FISHERIES ENVIRONMENT IN THE APFIC REGION WITH PARTICULAR EMPHASIS ON THE NORTHERN INDIAN OCEAN

by

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Abstract

The stocks of the small pelagics in the northern Indian Ocean are governed by different environmental factors such as wind pattern, currents, convergence, temperature, salinity, dissolved oxygen and vertical mixing processes. An attempt is made in this paper to correlate these factors with the fisheries for the small pelagics. In the northwest Pacific Ocean, successes or failures of recruitment of pelagic fishes are related to oceanographic factors, especially the direction of Kuroshio current. The information available on these aspects has been briefly reviewed.

INTRODUCTION

The marine ecosystem is a balanced network of biophysicochemical relationships. The limit to the amount of life that a given habitat can support, often referred to as the carrying capacity, is determined by various physicochemical processes, which in turn are determined by the terrestrial, atmospheric and oceanographic processes in operation. The total biomass of all living organisms present in a given area at any one time is referred to as the standing crop. The most important physical and chemical factors that determine the quality and quantity of both the standing crop and the carrying capacity of an ecosystem include temperature, hydrostatic pressure, salinity, density, dissolved oxygen, carbon dioxide, pH and the nutrients such as phosphates, nitrates and silicates. Vertical and horizontal distribution of these properties in the oceans together with the ocean circulation patterns as determined by atmospheric and geographical factors, play a major role in deciding the productivity of the marine ecosystems.

The stocks of small pelagics in the APFIC region are governed by different oceanographic and environmental conditions, which are unique to every area. Some of the major environmental conditions prevailing in the different areas of the APFIC region are given in Table 1.

NORTHERN INDIAN OCEAN

The northern Indian Ocean, which encompasses the northern part of the Western Indian Ocean (Arabian Sea) as well as the northern part of the Eastern Indian Ocean (Bay of Bengal), lies north of the 10°S latitude. The Arabian Sea and the Bay of Bengal are unique in many respects in that they differ drastically from the circulation pattern in similar latitudes in the northern hemisphere of the Atlantic and Pacific Oceans. The northern Indian Ocean, together with its two major bays, the Arabian Sea and the Bay of Bengal, is landlocked in the north by the Asian continent which separates the northern Indian Ocean from the deep-reaching vertical convection areas of the Arctic seas and the cold climate regions of the northern hemisphere. This geographic separation is a major factor, which determines the oceanographic conditions of the northern Indian Ocean.

Wind pattern

The northern Indian Ocean falls within the monsoon gyre, where the predominant wind direction changes gradually from northeasterly to northwesterly and later to westerly during March to May (Anon., 1966). In June, the direction changes to southwesterly and westerly with increasing velocities and by July, the velocity reaches Beaufort 5 to 7. During June to August, the predominant wind direction is from southwesterly to westerly. By the end of August, the wind velocity decreases and by October-November the wind starts blowing from northwesterly to east northeasterly with comparatively low velocities. Both sea and land breeze are common in this area except during the southwest monsoon (along the Indian west coast) and the northeast monsoon season (along the Indian east coast).

Currents

The broad aspects of the circulation pattern in the Arabian Sea and the Bay of Bengal comprise the monsoon current, the equatorial current and the equatorial countercurrent (Varadachari and Sharma, 1967). The monsoon current is westerly during the northeast monsoon period and easterly during the southwest monsoon period. The north equatorial current is westerly and the equatorial current, easterly. The coastal circulation becomes clockwise during the southwest monsoon season (May to October) and counterclockwise during the northeast monsoon season (October to December). In this broad pattern of current, eddies occur within a current system or between two current systems. During the southwest monsoon season, the northeasterly current is practically nonexistent and the equatorial current and the monsoon current dominate the area. In general, the speed of the current is greater in the Bay of Bengal and the Arabian Sea compared to the equatorial regions of the northern Indian Ocean, except off the central part of the east coast of India, particularly in the months of March and April. The stongest currents are generally found off the Somali coast.

During the southwest monsoon, there is a southerly flow along the Indian west coast, spreading over the entire shelf region. During the change from the southwest monsoon to the winter, the northerly current is established off the shelf. Adjacent to and on the seaward side of the northerly flow is present a southerly current limited to the southerly region. From winter to summer (February to April), the northerly current vanishes and the circulation breaks up into eddies. The southerly current persists in summer though it is limited to a narrow belt. Once again during the southwest monsoon period, this narrow southerly current spreads over the entire shelf. In general, the winter current appears to be stronger than the southwest monsoon current along the west coast of India.

During the southwest monsoon period (May to October), the surface current flows southwards along the west coast of India, thereby causing a lifting of the isolines for the different oceanographic parameters (temperature, salinity, dissolved oxygen and density) near the coast. In order to satisfy the basic theory of particle motion in relation to the Coriolis force, denser subsurface waters from the intermediate, subsurface levels are slowly induced upwards (upwelling) along the continental shelf to occupy the left side of the southerly current (near the coast). This ultimately results in the comparatively denser, colder and low oxygenated subsurface waters reaching the surface levels near the coast. During this season, oxygen deficient waters cover the whole continental shelf area over the bottom.

The southerly current transports the comparatively high-saline Arabian Sea waters southwards along the west coast, though during the rainy season the addition of freshwater from rainfall and river runoff causes a significant lowering of the surface salinity near the coast.

During the northeast monsoon period (November to March), the surface current reverses its direction and turns northerly. The northerly current advects low salinity equatorial waters northwards at the surface levels causing a convergence located between latitudes 10°N and 12°N where the high-saline Arabian Sea water sinks below the less-saline equatorial waters. The effects of winter cooling at the surface levels along the convergence zone lead to the process of sinking. During the winter season (January-February), the surface mixed layer covers most of the shelf. For the coastal areas south of Bombay on the northwest coast of India, the resultant speed of the current is reported to be more than 20 km/day during the southwest monsoon period (Banse, 1968). From November to January, a northward flowing current is observed. This drift appears to be shallow and seems to have little influence on the waters below the thermocline (Wyrtki, 1973).

The seasonal reversal of wind causes a corresponding change in the flow of the surface waters in the Bay of Bengal. During the SW monsoon season, there is a clockwise circulation noticed in the central Bay. The northerly flow is close to the central Indian continental shelf where the speed reaches 3 to 5 knots. During the NE monsoon, the surface circulation becomes anticlockwise with lesser speeds.

The currents along the west coast of India have a distinct annual cycle. The current turns equatorward in February, gets stronger with time and is most energetic during July and August. Thereafter it decreases in strength, vanishes and reverses its direction by October-November and flows away from the equator during November to January (Madhupratap *et al.*, 1994). In June, there is a shallow (75 m to 100 m deep) equatorward surface current, below which there are downwelling indications of a poleward undercurrent hugging the continental slope carrying low saline waters in the SW Bay of Bengal (Shetye *et al.*, 1990). Both the currents weaken towards the north upto the 15° latitude and cease to be noticeable at about the 20° latitude. The width of the surface current is about 150 km and the bottom 50 km. The winds during this period vary between WNW near the southern end of the Indian coast to WSW near the northern end. The longshore component of the wind stress is generally equatorward. Therefore, the coastal circulation of the west coast of India during the SW monsoon is dynamically similar to the wind driven eastern boundary currents found elsewhere in the oceans (Shetye *et al.*, 1990). Though this is true during the SW monsoon, the monthly mean longshore component of wind is comparatively very low between February and May (Shetye and Shenoi, 1988). Numerical experiments suggest early remote-forced upwelling in this area resulting from Kelvin waves originating in the Bay of Bengal (McCreary *et al.*, 1993).

During the NE monsoon, there is a poleward surface coastal current along the west coast of India, along a stretch which is 400 km wide near the southern end and approximately 200 m deep, carrying low saline equatorial surface water. This current is driven by a longshore pressure gradient which overwhelms the influence of the winds during the season (Shetye *et. al.*, 1991). Part of the driving force for these currents also comes from the Kelvin waves triggered by the collapse of the winds along the east coast of India as the SW monsoon withdraws and the NE monsoon sets in.

Convergence zone

The existence of convergence zone in the SE and NE Arabian Sea is evident from the horizontal salinity gradients observed during the period from January to March (Figs. 1 to 3). In 1973, salinity gradients indicated a zone of convergence between the Calicut section in the south and the Kasaragod section in the north, a distance of 150 km (Pillai, 1982; Fig. 1). In 1974, the sea surface salinity increased from 33 ppt to 35 ppt from the Karwar section in the south to the Ratnagiri section in the north, suggesting the existence of a convergence zone over a distance of 220 km. This salinity difference was less pronounced in 1975.

The variations in the sea surface salinity suggest that the convergence zone exhibits seasonal variations, spreading northwards with the intensity of the northward flow, which carries equatorial waters towards the northern latitudes (Darbyshire, 1967). During the southwest monsoon season, the salinity distribution at the surface level is not indicative of the convergence zone, mainly due to the effect of rainfall and river runoff.

Temperature

The monthly mean sea surface temperature in the southeastern and the central eastern Arabian Sea (1973 to 1978) shows large variations in space and time (Table 2; Pillai, 1982). In general, the sea surface temperature is comparatively low during January and February and from July to October (the lowest of 21.1°C in August off Cape Comorin in the southern tip of India) while it is relatively high along the different sections during May (the maximum of 30.2° C off Karwar on the middle of the southwest coast of India). The high values are associated with the summer season, just prior to the onset of the southwest monsoon. A steady increase in the highest monthly mean temperature (1973 to 1978) from the south to the north is noticed between Cape Comorin and Karwar (28.7°C to 30.2°C). The low values are noticed during January and February and during the peak upwelling season (July to October). The lowest values are observed in those areas where the intensity of upwelling is comparatively high (between Cape Comorin and Kasaragod).

The mean depth of the top of the thermocline reveals large variations from season to season (Table 3; Pillai, 1982). The top of the thermocline is the deepest during the period from December to February and the top reaches the surface layers during June to September (south of Cochin on the southwest coast of India) and October-November (north of Cochin). Off Tuticorin in the Gulf of Mannar on the southeast coast (immediately contiguous to the southwest coast), the vertical oscillation of the top of thermocline ranges from 32 m (June to September) to 78 m (December to February).

Off the southwest coast of Africa, the thermocline, in general, is shallow during the summer, deep during the spring and deepest during the winter (Duncun, 1964). The vertical time sections of seawater temperature for the sections representing the southwest tip of India (Cape Comorin and Quilon; Fig. 4), the central southwest coast of India (Cochin and Kasaragod; Fig. 5) and the northern southwest coast of India (Karwar and Ratnagiri; Fig. 6) clearly bring out the variations in the vertical movement of the various isotherms in space and time. The net vertical movement has been estimated from the oscillations of the 23°C isotherm, which exhibits the maximum movement on the vertical plane (Table 4). A comparison of the mean upward movement of the isotherm (1973 to 1978) indicates the maximum (110 m) off Quilon and minimum (79 m) off Cape Comorin. In certain years (e.g., 1977 July), the isotherm reaches the very surface off Quilon as well as Cape Comorin (Pillai, 1982; Figs 4 to 11)).

Salinity

The monthly mean sea surface salinity (1973 to 1978) in the southeastern and the central eastern Arabian Sea indicates two peaks, one during May-June before the onset of the southwest monsoon and another during September-October immediately after the southwest monsoon (Table 5; Pillai, 1982). The lowest values are associated with the monsoon rains and river run-off, which show a lot of variations from one area to another in different years. The monthly mean surface salinity varies from 32.5 ppt to 36.1 ppt. The salinity maximum characteristic of the tropical oceans is found at depths of 100 m to 150 m during the northeast monsoon and 30 m to 50 m during the southwest monsoon. The variations in salinity are characteristic of the surface layers above the salinity maximum layer. The surface salinity is the highest at the Karwar and Ratnagiri sections during May/June (35.6 ppt to 36.1 ppt). Comparatively low saline waters (33.0 ppt) occupy the surface at Cape Comorin in December when the equatorial surface waters advect northwards (Figs 1 to 3). The lowering of salinity during December and January in the Palk Bay and the Gulf of Mannar is attributed to the southerly current along the east coast of India. During these months, the surface salinity increases steadily from 33.0 ppt off Cape Comorin to 35.1 ppt off Karwar and Ratnagiri. The maxima, occurring comparatively late in the southern sections, are associated mainly with the advection of the high saline Arabian Sea water in the southerly flow and the presence of high salinity bottom water brought upward to the surface layer in the areas where upwelling is active. The minima occur first in the southern region and progressively move northwards following the trends in the monsoon rainfall and the development of the northerly flow (Pillai, 1982).

In general, the sections north of Kasaragod exhibit comparatively higher salinity conditions than the southern sections. At greater depths between 100 m and 500 m, there is a decreasing trend in the salinity values, north to south. In the sections off Quilon and Cape Comorin, this feature is observed as a salinity maximum at the depth of the thermocline. Here, the northern Arabian Sea corresponds to the subtropical zone of high salinity. The salinity maximum at the depth of the thermocline represents an intrusion of high saline water from the subtropical high salinity zone towards the equatorial zone below the less saline surface layer. It is quite likely that the comparatively high saline north Arabian Sea waters are spreading southwards slowly losing their high saline characteristics. This is in agreement with the general circulation in the upper layers in the tropical and subtropical waters. The salinity maximum associated with the main thermocline probably represents an intrusion of high saline waters below the less saline surface layers towards the equator.

Dissolved oxygen

The major disadvantage of the landlocked condition of the northern Indian Ocean and its separation from the cold climate regions is that the subsurface watermasses of the two northern bays could not be replenished with the oxygen rich deep circulation originating from the Arctic Seas, unlike in the Pacific and the Atlantic Oceans. Instead, the oxygen deficient high salinity surface waters of the Red Sea and the Persian Gulf sinking to the bottom, enter the northern Arabian Sea in the winter at a depth of 800 m and 300 m through the Gulf of Aden and the Gulf of Oman, respectively. These two watermasses together with the high salinity subsurface watermasses of the Arabian Sea that have sunk to about the upper level of the thermocline around 100 m at a temperature gradient of 22° to 26°C consequent upon intense summer evaporation, constitute what is termed the North Indian High Salinity Oxygen Minimum Intermediate Water (NIHSOMIW). With an almost uniform salinity vertically, the NIHSOMIW occupies a depth range of about 100 m to 300 m from the surface to about 1200 m in the entire monsoon gyre down to 10°S latitude.

Explorations by ORV *Sagar Kanya* along the west of 60°E meridian between the 4°N and 6°S latitudes indicated considerable difference in the dissolved oxygen content in the upper 200 m. Warm and nutrient rich water with low oxygen occurs along the 60°E meridian in contrast to the cool and relatively nutrient deficient water with high oxygen to the west of it; in addition, warm waters with high nutrients and low DO occur in the north and relatively cold water with low nutrients and high DO occur in the south. The Arabian Sea component of the NIHSOMIW (with subsurface salinity maximum in the upper thermocline) first turns south and then east with the SW monsoon surface current, penetrating the region south of Sri Lanka and flowing eastwards across the entire width of the ocean, ultimately spreading through the entire monsoon gyre north of 10°S. The Red Sea and the

Persian Gulf components of the NIHSOMIW, spreading east with the SW monsoon surface current, fill the entire Bay of Bengal including the region west of Sumatra below a depth of 300 m (Wyrtki, 1973). The northern Indian Ocean has been recognised as the largest region with the lowest oxygen concentration in the entire open world oceans (Dietrich, 1973).

