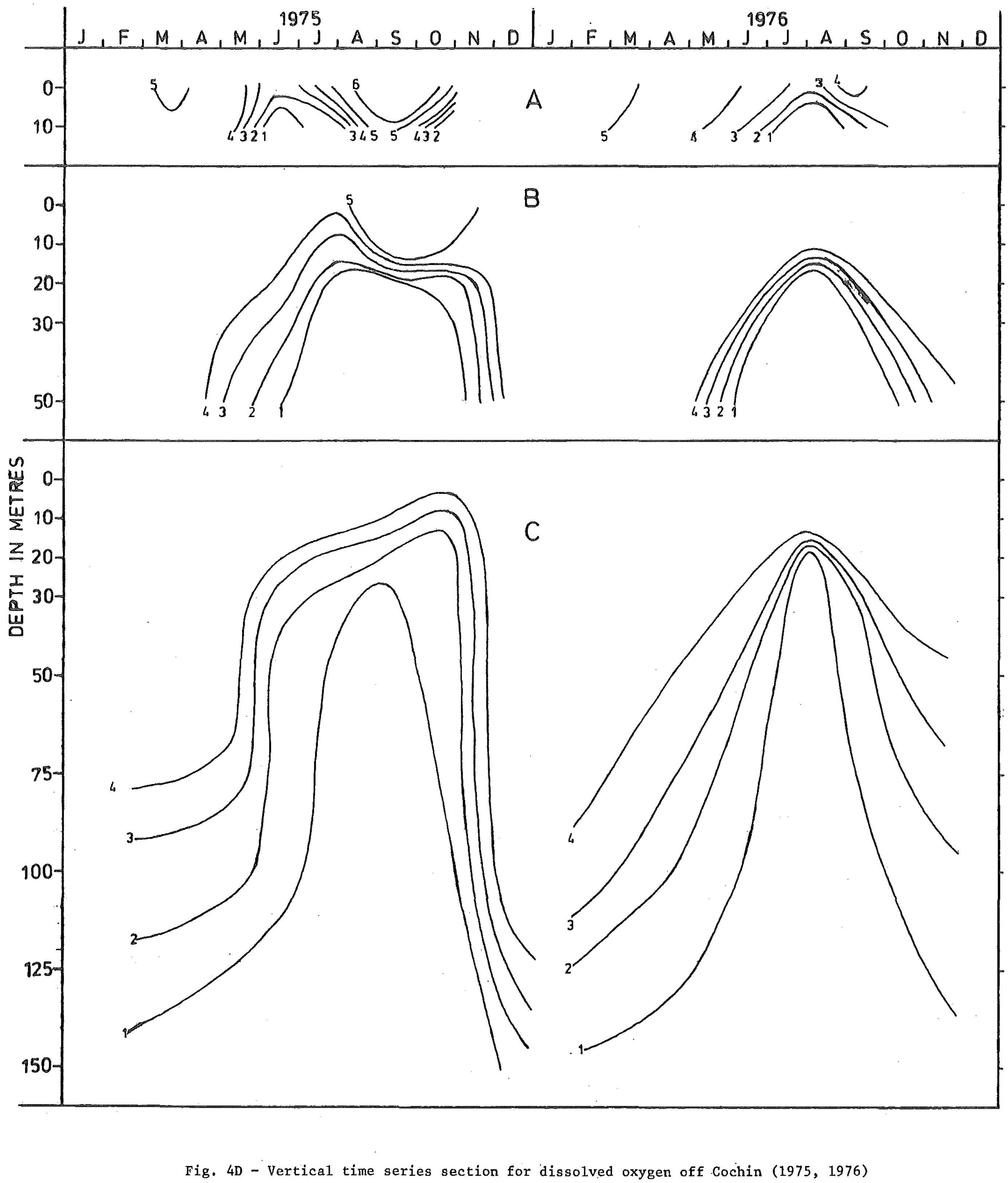

Fig. 4D - Vertical time series section for dissolved oxygen off Cochin (1975, 1976)

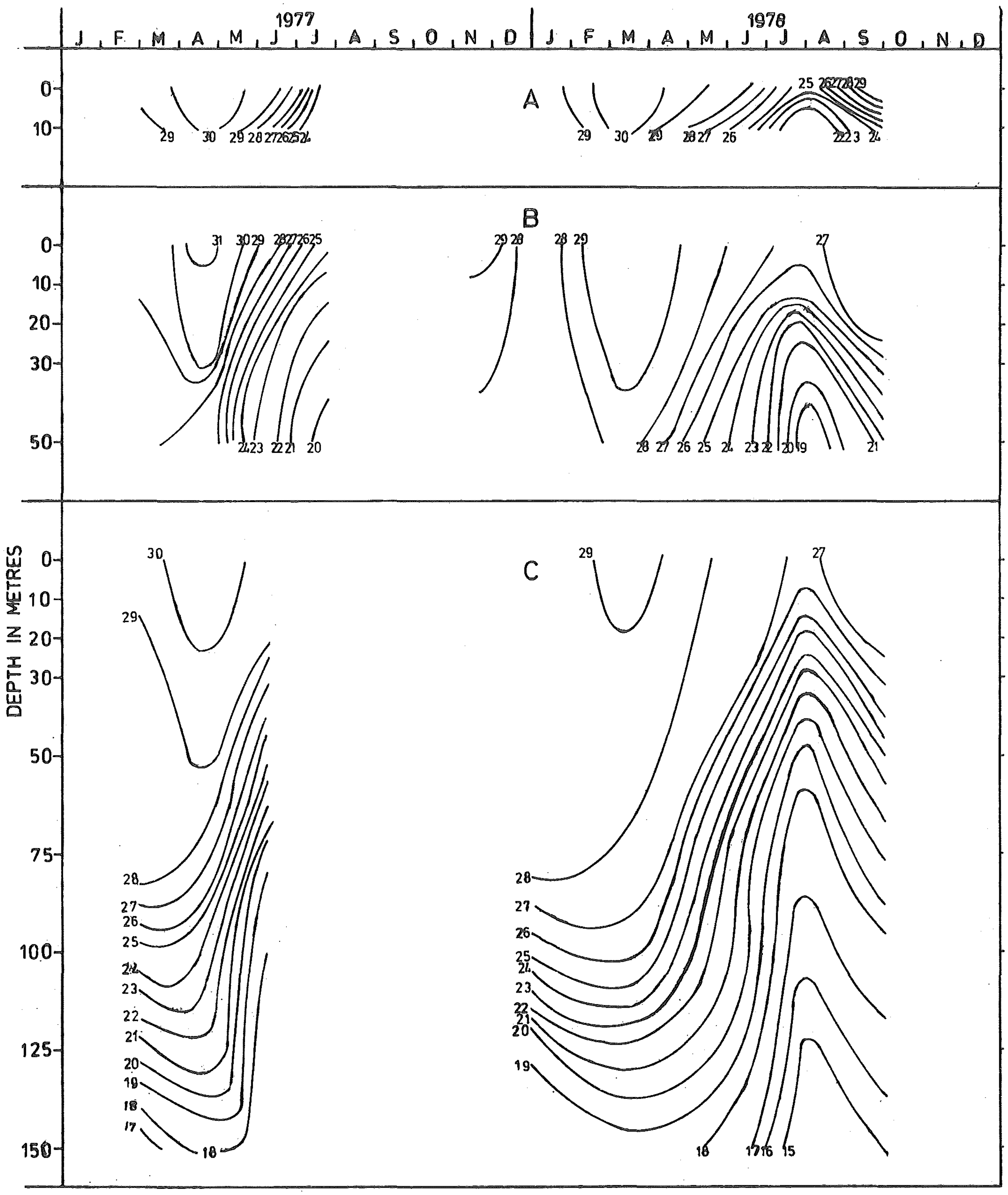

Fig. 4E - Vertical time series section for temperature off Cochin (1977, 1978)

