STUDIES ON UPWELLING AND SINKING IN THE SEAS AROUND INDIA

THESIS
SUBMITTED TO THE UNIVERSITY OF COCHIN
FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY
IN
PHYSICAL OCEANOGRAPHY
IN THE FACULTY OF MARINE SCIENCES

By

BASIL MATHEW, M. Sc.

DEPARTMENT OF MARINE SCIENCES, UNIVERSITY OF COCHIN
COCHIN - 682 016
OCTOBER, 1982

CERTIFICATE

This is to certify that this Thesis is an authentic record of research work carried out by Mr. Basil Mathew, M.Sc., under my supervision and guidance in the Department of Marine Sciences for the Ph.D. Degree of the University of Cochin and no part of it has previously formed the basis for the award of any other degree in any University.

Dr. G. S. SHARMA
(Supervising Teacher)
Professor and Head
Department of Marine Sciences
University of Cochin

Cochin - 682 016,
October, 1982.

ACKNOWLEDGEMENTS

I wish to express my deep sense of gratitude to Dr. G. S. Sharma, Professor and Head of the Department of Marine Sciences, University of Cochin, for suggesting the problem, the valuable guidance, the constant encouragements and critical scrutiny of the manuscript.

My thanks are also due to the authorities of Cochin University for providing the necessary facilities. I am grateful to the Council of Scientific and Industrial Research, for awarding a Junior Research Fellowship, during the tenure of which the present study was carried out.

CONTENTS

PREFACE

Of the several physical processes occurring in the sea, vertical motions have special significance because of their marked effects on the oceanic environment. Upwelling is the process in the sea whereby subsurface layers move up towards the surface. The reverse process of surface water sinking to subsurface depths is called sinking. Upwelling is a very conspicuous feature along the west coasts of continents and equatorial regions, though upwelling also occurs along certain east coasts of continents and other regions.

Upwelling influences the physical, chemical, biological and geological environment of the region. Since upwelled water is rich in nutrients high fishery resources are common and variations in the intensity of upwelling, both in space and time are known to cause variations in the production of biomass at various trophic levels. The high productivity is reflected in the deposition of sediments rich in organic matter, which may lead to formation of valuable quantities of petroleum or phosphorite. The effects of upwelling are reflected in the meteorological conditions as well; the cool and uneventful weather on the coasts of Peru and southern California is the result of upwelling. It has been known that variations in the Somali Coast upwelling affect the low level jet and hence the monsoon over India (Wooster, 1978). The 'El Nino' of 1972 not only affected the environmental conditions off Peru, but it had also a possible relationship with drought in Brazil (Caviedes, 1973).

Upwelling in the Indian Ocean is unique in many respects due to the periodic monsoon winds. Though upwelling in the Indian Ocean is not exclusively a phenomenon of the coast, regions of coastal upwelling are highly productive and heavily fished. For the better exploitation of various resources in the coastal regions a thorough knowledge of upwelling and sinking in these regions are necessary. In this Thesis it is attempted to find out the period and duration of upwelling and sinking off the Indian coasts, its causative factors and its major effects, and thereby it is aimed to get a detailed account of the physical process of upwelling and sinking. Particular importance is given to upwelling off the west coast of India.

The Thesis has been divided into six chapters, with further subdivisions and sectionalisations.

Chapter one has two sections. Section one deals with a general introduction, and in the other section the material and methods for the present investigation are presented.

The second chapter deals with the seasonal variation of temperature and density fields off the west and east coasts of India.

The surface vergence, windstress and sea level off the east and west coasts of India are dealt in chapter three.

Chapter four is concerned with the inferences on upwelling and sinking drawn from the study of temperature and density structure, vergence field, windstress and sea level variation off the west coast of India. Various other associated features are also discussed.

The fifth chapter has two sections. Section one deals with upwelling off the east coast of India, while section two is a comparison of upwelling off the east and west coasts of India.

The sixth chapter summarises the results of the present investigation and conclusion arrived at.

ABBREVIATIONS

°C : degree centigrade

cm : centimeter

Fig. : Figure

g/l : gram per litre

gCm^{-2} : gram Carbon per meter square

km : kilometer

m : meter

ml : milli litre

sec^{-1} : per second

‰ : parts per mille

µg at/l : micro gram atom per litre

CHAPTER I

SECTION I - INTRODUCTION

The mean speed of the vertical currents in the ocean is much less than that of the horizontal currents. But it is the most important process by which the sunlit regions of the sea are refertilised by the essential plant nutrients. According to Smith (1964,1968) upwelling means an 'ascending motion of some minimum duration and extent, by which water from subsurface layers is brought to the surface layer and is removed from the area of upwelling by horizontal flow'. This use of the term upwelling follows Sverdrup (1938) and Wyrtki (1963). Upwelling may occur anywhere but it is a very conspicuous phenomenon along the west coast of continents (the eastern boundary current region) and usually the upwelled water comes from a depth of few hundred meters.

Upwelling occurs along the coasts where the prevailing winds carry the surface water away from the coast. For that the winds need not be offshore since due to earth's rotation the wind driven transport will be perpendicular to the coast for a wind parallel to the coast. According to Hidaka (1954) the most intense upwelling occurs when the wind makes an angle of 21.5° with the coastline such that the transportation is offshore.

Upwelling also occurs in the regions of diverging currents, i.e. regions where surface water masses of the ocean move from each other or away from the coast, so that water from the deep must rise, as a feature of upwelling to replace them (Sverdrup, 1938; Sverdrup et al., 1942).

As upwelling brings subsurface water to the surface layers, it induces horizontal anomalies in physical and chemical properties that normally have marked vertical gradients. Such effects can be produced by wind induced mixing or by baroclinic adjustment of density field associated with an increase in geostrophic transport, but the persistence of such anomalies can be possible indicators of upwelling.

The presence of subsurface water at the surface is accompanied by a lowering of temperature in the regions of upwelling. The water becomes colder near the shore and temperature increases offshore. Along the Somali Coast during intense upwelling the surface temperature is <14°C (Swallow and Bruce, 1966; Warren et al., 1966), while during the period of sinking it is >28°C. In regions of summer upwelling the annual range of surface temperature is less (eg. California Coast), but in regions of winter upwelling the annual range is increased (eg. Peru Coast).

Generally, in the sea salinity decreases with depth. So the usual effect of upwelling is a decrease in salinity in surface layers. But off the west coast of America surface salinity increases due to upwelling (Wooster and Reid, 1963). However, the variation of salinity in the region of upwelling depends on the vertical structure of salinity in that region.

The density structure of the regions of upwelling will be similar to the temperature structure with isopycnals rising. During intense upwelling, the pycnocline reaches the surface or may even outcrop into the naviface. The vertical density gradient below 100 meters depth decreases in many regions of upwelling and a descent of isopycnals towards the shore below this depth is observed. This is associated with a poleward undercurrent off the west coast of continents and it is a conspicuous phenomenon associated with upwelling (Yoshida and Tsuchiya, 1957; Reid et al., 1958; Hart and Currie, 1960; Reid, 1962).

Generally, the oxygen value is minimum in the thermocline layer. During upwelling, subsurface water of relatively low oxyty ascends towards the surface and the surface oxyty decreases. Hence low oxygen content is a very common feature of major regions of upwelling.

The nutrients generally increase with depth in the oceans. So high values of phosphate and nitrate are usually associated with upwelling.

During upwelling, warm, less denser surface water is replaced by cold, denser, sub-surface water. In adjusting isostatically the mean sea surface is lowered (Patullo et al., 1955; Patullo, 1963).

The cold water near the coast in the regions of upwelling creates a pressure gradient from offshore to the coast and a geostrophic flow is resulted. Hence, strong coastal currents can be expected in regions of intense upwelling.

Upwelling has a marked effect on climate along the western coasts of continents (where upwelling is very conspicuous). The eastern boundary currents flow from higher latitudes and the water temperature is generally low, but upwelling makes it still cooler, than it would have been otherwise. The cool upwelled water along the coast cools the air and increases the relative humidity. Low stratus clouds or fog are common in such regions. Upwelling increases the atmospheric pressure gradient from sea to land and the resultant sea breeze is intensified. Upwelling in summer slightly reduces the back radiation, and there is considerable reduction in the conduction from sea to the atmosphere and heat loss due to evaporation (Lane, 1965b). Despite these, there is an increase of relative humidity.

Generally, the regions of upwelling are of very high productivity. Primary productivity can be measured with C^{14} techniques: the quantitative measure is the mass of inorganic carbon by photosynthesis per unit time per unit volume or surface area of ocean. The average primary productivity of the world ocean is of the order of 0.2 gCm^{-2} day^{-1} (Steeman Nielson and Jensen, 1957). The values of the order of 1 gCm^{-2} day^{-1} given by Holmes et al. (1957) off Peru and by Anderson (1964) off Oregon can be typical of coastal upwelling regions. But there are a number of other factors that affect the overall productivity of an upwelling region. Blackburn (1965) points out that the production of phytoplankton in an upwelling region can be temporarily limited by the coldness of water, some time will elapse for zooplankton bloom, and some more time will elapse for the fishery resources to prosper, during which time the biota involved may be transported away from the upwelling region. But it is obvious that the coastal upwelling regions and equatorial regions are the most productive regions of the oceans. Upwelling and the production of fish are discussed in detail by Cushing (1971).

The coastal upwelling zone generally has a width of 50 to 100 km and it depends on the latitude and stratification of water (Yoshida, 1955a,1955b,1958b). The width of the upwelling zone normally decreases with increasing latitude. Off southern California the upwelling zone has a width of 100-200 km (Lynn, 1967) but off Oregon its width decreases to about 50 km (Smith et al., 1966), which is in agreement with Yoshida's theory. However, there are some exceptions like the Arabian Coast where the upwelling zone has a width of about 400 km (Smith and Bottero, 1977). The width of the biological productive zone often exceeds the coastal upwelling zone and off California its width varies between 200-500 km (Thrailkill, 1956,1957,1959,1961,1963).

1.2. Early works on upwelling:

The conspicuously cold water along the west coast of Africa and America was observed and recorded by early explorers and conquerors. Till the nineteenth century it was generally believed that the cold water off the coasts of Southwest Africa, Peru and California were the result of cold water advected from higher latitudes. But later it was found that the temperature was not increasing with decreasing latitudes and in some regions coldest water was observed near the equator. De Tessan (1844) explains the cool water off Peru as a result of upwelling. Witte (1880) in a theoretical discussion concludes that upwelling can occur either by the effect of earth's rotation on meridional currents or by offshore winds driving the water away from the coast. Buchan (1895) summarising the Challenger expedition also held the view that offshore winds that drive surface waters offshore were responsible for upwelling.

It is the work of Ekman (1905) that provided the basis for understanding the effect of wind stress on oceanic circulation. It shows that due to earth's rotation and frictional forces, the net transport due to the wind stress is directed 90° to the right of the wind in the northern hemisphere and to the left in the southern hemisphere. Using Ekman's theory, Thorade (1909) explains upwelling off the west coast of America. It is shown that upwelling is a direct effect of the prevailing northerly winds blowing parallel to the coast. McEwan (1912) proves from temperature anomalies off California Coast that upwelling in this region is in satisfactory agreement with Ekman's theory.

1.3. Theoretical studies:

In applying Ekman's (1905) theory quantitatively to upwelling off southern California, Sverdrup (1938), Sverdrup and Fleming (1941) arrived at a dynamical interpretation of upwelling. Following Yoshida (1967) it is known as the Ekman-Sverdrup model. Hidaka (1954) put forward a steady-state model of coastal upwelling and found that maximum upwelling occurs when the wind is at an angle of 21.5° to the coastline such that the transportation is offshore. Saito (1956) extended Hidaka's theory to consider a transient state in which upwelling and coastal currents develop in an ocean initially at rest when a wind suddenly begins to blow. Yoshida (1955a) considers upwelling associated with winds of a few days to a week duration as a transient boundary phenomenon. His theoretical computations show good agreement with actual observations off the California Coast. Yoshida and Tsuchiya (1957) considers the poleward flowing countercurrent in subsurface layers as an indicator of upwelling. Yoshida (1967) in his quasi-steady state model had carried out a comprehensive study on upwelling. He also mentions the importance of internal Kelvin waves that travel poleward along the eastern boundaries and if resonance occurs between these waves and the forcing disturbance, the poleward moving internal waves attain appreciable amplitude and can produce localised upwelling without any apparent wind. Using a form of vorticity equation Arthur (1965) discusses upwelling in eastern boundary current regions.

Ryshkov (1959) devised a nomogram for calculating the vertical and horizontal scale of upwelling. Arthur (1965), Hidaka (1960,1961b,1965,1966,1968), Belevisch (1966), Ichiye (1966) and Yoshida (1958b,1959) derived theoretically the magnitude of upwelling. But the value of vertical velocity determined by several methods differ sometimes appreciably, possibly due to the differences in the various assumptions involved.

Recently, a number of theoretical model studies on upwelling have been carried out (Garvine, 1971,1974; Hsuh and Kenney, 1972; Allen, 1973; Hurlburt and Thompson, 1973; Kindle and O'Brien, 1974; Pedulosky, 1974a,1974b,1978a, 1978b; Paffley and O'Brien, 1976; Hamilton and Rattray, 1978) Gill and Clarke (1974) discusses wind induced upwelling, coastal currents and sea level variations. The role of mixing in upwelling dynamics has been discussed by Thompson (1978). Yoshida (1981) in his study of coastal undercurrent, used a two layer, flat bottom and f-layer approximations in discussing various aspects of upwelling.

The various theoretical works on coastal and equatorial upwelling have significantly increased our knowledge on the process of upwelling. However, neither of them is complete in all respects, mainly because the total process is highly complicated and for a theoretical model various assumptions have to be made, some of them will be too ideal which may not represent the actual conditions.

1.4. Regions of upwelling:

Upwelling is a conspicuous phenomenon of the eastern boundary current region. Qualitatively upwelling should occur in regions of diverging currents usually induced by wind. The most intense upwelling is in the coastal regions off the west coasts of continents where a one-sided divergence of the surface layer is induced by a windstress parallel to the coastal boundary.

Since major coastal upwelling regions are associated with eastern boundary currents, the current system itself is referred as the upwelling region. But seasonal upwelling does occur along the east coast of continents such as the Somali and Arabian coasts and east coast of India.

1.4.1. Peru Current System

The first scientific study of the Peru Current upwelling system was done by Schott (1931). Later investigations by Gunther (1936) suggests that upwelling in this region is in general agreement with Ekman's theory and concludes that upwelling takes place from a depth of 130 m. He observed a sub-surface poleward undercurrent also. Wooster and Gilmartin (1961) studied in detail about the Peru-Chile Undercurrent associated with upwelling. Wyrtki's (1963) calculations indicate that upwelling is limited to depths less than 100 m, and the vertical velocities at 100 m depth are of the order of 10^{-5} to 10^{-4} cm sec^{-1}. At shallow depths vertical velocities are higher. Among other works those of Posner (1957), Moeda and Kishimoto (1970), Beers et al. (1971), Smith et al. (1971), Smith (1978b), Zuta et al. (1978) are noteworthy. Johnson et al. (1980) discusses upwelling in the Humboldt coastal current near Valpariso, Chile.

An unusual phenomenon in the Peru Current upwelling region is the 'El Nino'. During abnormal southern hemisphere summer, upwelling ceases and the Peru coastal region is characterised by high surface temperature, northerly winds, and heavy rain, followed by mass mortality of living organisms. 'El Nino' has been known to have occurred in 1891,1925,1941,1953,1957-'58,1965,1972 and 1976. Various theories have been put forward for explaining 'El Nino'. Wooster (1960) attributes the cause of 'El Nino' to a general weakening of atmospheric circulation. Bjerknes (1961) suggests that 'El Nino' is due to the slightly fluctuating strength of the trade winds. The disappearance of southerly winds for any appreciable time results in the overflow of warm water of tropical origin (from Equatorial Countercurrent) over the cooler water of Peru Current causing 'El Nino'. Recent works by Wyrtki (1975) and Barnett (1977) also generally, support this theory. The characteristics of various 'El Nino' events are also studied in detail (Bjerknes, 1966; Guillen, 1971; Wooster and Guillen, 1974).