It is remarkable that the lower and the upper depth limits of the shallow water and deep water fish concentrations are outside the depth ranges (300 m to 1200 m) of the oxygen minimum layers in the Gulf of Oman and off the Somali coast. Both these areas are located within or very close to the major upwelling zones, where, however, the pelagic fishery stocks are far less than the expected levels for the levels of primary production taking place there. Most of the primary production is lost to the bottom in the form of dead organic matter, which through particulate feeders, support the substantial deepsea mesopelagic fishery resources.

The dissolved oxygen content of the surface layers of the SE and central eastern Arabian Sea shows large variations in space and time (Pillai, 1994). In most of the sections, a good correlation exists between the thermocline top and the oxycline. By May, the oxygen deficient waters begin to penetrate the shelf slowly. The upward tilting of the isolines of oxygen and the relative position of the oxycline are indicated in the vertical time sections for the southern region (Quilon; Fig. 12) and the central/northern region (Karwar; Fig. 13) of the southwest coast of India. By June-July, the oxygen deficient waters penetrate below the thermocline and cover the entire bottom of the shelf. In August, the oxycline becomes very shallow and in the areas of upwelling the low oxygen intermediate water reaches the very surface. The oxygen deficient water remains on the shelf until October, especially in the areas where upwelling is intense. By December, once again, the shelf waters become well aerated. The mean monthly sea surface values (1972 to 1978) range from 5.35 ml 0_2 to 1.10 ml 0_2 per liter (Table 6). Off the shelf, there is a well developed oxycline which is found approximately at the same depth as the thermocline. Below the oxycline, in general, the oxygen concentrations are higher in the southern sections than in the northern sections. Off Ratnagiri, the oxygen depleted intermediate waters reach the surface levels. In general, the concentration of dissolved oxygen at the surface levels during the upwelling season increases towards the northern sections corresponding to the decrease in the intensity of upwelling beyond Karwar. The period when the oxygen deficient waters remain in the continental shelf is longer in the northern region off Karwar than in the southern region. Off Karwar, the period is nearly 6 months compared to nearly 2 months off Quilon.

Vertical mixing processes: upwelling, sinking and their impacts on the Malabar upwelling system (southwest coast of India)

Upwellings are of great significance to biological productivity because of the high fertility they cause in the euphotic zone. Coastal upwellings occur mostly along the western coasts of the continents as exemplified by the coasts of Peru, California, northwest and southwest Africa, west coast of India etc. Exceptions to this pattern are found along the northeastern African coast, Somali coast, east coast of Arabia, east coast of India etc. Localised upwellings are found around the areas of divergences. Whereever upwelling is influenced by the monsoon wind system and accompanying currents, the phenomenon is more seasonal. In the coastal upwelling areas, sediments rich in organic matter are found. Attempts have also been made to chart the upwelling areas by mapping phosphatic deposits (Dragesund, 1970). The economic benefits of upwelling are mainly due to the large concentrations of commercially important fishes in these areas. Most of these resources consist of clupeoid fishes with short food chains and their predators like the tunas.

The best example of a highly productive upwelling area is the coast of Peru with its huge catches of anchovies. Other important productive upwelling areas are the southwest African coast with its rich fisheries for the pilchard and the Californian coast with its sardines. The major pelagic fishery resources of India like the Indian oil sardine, the Indian mackerel and the whitebaits inhabit the SW and SE coasts where regular seasonal upwelling is prevalent. It is estimated that the upwelling areas of the world constitute only a little over 0.1% of the ocean surface, but contribute about half of the world's fish supply.

Upwelling occurs in varying intensities along the west and east coasts of India, corresponding with the SW monsoon. The onset of the SW monsoon generates the Somali current, resulting in a general clockwise circulation in the Arabian Sea, which in turn develops into a relatively strong southerly current along the west coast of India. The comparatively cold, low-oxygenated and denser water from the subsurface is slowly brought upwards along the continental shelf, very near the coast. The depth at which the upward sloping motion of the subsurface watermass begins is dependent on the velocity, direction and duration of the prevailing wind system in a specific area, the bottom topography, the prevailing current system at the surface and the vertical stability of the water column. The speed of the ascending motion would also depend on the continuance of the favourable factors with more or less the same intensity. Along the west coast, upwelling sets earlier in the south and progressively shifts to the north. The process commences in the deeper waters as early as February and the effect reaches the coastal surface waters by May (Banse, 1968; Sharma, 1968) to July and continues through August to early September in the south and October in the north. The strong southerly flow with the coast on the left side induces the upward motion of the subsurface water near the coast. The winds, blowing with the northerly component parallel to the coast till April, help the process to intensify. The thermocline climbs up during the upwelling season and reaches the surface in June or July. There is no system of wind generated upwelling during the SW monsoon period along the west coast of India, where the dense bottom waters approach the surface because of the immediate interplay of the current with the tilting of the sea surface and thermocline (Darbyshire, 1967). Upwelling occurring around the Lakshadweep islands during November/December is attributed to the divergence of current systems in the vicinity of the islands (Rao and Jayaraman, 1966; Pillai and Perumal, 1975). Off Cochin, upwelling starts by mid August, establishes by late September and ends by mid October (Ramamirtham and Jayaraman, 1960). However, none of these processes may be directly applicable to the SW coast of India as a whole (Pillai, 1982).

Along the east coast of India, prior to the commencement of the SW monsoon (April), the southerly winds blow parallel to the coast. The coastal currents, flowing northerly throughout the coast are favourable to the development of upwelling along the east coast. In the northern hemisphere, a wind blowing parallel to the sea coast with the coastline to its left, or an offshore wind, will favour the process of upwelling. The prevailing current system and not the wind is regarded as the main cause generating and maintaining upwelling (Banse, 1968). Even if a uniform current velocity is considered all along the coast, the rise of dense, deep water will be stronger in the north farther away from the equator.

The peak in the zooplankton biomass normally follows the peak periods of upwelling along the SW coast of India (Fig. 14 to 19). The time lag is dependent on the incoming radiation and the inorganic nutrients in the upwelled waters to promote phytoplankton production. The time lag increases when the monsoon rains continue with a cloudy sky, thereby reducing the incoming solar radiation, while the nutrient content would depend on the depth from which the upwelled water originates and the time taken by the watermass to reach the surface. This interval varies from year to year and also from place to place (Pillai, 1982). The zooplankton biomass in the Cochin section is at its maximum during July-August and minimum during November and March (1976 to 1978). It is comparatively high in the areas of intense upwelling, as for example, in the sector between Kasaragod and Karwar. That the biomass in this sector during July-August, 1978 was two times higher than that during July-August, 1977, suggests considerable annual variations. In the Quilon and Cape Comorin sections however, the plankton biomass does not indicate a proportionate increase with the high intensity of upwelling during 1977 (Figs 14 & 15). The sea bottom of the narrow continental shelf between Quilon and Cape Comorin is mostly rocky, in contrast to the region north of Quilon where it is mostly muddy. During upwelling, the oxygen minimum layer (0.5 ml/l) emerges from 100 m to 150 m depth to the surface, especially in the areas between Quilon and Kasaragod. As a result, some fish populations move into the shallow surface waters while the others move offshore, away from the centre of strong upwelling. At times, the rate of upwelling suddenly intensifies, slowing down the replenishment of oxygen through surface aeration and wind mixing. Bulk of the pelagic populations comprising the Indian mackerel, oil sardine and whitebaits avoid temporarily the areas of intense upwelling and tend to concentrate into dense schools close to the surface and the coast in the nearshore grounds, affording good catches.

Sinking is characterised by the downward movement of comparatively denser surface layer. Winter cooling and surface evaporation increase the density of the surface layers, thereby promoting sinking. Converging current systems also facilitate sinking, provided there is appreciable difference in the density characteristics of the two current systems. Sinking brings the well aerated surface waters to the bottom, as a result of which, the pelagic fish populations disperse over a vast area of the shelf. Along the SW coast of India, sinking of the offshore waters (coastal convergence) occurs over the shelf from September to January and a well defined isothermal layer of about 75 m to 100 m thickness is present along the west coast (Ramamirtham and Jayaraman, 1960; Sharma, 1966; Pillai, 1982). Sinking is active along the entire SW coast between Cape Comorin and Ratnagiri between September and February, starting much earlier in the south from Cape Comorin to Quilon; it begins during September along the Cochin to Kasaragod sector and October or November further north from Karwar to Ratnagiri; comes to an end earlier (January) in the south and later in the north (March) of the SW coast. Sinking is closely associated with the cessation of upwelling, and more or less follows the same trend from south to north along the SW coast. The vertical oscillation of the 23°C isotherm which shows the maximum movement on the vertical plane is taken as an indicator of the process of sinking. An approximate estimation of the velocity of sinking at the various sections (1974) indicates that the velocities range from 79 cm to 139.5 cm/day. The maximum velocity of 139.5 cm/day is observed off Kasaragod and the minimum of 79 cm/day off Ratnagiri. As in the case of upwelling, the sinking velocities also show large variations from year to year and also from one area to another (Table 7; Fig.20; Pillai, 1982).

The period of peak sinking activity along the SW coast (October to March) coincides with the peak fishing season for the oil sardine and mackerel fisheries. The warming of the upwelled cooler surface layer by the northerly warm equatorial current provides the conditions necessary for the small pelagic fisheries during peak sinking (October to February). In December, the surface isothermal layer resulting from sinking (convergence) in the shelf is about 75 m to 100 m thick along the west coast of India (Ramamirtham and Jayaraman, 1960). Convergence facilitates the concentration of zooplankton, which in turn results in the formation of dense schools of the small pelagics such as the oil sardine, mackerel and whitebaits which feed predominantly on the zooplankton (Hela and Laevastu, 1970; Noble, 1972). The northerly migration of the whitebaits starts from the central Gulf of Mannar by early November. The dissolved oxygen concentration is comparatively high in the northerly current of the postmonsoon season (October-November) along the SW coast. The gradual rise in the sea surface temperature coupled with higher DO concentration during this season enriches zooplankton production, followed by proportionately high whitebait biomass. By December, the whitebaits spread almost all along the SW coast between Tuticorin in the Gulf of Mannar and Ratnagiri on the northern tip of the SW coast (Arabian Sea). During the southward and northward migrations of the whitebaits, the respective surface currents prevailing during these migrations favour the passive transport (floating and drifting). The rich phytoplankton and zooplankton biomass during the sinking season provides them the required food. The catches of the oil sardine and mackerel are maximum during sinking in the winter season when the northerly drift prevails along the SW coast.

Along the west coast of India, the phytoplankton bloom is rich during the SW monsoon off the Trivandrum coast from January onwards and reaches the peak in May, but further north, off Calicut and northwards, the peak is attained in July-August, thereby indicating the commencement of upwelling in the subsurface layer much earlier, even when the current is northerly along the west coast; from September onwards, the phytoplankton bloom vanishes, indicating the cessation of upwelling from thereon (Subramonyan, 1973).

The average primary productivity of the west coast of India, within the surface and 50 m depth in terms of carbon production beneath a square meter of the sea surface is 1.19 $gC/m^2/day$ (Nair *et al.*, 1973; Table 8). This is equivalent to an annual gross production of 434 $gC/m^2/year$ which is quite high compared to several other areas of the world (Table 9). The productivity is higher along the coast than along the edge of the shelf and the least outside the shelf. In the shelf area beyond the 50 m isobath, the mean primary production is only 0.43 $gC/m^2/day$, which indicates an annual net production of only 25 $gC/m^2/year$. Based on these values, it was estimated that 1 200 000 mt of fish could be harvested from the area within the 50 m isobath of the west coast (Nair *et al.*, 1973). This figure is about the same as the present annual yield of 1.2 million mt from the west coast. The primary production in the different states and depth zones of the southeastern Arabian Sea area (Nair *et al.*, 1973) is furnished in Table 10.

In the main upwelling area of the west coast, between Kasaragod and Quilon, the peak of zooplankton occurs in July-August with another peak from October to December. The latter period is also the peak for the northern region between Karwar and Ratnagiri. In the Gulf of Mannar, the highest zooplankton production occurs in July and again in November-December. There is good correlation between upwelling (evident from the upward movement of the 23°C isotherm and the 1 ml/l O_2 isoline) and zooplankton biomass at Cape Comorin (1973 to 1975), Quilon (1973 to 1975), Cochin (1973 to 1978), Kasaragod (1973-1975), Karwar (1973 to 1975) and Ratnagiri (1973 to 1975) (Figs 14 to 19; Pillai, 1982). The ichthyoplankton is abundant between May and September, with peak in July to September, moderate abundance in October and November and low adundance during December to April. The sardine larvae are found all year round, but mostly between June and August. The main spawning ground is located between the 8° and 10° 30'N latitudes in the middle and outer shelf in a 10 to 15 nautical miles band, 20 nautical miles offshore (40 m to 80 m). Moderate spawning activity of sardines takes place south of Quilon on the southwest coast and the southeast coast off Tuticorin in the Gulf of Mannar. The Indian mackerel seem to have an extended spawning season than the oil sardine. High density of mackerel larvae is found in April, July, August and November, but neither eggs nor larvae are found in January, March and December. The main spawning ground is believed to be between 8° and 15°N latitudes in a 10 nautical miles belt (mostly between 55 m and 100 m depths), with most of the larvae occurring off Cochin and Karwar. The major part of the whitebait ichthyoplankton is found between April and August in the surface waters above the depth of 20 m to 60 m. Peak spawning occurs in the central area between Quilon and Kasaragod (7° 30' to 11°N) during May to July and in the south between Quilon and Cape Comorin during October-November.

The average zooplankton biomass in the midshelf for the southeastern Arabian Sea (Table 11 for 1971 to 1978) and the abundance of zooplankton along the southwest coast during the monsoon period (for 1971 to 1975) indicate a recurring pattern in the zooplankton distribution and abundance in the shelf waters. In general, the period from July to September is found to be the peak season for plankton production, with a fairly uniform concentration of plankton beyond the nearshore waters all along the coast. Thereafter until December, a shoreward shift in the concentration is evident, especially in the south. At the same time, the continuous distribution breaks up, becomes patchy and the overall abundance is greatly reduced to the lowest level in January and February. The biological cycle is clearly influenced by the process of upwelling especially in the central and southern region (Figs. 21 to 23). Studies made onboard FORV *Sagar Sampada* during the period 1984 to 1994 also confirm the above findings.

There have been attempts in the past to correlate the oil sardine and mackerel fisheries with rainfall. Normally, bulk of the oil sardine catch is landed following the period of heavy rainfall during the SW monsoon season. However, the oil sardine catch at Ullal near Mangalore in the SW coast was found to be the lowest (52 mt) during 1963-64 when rainfall was the heaviest (306.5 cm). The catches were better during 1965-66 and 1966-67 (283.7 mt and 385.6 mt, respectively) when the annual rainfall was comparatively low (274.1 cm and 283.6 cm, respectively). An inverse relation exists between the annual rainfall and the mackerel catches off Calicut on the SW coast (Pradhan and Reddy, 1962). High temperature and salinity affect the mackerel fishery adversely. The mackerel season in the north Kanara district on the SW coast coincides with the transition from the low salinity and temperature conditions of the SW monsoon to the high salinity and warmer conditions of the summer (Ramamurthy, 1965).