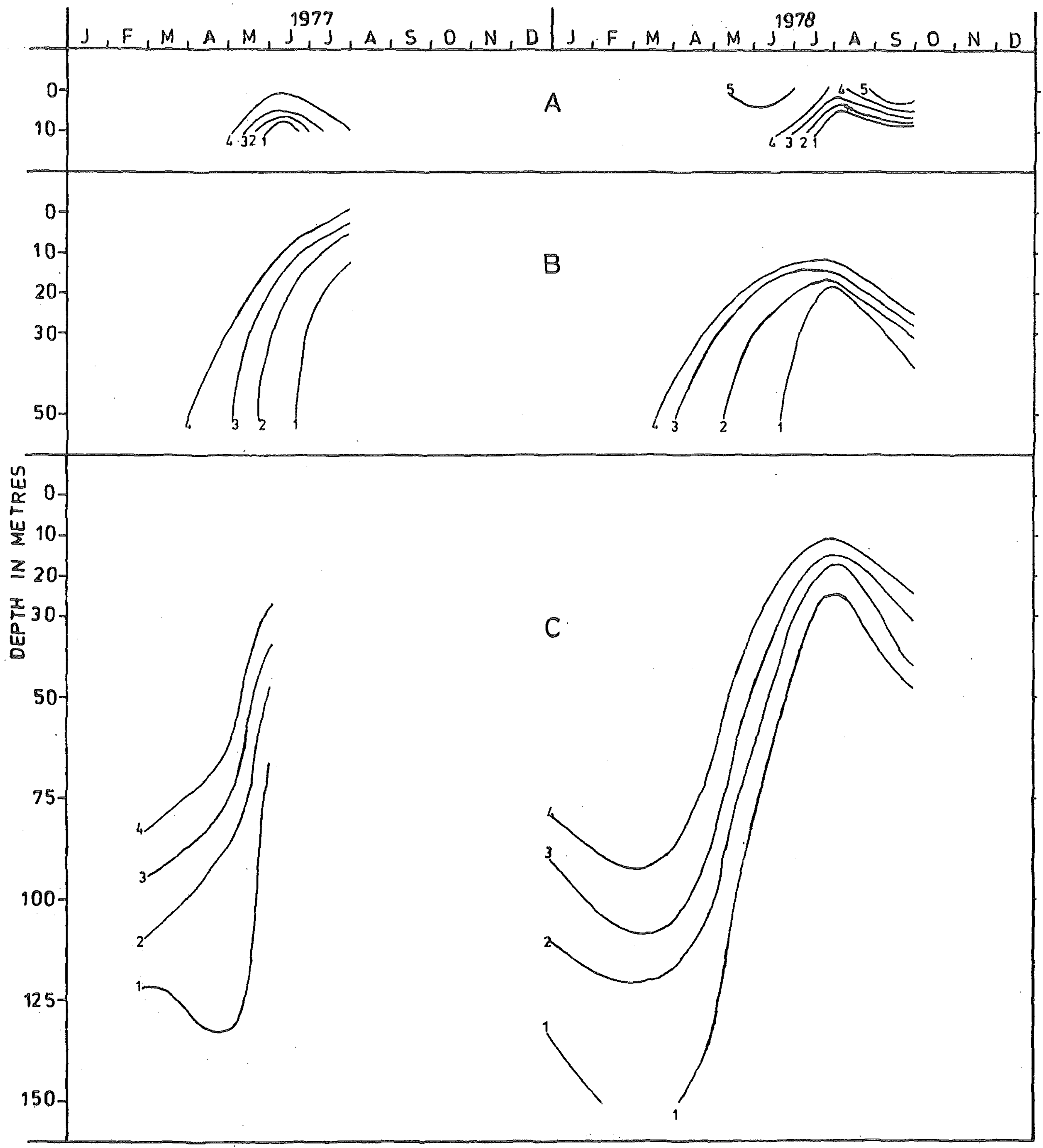

Fig. 4F - Vertical time series section for dissolved oxygen off Cochin (1977, 1978)

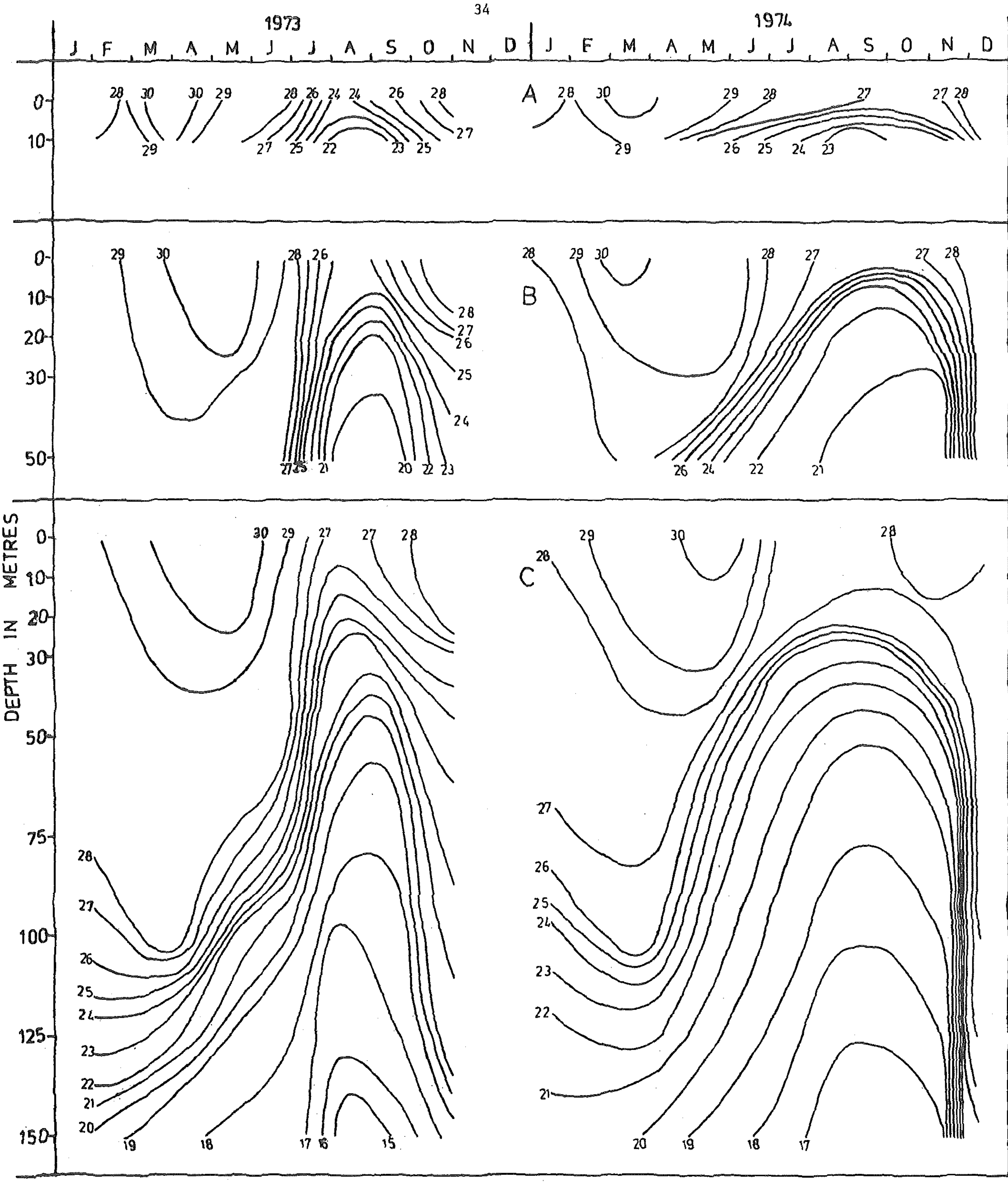

Fig. 5A - Vertical time series section for temperature off Kasaragod (1973, 1974)

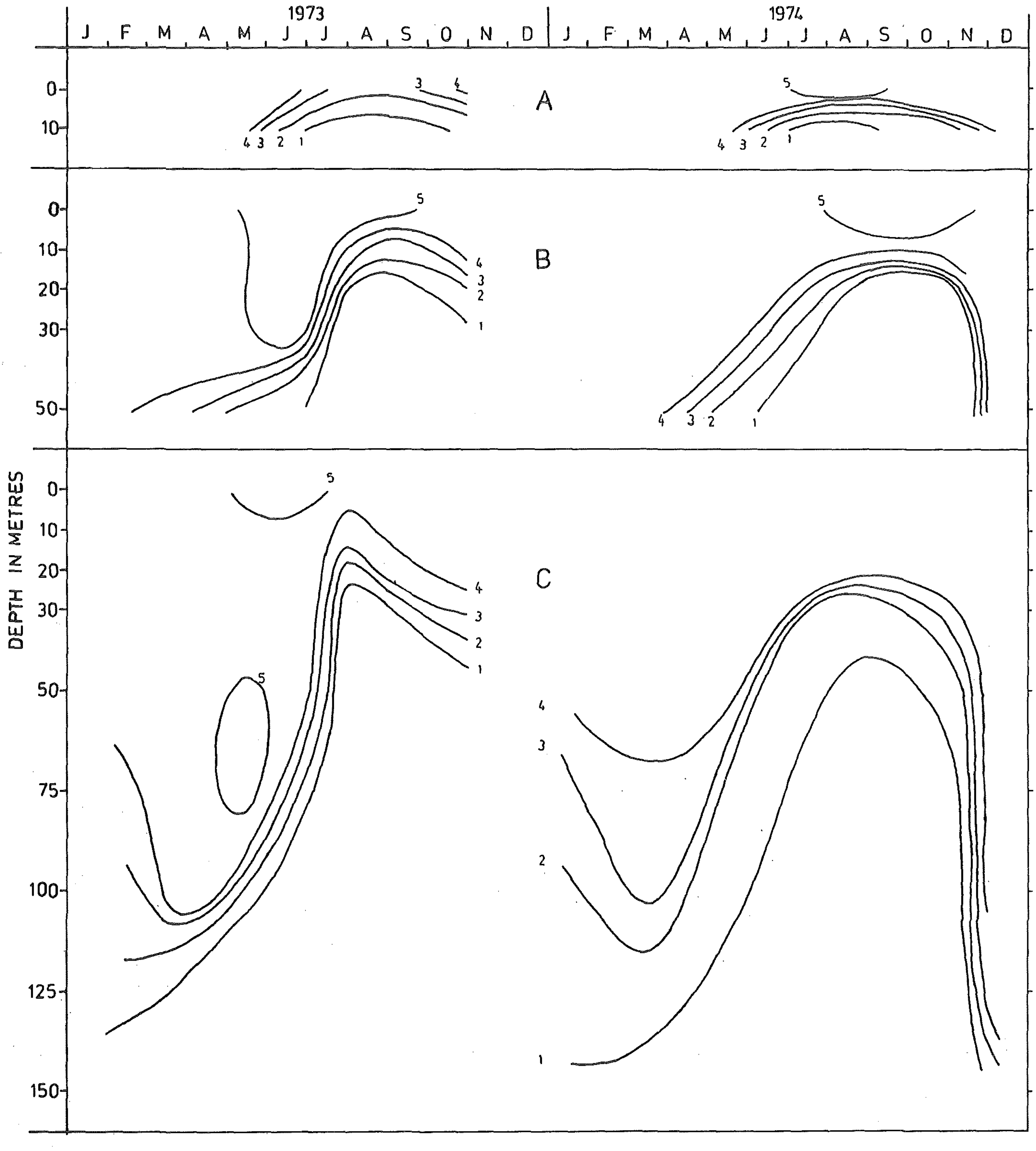

Fig. 5B - Vertical time series section for dissolved oxygen off Kasaragod (1973, 1974)