1.4.2. California Current System

Upwelling is seasonal in the California Current System. The northerly winds are strongest off Baja California in April and May, off southern California in May and June and off Oregon and Washington in July and August (Smith, 1968). Upwelling in the California Current System has been studied by Sverdrup (1938), Sverdrup and Fleming (1941) and Yoshida (1955a,1955b). The subsurface poleward flowing narrow undercurrent is very well developed during the period of upwelling (Reid et al., 1958; Reid, 1962; Wooster and Jones, 1970). Upwelling off the Oregon coast has been one of the most extensively studied (Smith, 1964, 1974; Smith et al., 1966; Steffanson and Richardson, 1964; Halpern, 1974,1976; Burt et al., 1974; Moers et al., 1976; Huyer et al., 1975b; Huyer and Smith, 1974; Huyer, 1976,1977).

1.4.3. Benguela Current System

The first major report on the Benguela Current upwelling system was made by Defant (1936a). Upwelling in this region is closely associated to the wind and it is maximum during summer (Jones, 1971). From summer to winter the upwelling shifts to the northern region with the shift of the wind. Various aspects of upwelling in this region are discussed by Hart and Currie (1960), Shannon (1964), Schell (1970), Calvert and Price (1971), Jones (1971) and Andrews and Hutchings (1980), and direct measurement of current at the shelf edge of southern Benguela were made by Bang and Andrews (1974).

1.4.4. Canary Current System

Upwelling off the northwest coast of Africa is connected with the Canary Current System. Temperature anomaly charts indicate maximum influence of upwelling in spring and summer (Wooster and Reid, 1963). Wooster et al. (1976) indicates strong upwelling between 20°N and 25°N during winter and spring. Recently, detailed study has been carried out by Jones (1972), Hughes and Barton (1974), Johnson et al. (1975), Halpern et al. (1976), Huyer (1976), Barton et al. (1977) and Tomczak (1977).

Another interesting region of upwelling is the zonally oriented Guinea Current System (Ghana upwelling).

The sudden onset of upwelling in this area without any notable change in wind has attracted many scientists. Houghton (1976) attributes this to coastally trapped waves of equatorial origin. Houghton and Beer (1976) carried out a detailed study of the wave propagation during Ghana upwelling. Ingham (1970) gives a very detailed account of the hydrography of this area during the period of upwelling. Recently, Bakun (1978), Philander (1979) and Clarke (1979) have discussed Guinea Current upwelling system. Upwelling starts in June and continues upto October (Philander, 1979).

1.4.5. Equatorial Upwelling

Defant (1936b) recognised two regions of divergence in the equatorial regions, one at the equator due to winds and the other at the northern boundary of the Equatorial Countercurrent. It is noted that the equatorial upwelling regions are of very high productivity (Dietrich, 1957). Now it is generally accepted that upwelling at the equator is closely associated with the Equatorial Undercurrent. In the Pacific, Equatorial upwelling is discussed by Cromwell (1953), Austin (1958), Wooster and Cromwell (1958) and Wyrtki (1981). Austin and Rinkel (1958) discusses the variation of upwelling in the equatorial Pacific. Wyrtki (1981) indicates the velocities of upwelling to be of the order of 1 m day^{-1} in the equatorial Pacific, which is much less than the value obtained by Halpern (1980) from surface current divergence. The results of Austin and Rinkel (1958) suggest that the most intense upwelling occurs in the eastern and central Pacific and there is no evidence of upwelling in the western Pacific. According to Cromwell (1958) the shallow thermocline at the equator is due to upwelling as evidenced by the high phosphate content, but the northern boundary of the Equatorial Countercurrent does not indicate upwelling but only 'ridging'. However, Wyrtki (1966) feels that upwelling and 'ridging' reflect only the intensity of divergence rather than the associated currents.

In the Atlantic also strong equatorial upwelling is expected since the undercurrent is well developed (Neuman, 1960; Knauss, 1963).

The wind system and circulation in the Indian Ocean differ markedly from those of the other major oceans. But upwelling is evident when the Equatorial Undercurrent is established (Taft and Knauss, 1967) and evident from the works of Swallow (1964) and Sharma (1968b). But to date no comprehensive work is done on equatorial upwelling in the Indian Ocean. Also there are indications of a 'ridging' of thermocline at about 6° to 8°S, at the southern boundary of the Equatorial Countercurrent or Monsoon Current, as is evident from the works of Sharma (1976) and Sharma et al.(1982

There is also upwelling in the eastern tropical Pacific which is not directly associated either with the eastern boundary currents or the Equatorial Undercurrent (Wyrtki, 1966). Such regions include the Gulf of Tehuantepec (15°N, 95°W), the Gulf of Panama and the Costarica Dome. In the Gulf of Tehuantepec the effects of upwelling are observed between November and March (Blackburn, 1962; Roden, 1961), in the Gulf of Panama upwelling occurs from November to March (Schaefer et al., 1958; Roden, 1962; Forsberg, 1963). Upwelling is evident in the Costarica Dome from November to May (Wyrtki, 1964b).

1.4.6. Antarctic

In the Antarctic waters between 40°S and 60°S, strong westerly winds drive the West Wind Drift. Due to the effect of the Coriolis force there is some northward component to the surface flow. Near the Antarctic continent, easterly winds drive the East Wind Drift. The region between the West and East Wind Drifts is a region of divergence and hence upwelling (Deacon, 1963). There is another significant divergence zone in the Atlantic Antarctic - the Bouvet Divergence, between the Antarctic Divergence and Antarctic convergence to the north (Dietrich, 1957).

1.4.7. Indian Ocean

Theoretically upwelling was predicted along the west coast of Australia (Schott, 1933; Wooster and Reid, 1963), but actual observations failed to indicate any significant effect of upwelling. Wyrtki (1962) reported upwelling between Java and Australia during the southeast monsoon with vertical velocities of the order of 0.5×10^{-3} cm sec^{-1}.

The importance of vertical motions in the Arabian Sea and off the African Coast was mentioned by Puff (1890) as early as 1890. On the western side of the Indian Ocean, seasonal upwelling is present off the Arabian Coast (Bobzin, 1922; Smith and Bottero, 1977; Sastry and D'Souza, 1972; Currie et al., 1973). The intensity of upwelling is maximum during southwest monsoon. During March and May there was no indication of upwelling off the Arabian Coast (Royal Society, 1965).

Another region of intense upwelling is the Somali Coast, which starts in late April or early May and continues till October (Bruce, 1974), in a western boundary current. Due to the influence of upwelling, surface temperature in this region is lowered by about 15°C in 1964 (Swallow and Bruce, 1966; Warren et al., 1966). The cold water area is apparently related to baroclinic adjustment of the Somali Current, but the winds in this region are strong giving rise to an offshore Ekman transport. This unique western boundary current was studied in detail by Stommel and

Wooster (1965), Swallow and Bruce (1966), Warren et al. (1966), Bruce (1973,1979), Evans and Brown (1981) and Murthy et al. (1982). Surface divergence in the northern Indian ocean are discussed in detail by Sharma (1971).

Intense upwelling takes place off the west coast of India (Ramasastry and Myrland, 1959; Ramamirtham and Jayaraman, 1960; Banse, 1959,1960,1968,1972; Sharma, 1966, 1968a,1978; Ramamirtham and Rao, 1973). Various aspects of upwelling and its influence on fishery are evident in earlier works (Chidambaram and Menon, 1945; George, 1953; Carruthers et al., 1959; Jayaraman and Gogate, 1957; Subrahmanyam, 1959,1973; Subrahmanyan and Sharma, 1965; Sankaranarayanan and Qasim, 1967). Some other works related to upwelling are carried out by Ramasastry (1959), Ramamirtham and Patil (1965), Patil et al. (1964), Jayaraman et al. (1959,1961), Ramamurthy (1963), Darbyshire (1967), Reddy and Sankaranarayanan (1968), Noble (1968), Rao et al. (1974), Purushan and Rao (1974) and Lathifa and Murthy (1978).

Seasonal upwelling takes place off the east coast of India (Sewell, 1929; LaFond, 1954,1957; Varadachari, 1956, 1958,1961,1963; Murthy and Varadachari, 1968). A few other works related to upwelling are done by LaFond and Borreswara Rao (1955), Ganapati et al. (1956), Balaramamurthy (1957), Ramasastry and Balaramamurthy (1957), LaFond and Bhavanarayana (1957), Raghuprasad (1957), Ganapati and Sarma (1958), LaFond (1958a,1958b), Varma and Reddy (1959), Ramasastry (1963), Jayaraman (1965), LaFond and LaFond (1968) and Anand et al. (1968). Panikkar and Jayaraman (1966) discusses in detail the biological and oceanographical differences of the Arabian Sea and Bay of Bengal. On the eastern side of the Bay of Bengal, off the Burma Coast upwelling takes place during the pre-monsoon period (LaFond and LaFond, 1968).

1.4.8. Other regions

Localised upwelling does occur in many coastal regions. Upwelling off Nova Scotia is very much related to the coastal winds (Hachey, 1937; Longard and Banks, 1952). Garner (1961) reports upwelling off the northeast coast of South Island of New Zealand. Upwelling has been reported off northeast coast of Florida (Green, 1944), North Carolina (Wells and Gray, 1960) off Brazil (Emilsson, 1961), in the Gulf of Mexico (Roden, 1972), and in the Carribean Coast of Venezeula (Richards, 1960; Fukuoka et al., 1964; Hulburt, 1966; Fukuoka, 1965,1966). There are also evidences of upwelling off the coast of Yucatan in Mexico and north coast of Cuba (Bogadanov et al., 1968; Khromov, 1965b). Recently, upwelling has been reported off the Cantebury Coast (Heath, 1972), off the eastern coast of Taiwan (Mashahida, 1972), in the Beaufort Sea (Hufford, 1974) and in smaller bodies of water like Lake Superior (Neibauer et al., 1977).

1.5. DESCRIPTION OF THE AREA

The west coast of Peninsular India forms a narrow belt of low land lying between the sea and the Western Ghats which extends throughout the whole length of the Peninsula varying in width from 30 to 169 km inland and running in a direction north-northwest to south-southeast. There are a number of short rivers, many of which drain into the backwaters of varying width parallel to the coast. The continental shelf is about 50 to 60 km wide off the southwest coast of India and increases northward, and off Bombay it is about 220 km wide.

The east coast of India lies approximately in a south-north direction between 10°00N to 16°00N. Between 16°00N and 20°00 the coast lies in a south-southwest to north-northeast direction. The number of rivers that drain into the Bay of Bengal is less but the influence of these rivers on the oceanography of the Bay of Bengal is marked since they bring large volumes of freshwater into the sea. The continental shelf is narrow off the east coast compared to that off the west coast of India and it is less than 45 km in most of the regions.

The northern Indian Ocean which includes the Arabian Sea and Bay of Bengal is characterised by the periodic monsoons. A seasonal low pressure area developing in Jacobabad during summer causes the wind systems to blow persistently from the southwest during this period. During winter, the monsoons issuing from a high pressure source forming over Tibetan Plateau, come from the northeast. The northern Indian Ocean wind system coupled with the Himalaya mountains, thus creates the worlds heaviest rainfall. The heaviest rains that occur in the Himalayan valleys during southwest monsoon and the rains that occur on the east coast of India during autumn when the wind system is unstable and reversing, drain into the Bay of Bengal, while the southwest monsoon rains that occur due to orographic precipitation over the Western Ghats drain into the Arabian Sea.

The direction and strength of the monsoons vary from one locality to the other. The northeasterly winds of the northeast monsoon begin to blow in the northern part of the Bay of Bengal from October but it is not fully established in the southern part of the Bay until the middle of November and these winds continue till the end of January. In the Arabian Sea northeasterly winds prevail from November to March but these winds are generally weak. The winds in the Bay of Bengal changes its direction from February and an anticyclonic circulation develops in March (Anon., 1952). During March, April and

May the coastal winds off the east coast are southerly, or slightly south-westerly (Anon., 1952). The southwest monsoon is established in the Arabian Sea by late May but in the Bay of Bengal it is fully established only by the middle of June. The winds are strongest in July-August. Of the two monsoons, the southwest monsoon prevails over a much longer period of the year and is stronger and steadier than the northeast monsoon in the Arabian Sea. The northeast monsoon predominates in the eastern part of the Indian Ocean while the southwest monsoon plays a major role in determining the oceanographical conditions of the western Indian Ocean. The winds are generally weak and variable during the transition periods, March-April and October-November.

The surface currents in the Arabian Sea and Bay of Bengal undergo seasonal variations. The surface currents off the west coast of India flow towards south from February to October and are reversed during the remainder of the year. The current is strongest during July-August. The maximum speed for any 2^{o} latitude - longitude quadrangle in the eastern Arabian Sea is less than 40 cm sec^{-1} (Anon., 1952). But near the coast greater velocities can be expected. The northerly currents are generally weak.

Off the east coast of India the coastal current is towards north from February to August and are reversed during the remainder of the year. The northerly currents are strongest during April-May. The maximum speed for any 2° latitude - longitude quadrangle in the Bay of Bengal is about 40 cm sec^{-1} or slightly higher in some places. Near the coast the velocities are much greater and off the Andhra Coast speeds upto 200 cm sec^{-1} (4 knots) are observed (Ganapati and Murthy, 1954). The southerly currents are generally weak.

1.6. SECTION II - MATERIALS AND METHODS

In the present study inferences on upwelling and sinking are drawn from the seasonal variation of temperature and σ_t. Additional inferences are made from the divergence of surface currents, windstress and sea level variations off the west and east coasts of India.

1.6.1. Analysis of temperature and σ_t

The data used for the analysis of temperature and σ_t have come from the cruises of various research vessels. For a better understanding of the process of upwelling vertical sections of temperature and σ_t are used. Temperature and σ_t are better indicators of upwelling than the rest of the variables like salinity, oxygen and phosphate. The oxygen and phosphate values are liable to fluctuations due to biochemical process and salinity is not at all a dependable indicator of upwelling especially for the Indian coasts because its distribution is controlled by heavy rainfall and coastal currents. Temperature is selected because its distribution with depth in the sea is monotonic. Stratification of the water is governed by the density and so the isolines of density in the vertical section indicate the movement of water along the isopycnals. So vertical sections of temperature and σ_t are prepared in the present study.

For the west coast of India oceanographic data collected during April 1964 to April 1965 by R.V.Varuna of CMFRI have been used for monthly vertical sections of temperature and σ_t along 10°00N and 8°50N (Stn.No.2000 to 3000,- Anon., 1967). Due to unavailability of data along 10°00N for November and December of 1964 the previous years data is used. The section along 8°50'N has data for only 8 months (from March to October) and for January and February sections along 9°00 are used. For the sections off Kasaragod and Karwar diagrams are reproduced from FAO/PFP progress reports (Anon., 1973; Anon., 1976). The Kasaragod section is covered in 1974, while the Karwar section is covered during 1971-'72. Two sections off Ratnagiri and a time series section of temperature off Cochin are also presented and the figures are reproduced from Anon (1973).

Off the east coast of India, the data is not so continuous except off Waltair where monthly variations of temperature and σ_t are available except for June, July and August (from Varadachari, 1963). For vertical sections off Waltair and Madras, data collected during I.I.O.E. by INS KISTNA and R.V.Anton Brunn are utilised. Further a few figures are reproduced from LaFond and LaFond (1968), Murthy and Varadachari (1968).

1.6.2. Surface divergence

Current data from the Dutch Atlas (Anon., 1952) for each 2^o latitude - longitude quadrangle have been used to evaluate the horizontal divergence.