Sea level can be an indicator of upwelling (Longhurst and Wooster, 1990). The variations in the oil sardine abundance relate well with sea level, which is a good index of upwelling at Cochin while the monsoon rainfall is a good indicator of recruitment success. The invasion of the continental shelf by the oceanic oxygen poor waters during the Malabar upwelling tends to exclude the oil sardine stock from the coastal waters where the plankton blooms are most intense. Therefore, unlike that of the Indian mackerel, the spawning strategy of the Indian oil sardine places its recruitment at risk as evident from the statistical relationship between sardine recruitment failure and unusually early, remotely forced upwelling. The abundance of the oil sardine along the Malabar coast (Indian SW coast) is highly variable in the decadal scale. The 0-year group recruitment into the fishery begins towards the end of the summer monsoon (SW monsoon) when the sea level indicates remotely forced upwelling (caused by the geostrophic upsloping of the isopleths towards the coast) rather than the wind driven upwelling that occurs during the monsoon. Unusually early remote forcing appears to inhibit subsequent recruitment, perhaps through the exclusion of the spawning fish from the neritic zone by the oxygen deficient upwelled water (Longhurst and Wooster, 1990). The oil sardine and the Indian mackerel synchronise their spawning with the productive conditions of the SW monsoon seasons (Madhupratap *et al.*, 1994). Sea level anomaly shows that the levels have been low during 1940 to 1947, high during 1948 to 1957, higher during 1958 to 1964 and fluctuating thereafter. By comparison, the sardine catches have been found to be poor during 1941 to 1949 (<5 000 mt per year), moderate during 1950 to 1956 and high from 1957 onwards. Between 1900 and 1940, the oil sardine catches have been generally low, whereas the Indian mackerel fishery has had very poor seasons. There was no correlation between the sea level and the oil sardine or Indian mackerel landings during 1960 to 1990. In 1963, for example, when the oil sardine catches fell below 100 000 mt, the sea level in April, 1962-63 was not low. The very low oil sardine landings in the 1940s and the earlier years seem to have been caused by a combination of factors while the increase in the recent years could be due to mechanised fishing and the use of synthetic gear material. The argument that the late arrival of the SW monsoon causes low oil sardine catches does not appear tenable. Years with very less rainfall in the recent past (1965, 1966, 1972, 1979, 1982, 1985, 1987) also did not particularly affect the oil sardine fishery (Madhupratap *et al.*, 1994). The presence of a correlation does not imply cause and effect. The correlation holds good for a few years and then breaks down.

Three factors seem to dominate the processes controlling the oil sardine and other major fisheries in the SW coast of India (Madhupratap *et al.*, 1994):

(i) Wind driven upwelling, which is an annual feature, brings up not only the nutrients to the euphotic zone triggering the production of plankton, it also upslopes the cool low oxygen layer towards the surface and coast, forcing the fish stocks into the thin oxygen rich surface layer close to the SW coast.

(ii) Early remote forced upwelling during February to May (much before the wind-induced upwelling) is caused by the effect of the Coriolis force on the Gulf of Aden-Gulf of Oman surface watermass of low oxygen. This watermass sinks and pervades throughout the northern Indian Ocean, north of 10°S latitude. The emergence of this watermass towards the sea surface causes the early appearance of the stocks in the surface layer, and any interannual variability pattern in the upwelling will reflect in the movement and abundance of the stocks.

(iii) River runoff contributes, through the enrichment of the coastal waters and the microbial loop, to the development of high zooplankton populations.

Once the monsoon and upwelling progress northward during June to September, the stocks of larvae and juveniles benefit significantly from the rich plankton, and hence, any mismatch between the time of spawning and the peak plankton production (through a break in the monsoon and upwelling) could be detrimental to recruitment. Studies undertaken onboard FORV *Sagar Sampada* during the peak of the SW monsoon in July, 1991 and July, 1992 confirm that upwelling can be positive or negative depending on the nutrient level, which determines the magnitude of plankton productivity (Pillai, 1994). The plankton blooms occur after a certain duration from the time of upwelling away from the areas occupied by the upwelled water due to the following factors (Pillai, 1994):

(a) Quantum of inorganic nutrients in the upwelled water: Nutrients, especially phosphates, determine chlorophyll production, and hence, even in areas with cloud-free skies, upwelling may not result in a high enough phytoplankton production without adequate quantity of nutrients. Nutrients in the upwelled water depend on the origin and velocity of upwelling, i.e., the time taken by the upwelled water to reach the surface layer from the depths it originates as evident from the observations made for Quilon and Cape Comorin sections (in 1977) where inspite of higher upwelling velocities, the zooplankton biomass does not indicate a proportionate increase during the months following peak upwelling, due to the shallow shelf of mostly rocks. This is in sharp contrast to the conditions in the Cochin and Kasaragod sections which indicate proportionate increase in the zooplankton biomass, following the peak upwelling season, due to the deeper and muddy shelf (Figs 14 to 19). Cochin shelf does not reveal a monsoon maximum for chlorophyll-a in certain seasons due to the late onset or scanty monsoon and exhibits positive correlation of phosphates with chlrophyll-a as seen in 1987 and 1988 (Balachandran *et al.*,1989).

(b) Incoming radiation: Since upwelling along the SW coast of India synchronises with the cloudy SW monsoon, sufficient light does not reach the sea surface to promote photosynthetic activity.

(c) Velocity of surface currents: Very often higher zooplankton biomass is observed away from the point where the upwelled water reaches the surface layer, and the biomass varies from year to year as the upwelled water is carried away by the wind induced surface currents, which show minor changes in their velocity directions, both in space and time (Pillai, 1994).

The wind driven offshore transport off Cape Comorin at the southern extremity of India reveals that the strong westerly monsoon winds are tangential to the land mass and drive a very strong offshore Ekmann transport. This strong upwelling signal would tend to propagate northwards along the Indian coast through the coastally trapped wave mechanism. In such a case, while seeking an index of inter-annual variability in upwelling in this area, one should perhaps look at the coastal upwelling index off Cape Comorin (Bakun, 1993). The seasonal upwelling effects along the southwest coast of India are a propagated response to the wind driven offshore Ekmann transport occurring some distance to the south off Cape Comorin. In such a case, fish are benefitting from an upwelling cycle that peaks in June. This propagating upwelling signal continues to be substantial from July through October (Bakun, 1993). This also happens to be the period of the year when spawning activity of the Indian oil sardine is most prevalent (Longhurst and Wooster, 1990).

The turbulent mixing index near Cape Comorin, where this upwelling would have its wind generated origin, is substantial during most of this period. By the time the Somali current reaches the southwest coast of India, the flow is much less intense and has developed a more diffuse, meandering tendency (Wyrtki, 1971) characteristic of the eastern ocean coastal upwelling systems. Thus, the Indian oil sardine which support the Western Indian Ocean's one of the largest pelagic fisheries, spawn in relatively mild offshore transport and wind driven turbulence regimes of a tropical coastal upwelling system. Such spawning during the upwelling seasons is a recurrent pattern noted in other eastern ocean, low latitude pelagic fish stocks (Roy *et al.,* 1992).

Upwellings in other regions of Indian Ocean

(i) *Somali coastal upwelling*: This appears by far the most intense seasonal scale upwelling occurring in the world. The wind induced upwelling component during June to August appears to be far stronger than what occurs in the most intense upwelling zones (Bakun, 1993). The driving force behind this exceptional upwelling is a tropospheric wind current called "Findlater Jet", which extends northwestward from the coast of Somalia cutting diagonally across the Arabian Sea.

(ii) *Upwelling off Oman*: The extension of the "Findlater Jet" into the northern part of the Arabian Sea influences the coastal region of the Arabian peninsula off Oman. Eventhough the mean position of the axis of the Jet is located about 500 km off the Oman coast, substantial wind levels associated with the feature do extend to the continental boundary where they produce very high offshore Ekmann transport and associated coastal upwelling.

(iii) *Coastal upwelling within the Gulf of Aden*: Inside the Gulf of Aden, the wind is easterly for most of the year producing offshore Ekmann transport favourable for coastal upwelling off the southern coast of the gulf. However, during the SW monsoon, with the prevailing southwesterlies, the wind driven Ekmann transport is directed towards the southern coast during June, July and August.

(iv) *Upwelling off Madagascar*: The coastal upwelling that may occur off southern Madagascar is apparently accompanied by quite high levels of wind induced turbulent mixing. Off the southern coast of the island, the easterly trade winds produce offshore Ekmann transport throughout the year with a peak in late winter.

(v) *Upwelling off Tanzania and northern Mozambique*: The large coastal area off the Sofala Bank of Mozambique looks most promising as a reproductive habitat for small pelagic fishes. Since this area is a coastal bight located downstream of a zone of wind driven offshore transport of surface waters, it has many characteristics of the most common type of sardine spawning habitat. In this area, the coastal topography shelters the interior of the bight from strong wind induced mixing and the enclosed gyral circulation helps to retain the pelagic eggs and larvae.

In fact, the configuration of the Sofala Bight is very similar to that of the southeastern Brazilian Bight of the eastern tropical south America which has supported a major sardine fishery for many years. The annual sardine landings initially grew rapidly to a peak of 228 000 mt in 1973 and then declined to a level of 120 000 mt to 140 000 mt (Saccardo, 1983), which was maintained till 1986. The major differences are that in the Brazilian case, there is a definite local upwelling centre where the surface characteristics of an upwelling zone are clearly apparent just upstream (equatorward) of the bight. Even so, the seasonal cycles of chlorophyll look rather similar with two bight areas. This leads one at least to suspect that a significant small pelagic fish component could find acceptable spawning habitat within the Sofala Bight, perhaps in waters too shallow for detection by large acoustic survey vessels. Further south, in the Maputo Bay along the Natal coast, the characteristic wind mixing values rising to well above 250 m^3 S^3 appears to favour successful spawning of substantial coastal pelagic populations.

NORTHWEST PACIFIC OCEAN

The northwest Pacific Ocean is a region where intensive efforts have been made to relate the environmental factors and the variations in fisheries, especially to find out the causes for the rises and collapses of the Japanese sardine. The continental shelf around Japan is narrow except in the West China Sea and hence, the abundance of demersal fishes is rather small. On the contrary, pelagic fishes are abundant due to the oceanographic conditions. The Kuroshio warm current approaches Japan from the south and flows eastward along the southern coast of Japan and meets the Oyashio current which comes down from the north. Frontal zones and mixing zones are formed in the areas where the currents meet. It is becoming increasingly clear that the pelagic fish stocks are variable depending on the changes in the oceanographic conditions. Particularly, successes or failures of recruitment due to changes in the oceanographic factors determine variations in the entire stock (Tanaka, 1983).

The important pelagic species such as the Japanese sardine, anchovy, round herring, mackerels and saury are plankton feeders and are under the influence of the Kuroshio current. These warm water fishes generally spawn in coastal waters inside the Kuroshio current off southwestern Japan in winter and spring. Larval fish are transported eastward or northward by the Kuroshio current and feed on abundant food and grow rapidly in the coastal waters of northern Japan or in frontal or mixing zones in the offshore waters in summer and autumn. Depending on the presence or absence of the cold watermass in the Pacific off central or western Japan, the Kuroshio often changes its route. The change in route is a turning point on the distribution and movement of fish shoals and mortality in early life stages which cause changes in stock size (Watanabe, 1982). For the sharp decline in the sardine stock in the 1940s, Nakai (1949) explained that the Kuroshio began meandering in and after 1934, and left the coast in the middle of the 1940s, reaching southward following the appearance of a large cold watermass which changed the normal route of the Kuroshio. This resulted in the drifting of the larvae from the main spawning ground to far offshore waters which was unfavourable for the larvae. The larvae were reported to die of starvation, causing severe reduction in recruitment. The major reason for the spurt in the landings in the 1980s was due to very successful spawning by the Ashizuri subpopulation of the sardine which as a result migrated into the Japanese waters in substantial numbers. The spawning ground extended to a very vast area during those years. The meandering of the Kuroshio disappeared in the southwestern region and the eggs and larvae were entrained favourably in a counterclockwise direction into the Kuroshio current leading to recruitment success.(Matsushita *et al.*, 1989) considered that the recruitment potential of pelagic fish is significantly influenced by inshore-offshore dispersal. As the pelagic eggs and larvae have limited motility, their fate is influenced by the physical movement of water. If the drift is towards a favourable area, recruitment becomes successful. From the repeated studies on the Japanese sardine, the following dispersal patterns of eggs and larvae, which determine the status of the stock, are discernable: (i) If spawning occurs in the coastal waters, the survival of the larvae is better and a significant stock size ensured. (ii) If spawning occurs in the upstream regions of the Kuroshio current, the larvae are transported and dispersed widely, which is an adaptation for the expansion of the stock. In other words, the shift of the main spawning grounds to the upstream regions of the Kuroshio could be beneficial in increasing the stock. (iii) On the other hand, if the current is not favourable, the eggs and larvae spawned in the coastal waters could be shifted to unfavourable offshore areas leading to a decrease in the stock.

Kondon (1988) proposed a theory that the dominant yearclass of sardine is formed only when three conditions, (i) the spawning frequency of adult sardines, (ii) the distribution area of copepod nauplii which form the first bait for the larvae of sardines, and (iii) the change in the path of the Kuroshio current are satisfied concurrently. In other words, the transition of the path of the current from meander to straight runs, or from straight runs to meander are the vital considerations.

The changes in the direction and meander of the Kuroshio current and the consequent change in the stock of the sardines are largely influenced by the environmental changes affecting the Pacific Ocean or the global environmental changes in general. The changes in the stock of the sardines are analogous, in phase, with those of the stocks of the far eastern sardines, i.e., the Californian sardines and the Chilean sardines (Kawasaki, 1982). Significant correlations between the Japanese, Californian, northwest Atlantic and Humboldt systems support the hypothesis that the sardines in these regions are influenced simultaneously by trans-oceanic climatic linkages operating on a wider scale (Crawford *et al.*, 1989). The transpacific linkages were less apparent for the chub mackerels and the anchovies, indicating that the sardines are the most susceptible to global climatic changes. An explanation with some empirical support is that the changes in the sea temperature, possibly influenced by solar radiation and air temperature, cause large changes in the extent of the habitat suitable for the sardines. Kawasaki and Omori (1988) suggested that the variations in the solar radiation lead to variations in primary production, and therefore, in the availability of suitable food items to the sardines. Crawford, *et al.* (1989) observed that solar radiation was positively related to air temperature two years later and the air temperature in turn was related to the SST of the same year in the north Atlantic, and to the SST of two years earlier in the north Pacific. The two year lag between influences of solar radiation on the north Pacific and north Atlantic Oceans is of interest in that it reflects the similar significant lag between the catches of sardine off Japan and England.

DISCUSSION

Comparative studies of fish reproductive habitats have tended to identify a fundamental "triad" (Bakun, 1996) of 3 major classes of processes that combine to yield favourable reproductive habitats for coastal pelagic fishes: (i) Enrichment (upwelling, mixing etc), (ii) concentration (convergence, frontal formation, water column stability, ergoclines etc), and iii) processes favouring retention within appropriate habitats.