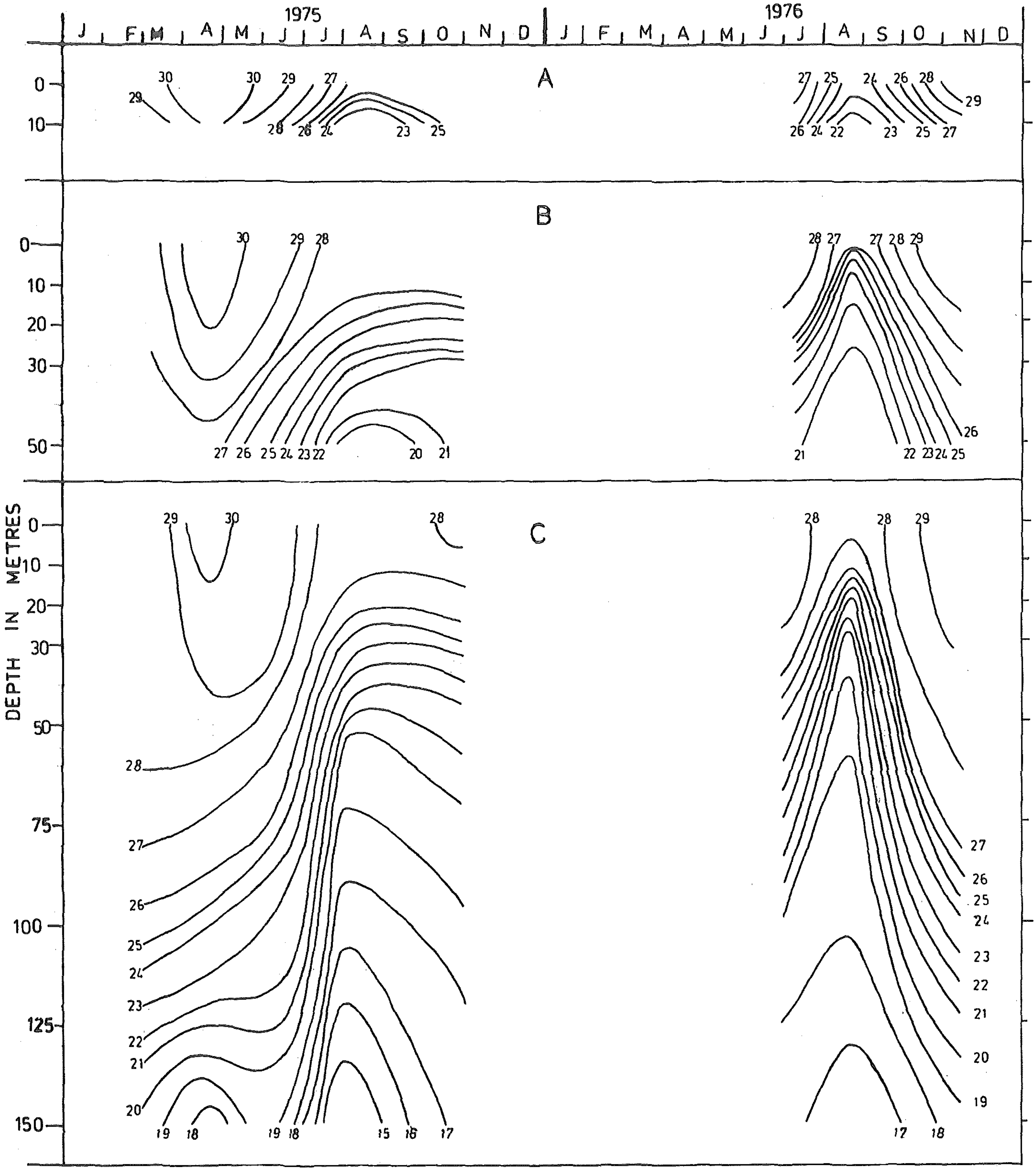

Fig. 5C - Vertical time series section for temperature off Kasaragod (1975, 1976)

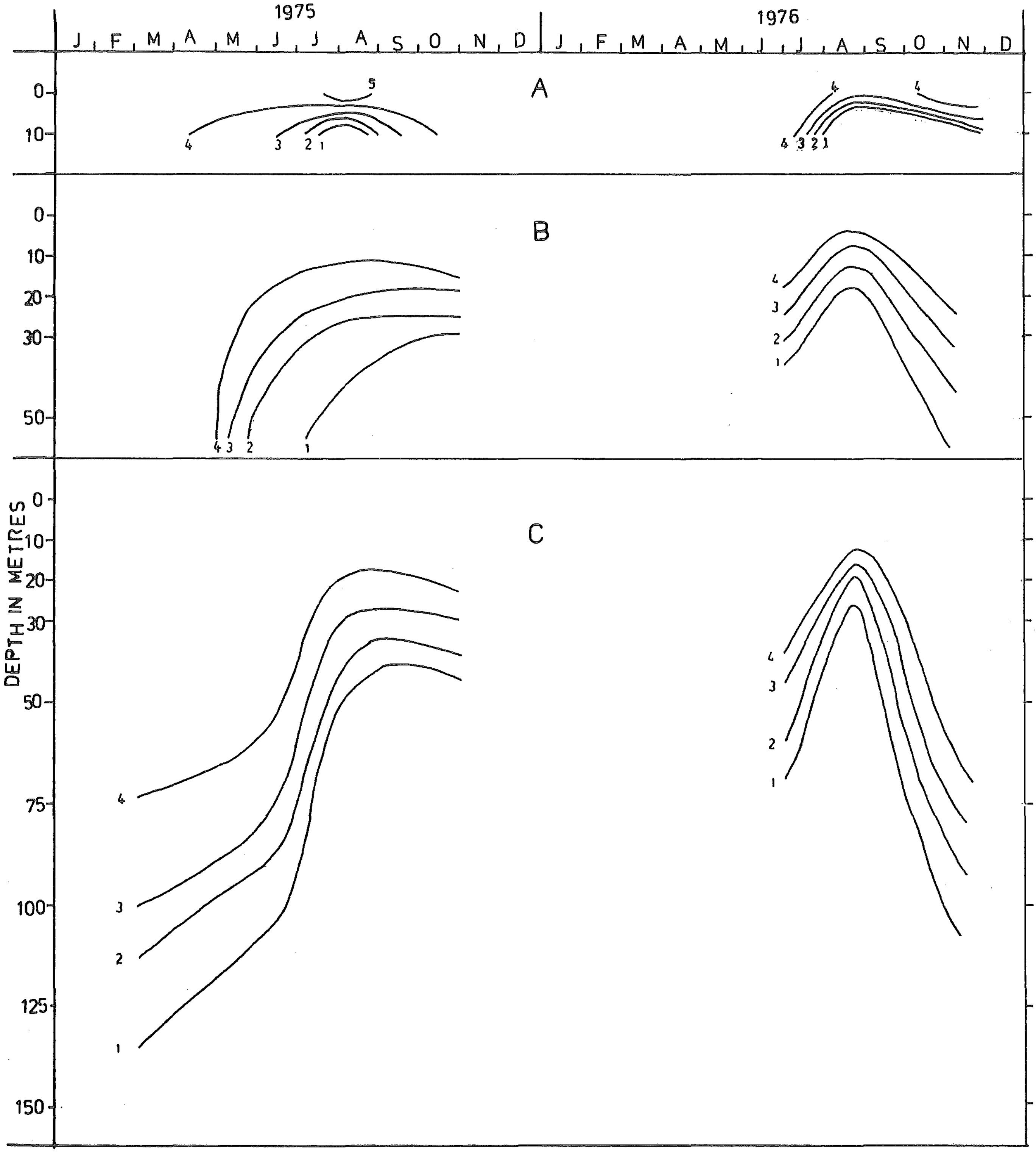

Fig. 5D - Vertical time series section for dissolved oxygen off Kasaragod (1975, 1976)

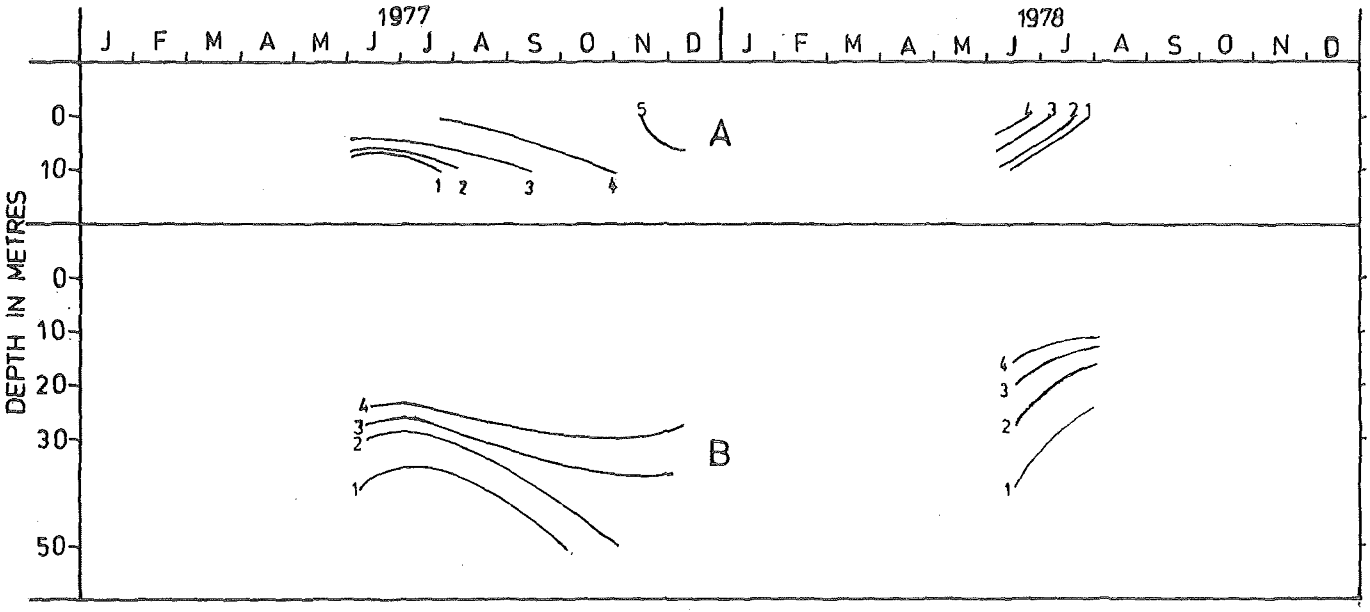

Fig. 5E - Vertical time series section for dissolved oxygen off Kasaragod (1977, 1978)