Horizontal divergence is given by

$$\nabla_H \cdot \vec{V} = \frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} - \frac{v \tan \Phi}{R} \qquad (1.1)$$

Using finite differences in place of partial differentials

$$\nabla_H \cdot \vec{V} \approx \frac{\Delta u}{\Delta x} + \frac{\Delta v}{\Delta y} - \frac{v \tan \Phi}{R} \qquad (1.2)$$

where x and y are directed towards the east and north respectively, and u and v are the components of the current vector along east and north respectively, Φ the latitude of the place and R the radius of the earth (Sherman, 1952). The term $\frac{v \tan \Phi}{R}$ in equation (1.2) represents a contribution to divergence due to convergence of meridians, and this term will be of importance only at higher latitudes and greater meridional components. For the area under consideration this term can be neglected.

Hence, using the formula

$$\nabla_H \cdot \vec{V} \approx \frac{\Delta u}{\Delta x} + \frac{\Delta v}{\Delta y} \qquad (1.3)$$

the horizontal divergence of the surface current vectors has been computed for all the 12 months off the east and west coasts of India. The result obtained does not represent a synoptic picture, but an average of a few hundred kilometers, and it can give only qualitative inference about the process of upwelling. Furthermore, its representation near the coasts is of a limited nature.

1.6.3. Windstress

Seasonal distribution of windstress components normal and parallel to the average trend of the coastline off Cochin, Karwar and Bombay on the west coast, and off Madras and Visakhapatnam on the east coast are computed. The wind data are from the Dutch Atlas (Anon., 1952).

Windstress τ (dynes cm^{-2}) is computed using the formula

$$\tau = \rho C_D W^2 \qquad (1.4)$$

where ρ is the density of air (in g/cc), C_D is the drag coefficient and W is the wind velocity (in cm sec^{-1}).

The value of C_D is different from that used by Hidaka (1958). For the present computation the value of C_D used is 1.3×10^{-3} following Brocks and Krugermeyer (1972).

1.6.4. Sea level

Monthly sea level variations are studied for Cochin and Mormugao along the west coast and for Visakhapatnam and

Madras along the east coast. The data used for the present study are from Banse (1968), Kesava Das (1979), Ramanadham and Varadarajulu (1964), and Varadarajulu and Dhanalakshmi (1975).

CHAPTER II

SEASONAL VARIATION OF TEMPERATURE AND DENSITY OFF THE WEST AND EAST COASTS OF INDIA

The analysis of temperature and density have immense importance in the study of upwelling and sinking. Variations in upwelling and sinking will be reflected in the temperature and density fields. In this chapter the seasonal variation of temperature and density at different localities off the west and east coasts of India are presented and the surface and subsurface currents are inferred from the slope of isotherms and isopycnals. No conclusions are drawn regarding upwelling and sinking since these are dealt in separate chapters.

Temperature and density fields off the west coast of India

Vertical sections of temperature and σ_t are prepared off Quilon ($8^{o}50'$N), off Cochin ($10^{o}00'$N), off Kasaragod ($12^{o}31'$N) and off Karwar ($14^{o}47'$N). Two sections off Ratnagiri ($16^{o}59'$N) are also presented.

2.1. Vertical sections of temperature and σ_t off Quilon (along $8^{o}50'$N):

Vertical sections of temperature and σ_t off Quilon are presented in Figs.1-10. The section along $8^{o}50'$N were covered during the period March 1964 to October 1964. Due to lack of data for November and December it could not be presented. For January and February sections along 9°00'N are utilised.

2.1.1. March

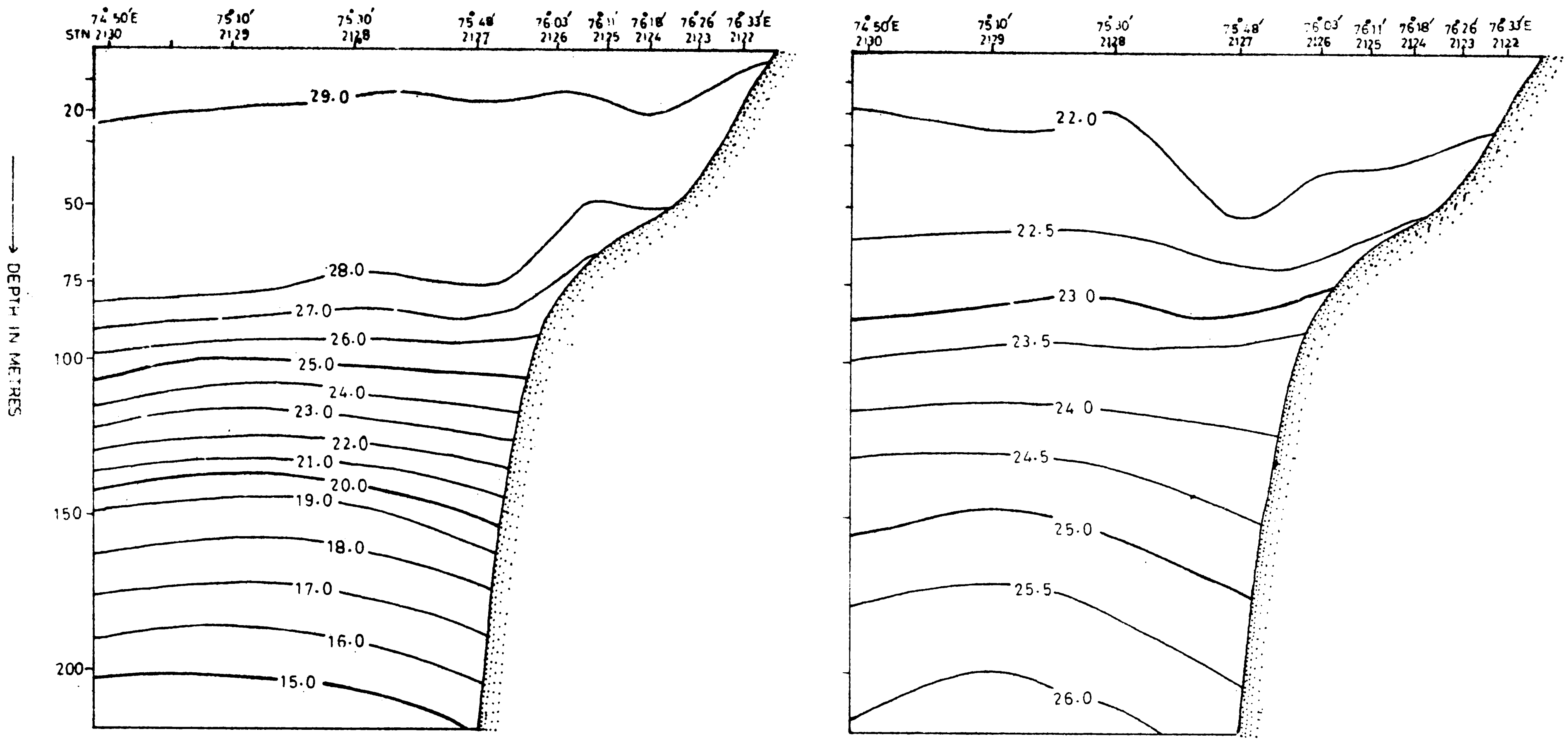
The isotherms and isopycnals slope up towards the coast from about 90 km indicating a southerly current in the upper 100 m (Fig.1). The downward tilt of isopycnals towards the coast represents a northerly current in the layers below 100 m. The depth of mixed layer is about 90 m and the surface temperatures are fairly high over 29°C.

2.1.2. April

The depth of the mixed layer decreases during April compared to that present in the previous month, though the surface temperature has increased to over 30°C (Fig.2). The upward tilting of isotherms and isopycnals towards the coast is marked suggesting a strengthening of the southerly flow. The offshore-onshore density gradient is positive above 80 m but it is very weak.

2.1.3. May

The isotherms and isopycnals continue to slope more and more towards the surface indicating a continued increase in the strength of the southerly current in the



(a) (b)

FIG.1. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 8°50'N, MARCH 7, 1964.

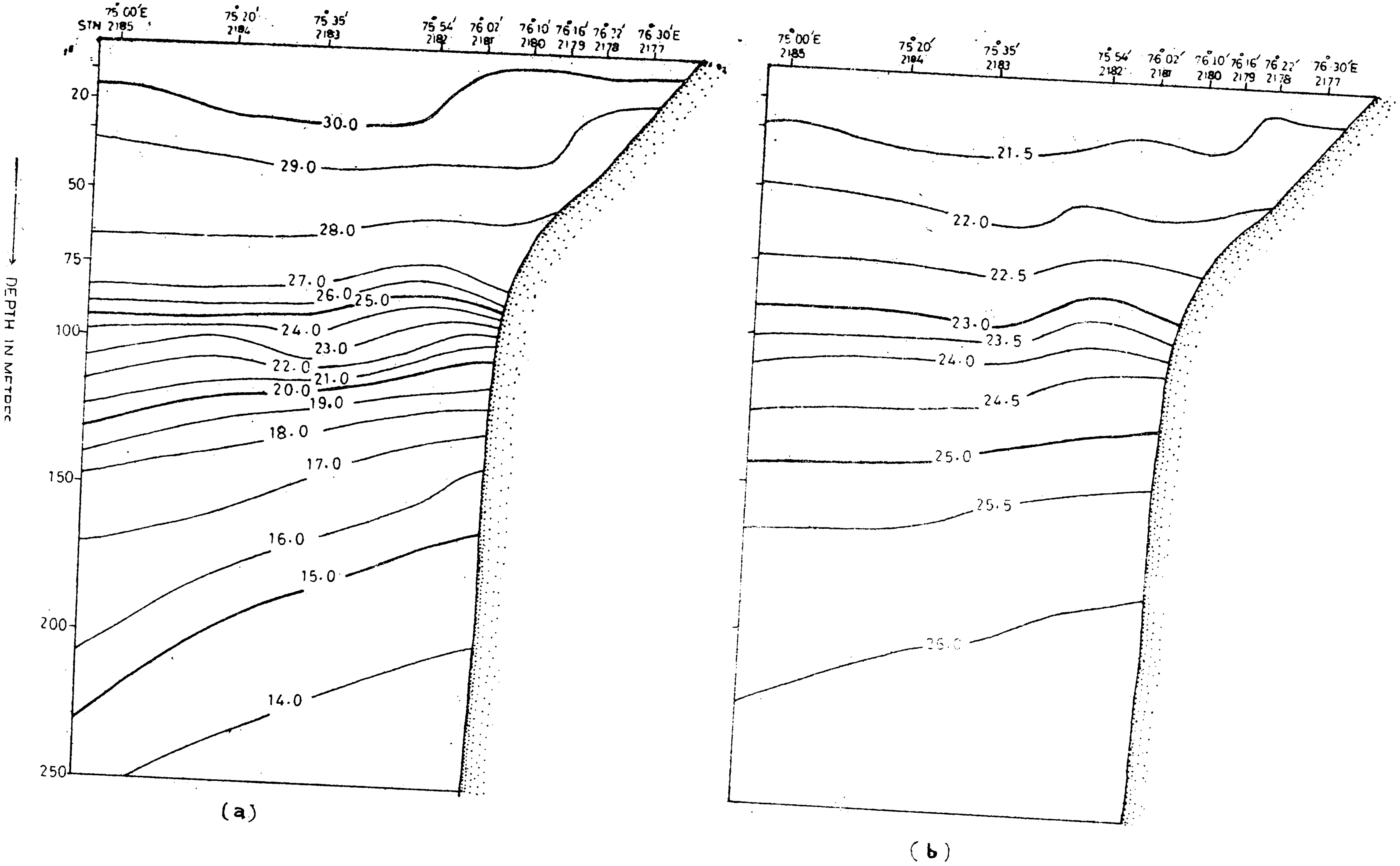
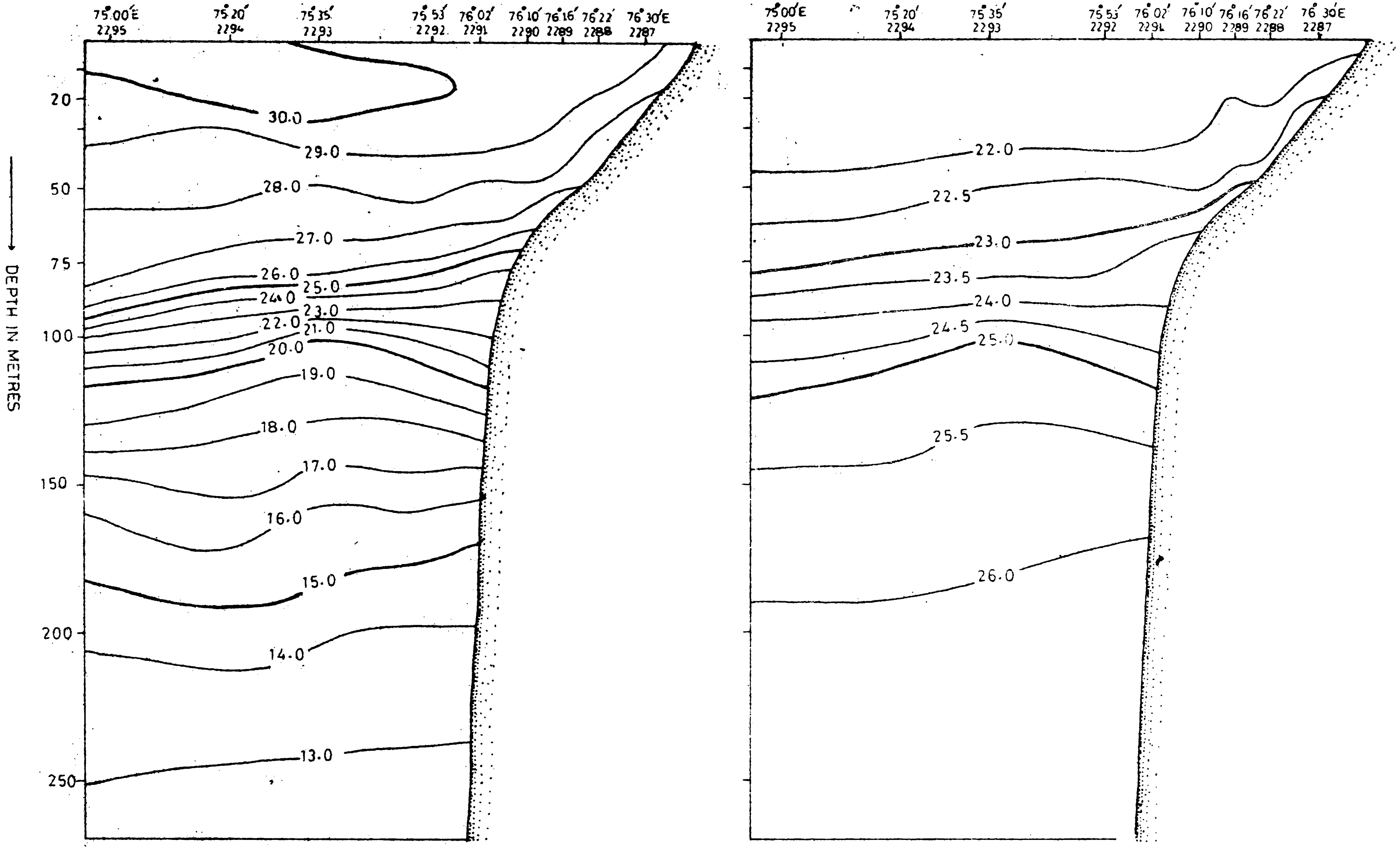


FIG.2. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 8°50'N, APRIL 6, 1964.



(a)

(b)

FIG.3. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 8°50'N, MAY 10-11, 1964.