The importance of enrichment processes is quite widely understood as evident from the detailed surveys of the regional upwelling systems, described above. Perhaps less widely appreciated is the importance of the concentration processes. For very small organisms such as the fish larvae and other important components of the planktonic food web, seawater represents a viscous fluid; a major energy expenditure may be necessary just to move from one food particle to another. Thus, large amounts of energy needed for the rapid growth, required for the quick passage through the various size related levels of intense predation that pervade the ocean environment, may be expended in feeding activity. Consequently, the availability of processes, whereby food particles are concentrated tends to be vital. This is probably a major reason why various types of interfaces or ergoclines (Legendre and Demers, 1985) tend to be sites of enhanced biological activity in the ocean. The interfaces tend either to maintain or to be maintained by the mechanisms of concentration (Bakun, 1996). Ocean fronts are obvious examples. An innate attraction to drifting objects serves to position the fish within the zones of enhanced biological activity and correspondingly improved feeding conditions (Bakun, 1993; 1996). Conversely, turbulence is a dispersive process, and so, acts counter to the concentration processes. Thus intense turbulent mixing events have appeared to be detrimental to larval survival by disrupting local food concentrations (Lasker, 1978; 1981a; b; Peterman and Bradford, 1987; Wroblewski and Richmond, 1987).

The third factor in the "triad" is retention. Life cycles of marine organisms tend to include at least one stage of passive larval drift. Thus, in a dispersive fluid medium, the loss of early life stages from the population habitat may represent serious wastage of reproductive resources. Consequently, fish populations tend to spawn in locations and seasons that minimize such losses (Parrish *et al.*, 1981; Sinclair, 1988). Interspection of the optimal environmental window in terms of the "fundamental triad" of enrichment, concentration and retention appears to be straightforward. The control on the "low wind" side can be explained as a lack of sufficient enrichment of the trophic system by either wind induced upwelling or mixing. The control on the "high wind" side could be a combination of the adverse impacts on the retention element of the triad due to the resulting excessive offshore transport and on the concentration element due to intense turbulent mixing which could: (i) disperse the concentration of appropriately sized nutritious food particles; (ii) inhibit basic photosynthetic production by mixing phytoplankton cells beyond their "eutical depth"; and, (iii) impair a larva's ability to physically capture prey. While the fish may feed well as relatively strong swimming filter feeding adults due to the particularly high primary productivity of these systems, survival of their early stages may be severely limited by the other two triad elements (Bakun, 1996).

However, Bakun (1993) noted that there were no known changes in marine climate that corresponded with the biological record. He concluded that the environmental changes could have influenced directly the very large fluctuations in the sardine stocks, but might have acted instead on the structure of the ecosystems. As an example of possible ecosystem change influencing sardine abundance, he drew attention to the increased abundance of sardines off Japan in the 1980s coinciding with the collapse of a very large stock of oceanic squids under heavy fishing in the same region. The squids are voracious predators of sardines and their collapse is not attributed to environmental change. Hence, it may be difficult to assess the climatic impact on the ecosystem as a whole.

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Table 1. Major environmental factors influencing fisheries in the APFIC area.

Area	Factors
I. Western Indian Ocean	(i) Tropical monsoon regime; (ii) conspicuous effect of southwest monsoon current (iii) seasonal upwelling and areas of high productivity
II. Eastern Indian Ocean	(i) Tropical monsoon regime; (ii) severe cyclonic weather conditions during northeast monsoon in the northern part; (iii) heavy freshwater runoff in the northern part
1. Western Australian Sea	(i) Seasonal occurrence of southward flow of Leeuwin current along the shelf break; (ii) wind-driven coastal currents reverse direction seasonally
III. Northwest Pacific Ocean	(i) Warm, tropical watermass in the south; cold, subarctic watermass in the north; and convergence of the two in the central part; (ii) formation of numerous eddies
1. Okhotsk Sea	(i) Formation of cold, counterclockwise gyre; (ii)heavy ice cover and vertical mixing in winter
2. Japan Sea	(i) Formation of a warm water and a cold water current without convergence
3. Yellow Sea & East China Sea	(i) Strong and warm monsoon current from the South China Sea towards the Yellow Sea in the north and through the East China Sea during summer; (ii) equally strong cold current in the reverse direction during winter
IV. Western Central Pacific Ocean 1. Java Sea	(i) Tropical monsoon regime; (ii) strong south equatorial current during the southeast monsoon brings nutrient rich water; (iii) strong upwelling along the south Java Sea and Sumatra in August
2.South China Sea	(i) Tropical monsoon regime; (ii) high discharge of nutrient rich freshwater from rivers
3. Philippine Sea	(i) Tropical monsoon regime; (ii) the north Pacific equatorial current dominates; (iii) a giant eddy dominates on the eastern side

Table 2. Monthly mean sea surface temperature values (°C) at the different sections along the southwest coast of India during 1973-1978 (Pillai, 1982).

Month	Cape Comorin	Quilon	Cochin	Kasaragod	Karwar	Ratnagiri
January	27.73	28.26	28.07	27.56	27.09	27.04
February	26.96	27.88	28.28	28.02	27.65	26.50
March	28.67	29.12	29.39	29.21	28.39	28.77
April	28.73	29.82	30.01	29.70	29.46	27.83
May	27.23	28.24	29.05	29.46	30.15	30.03
June	26.10	27.42	27.70	28.28	28.65	29.55
July	24.87	24.96	25.04	27.09	26.64	27.84
August	21.13	24.58	24.11	23.17	24.71	27.99
September	-	24.26	23.57	21.78	25.57	27.56
October	25.31	25.98	27.18	27.01	23.86	27.78
November	27.98	28.20	28.05	26.68	27.35	28.26
December	27.09	28.47	28.12	28.56	27.94	27.05

Table 3. Mean depths of the top of the thermocline at the different oceanographic sections along the southeast and southwest coast of India during 1973-1978 (Pillai, 1982).

Section	Shallowest (m)	Period	Deepest (m)	Period
Ratnagiri	11	Oct.-Nov.	39	Dec-Feb.
Karwar	10	Oct.-Nov.	61	-do-
Kasaragod	13	Jan. to Sept.	56	-do-
Cochin	10	-do-	61	-do-
Quilon	16	-do-	66	-do-
Cape Comorin	20	-do-	63	-do-
Tuticorin(SE)	32	-do-	78	-do-

Table 4. Position of the 23°C isotherm (sectionwise/yearwise) within the areas of observation along the southwest coast of India during 1973 to 1978 (Pillai, 1982).

Section	1973		1974		1975		1976		1977		1078	
	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.	Sep.	Jan.	Nov.	Mar.	Oct.	Jan.	Aug.	Jan.	Sep.	Jan.	Oct.
Depth(m)	128	16	120	34	138	35	134	48	134	22	134	15
Ratnagiri	Feb.	Nov.	Jan.	Nov.	Feb.	Oct.	-	-	Feb.	Sep.	Feb.	Oct.
Depth(m)	125	50	122	56	·170	45	-	-	170	70	170	70

Table 5. Monthly mean sea surface salinity values (ppt) at the different sections along the southwest coast of India during 1973 to 1978 (Pillai, 1982).

Month	Cape Comorin	Quilon	Cochin	Kasaragod	Karwar	Ratnagiri
January	34.51	34.09	33.70	32.71	32.90	-
February	33.91	33.34	33.66	34.43	35.62	35.46
March	34.21	34.03	34.33	34.16	33.84	34.90
April	33.79	34.69	34.31	34.64	35.13	35.63
May	34.95	34.90	35.11	35.55	36.12	36.02
June	34.71	35.23	35.21	34.64	35.60	35.83
July	34.93	34.66	34.63	35.07	34.41	35.14
August	34.99	34.70	34.43	34.94	34.89	34.81
September	-	34.97	35.22	35.29	35.32	35.63
October	35.26	35.34	34.77	34.71	35.26	34.78
November	34.35	34.66	34.67	34.53	35.45	35.19
December	33.03	33.69	32.50	34.20	35.08	35.08

Table 6. Monthly mean sea surface dissolved oxygen values ml/l) at the different sections along the southwest coast of India during 1973-1978 (Pillai, 1982).

Month	Cape Comorin	Quilon	Cochin	Kasaragod	Karwar	Ratnagiri
January	4.61	4.64	4.91	4.65	3.00	4.33
February	4.91	4.97	4.82	4.90	4.89	4.61
March	4.54	4.52	4.64	4.40	4.61	4.79
April	4.67	4.50	4.58	4.23	4.63	4.62
May	3.91	4.46	4.71	4.65	4.69	4.61
June	4.26	4.23	4.22	4.43	4.44	5.02
July	4.03	3.75	3.71	3.15	3.73	4.33
August	2.30	3.72	3.83	2.14	3.32	4.54
September	-	-	2.46	1.10	5.35	4.30
October	4.20	4.22	3.34	4.43	1.39	4.53
November	4.55	4.76	4.60	3.88	4.00	4.67
December	4.64	4.56	4.62	4.98	4.97	5.04

Table 7. Sinking intensity based on the vertical movement (m) of 23°C along the southwest coast of India during 1973 to 1978 (Pillai, 1982).

Section	Year	Period From	Period To	Duration (days)	Downward movement From	Downward movement To	Vertical distance	Speed (cm/day)
Cape Comorin	1973	Jul.	Jan.	193	57	140	83	43.0
	1974	Oct.	Jan.	96	125	125	82	85.4
Quilon	1973	Jul.	Jan.	195	20	140	120	61.5
	1974	Sep.	Jan.	123	23	140	117	95.1
	1975	Aug.	Feb.	185	21	80	59	31.9
Cochin	1973	Sep.	Jan.	125	17	140	123	98.4
	1974	Aug.	Jan.	142	16	150	134	94.4
	1975	Sep.	Jan.	134	17	150	133	99.3
	1976	Aug.	Apr.	262	18	115	97	37.0
Kasaragod	1973	Aug.	Mar.	224	24	119	95	42.4
	1974	Sep.	Dec.	86	30	150	120	139.5
	1975	Sep.	Dec.	182	35	90	65	35.7
	1976	Aug.	Nov.	93	19	108	89	95.7
Karwar	1973	Oct.	Mar.	151	47	133	86	57.7
	1974	Oct.	Jan.	93	34	150	116	124.7
	1975	Oct.	Jan.	92	35	130	95	103.3
Ratnagiri	1973	Nov.	Mar.	119	45	133	88	73.0
	1974	Oct.	Feb.	119	56	150	94	79.0

Table 8. Daily primary production at some stations along the west coast of India expressed as grams carbon fixed beneath a square metre of sea surface (within 50 metres depth) (Nair *et. al.*, 1973).

Date	Latitude	Position	Longitude	Depth in metres	Production $gC/m^2/day$
05/06/1965	8° 00'		77° 20'	38	2.09
15/12/1965	13° 25'		75° 10'	40	0.95
16/12/1965		Karwar Bay		7	1.39
03/02/1966	9° 40'		76° 00'	40	0.18
06/09/1966	9° 00'		76° 28'	25	1.24
07/08/1967	14° 08'		74° 18'	30	0.61
06/09/1967	9° 52'		76° 10'	18	2.37
07/09/1967	9° 20'		76° 51	50	1.18
07/09/1967	8° 42'		76°35'	35	1.26
09/09/1967	7° 45'		77° 19'	50	0.48
09/09/1967	7° 45'		78° 00'	47	1.43
20/07/1968	8° 53'		76° 21'	50	1.12
21/07/1968	10° 29'		75° 51'	37	0.89
22/07/1968	11° 19'		75°36'	28	1.34
24/07/1968	12° 08'		74°58'	37	2.45

Table 9. Annual primary productivity (gross) in a few marine localities as grams carbon per square metre of sea surface (Nair *et. al.*, 1973).

Locality	Production
Barents Sea	170 - 330
English channel	60 - 98
Georges Bank	309
North Sea	57 - 82
Long Island Sound	470
Off Hawai (open ocean)	21
Off Hawai (inshore)	123
Turtle grass bed (Florida)	4650
Hawaiian coral reef	2900
Shelf waters of New York	
Shallow coastal region	160
Continental slope	100
North Central Sargasso Sea	78
Gulf of Mannar(inshore within 10m depth)	745
Temperate oceans	100 to 150
Equator	110 to 146
Barren tropical oceans	50
West coast of India (within 50m depth)	434
East coast of India(continental shelf)	230

Table 10. Summary of primary production values for different zones along the west coast of India in $gC/m^2/day$ (Nair *et. al.* 1973).

States	Upto 50m depth			50 to 200m depth			> 200m depth		
	No.of stns	Total	Average	No.of stns	Total	Average	No.of stns	Total	Average
Kanyakumari district.	3	4.00	1.33	5	1.49	0.37	6	1.08	0.18
Kerala	10	12.17	1.22	13	3.20	0.25	22	3.80	0.17
Karnataka	6	6.50	1.08	4	0.77	0.19	3	0.84	0.28
Maharashtra	-	-	-	2	0.23	0.12	-	-	-
	19	22.67	1.19	24	5.69	0.23	31	5.72	0.18

Table 11. **Plankton biomass values (ml/m^3) in the mid shelf off the southwest coast of India (3rd station from the coast) in space and time (Source: PFP records); H-Highest monthly average; L-Lowest monthly average.**

Section	1971	1972	1973	1974	1975	1976	1977	1978
Ratnagiri	H.--	0.87(Aug.)	0.66(Aug.)	3.58(Aug)	0.43(Oct.)	0.83(May)	0.83(Dec.)	-
	L--	0.35(Dec.)	0.13(Jun.)	0.04(Apr.)	0.14(May)	-	0.13(Jul.)	0.33(Jun.)
Karwar	H1.44(Oct.)	1.75(Sep.)	1.10(Nov.)	1.02(Aug.)	0.31(Jun.)	1.87(Aug.)	0.73(Dec.)	1.02(Jun.)
	L--	0.01(Dec.)	0.28(Mar.)	0.04(Mar.)	0.16(Oct.)	0.12(Apr.)	0.22(Jul.)	
Kasargod	H0.55(Sep.)	0.93(Jul.)	0.73(Jun.)	2.72(Dec.)	0.5(Oct.)	0.19(Jul.)	-	-
	L.0.20(Nov.)	0.02(Dec.)	0.06(Nov.)	0.10(Jan.)	0.11(Apr.)	0.06(Apr.)		
Cochin	H1.25(Sep.)	4.85(Sep.)	1.20(Jul.)	1.70(Feb.)	0.88(Sep.)	0.34(Aug.)	0.69(Jul.)	1.05(Julk.)
	L0.07(Oct.)	0.06(Jul.)	0.14(Jan.)	0.03(Sep.)	0.03(Mar.)	0.12(Apr.)	0.09(Mar.)	0.08(Jan.)
Quilon	H1.25(Sep.)	4.85(Sep.)	1.20(Jul.)	1.70(Feb.)	0.88(Sep.)	0.34(Aug.)	0.69(Jul.)	1.05(Jul.)
	L0.07(Oct.)	0.06(Jul.)	0.14(Jan.)	0.03(Sep.)	0.03(Mar.)	0.12(Apr.)	0.09(Mar)	0.08(Jan.)
CapeComorin	H-	-	1.6(Aug.)	0.63(Oct.)	1.62(Nov.)	0.34(Nov.)	0.93(Jul.)	0.43(Jul.)
	L-	-	1.21(Jan.)	0.20(Apr.)	0.09(Mar.)	0.19(Jun.)	0.06(Nov.)	-