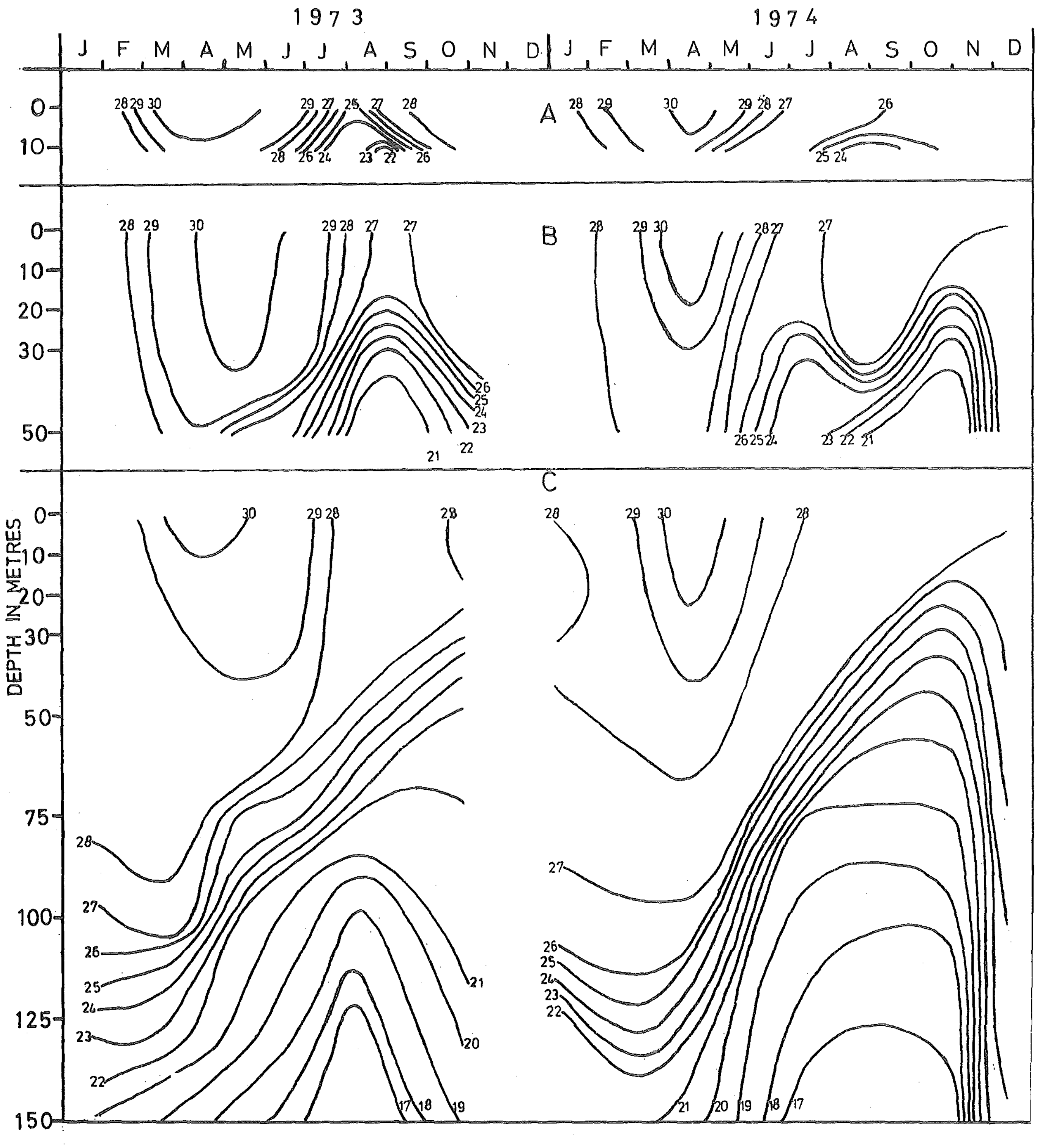

Fig. 6A - Vertical time series section for temperature off Karwar (1973, 1974)

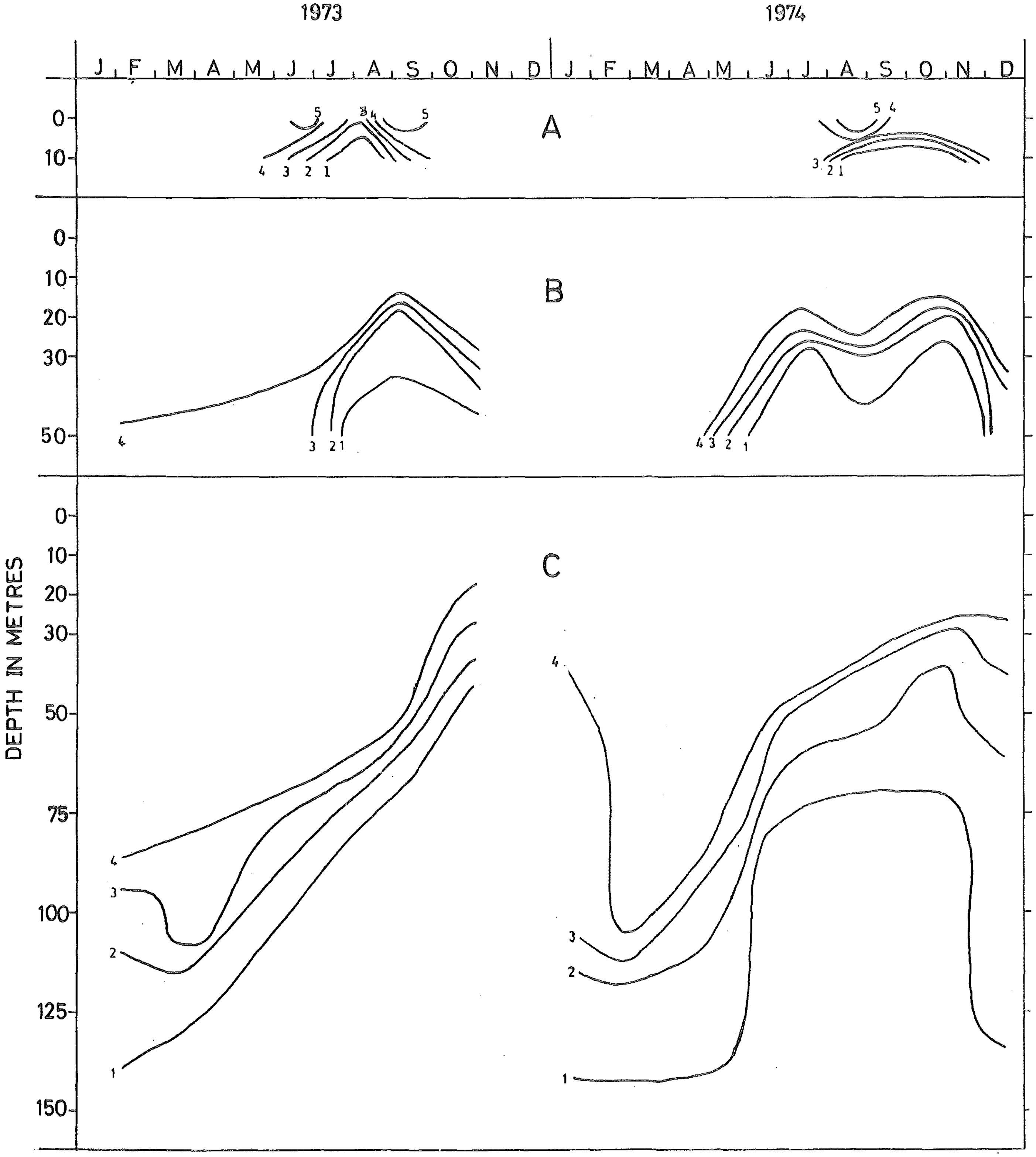

Fig. 6B - Vertical time series section for dissolved oxygen off Karwar (1973, 1974)