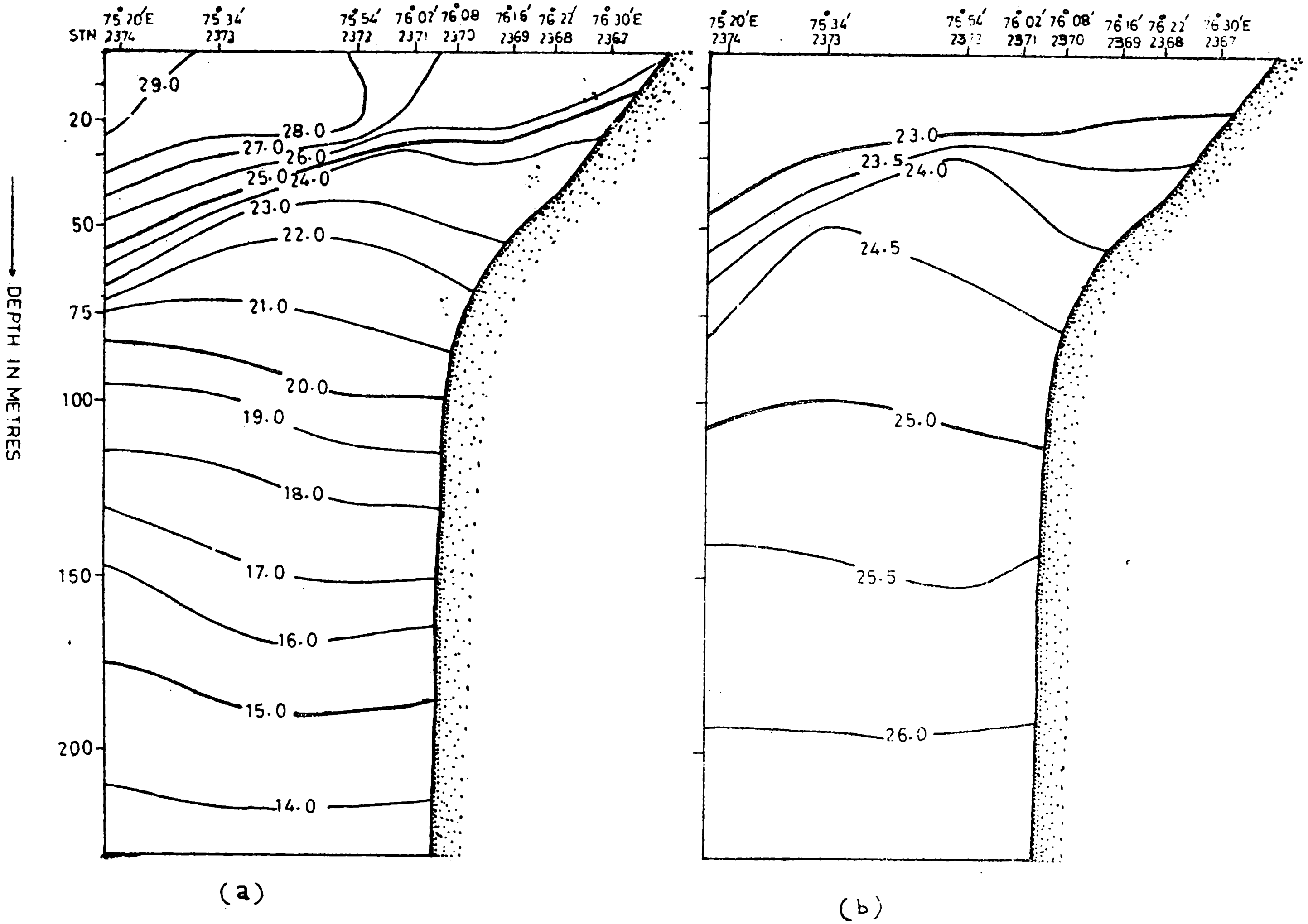
upper 100 m (Fig.3). A weak northerly flow below 100 m in the continental slope is also evident. The surface temperature is above 29°C and the thermal structure shows a negative gradient towards the coast between 20 and 85 m. A decrease in temperature and an increase in density at all depths above 200 m are noticed during the period April to May and this variation is conspicuous between 50 and 100 m. The depth of mixed layer is about 60 m in nearshore regions and it increases offshore.

2.1.4. June

The surface temperature drops considerably from May to June. It is slightly above 26°C near the coast and gradually increases offshore (Fig.4). The orientation of isotherms and isopycnals suggests a southerly current in the surface layers and a weak countercurrent below 60 m. The thermocline is observed very near the surface and the depth of mixed layer increases offshore. A decrease in temperature and an increase in density are found in the upper 200 m between May and June, and the decrease of temperature is conspicuous in the depth range of 20 to 75 m

2.1.5. July

The thermocline reaches the surface in nearshore regions (Fig.5). Several of the isotherms do even outcrop into the naviface. The surface temperature is less than

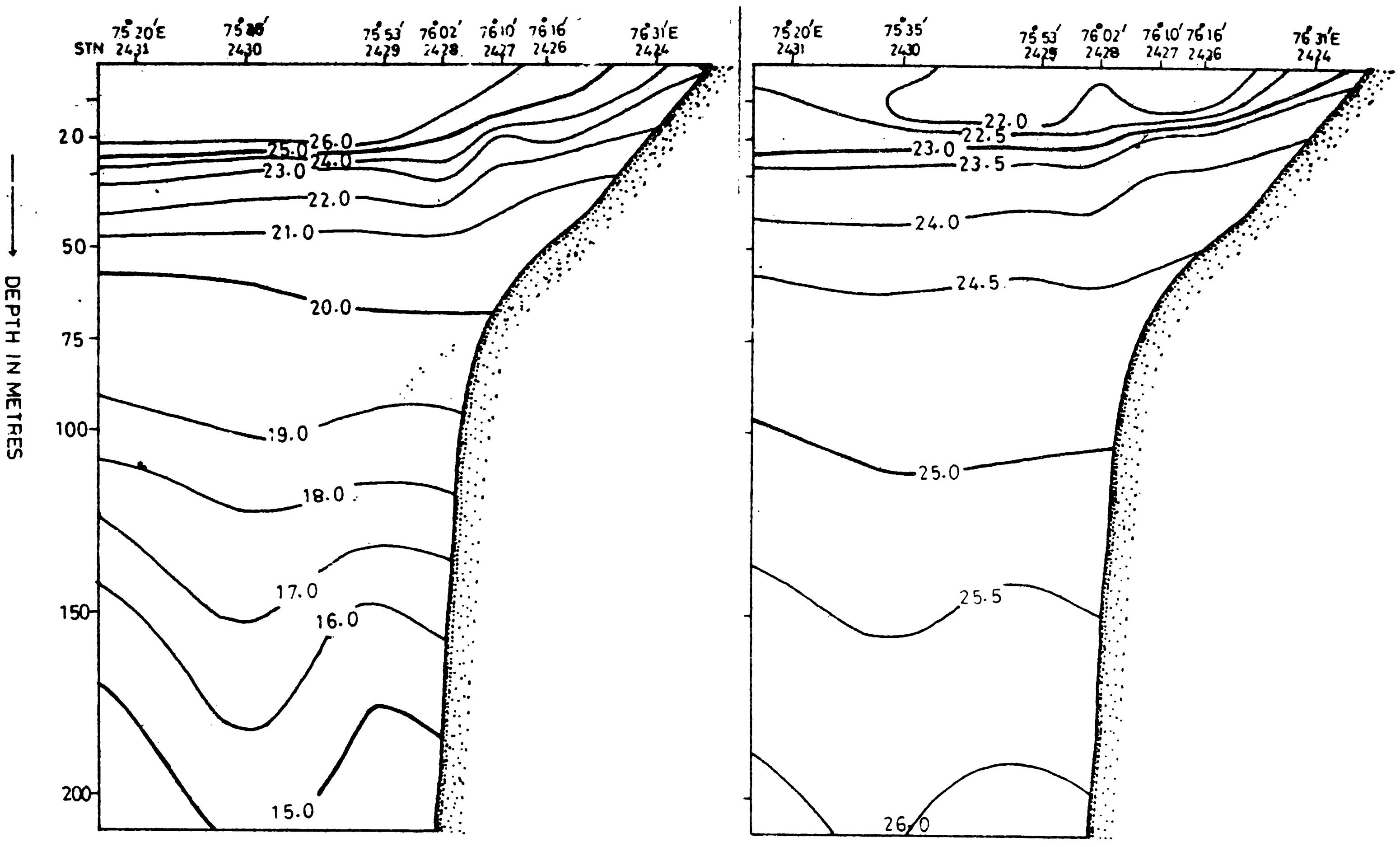


(a)

(b)

FIG. 4. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 8°50'N, JUNE 7, 1964.



(a) (b)

FIG.5. VERTICAL SECTIONS OF (a) TEMPERATURE(°C) AND (b) σ_t (g/l)

ALONG 8°50'N, JULY 9-10, 1964.

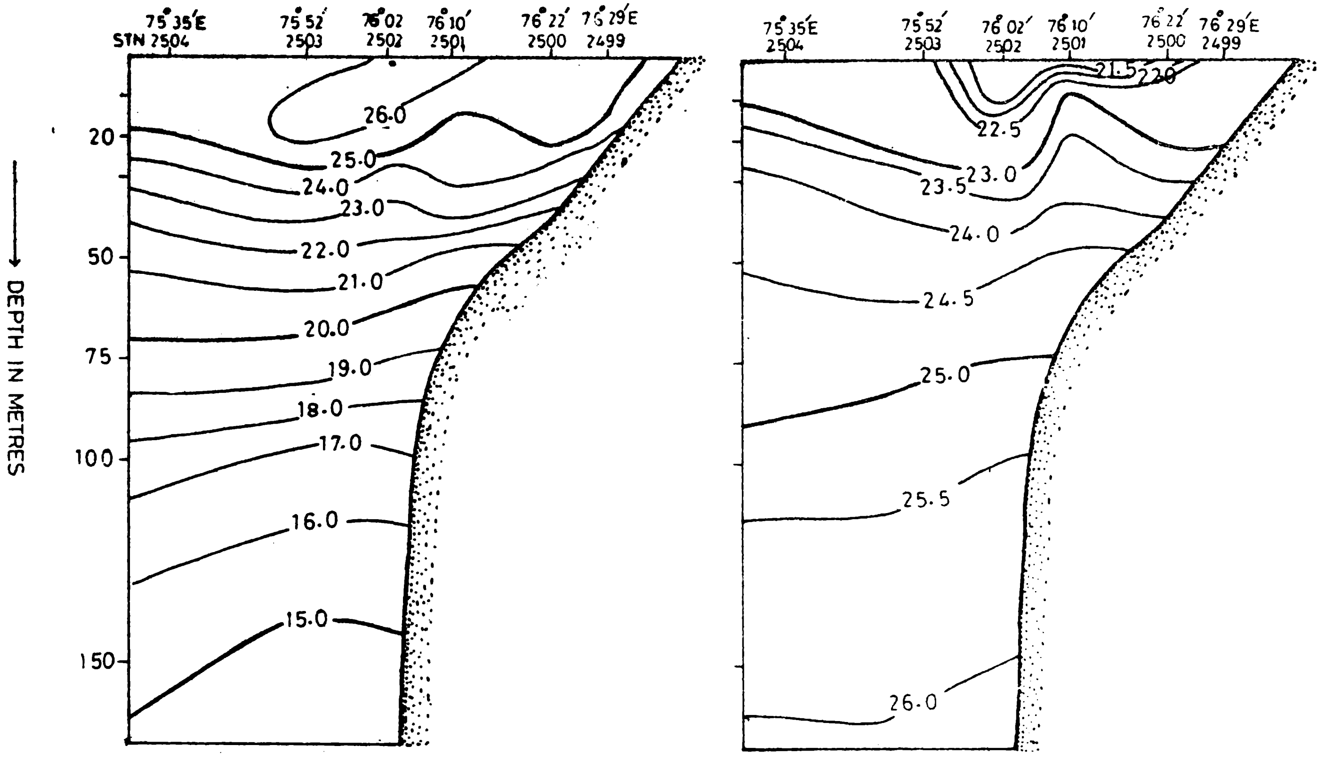
24°C near the coast and increases offshore. The upsloping of isotherms and isopycnals towards the coast suggests a strong southerly flow and a subsurface countercurrent is indicated below 150 m. Although there is a decrease of temperature at all depths from June to July, the density in the upper 10 m decreases due to heavy rains and river discharge. The offshore-onshore temperature gradient is negative in the upper layers and strongest at about 30 m.

2.1.6. August

During this month the upsloping of isotherms and isopycnals towards the coast is less marked compared to July indicating a weakening of the southerly current in the outer shelf (Fig.6). In the inner shelf region the flow is weak northerly. The surface temperature in nearshore and offshore regions are below 26°C and the thermocline is found very close to the surface. Between July and August, there is a slight increase in temperature at the surface and at subsurface depths.

2.1.7. September

There is an increase in temperature and a decrease in density at all depths in the continental shelf and slope region compared to the previous month (Fig.7). The density distribution suggests a strong southerly current in offshore



(a)

(b)

FIG. 6. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 8°50'N, AUGUST 6-12, 1964.