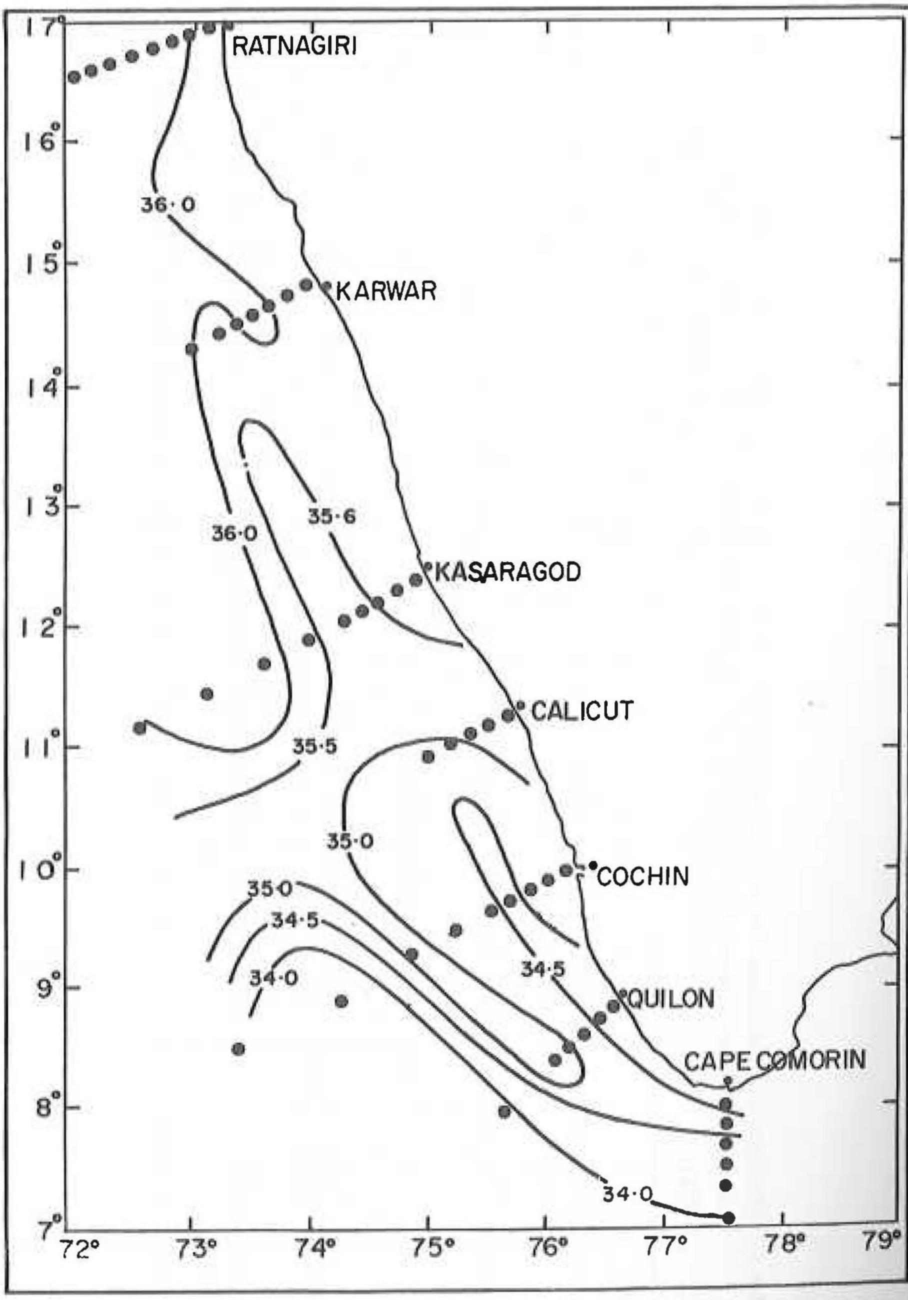

Fig. 1. Horizontal distribution of sea surface salinity along the SW coast of India during January to March 1973.

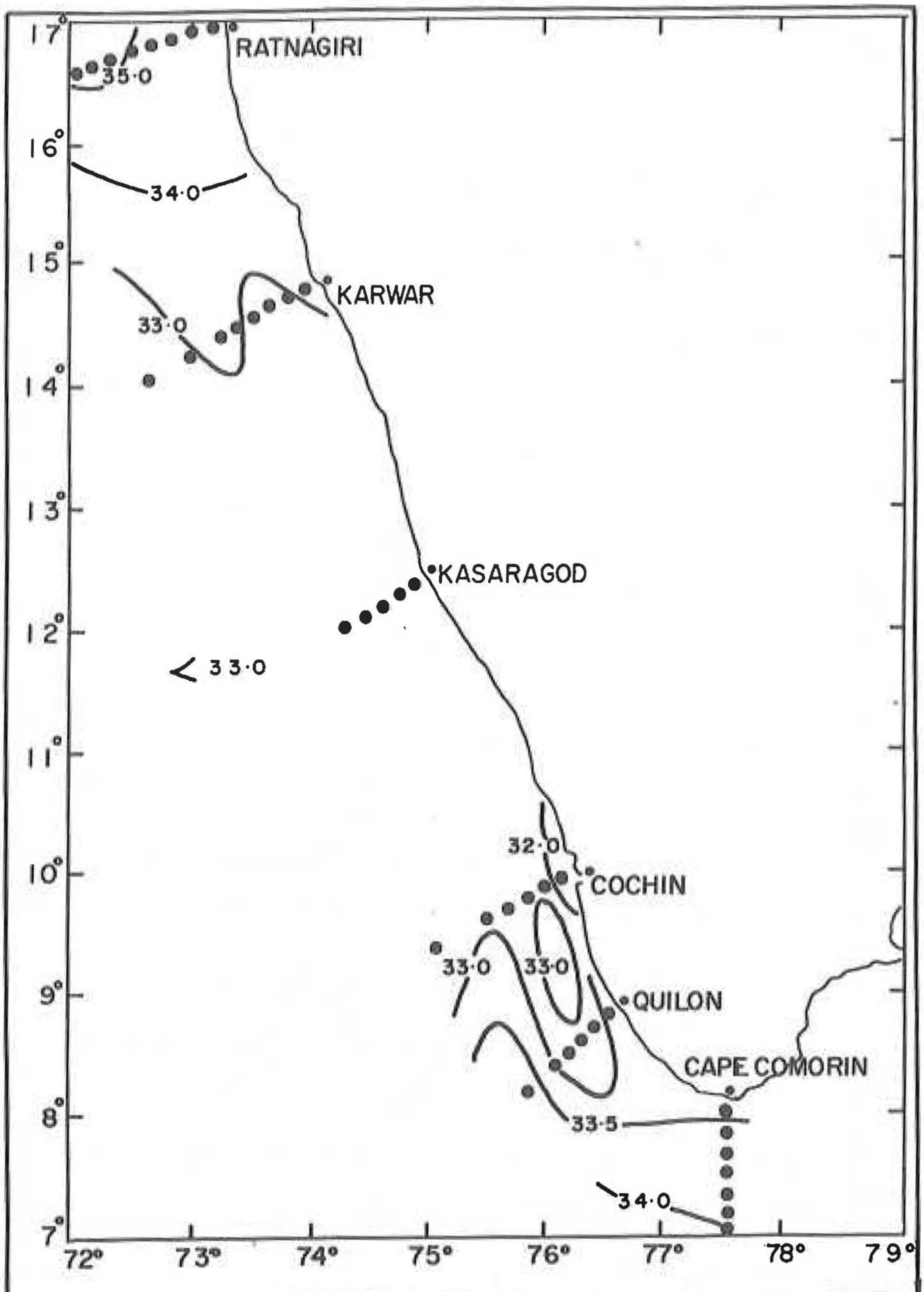

Fig. 2. Horizontal distribution of sea surface salinity along the SW coast of India during January to March 1974.

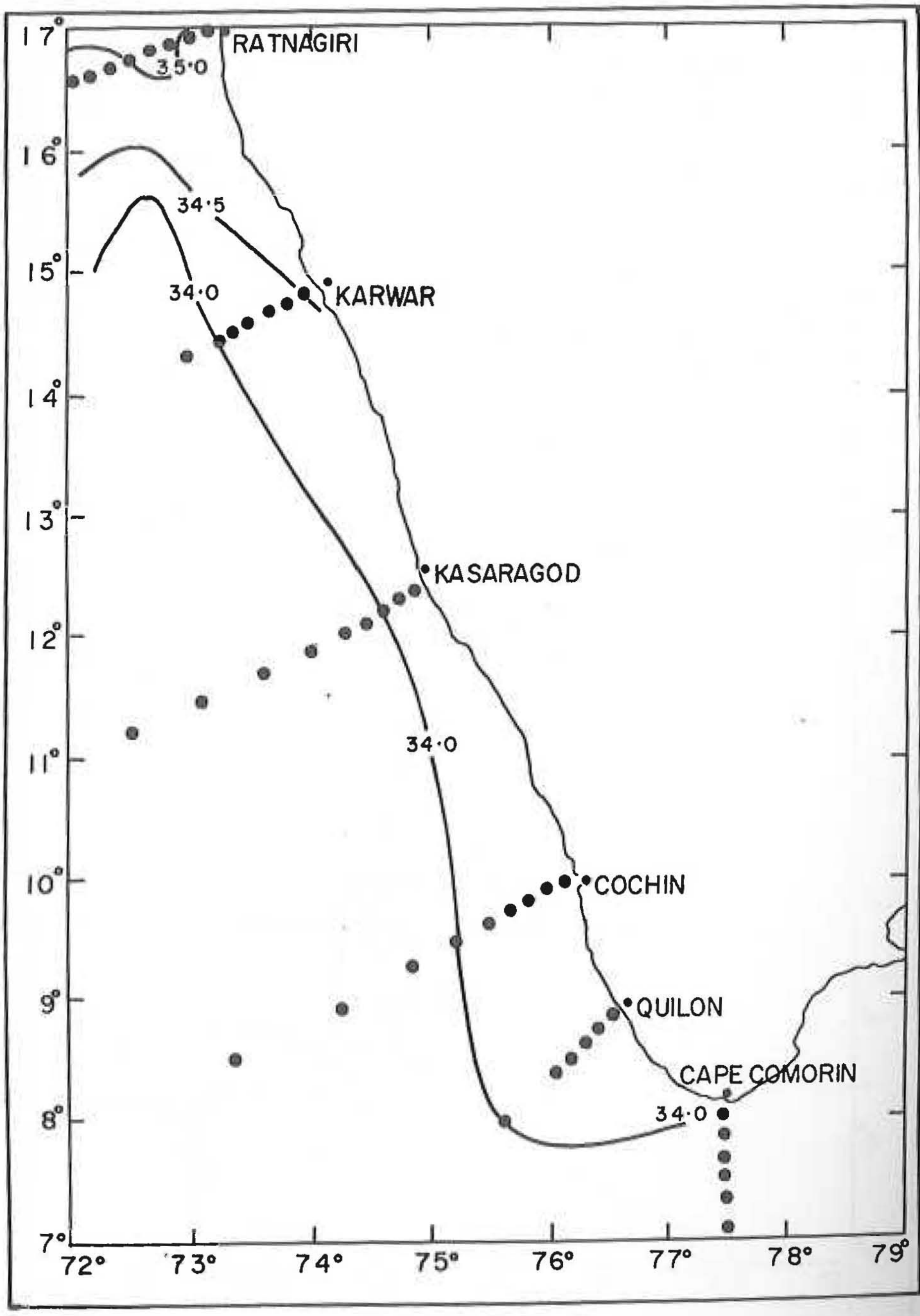

Fig. 3. Horizontal distribution of sea surface salinity along the SW coast of India during January to March 1975.

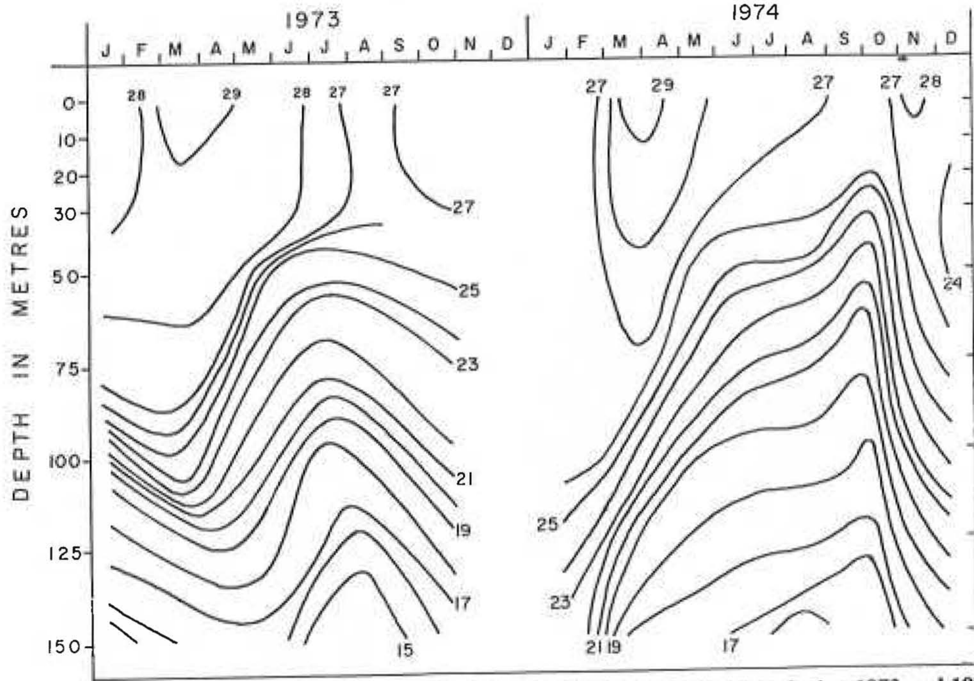

Fig. 4. Vertical time section for seawater temperature off Cape Comorin during 1973 and 1974.