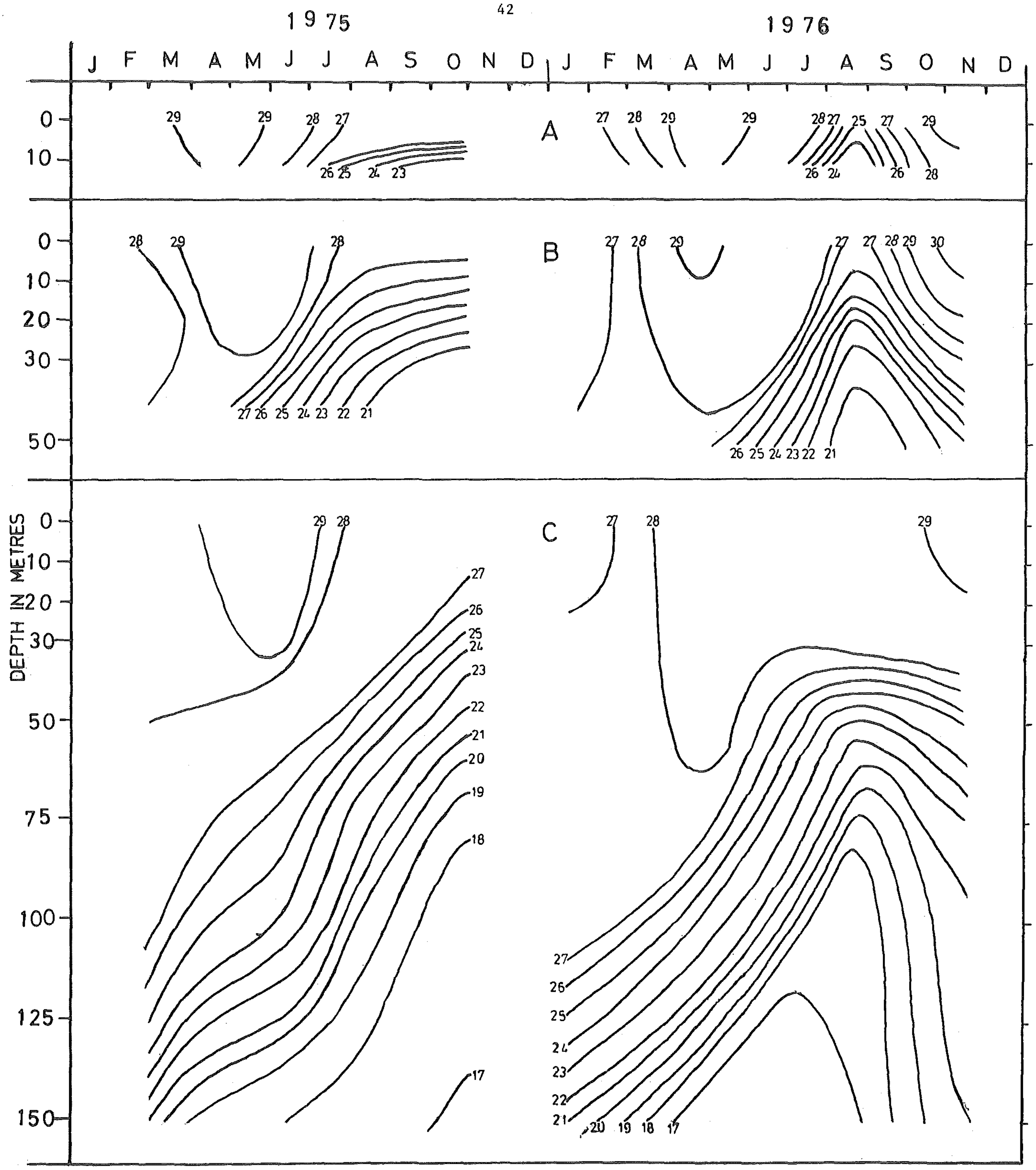

Fig. 6C - Vertical time series section for temperature off Karwar (1975, 1976)

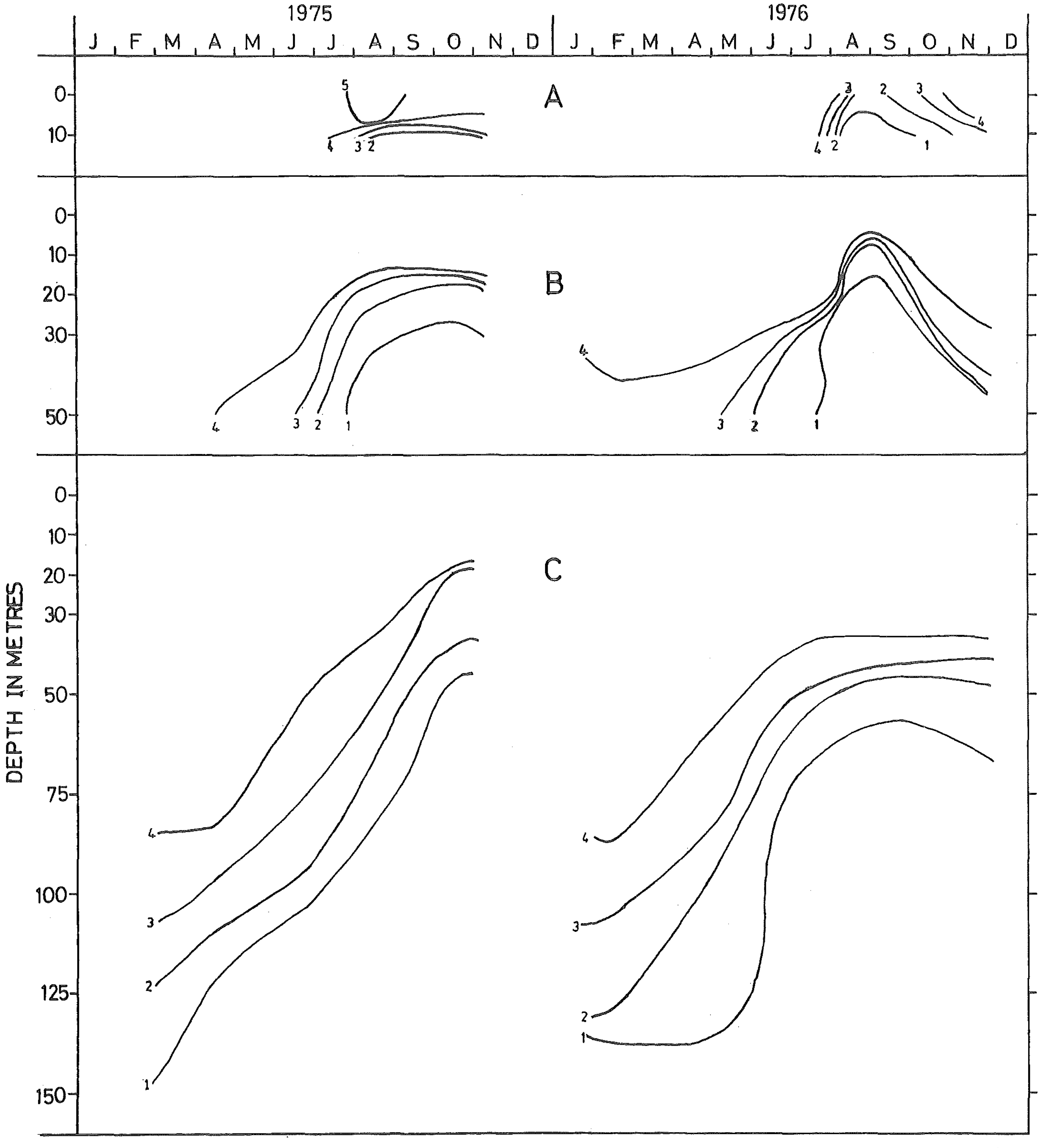

Fig. 6D - Vertical time series section for dissolved oxygen off Karwar (1975, 1976)

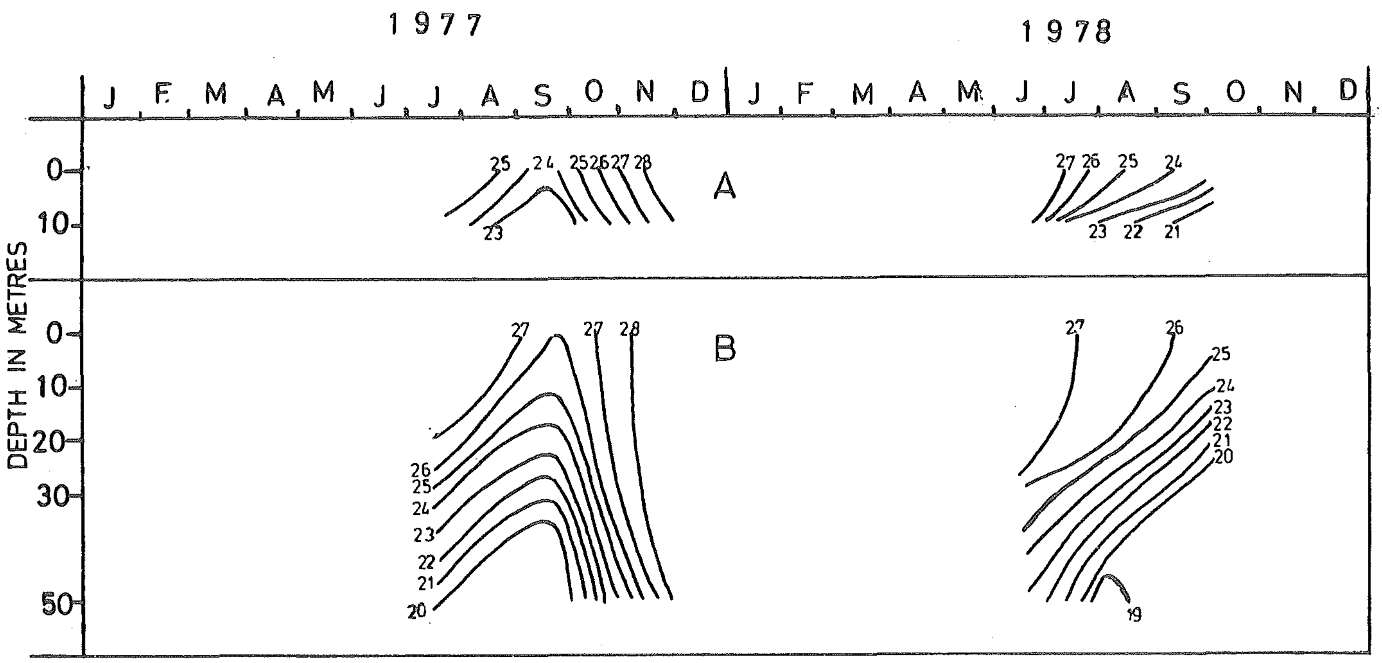

Fig. 6E - Vertical time series section for temperature off Karwar (1977, 1978)