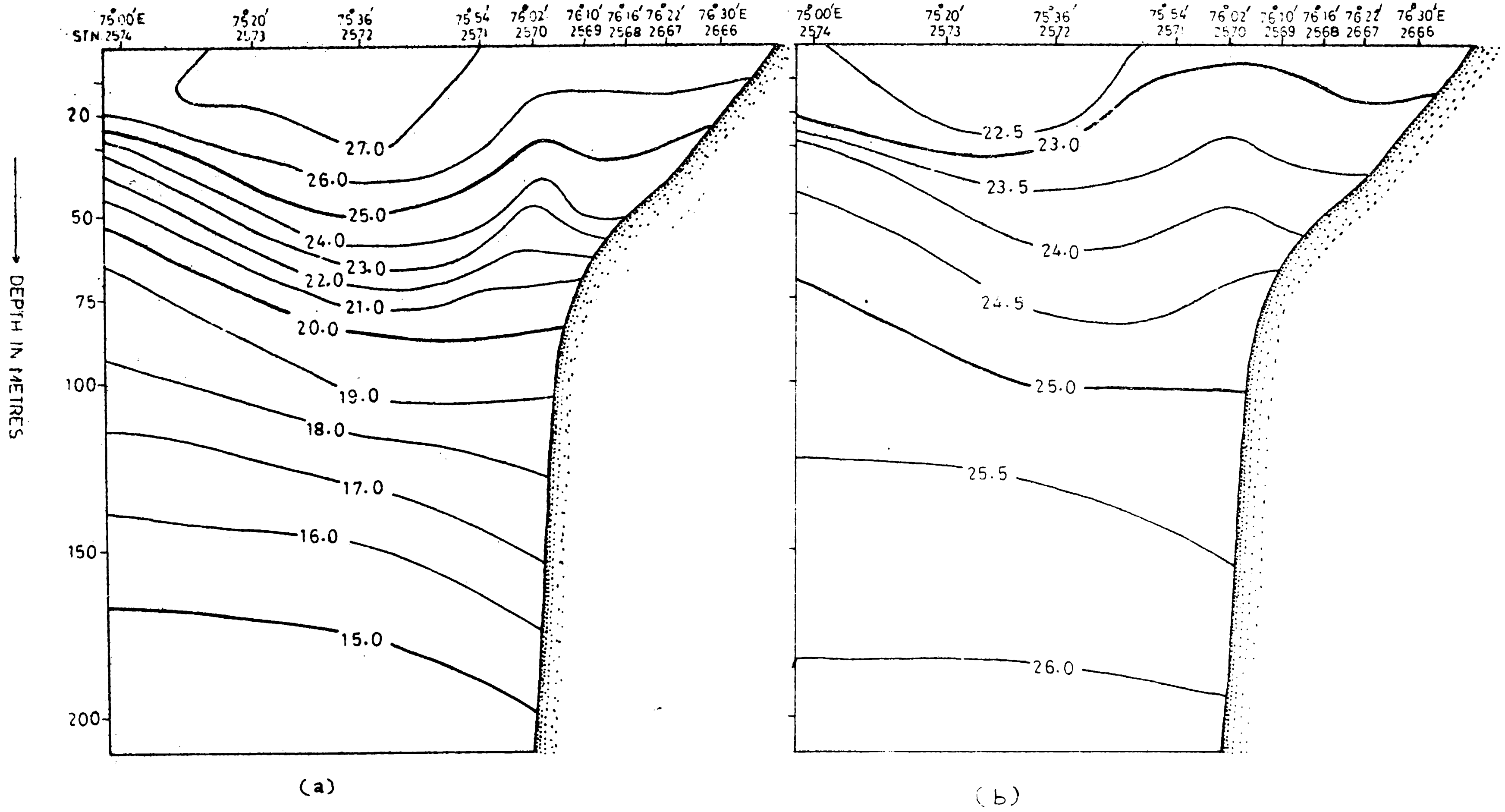
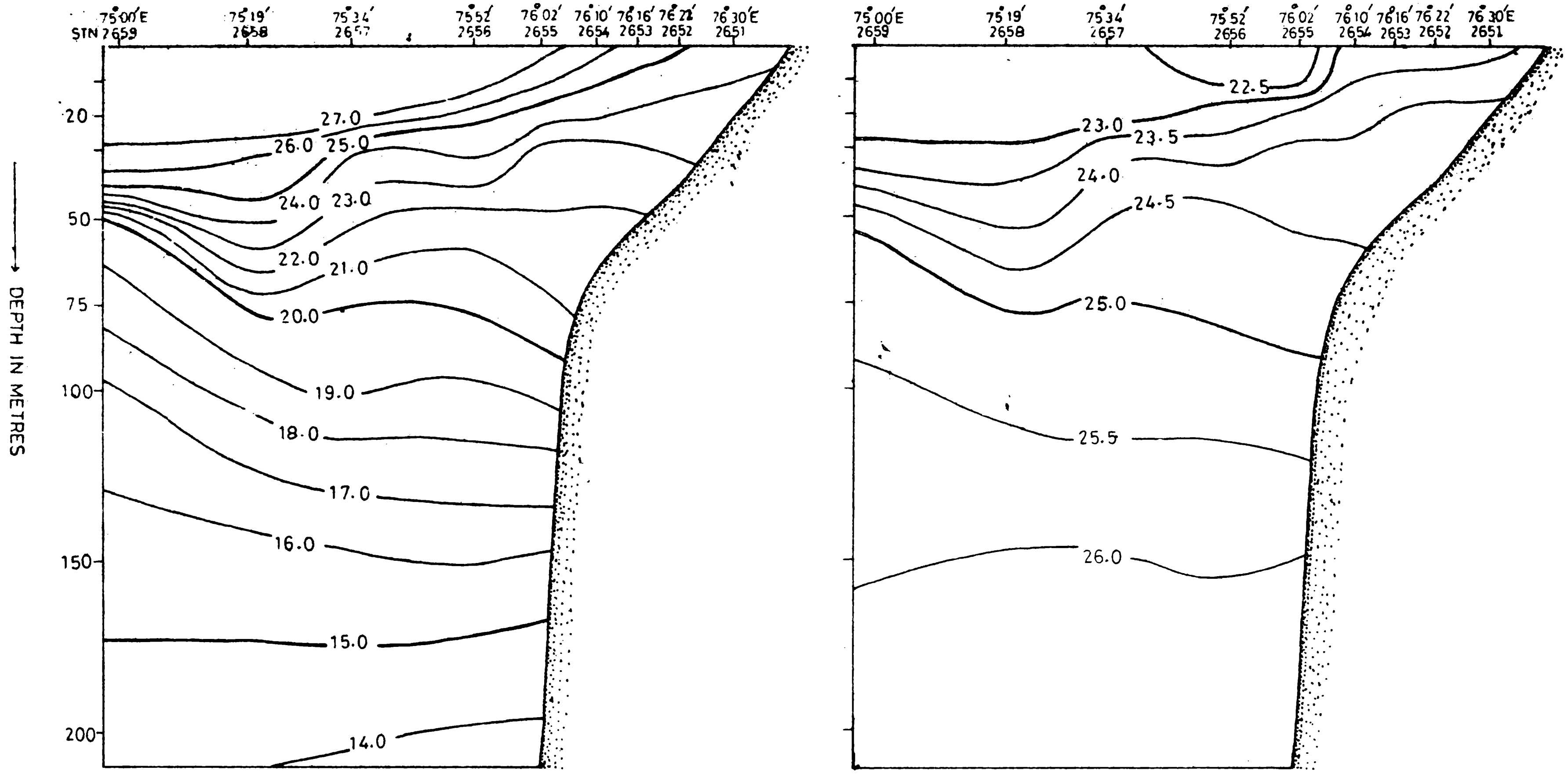


FIG.7. VERTICAL. SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 8°50'N, SEPTEMBER 12-13, 1964.



(a)

(b)

FIG.8. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 8°50'N, OCTOBER 10-11, 1964.

regions, but in nearshore regions the flow is weak northerly in the upper 30 m. The surface temperatures are above 26°C and the depth of the mixed layer is about 40 m in the continental shelf.

2.1.8. October

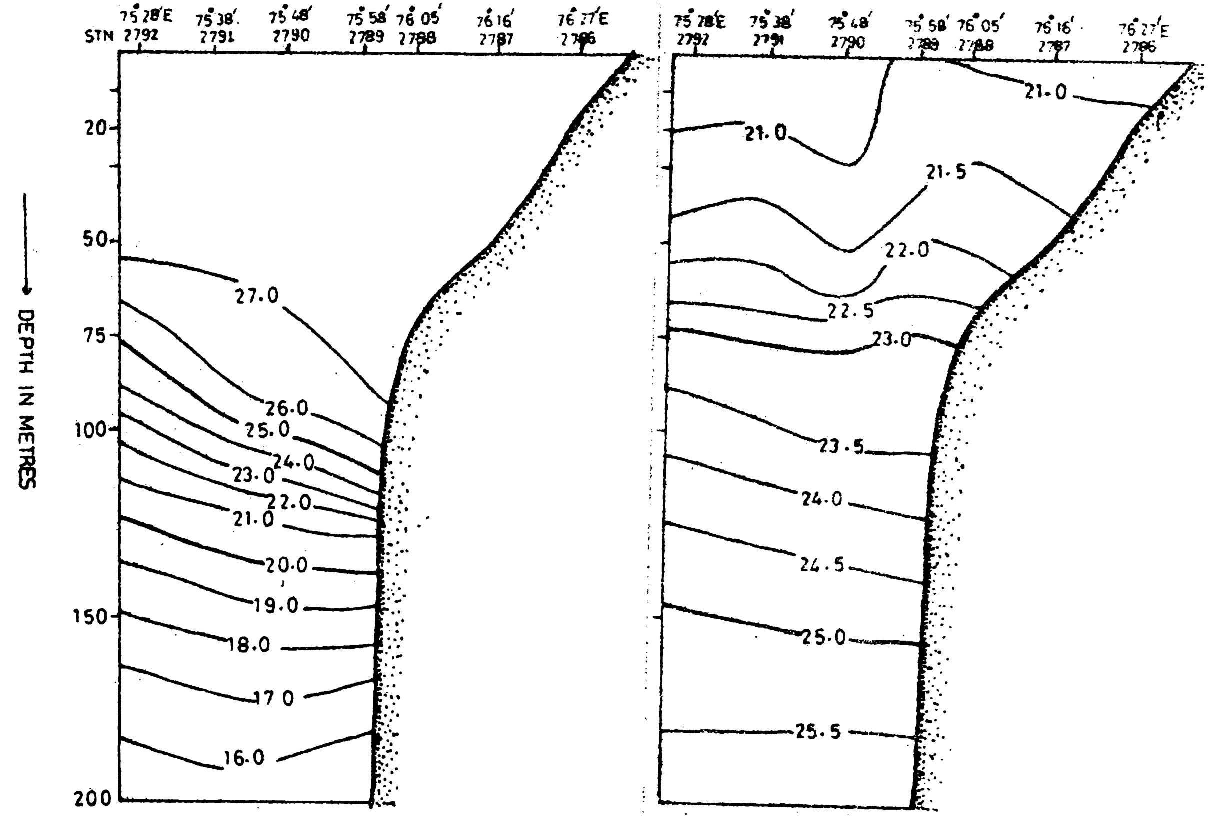
The oceanographical conditions change considerably from September to October. Near the coast, the surface temperature is below 25°C and increases offshore (Fig.8). The surface flow is southerly, but below 50 m a counter-current is indicated. The thermocline is observed at the surface in the continental shelf. An increase in density and a decrease in temperature at all depths occur from September to October, and they are conspicuous in the upper 50 m of the continental shelf.

2.1.9. January

In this month the isopycnals slope down towards the coast indicating a northerly current in the nearshore regions (Fig.9). The depth of mixed layer is more than 100 m in the nearshore and slightly less in offshore regions. The surface temperatures are uniform - over 27°C.

2.1.10. February

The condition in the surface layers continues to be the same as in January (Fig.10). However, below 75 m

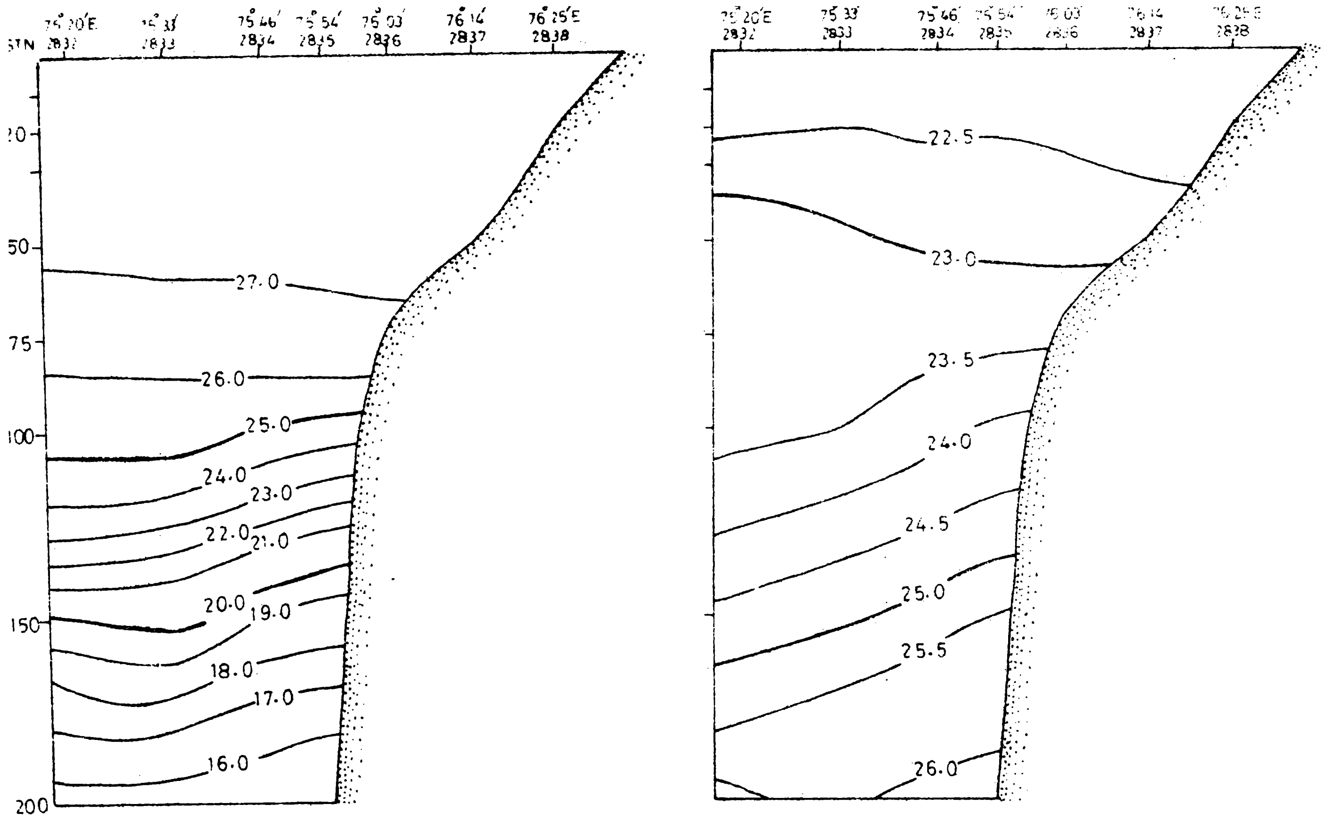


(a)

(b)

FIG. 9 . VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 9° 00′N, JANUARY 7, 1965.



(a)

(b)

FIG.10. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 9 00 N, FEBRUARY 6, 1965.

the isotherms and isopycnals slope up towards the coast which suggest a southerly current in that region, though the surface current is a weak northerly. An increase in density and a decrease in temperature are evident below 75 m from January to February.

2.2. Vertical sections of temperature and σ_t off Cochin:

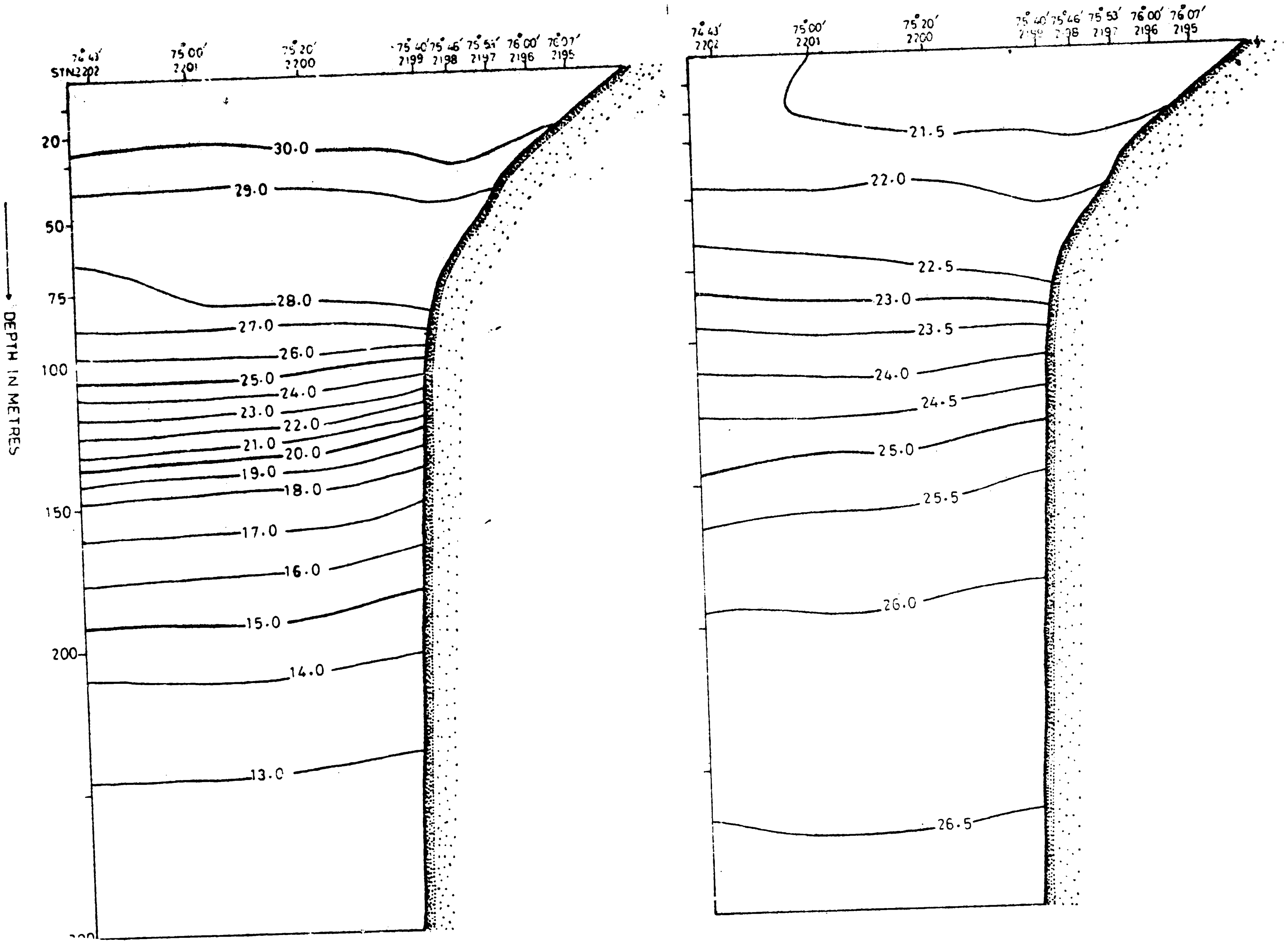
For the present study oceanographic data collected during April 1964 to March 1965 are used (Figs.11-22). Due to unavailability of data for November and December of 1964 the previous years data are used. Except for November and December the data were collected along 10°00'N, whereas for November and December the stations were occupied in a direction almost perpendicular to the coast.