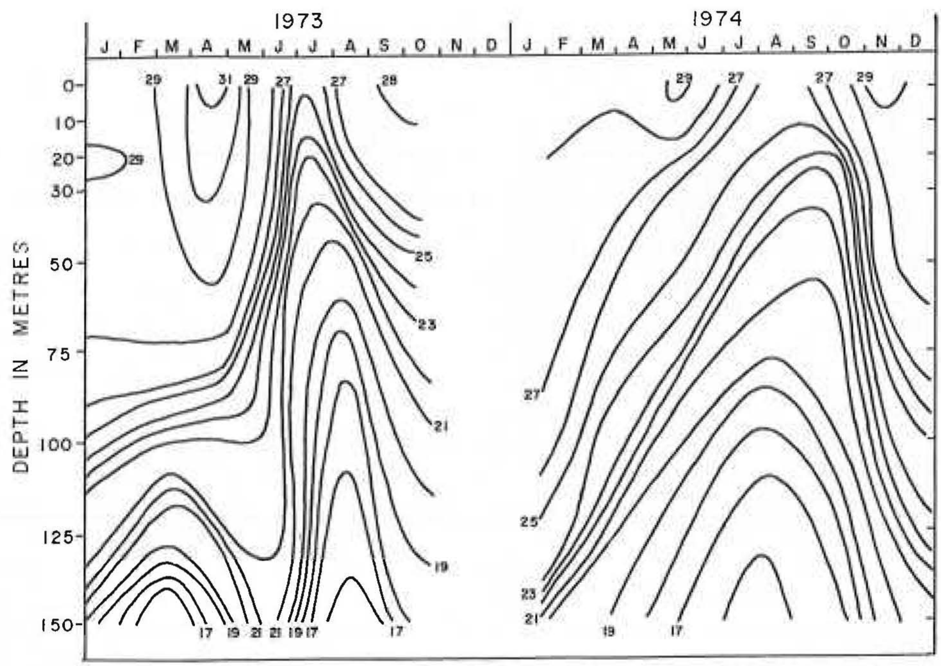

Fig. 5. Vertical time section for seawater temperature off Quilon during 1973 and 1974.

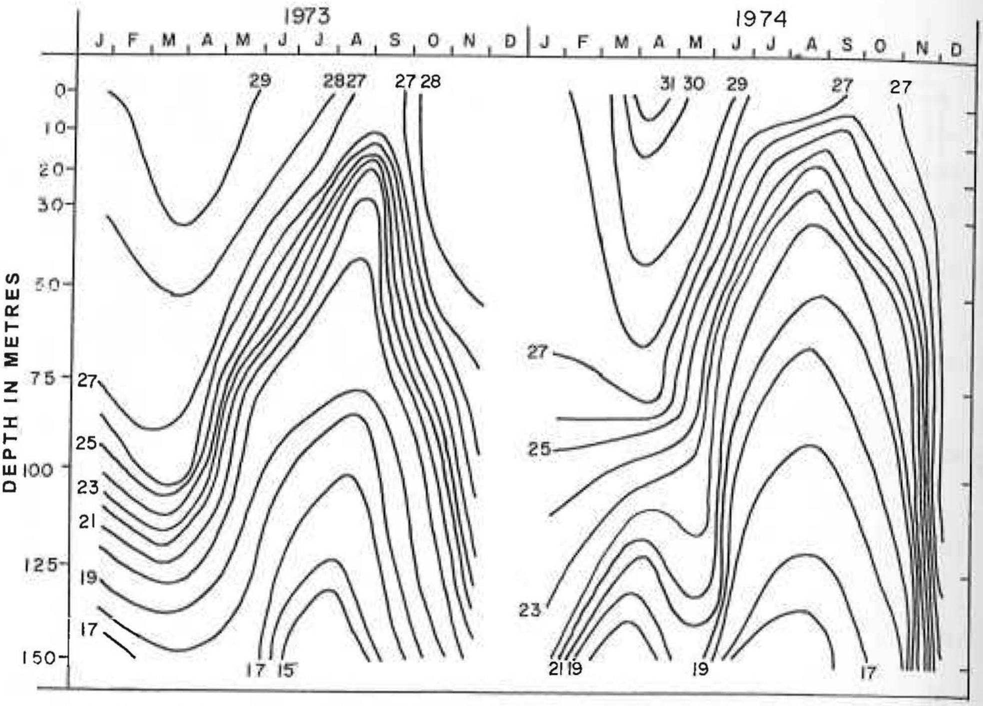

Fig. 6. Vertical time section for seawater temperature off Cochin during 1973 and 1974.

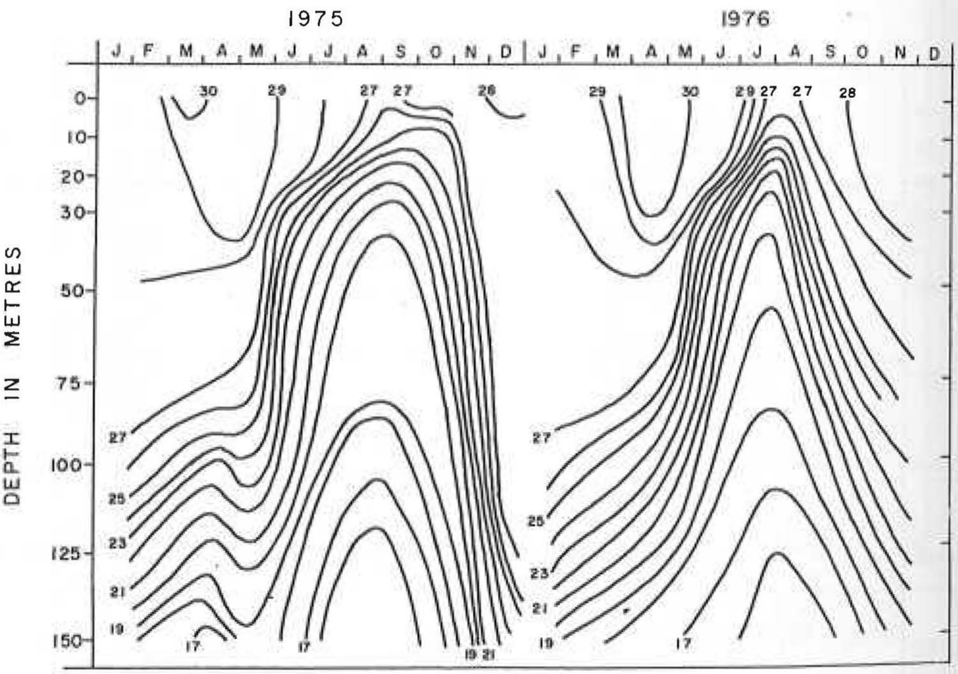

Fig. 7. Vertical time section for seawater temperature off Cochin during 1975 and 1976.

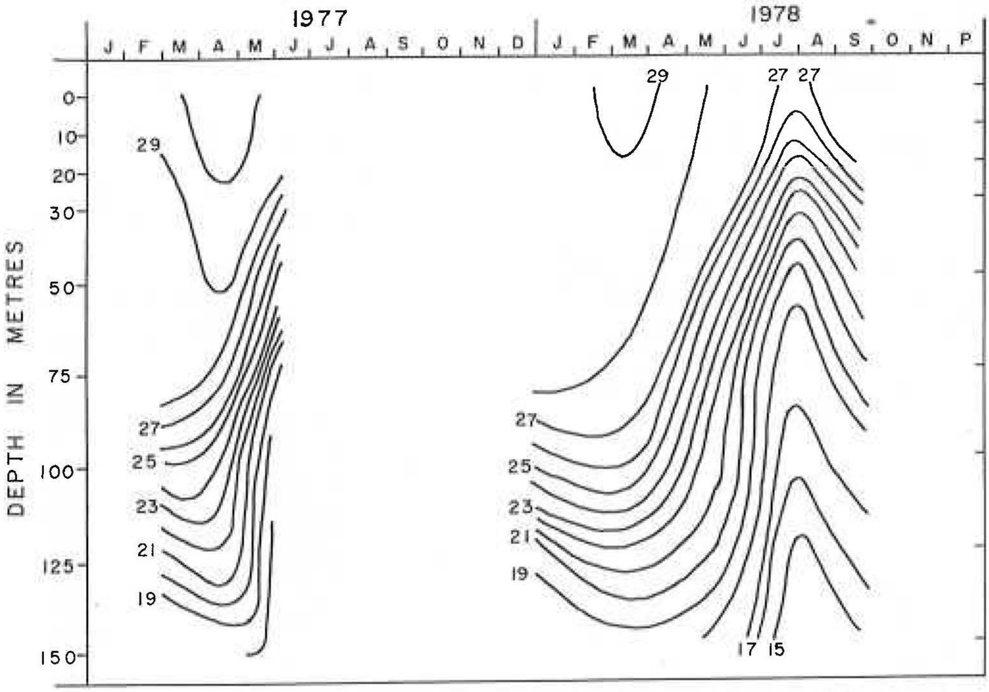

Fig. 8. Vertical time section for seawater temperature off Cochin during 1977 and 1978.

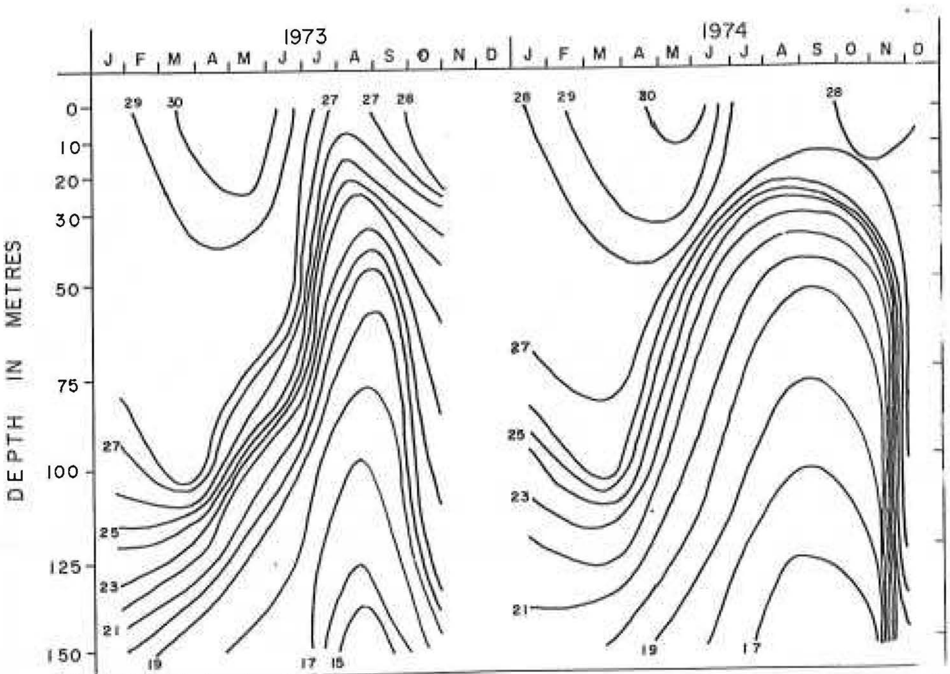

Fig. 9. Vertical time section for seawater temperature off Kasaragod during 1973 and 1974.

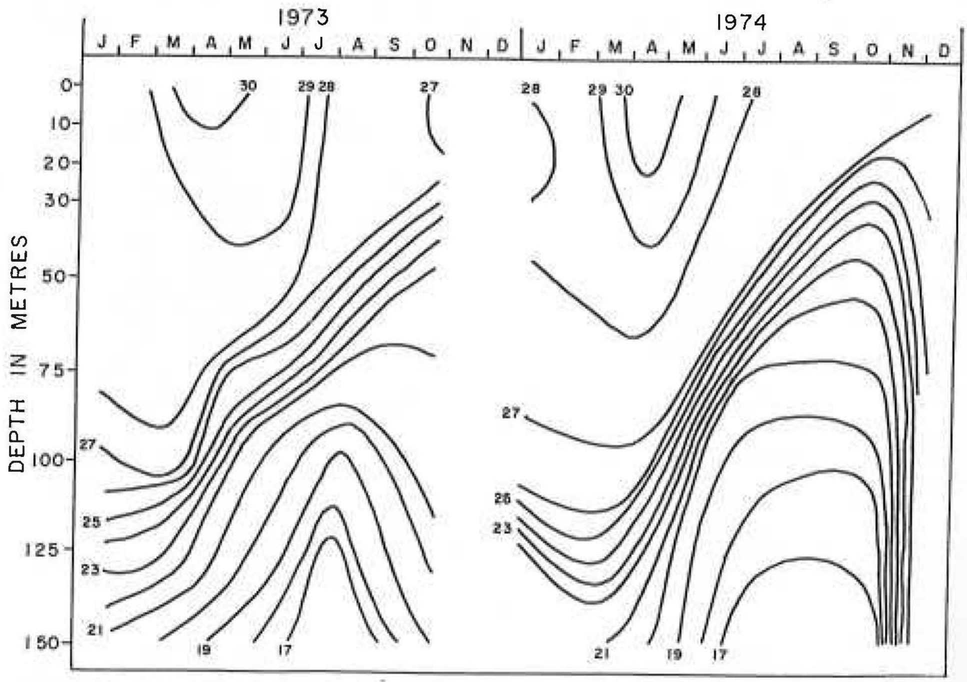

Fig. 10. Vertical time section for seawater temperature off Karwar during 1973 and 1974.

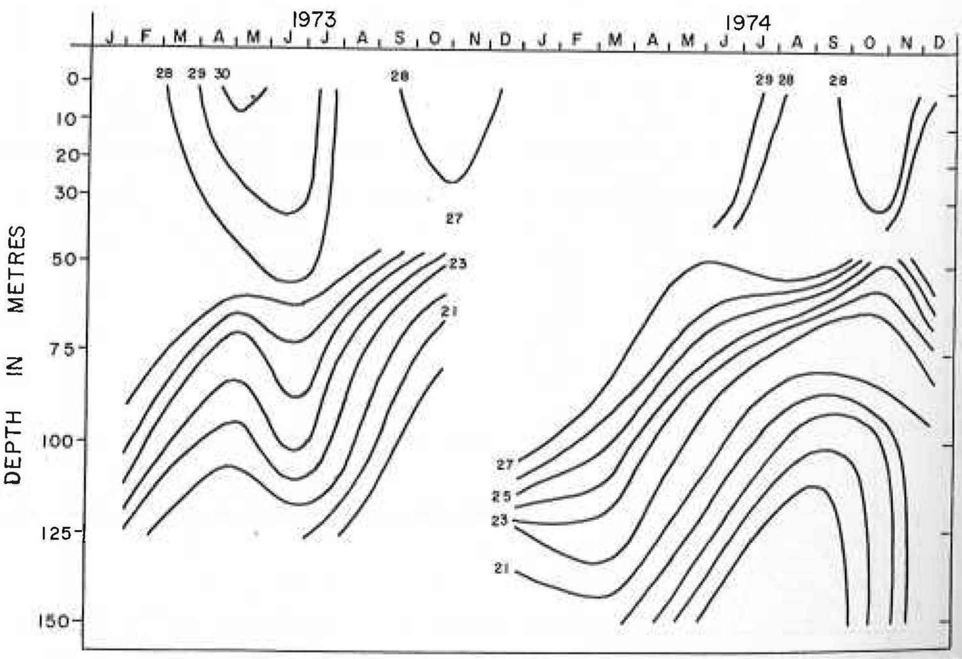

Fig. 11. Vertical time section for seawater temperature off Ratnagiri during 1973 and 1974.