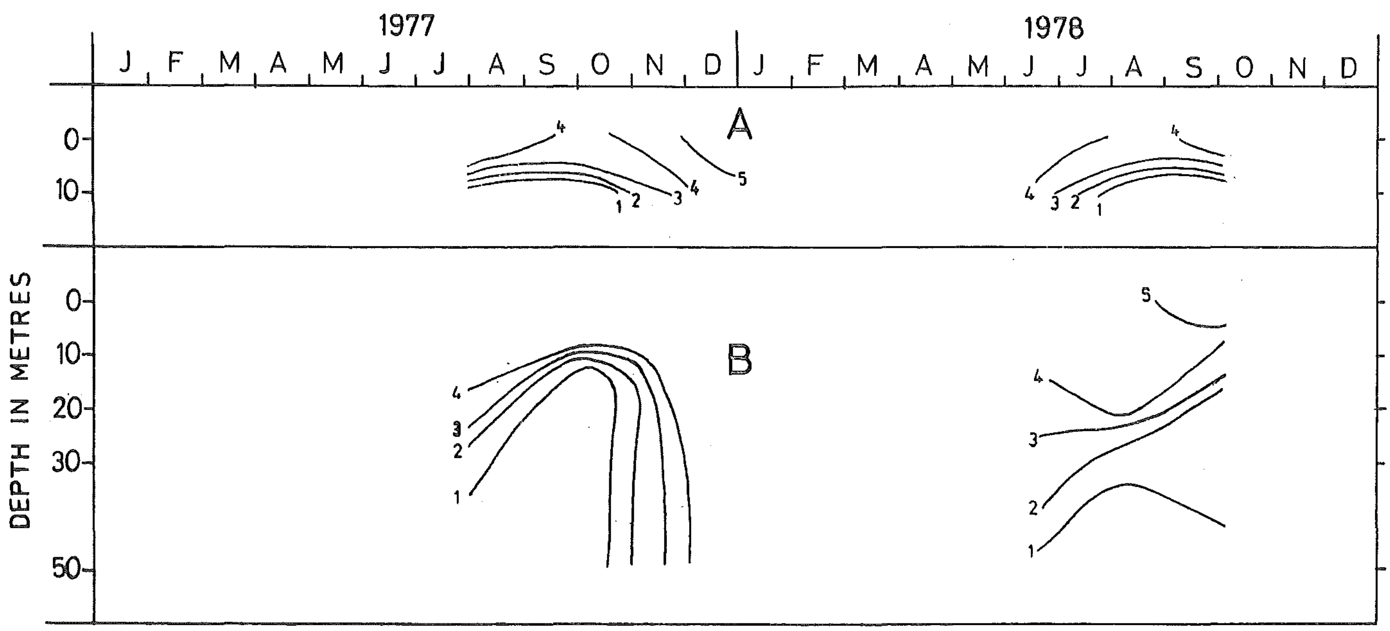

Fig. 6F - Vertical time series section for dissolved oxygen off Karwar (1977, 1978)

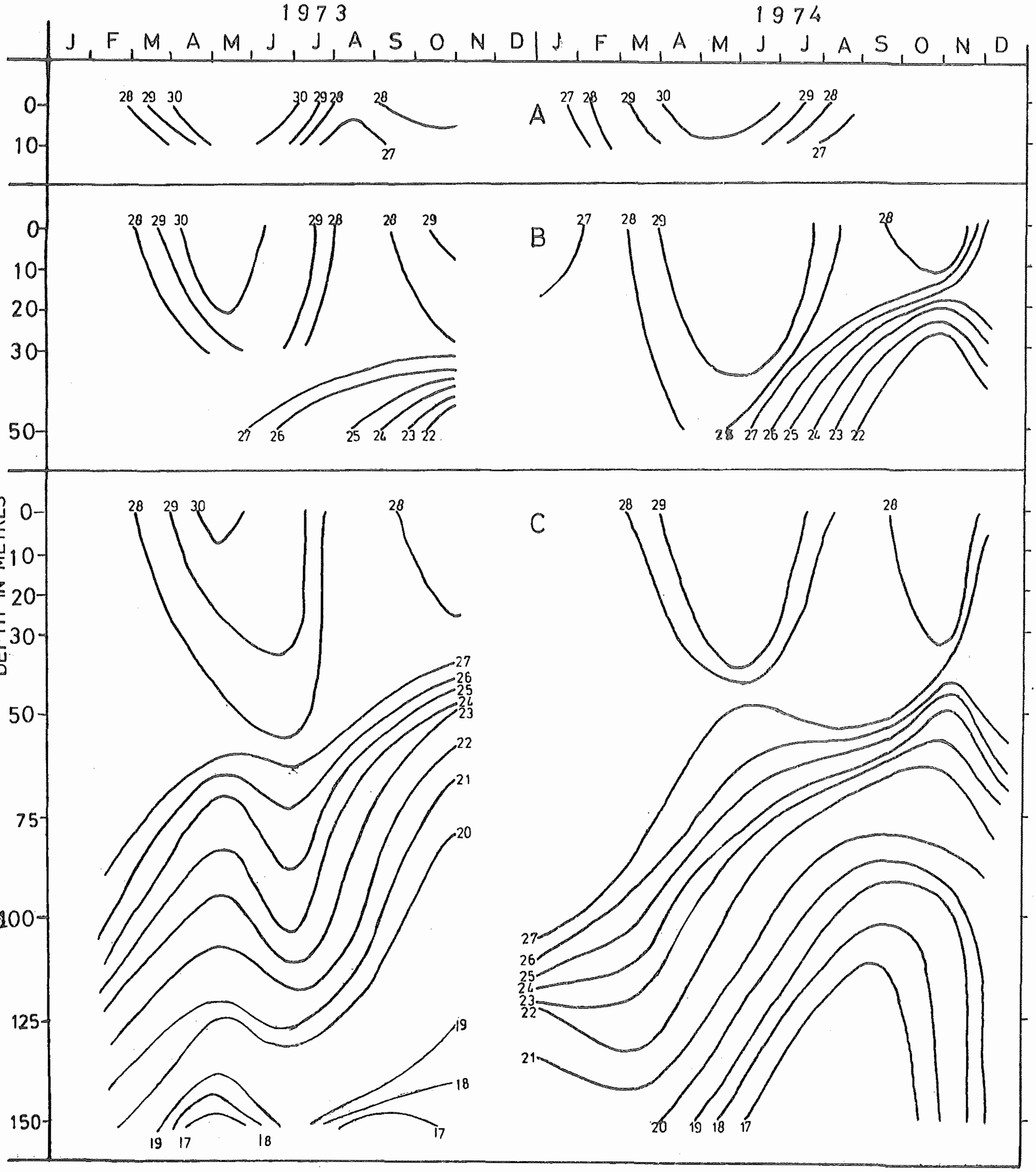

Fig. 7A - Vertical time series section for temperature off Ratnagiri (1973, 1974)

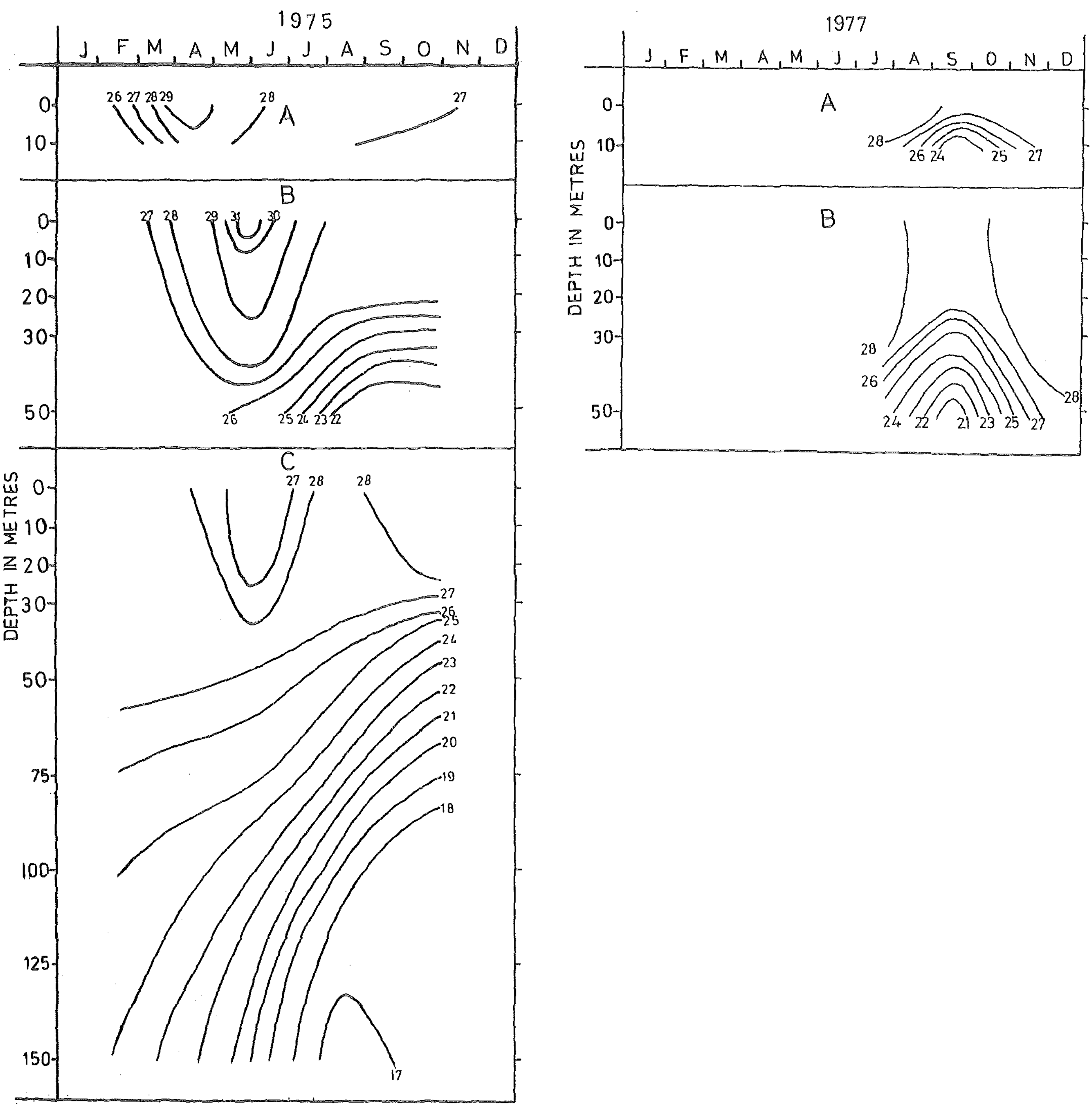

Fig. 7B - Vertical time series section for temperature off Ratnagiri.
(1975 and 1977)