2.2.1. April

The isotherms and isopycnals slope up towards the coast indicating a southerly current in the surface layers and a weak northerly current is indicated between 75 m and 100 m (Fig.11). The surface temperature is above 30°C and is fairly uniform in nearshore and offshore regions. The depth of mixed layer is about 90 m in the continental slope region and it increases offshore.

2.2.2. May

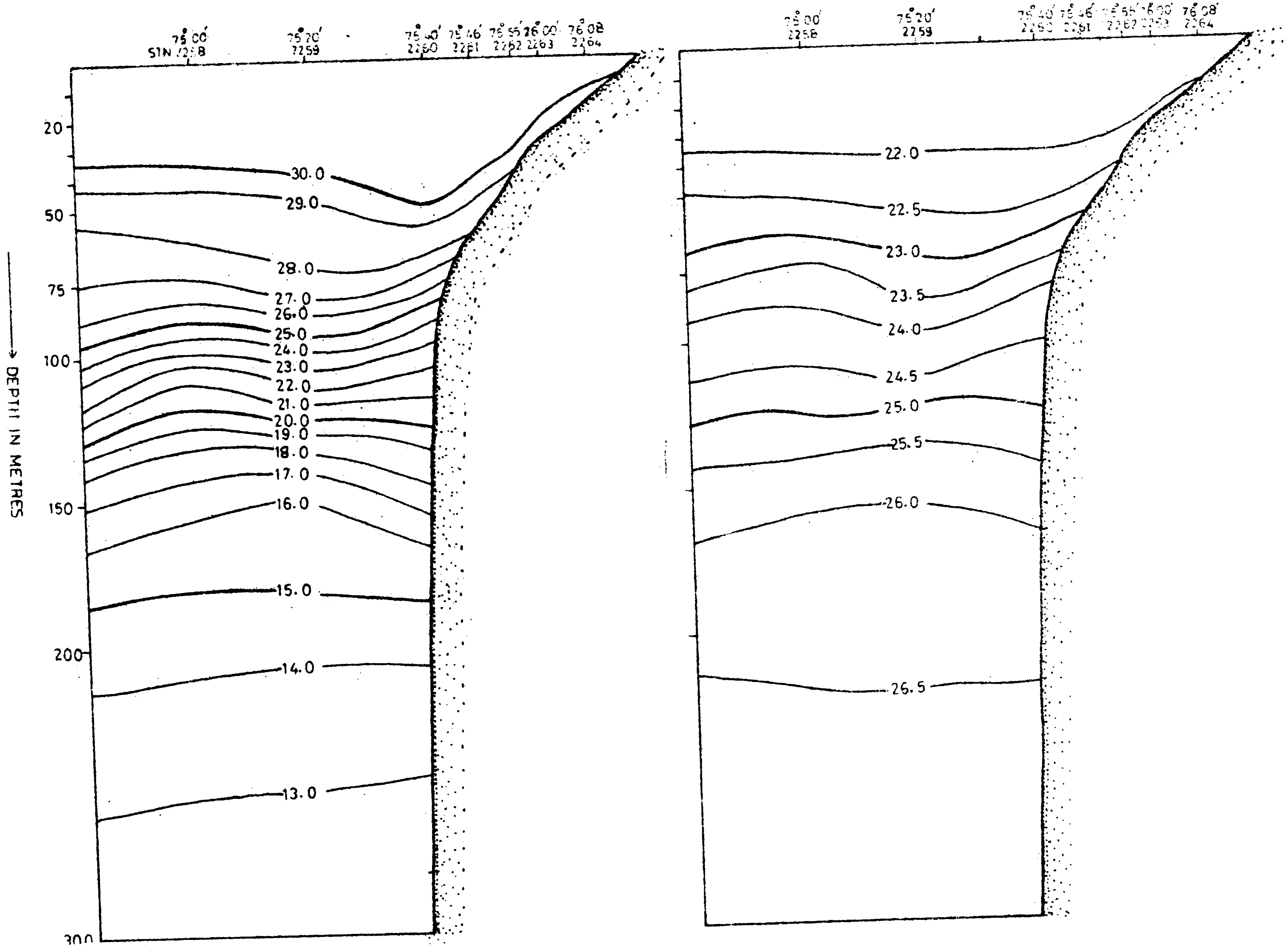
The baroclinic field is well developed by May (Fig.12). In the nearshore regions the isotherms



(a) (b)

FIG. 11. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 10°00′N, APRIL 8, 1964.



(a) (b)

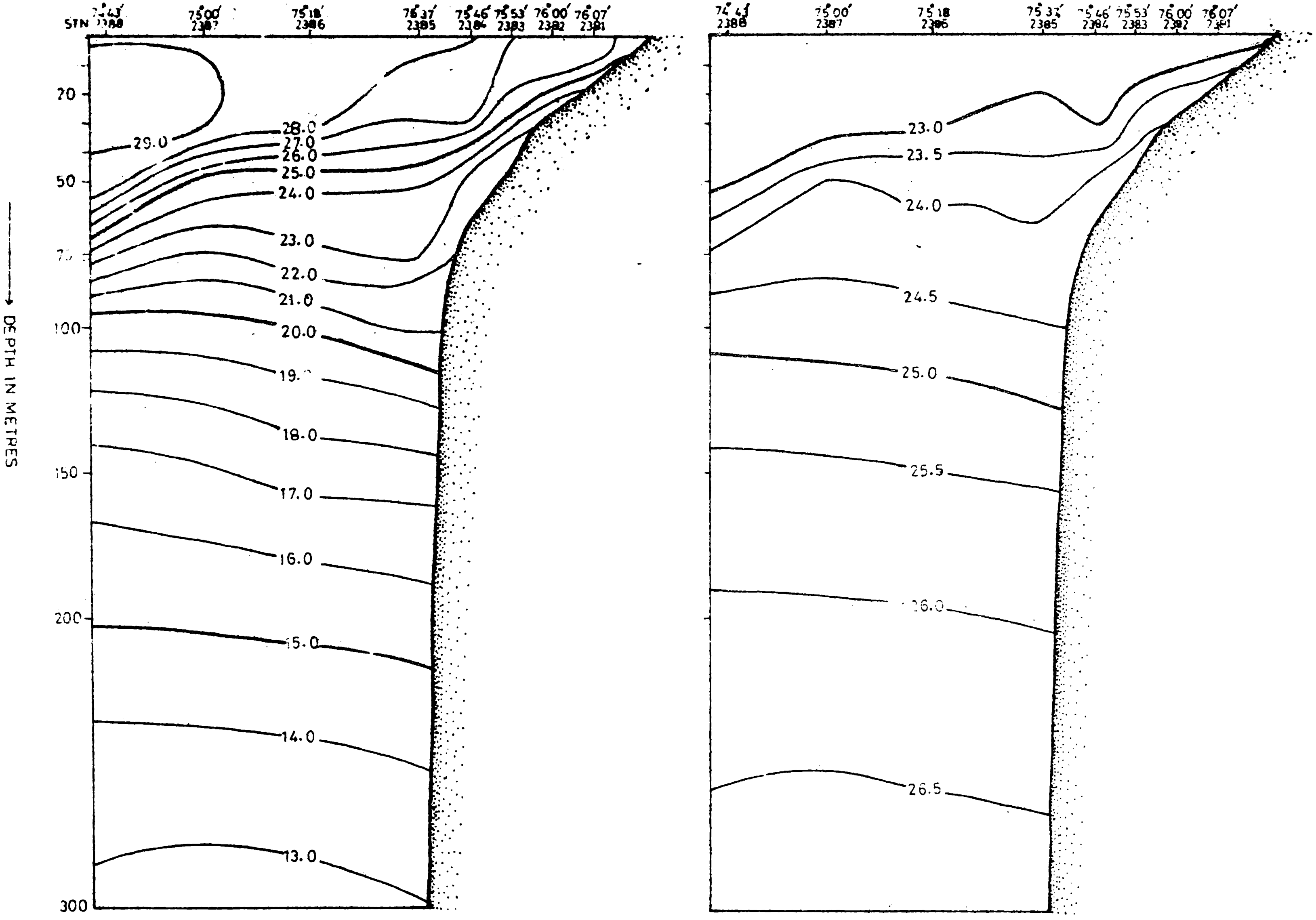
FIG. 12. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 10°00'N, MAY 4-5, 1964.

and isopycnals show marked upsloping indicating a stronger southerly current than in April. The surface temperature continues to be above 30°C, but the depth of mixed layer has decreased considerably in the nearshore regions compared to April to a value of about 60 m in nearshore regions and increases offshore. Between 50 and 150 m a general decrease in temperature and an increase in density is observed from April to May. The downward tilting of isopycnals towards the coast below 120 m indicates a northerly current in that region.

2.2.3. June

By June the nearshore surface temperature decreases to less than 26°C (Fig.13). The surface temperature increases to 28°C at about 45 km from the coast. The thermocline is found almost at the surface in the continental shelf. The marked upsloping of isotherms and isopycnals towards the coast indicates a strong southerly current. Below 80 m, a countercurrent along the continental slope is again indicated. Above 200 m considerable decrease in temperature and increase in density are noticed from May to June and they are more prominent in nearshore regions. The offshore→onshore temperature gradient is negative from about 100 km in the upper 75 m.



(a)

(b)

FIG.13. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

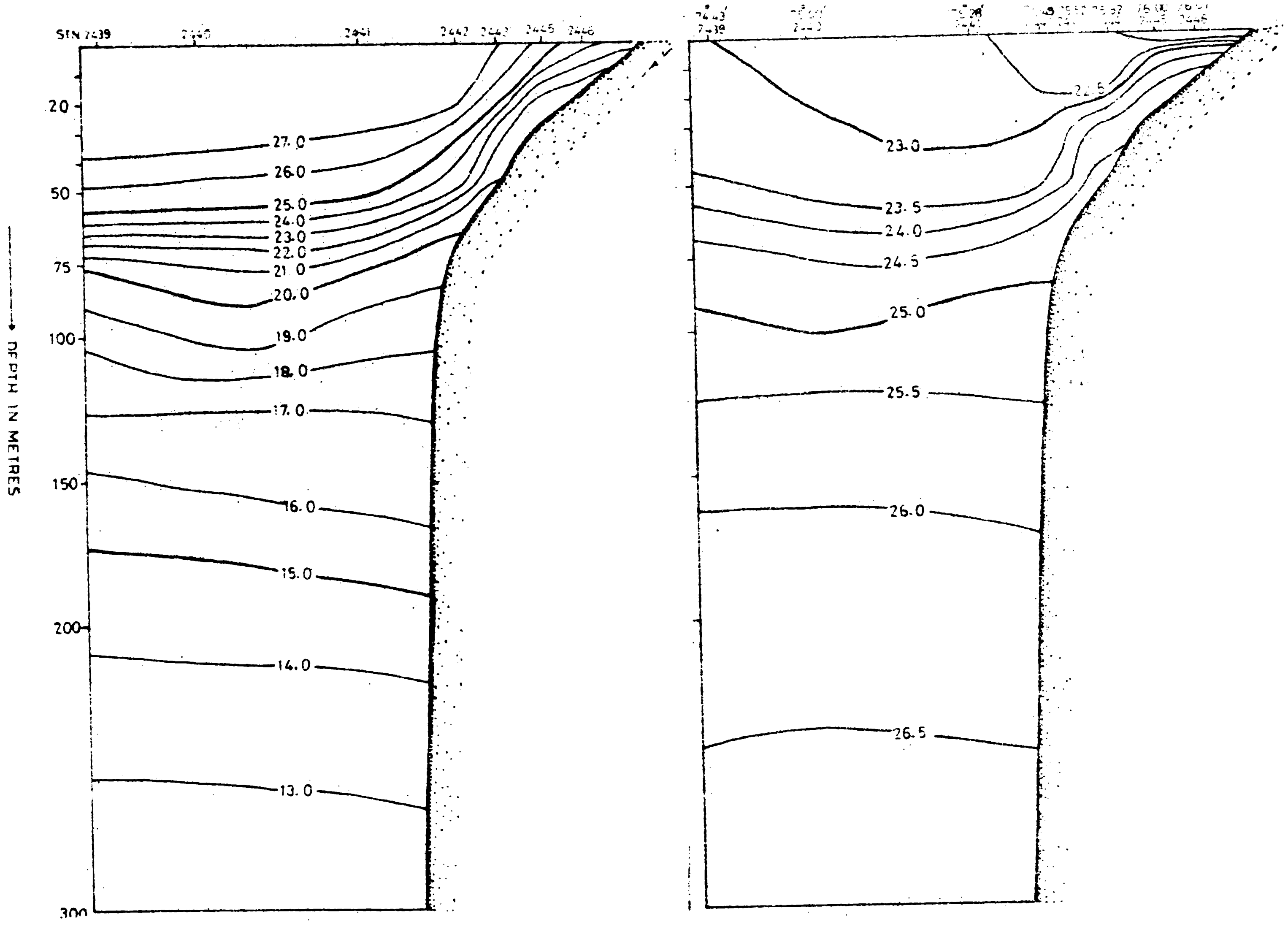
ALONG 10°00′N, JUNE 10-11, 1964.

2.2.4. July

By July the surface temperature is lowered further both in nearshore and offshore regions (Fig.14). Near the coast the surface temperature is about 24°C and it increases to about 27°C at 45 km. The marked upward tilting of isotherms and isopycnals suggests a strong southerly current in the surface layers. The isotherms and isopycnals slope down towards the coast indicating a countercurrent below 110 m. The density structure suggests strong stratification in the upper 10 m in the inner continental shelf. The isotherms and isopycnals are pushed up towards the surface from June to July and several of the isotherms outcrop into the naviface. The offshore-onshore temperature gradient is negative above 100 m but strong gradients are confined to the upper 30 m of the continental shelf.

2.2.5. August

For this month the observations are mainly confined to the continental shelf only (Fig.15). In this region the surface temperature is further lowered in the entire continental shelf to values less than 26°C, while near the coast it is even less than 24°C. The upsloping of isotherms and isopycnals are less, compared to that in July, but the surface flow continues to be



(a) (b)

FIG.14. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (‰)

ALONG 10°00′N, JULY 14, 1964.