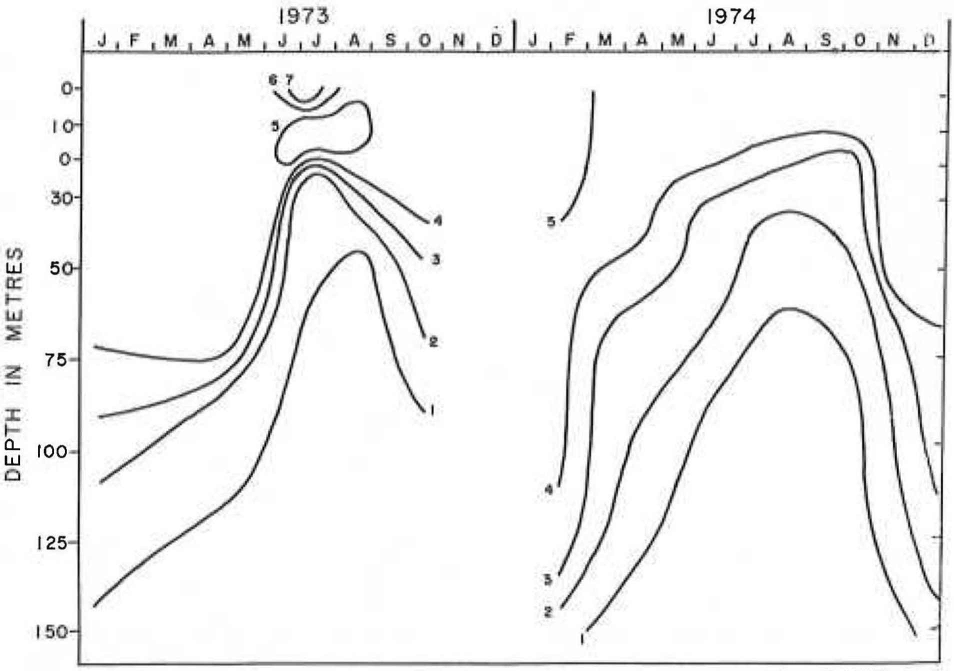

Fig. 12. Vertical time section for dissolved oxyen off Quilon during 1973 and 1974.

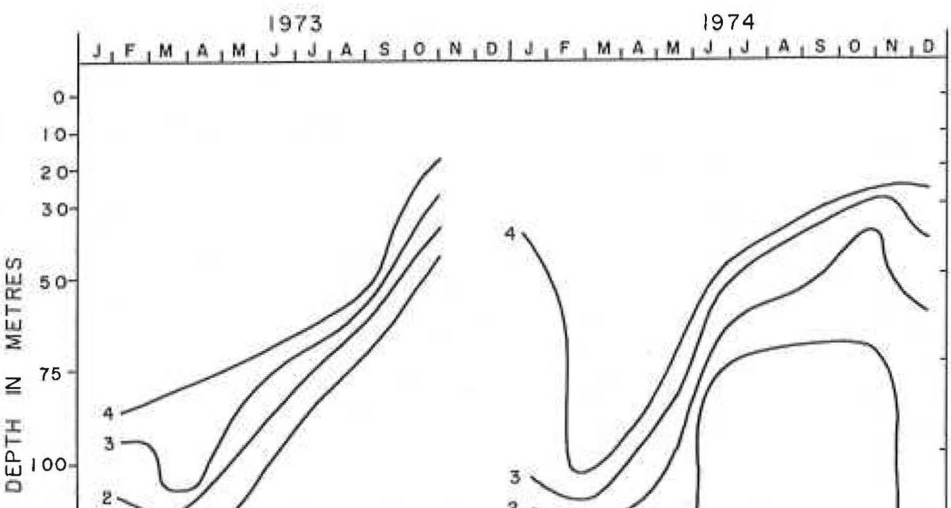

Fig. 13. Vertical time section for dissolved oxyen off Karwar during 1973 and 1974.

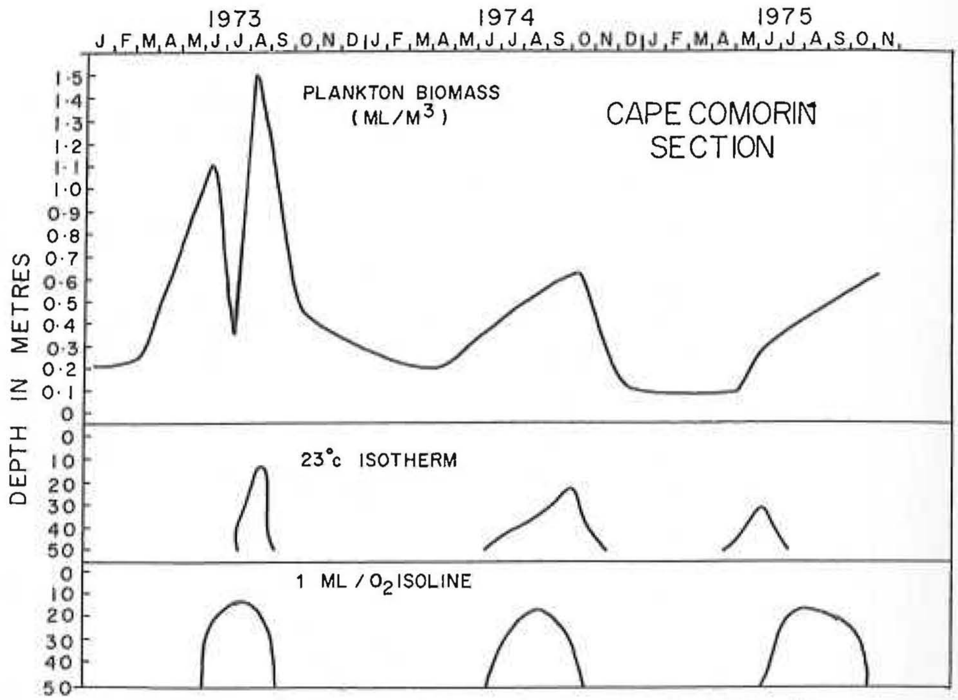

Fig. 14. Relationship between upwelling (in terms of vertical oscillation of 1 ml/l oxygen isoline and 23°C isotherm) and zooplankton biomass off Cape Comorin during 1973-1975.

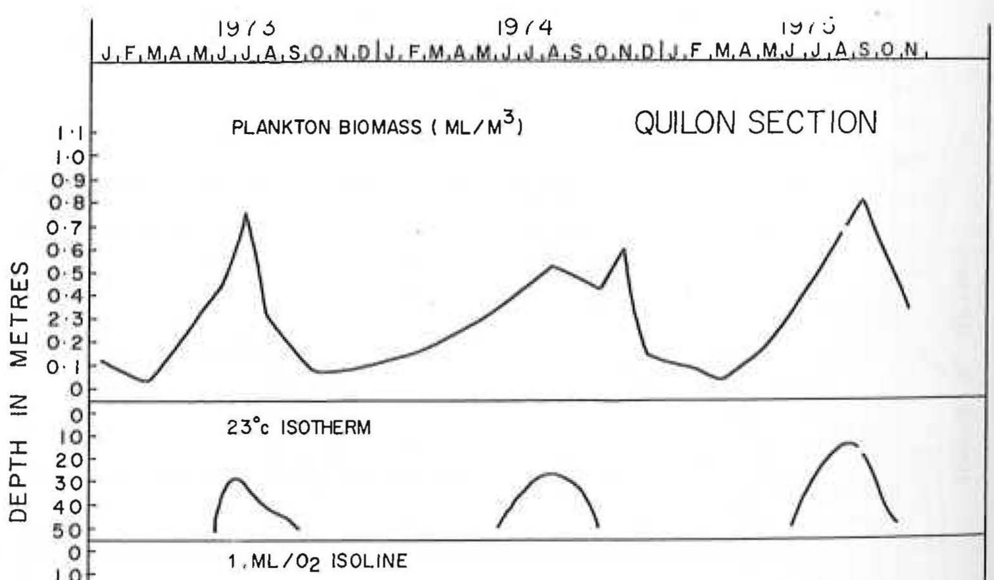

Fig. 15. Relationship between upwelling (in terms of vertical oscillation of 1 ml/l oxygen isoline and 23°C isotherm) and zooplankton biomass off Quilon during 1973-1975.

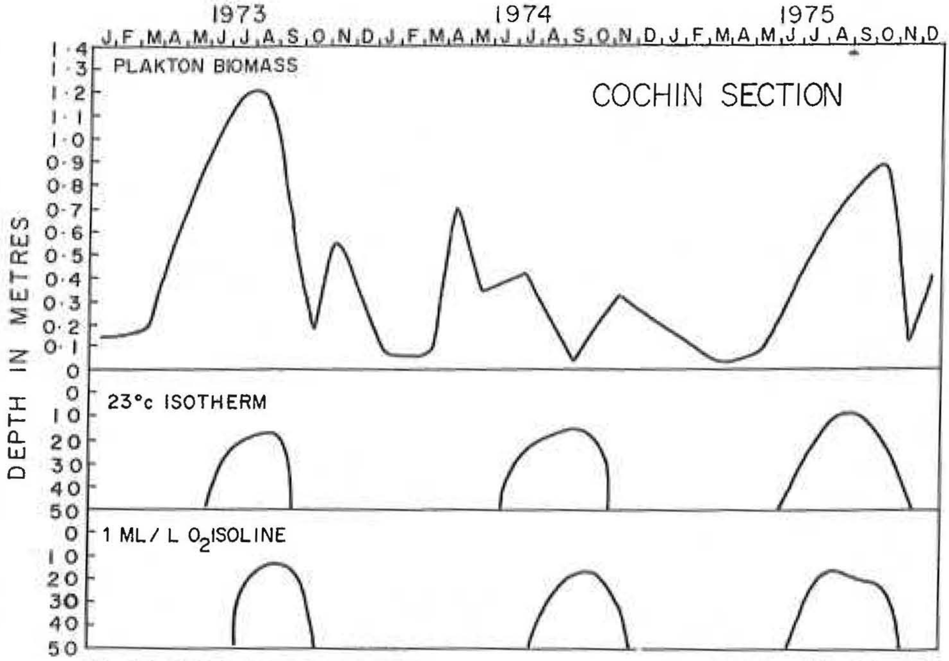

Fig. 16. Relationship between upwelling (in terms of vertical oscillation of 1 ml/l oxygen isoline and 23°C isotherm) and zooplankton biomass off Cochin during 1973-1975.

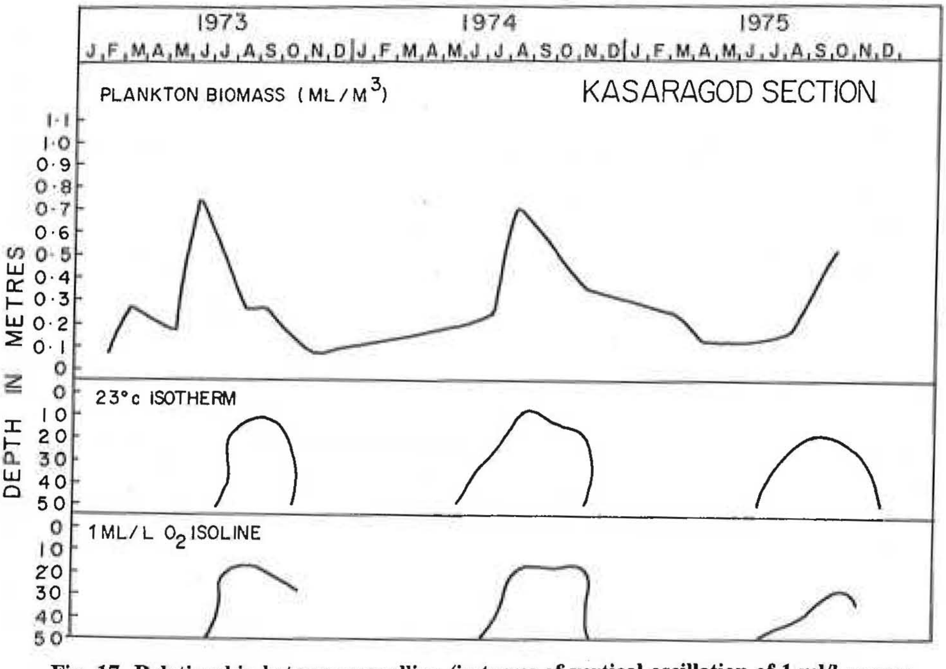

Fig. 17. Relationship between upwelling (in terms of vertical oscillation of 1 ml/l oxygen isoline and 23°C isotherm) and zooplankton biomass off Kasaragod during 1973-1975.

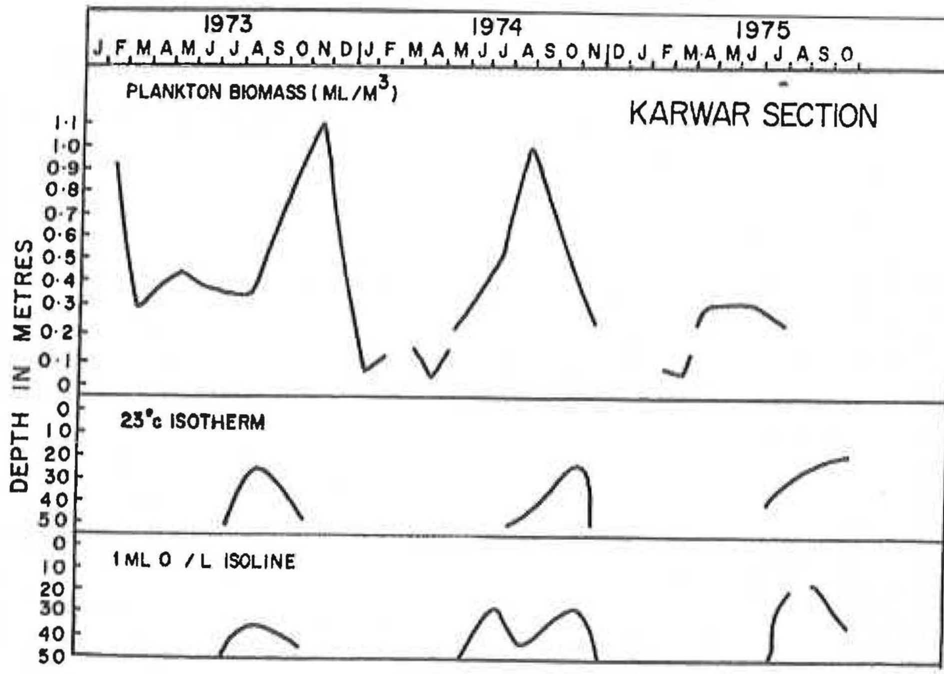

Fig. 18. Relationship between upwelling (in terms of vertical oscillation of 1 ml/l oxygen isoline and 23°C isotherm) and zooplankton biomass off Karwar during 1973-1975.