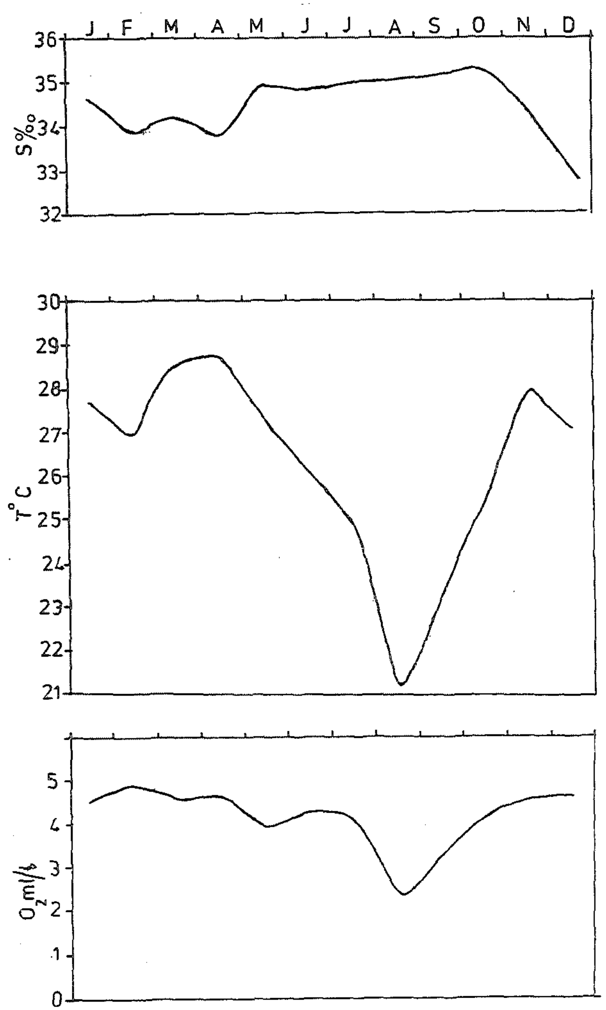

Fig. 8 - Mean sea surface salinity, temperature and dissolved oxygen off Cape Comorin (1972-78)

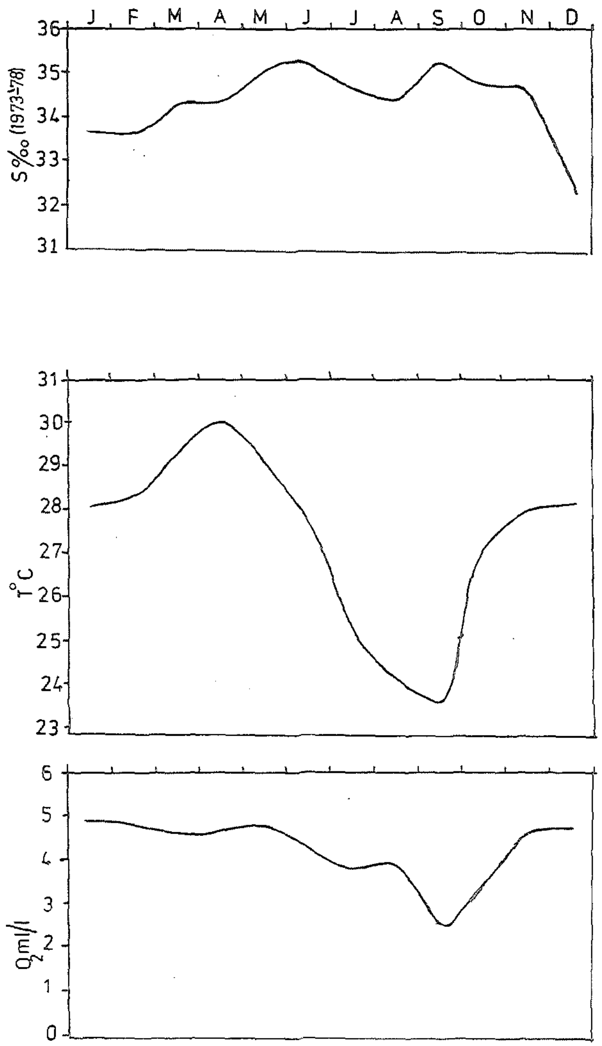

Fig. 9 - Mean sea surface salinity, temperature and dissolved oxygen off Cochin (1972-78)

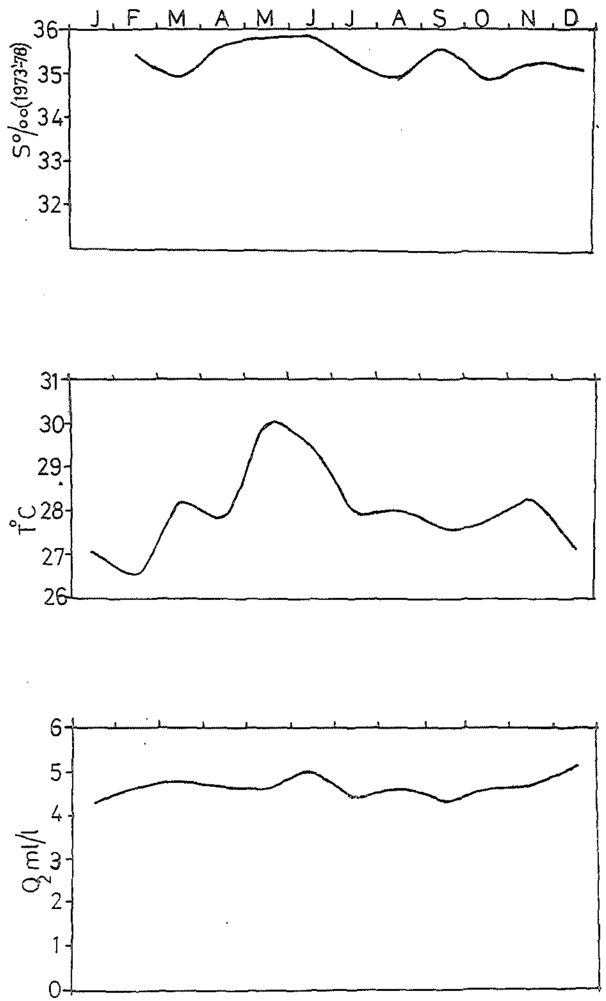

Fig. 10 - Mean sea surface salinity, temperature and dissolved oxygen off Ratnagiri (1972-78)