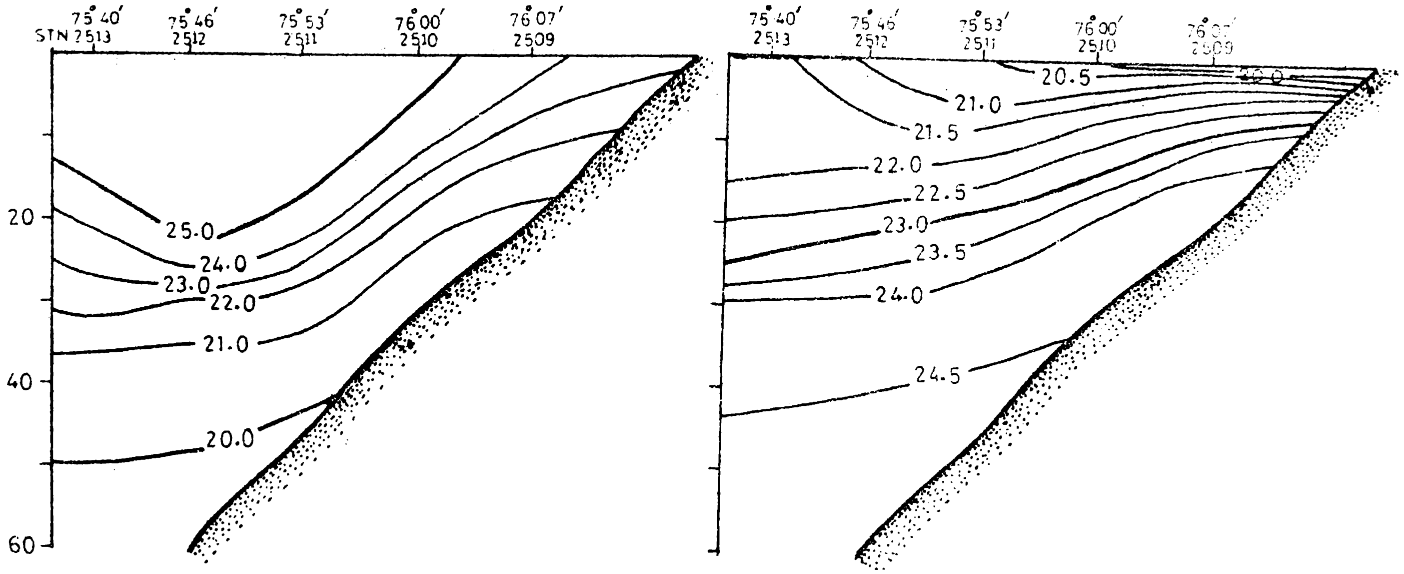


FIG.15. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l) ALONG 10°00′N. AUGUST 12. 1964.

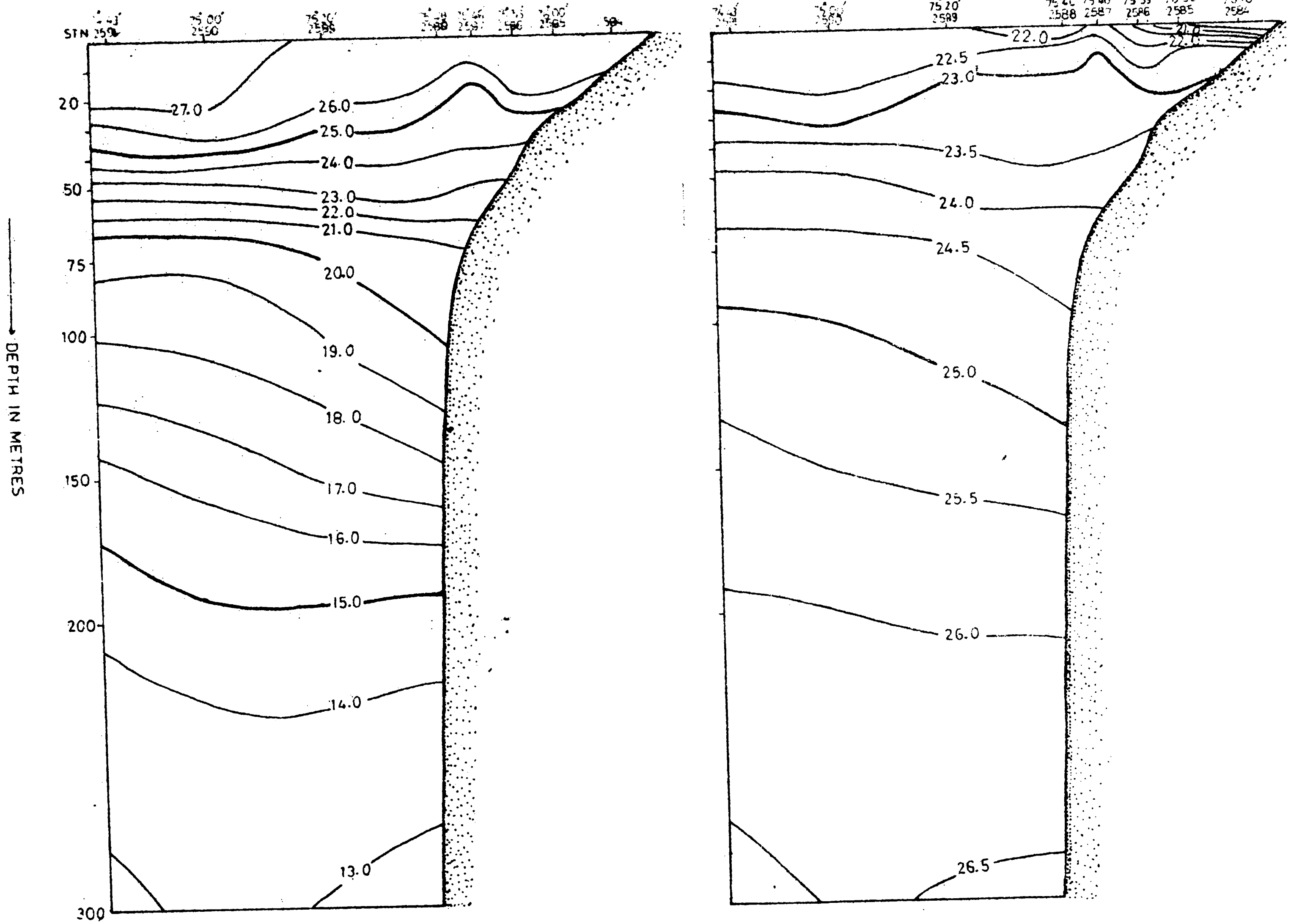
southerly. Low density water is observed in the surface layers in the entire continental shelf, below which there is not much variation in the oceanographic conditions from July to August.

2.2.6. September

There is an increase in temperature and a decrease in density at all depths above 300 m from the previous month (Fig.16). The surface temperature is slightly above 26°C and there is no significant onshore-offshore variation. The mixed layer is about 20 m deep in nearshore regions. The slight upsloping of isopycnals indicates a weak southerly current in the surface layers, but between 75 and 150 m the flow is northerly. The presence of low density water is evident in the upper 10 m of the nearshore regions.

2.2.7. October

By October the temperature at all depths decreases again, and a corresponding increase in density is also observed (Fig.17). The nearshore sea surface temperature is less than 26°C and it increases towards offshore. In the nearshore and offshore regions the thermocline is found almost at the surface. The upward tilting of isotherms and isopycnals towards the coast indicates a southerly current in the surface layers. Below 50 m, a subsurface

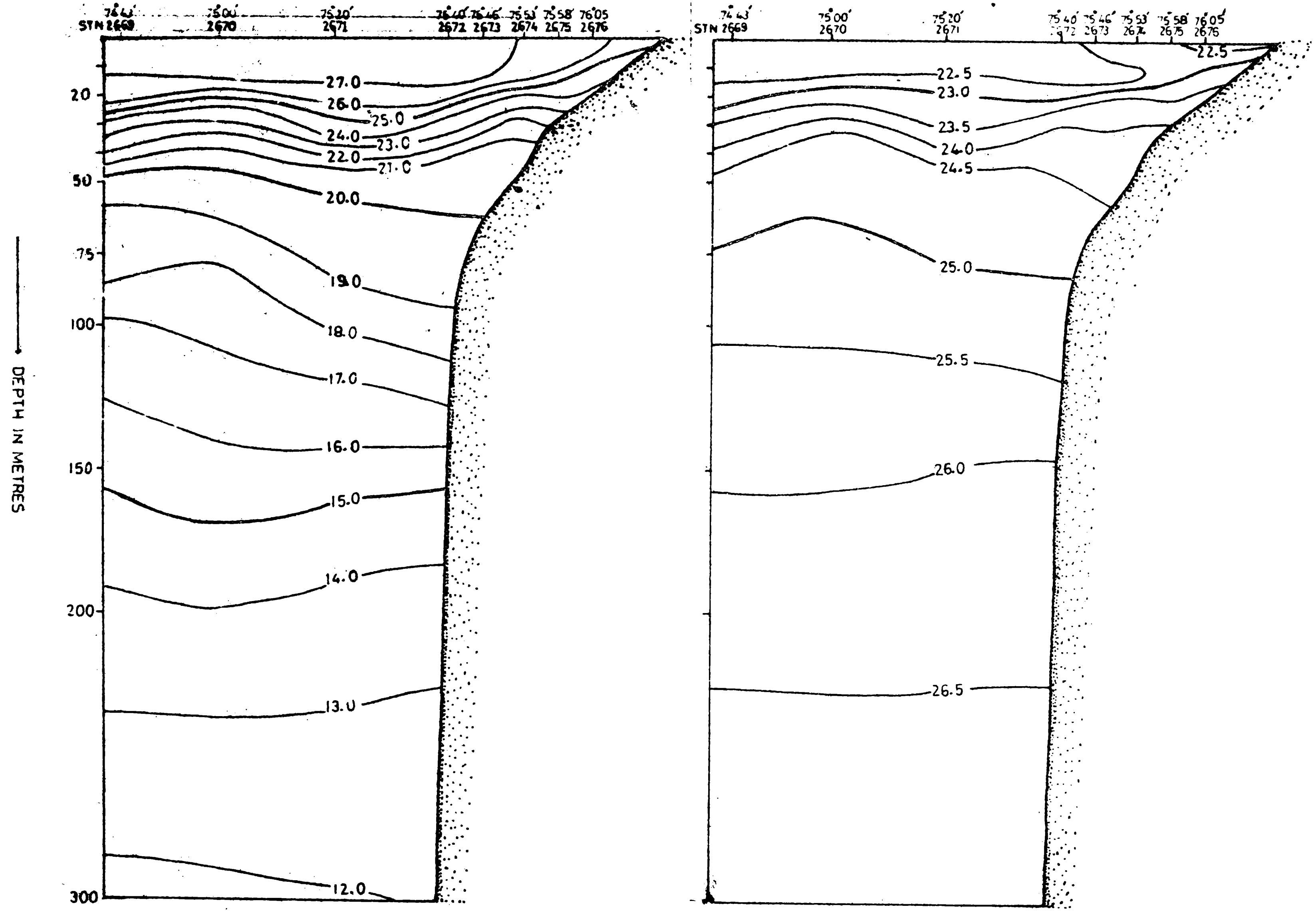


(a)

(b)

FIG.16. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 10°00'N, SEPTEMBER 12, 1964.



(a)

(b)

FIG.17. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l).

ALONG 10°00'N, OCTOBER 12, 1964.

countercurrent is evident though not so strong as in September. The isotherms and isopycnals are displaced to upper levels considerably from September to October.

2.2.8. November

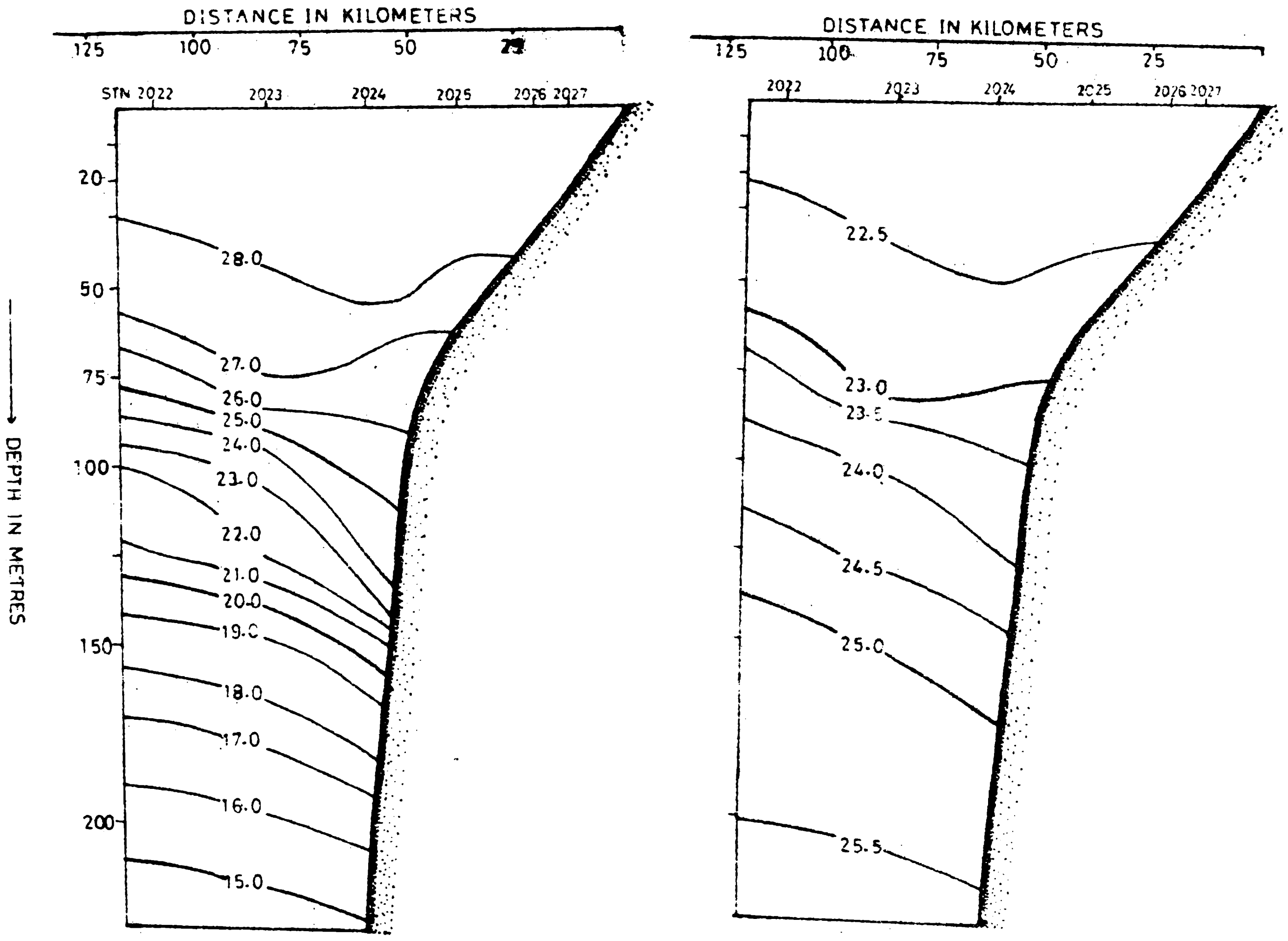
A drastic change occurs between October and November (Fig.18). The isotherms and isopycnals slope downward from 70 m down to 300 m which suggests a northerly current in this region. The temperatures in the surface layers are increased to 28°C and the mixed layer is more than 100 m. At all the observed depths the density has decreased considerably from October to November while the temperature is increased and the changes are more prominent in the nearshore regions.

2.2.9. December

The conditions in the surface layers do not show much variation from those of November except that there is a slight decrease in the depth of mixed layer (Fig.19). The downward sloping of isopycnals towards the coast is less prominent possibly because the surface current becomes considerably weak. Below 120 m the flow is weak southerly.