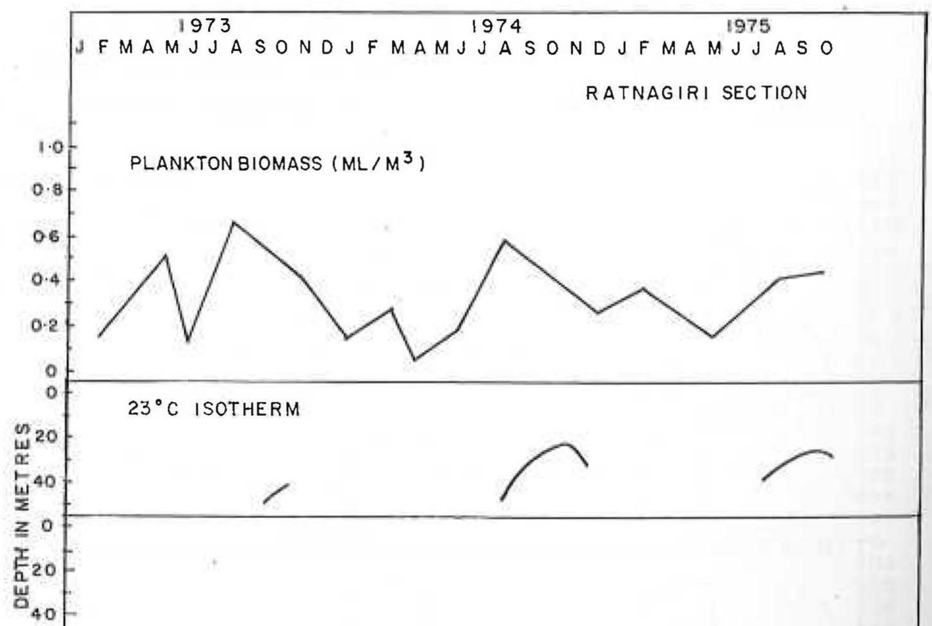

Fig. 19. Relationship between upwelling (in terms of vertical oscillation of 1 ml/l oxygen isoline and 23°C isotherm) and zooplankton biomass off Ratnagiri during 1973-1975.

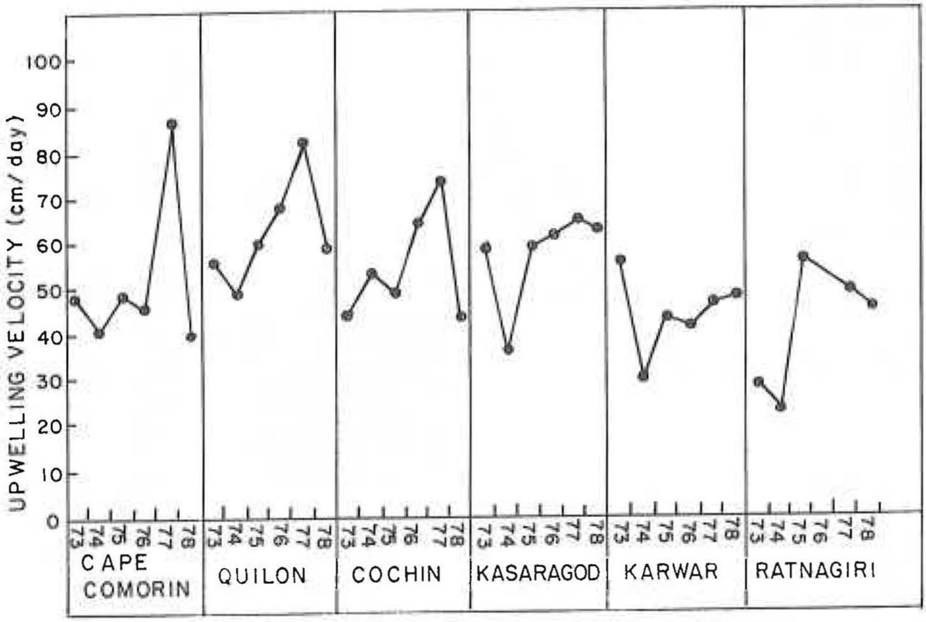

Fig. 20. Diagramatic representation of upwelling velocity (cm/day) off different locations along the SW coast of India during 1973 to 1978.

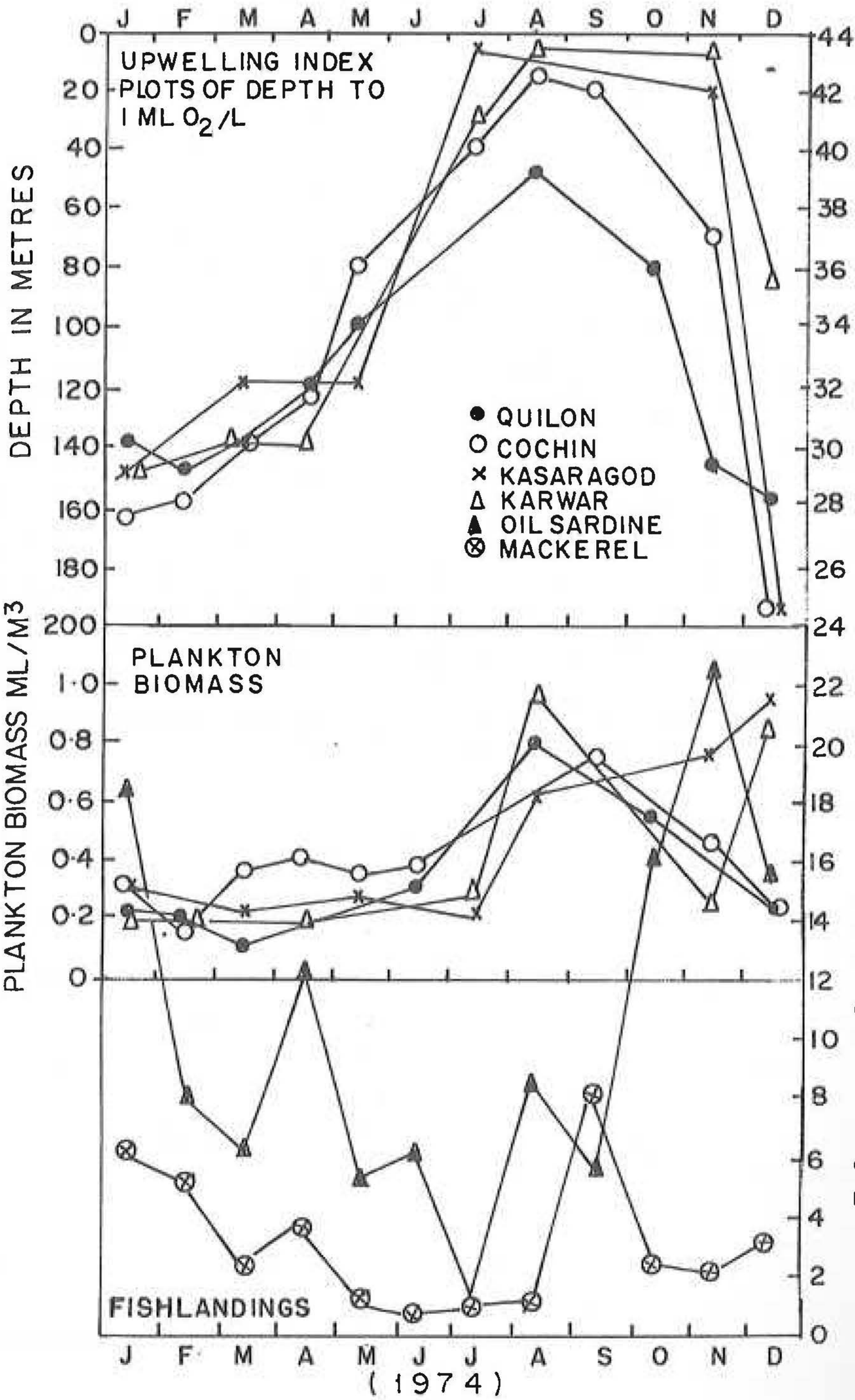

Fig. 22. Relationship between upwelling, zooplankton biomass and landings of oil sardine and Indian mackerel during 1974.

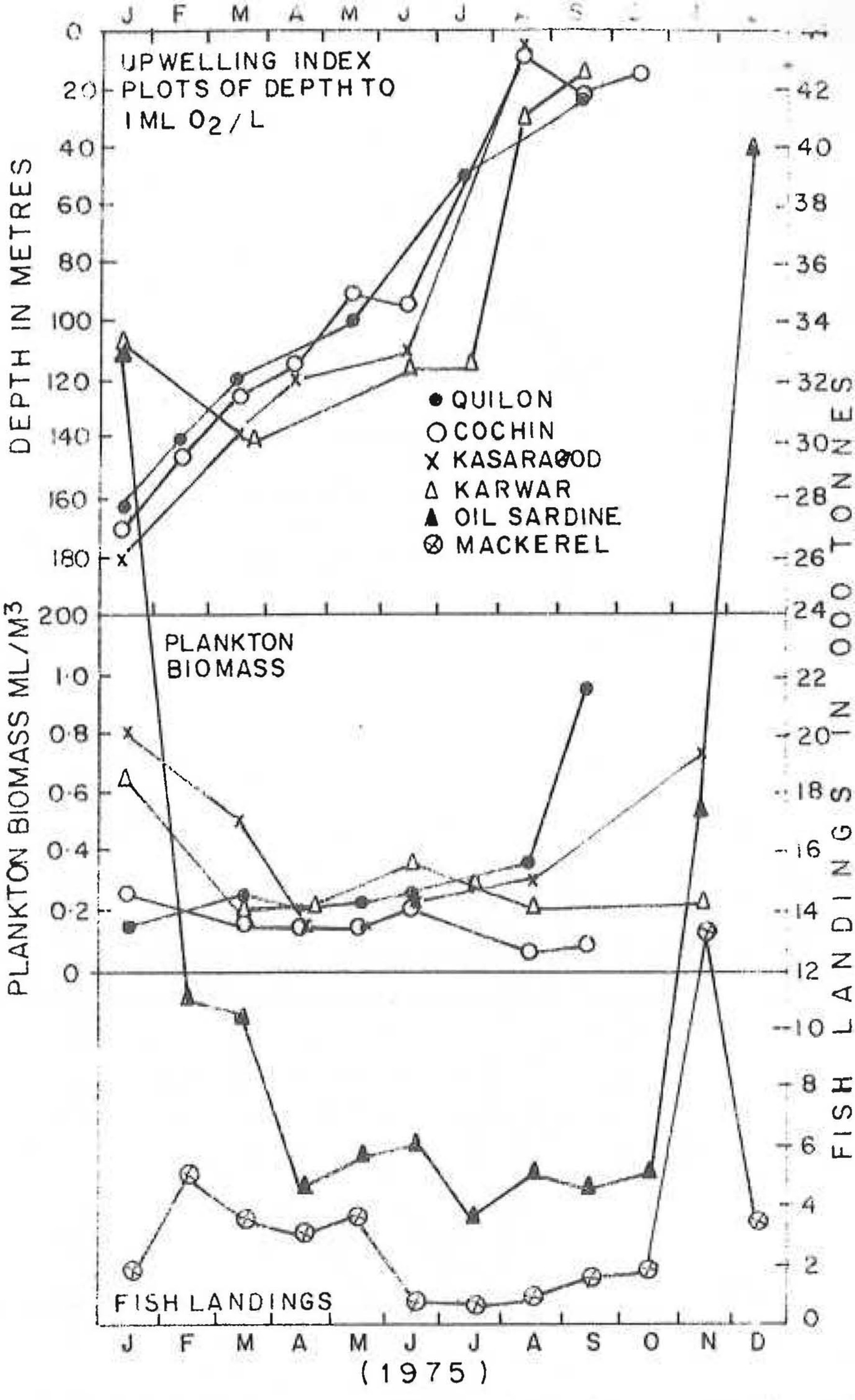

Fig. 23. Relationship between upwelling, zooplankton biomass and landings of oil sardine and Indian mackerel during 1975.

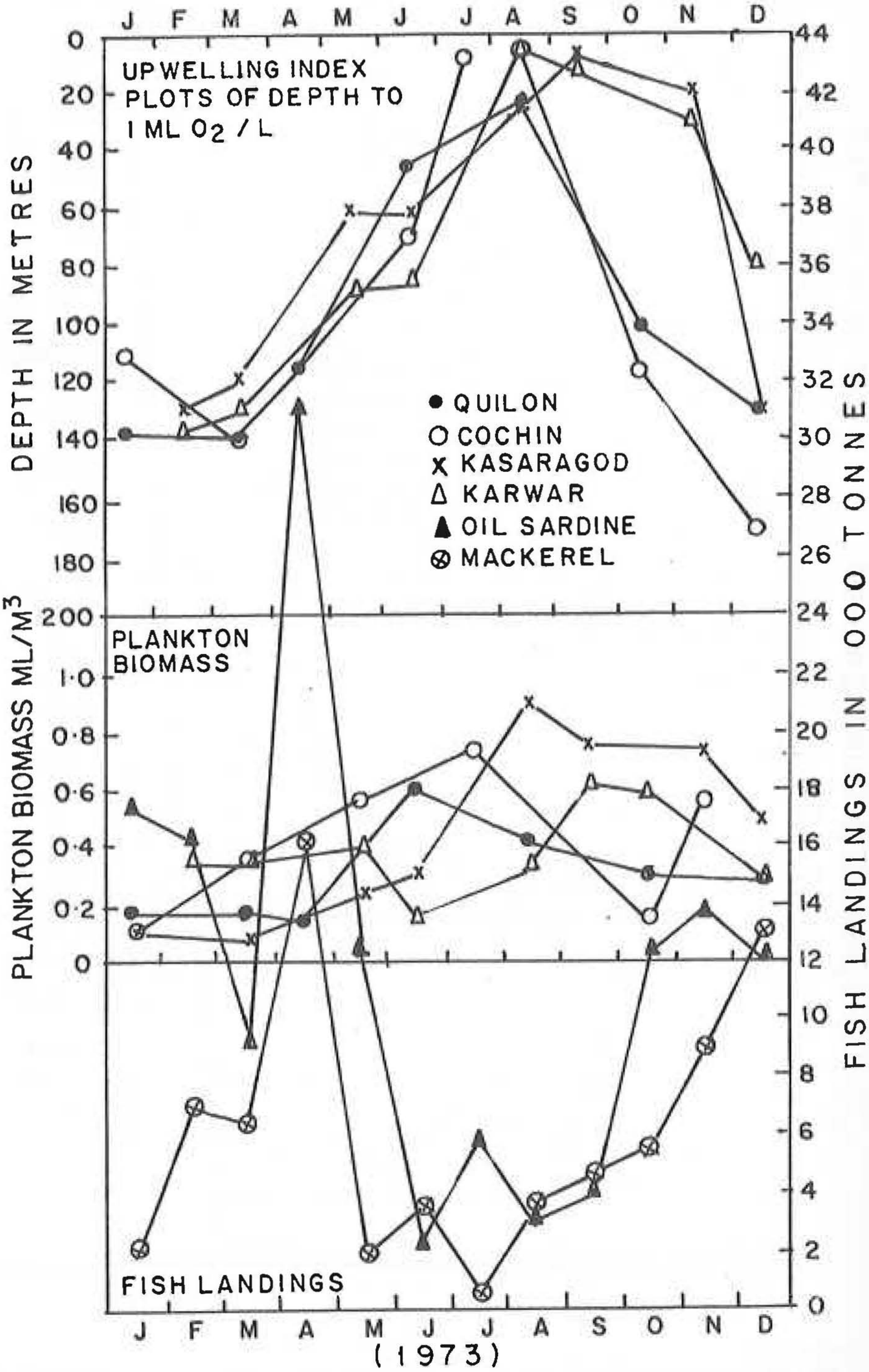

Fig. 21. Relationship between upwelling, zooplankton biomass and landings of oil sardine and Indian mackerel during 1973.