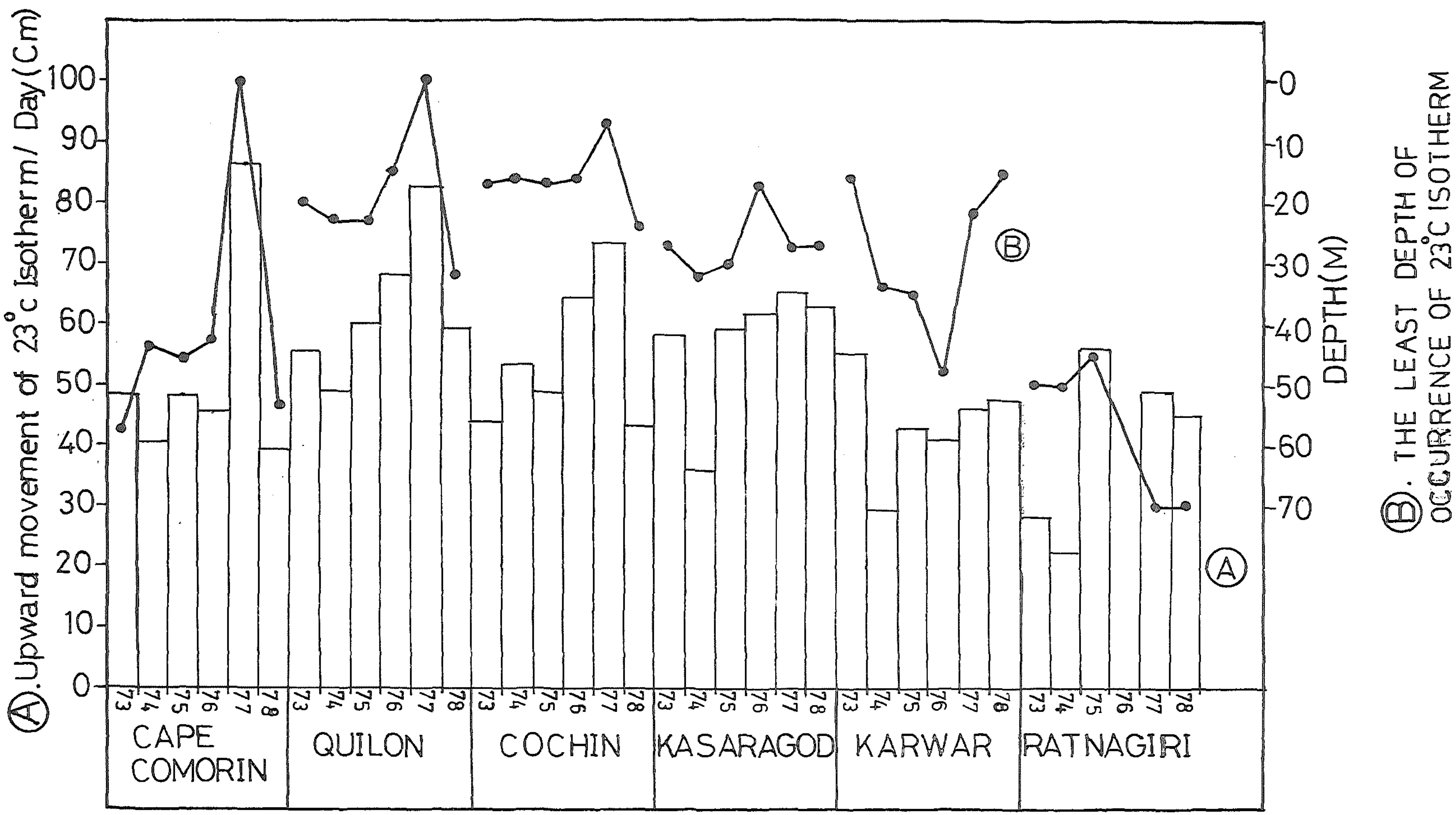

Fig. 11 - Diagrammatic representation of the upward movement of 23°C isotherm sectionwise/ yearwise (A) together with least depth of occurrence of isotherm (B)

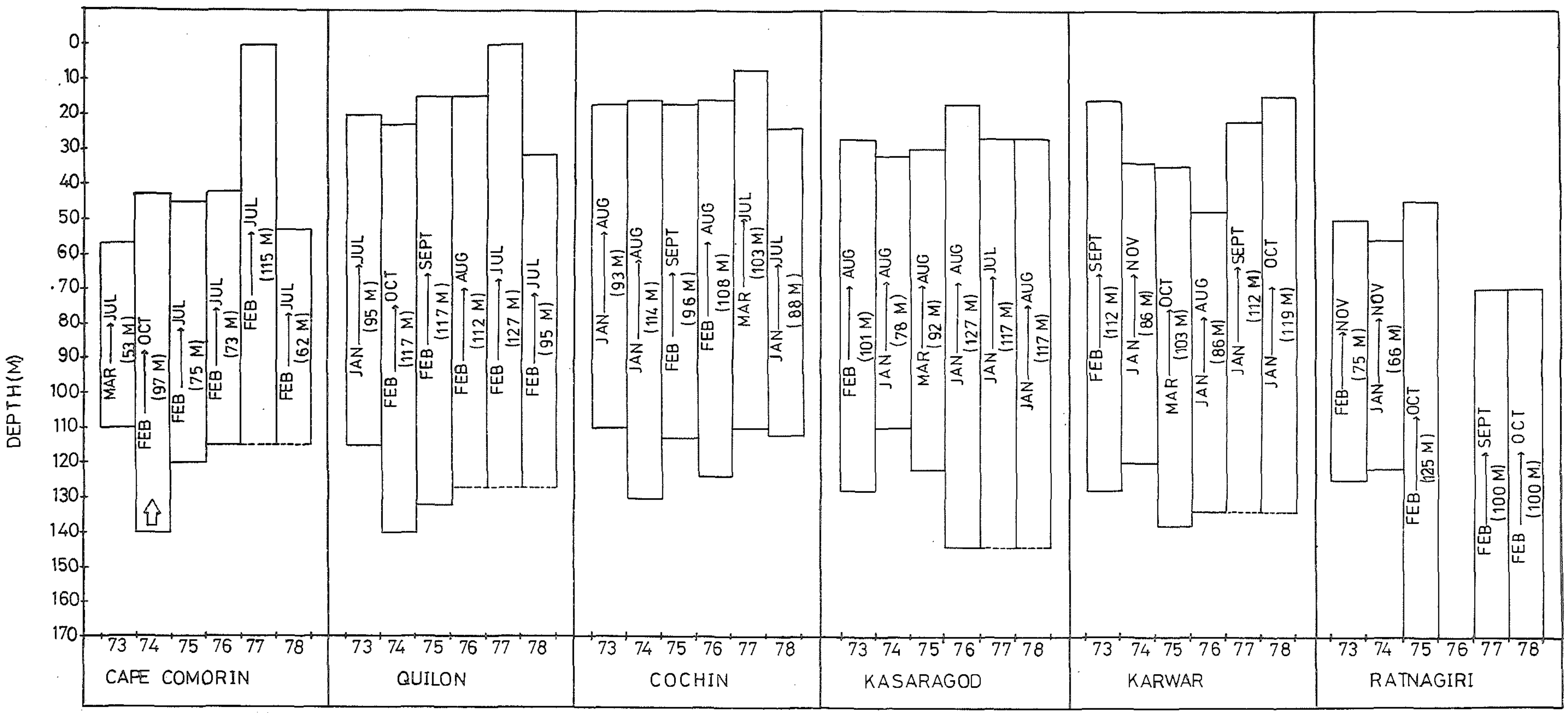

Fig. 12 - Extent and duration of vertical tilting of the 23°C isotherm sectionwise/yearwise (Cape Comorin - Quilon - Cochin - Kasaragod - Karwar - Ratnagiri)

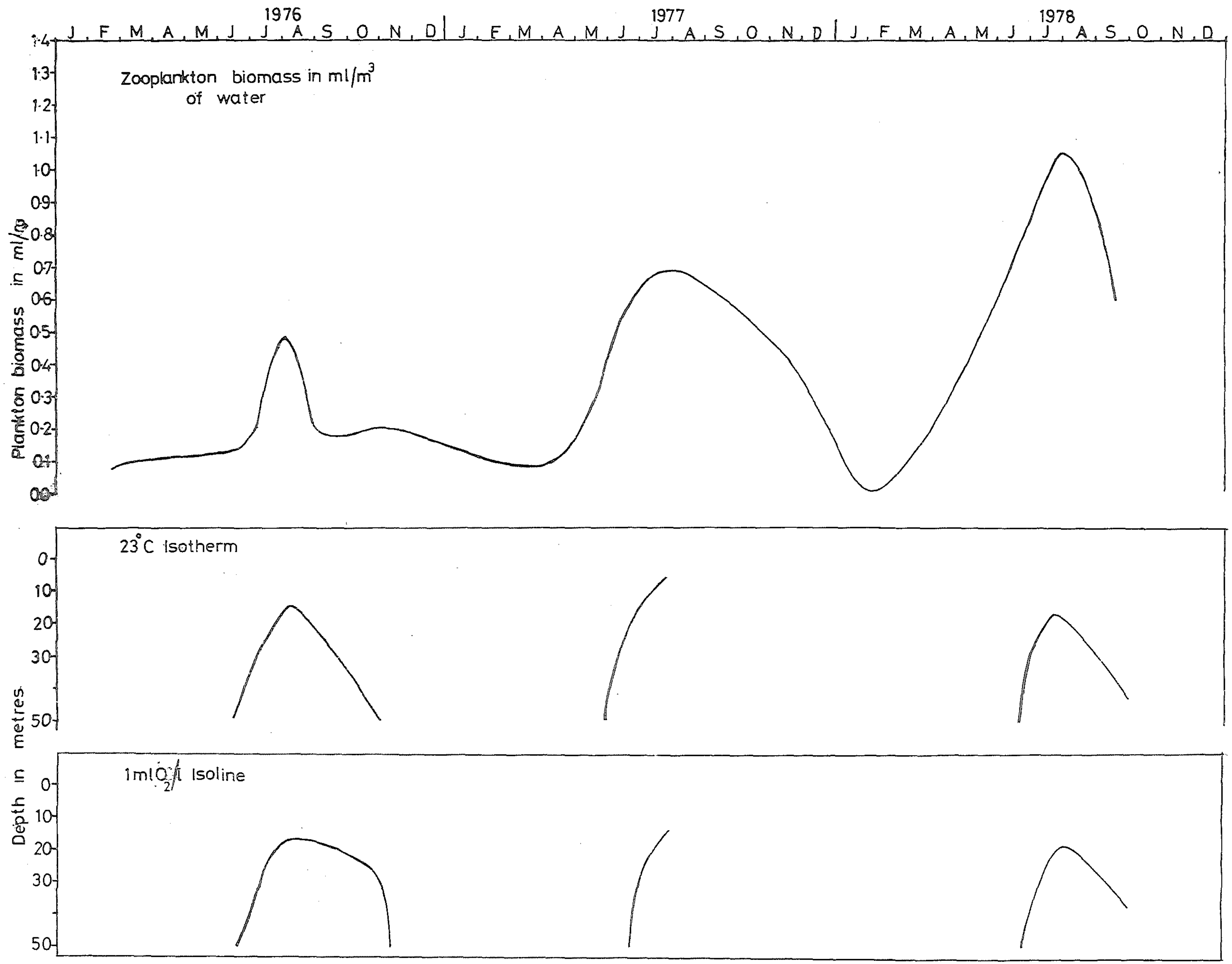

Fig. 13 - Relationship between the process of upwelling (in terms of vertical oscillation of 1 ml/O_2/l isoline and 23oC isotherm) and zooplankton biomass in ml/m^3 off Cochin