2.2.10. January

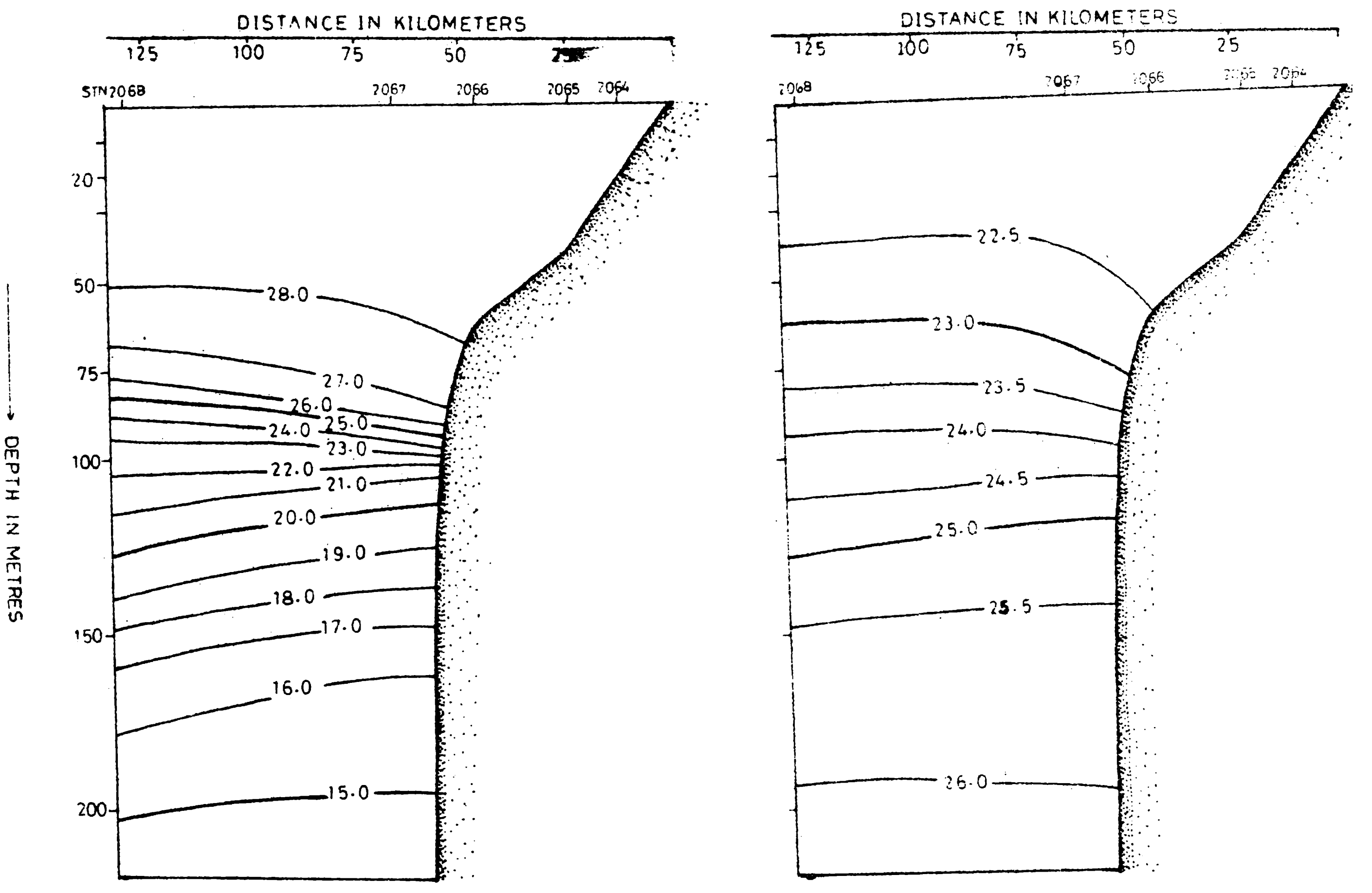
The isotherms and isopycnals tilt down towards the coast indicating a northerly current (Fig.20). Unlike



(a)

(b)

FIG.18. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l) OFF COCHIN, NOVEMBER 18, 1963.

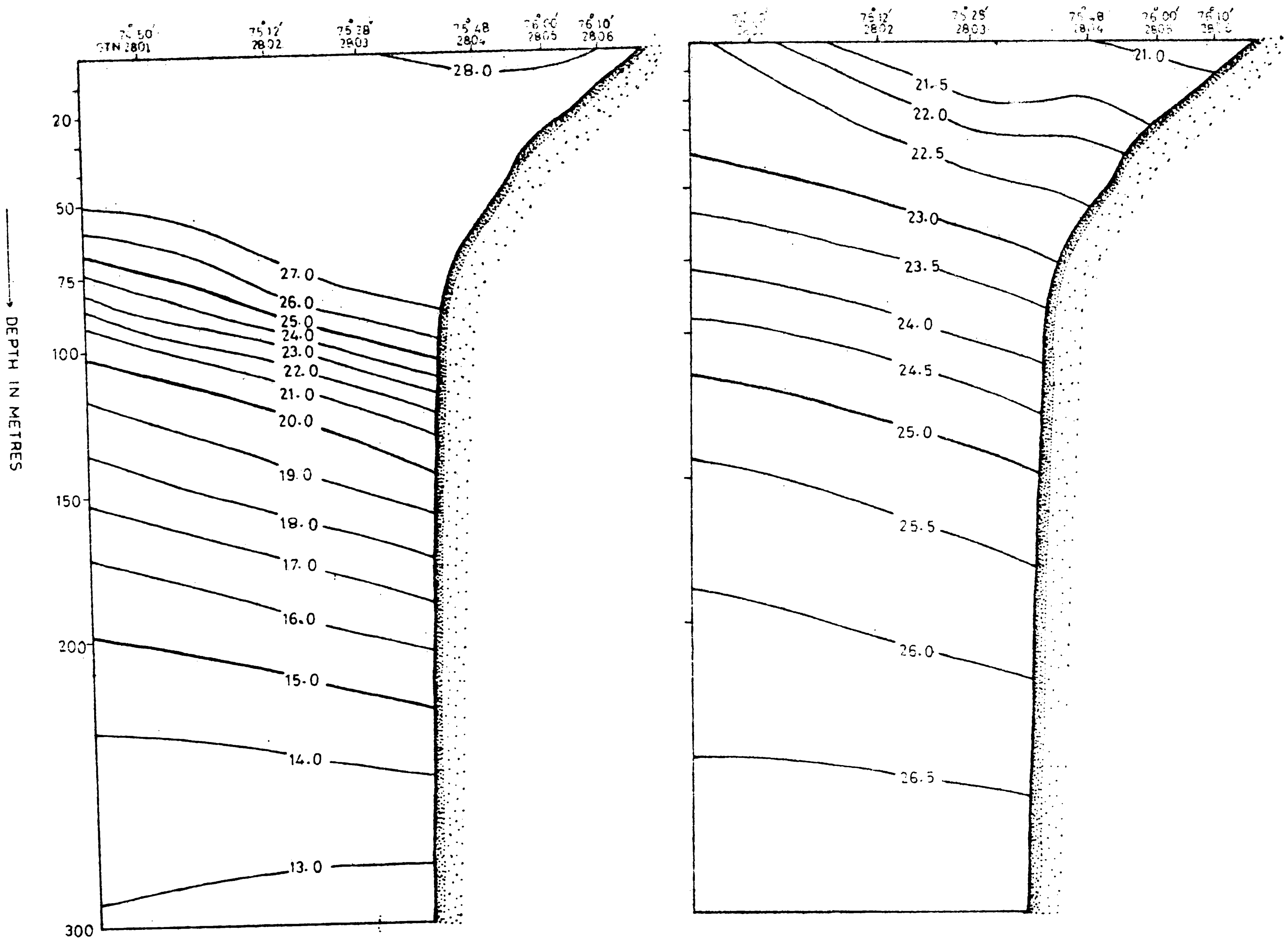


(a)

(b)

FIG.19. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

OFF COCHIN, DECEMBER 18, 1963.



(a)

(b)

FIG. 20. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 10°00'N, JANUARY 8, 1965.

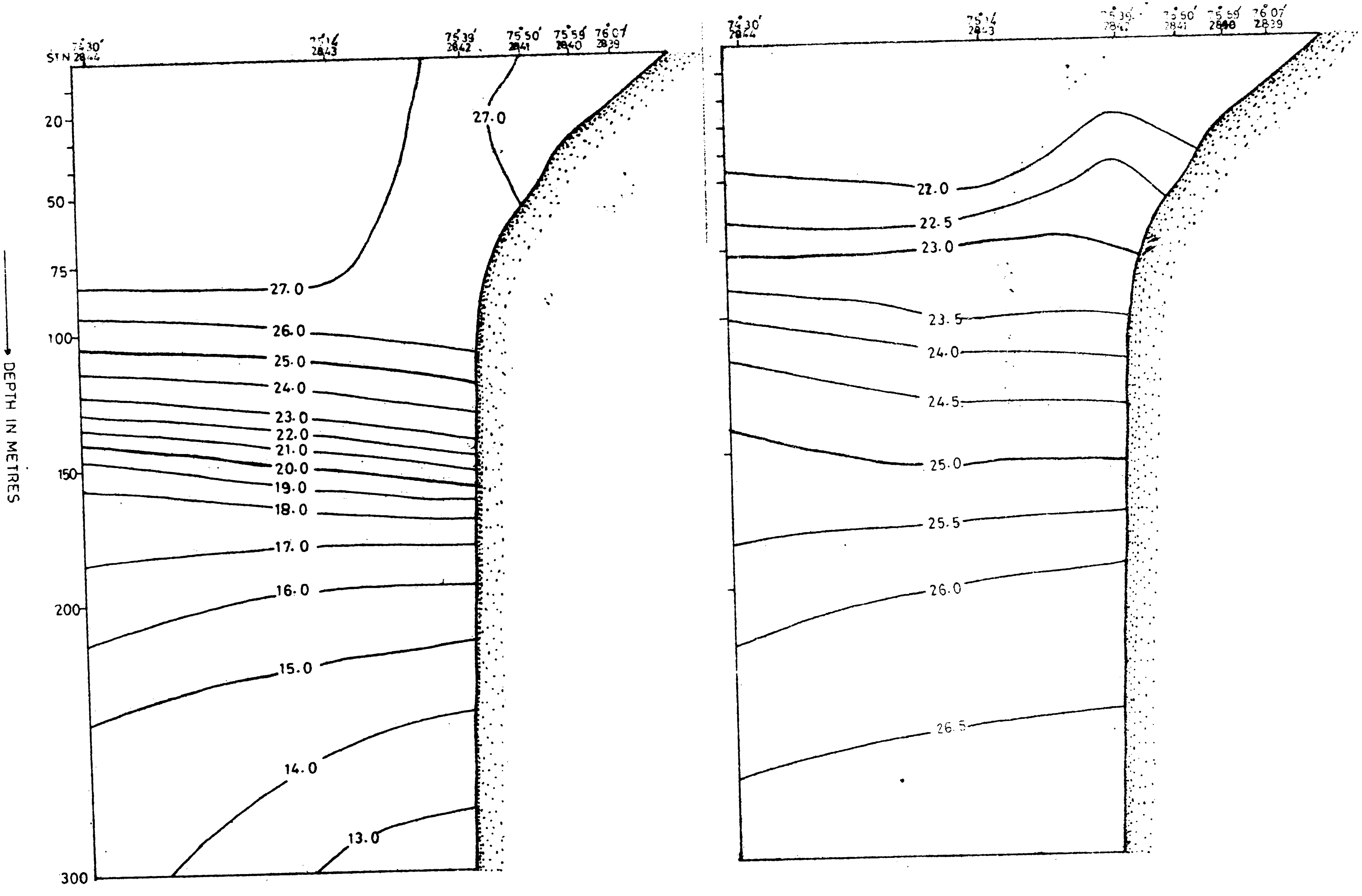
the southerly current in June-July this current is extended to a depth of about 300 m. The surface temperatures are about 28°C and the depth of mixed layer is about 90 m in nearshore regions. The low density of the surface layers indicates the presence of low salinity water in this region.

2.2.11. February

A slight decrease in surface temperature is observed in this month compared to the previous month (Fig.21). However, the depth of mixed layer increases to 110 m in the continental slope. The isopycnals show a downward sloping towards the coast in the upper 100 m indicating a northerly current, below which the current is weak southerly.

2.2.12. March

The surface temperature has increased to above 29°C in nearshore regions by March, while in the offshore regions the temperature is slightly less, but above 28°C (Fig.22). The depth of mixed layer is more than 100 m and the temperature gradient in the thermocline is sharp compared to that in the previous month. The isopycnals in the upper 100 m slope down towards the coast indicating a northerly current, but below 100 m the current is southerly. There is an increase in temperature between February and March in the upper 100 m. However, there is a decrease of temperature by about 3°C at 150 m and an increase in

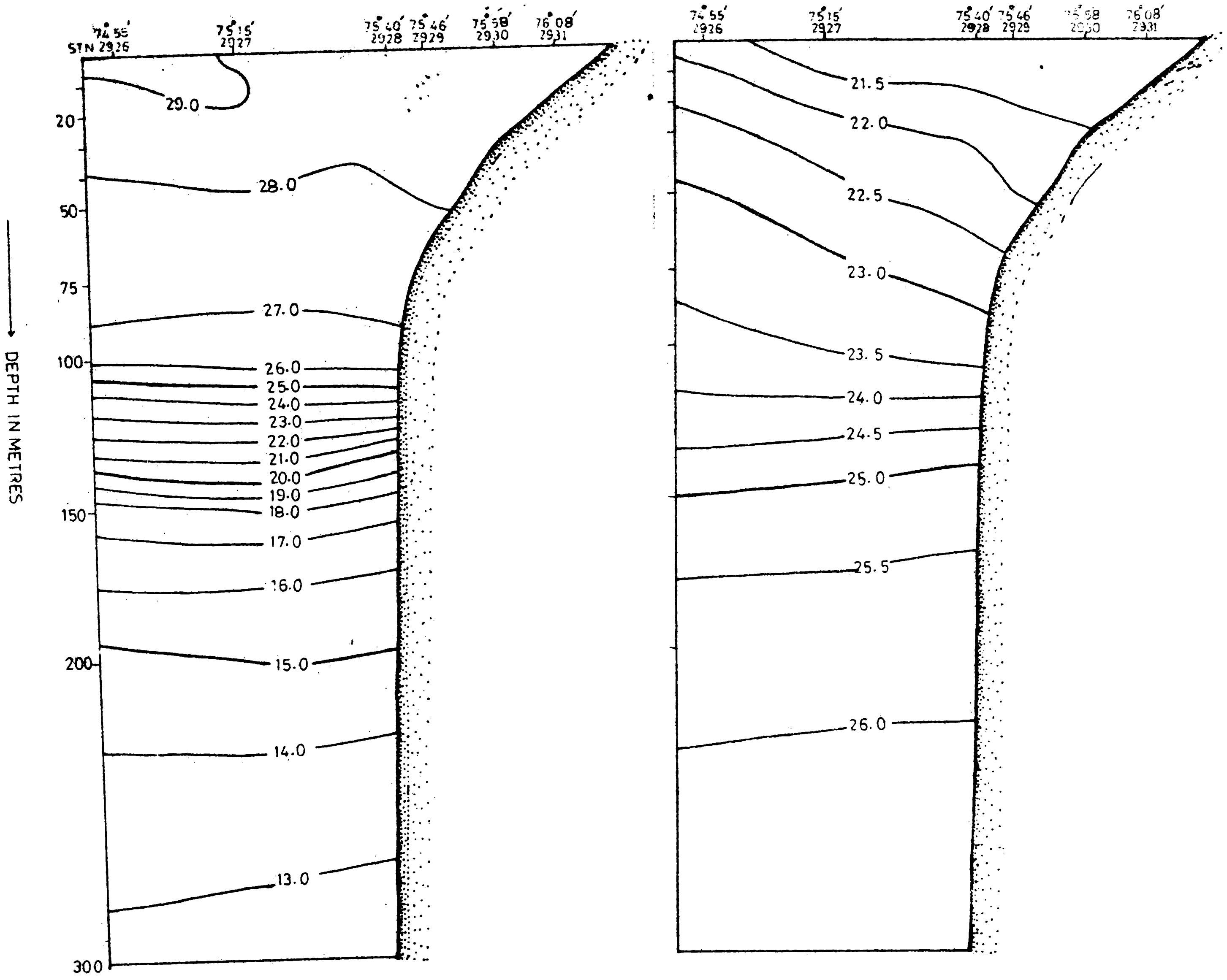


(a)

(b)

FIG.21. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 10° 00′ N, FEBRUARY 7-8, 1965.



(a)

(b)

FIG.22. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l)

ALONG 10°00'N, MARCH 11-12, 1965.

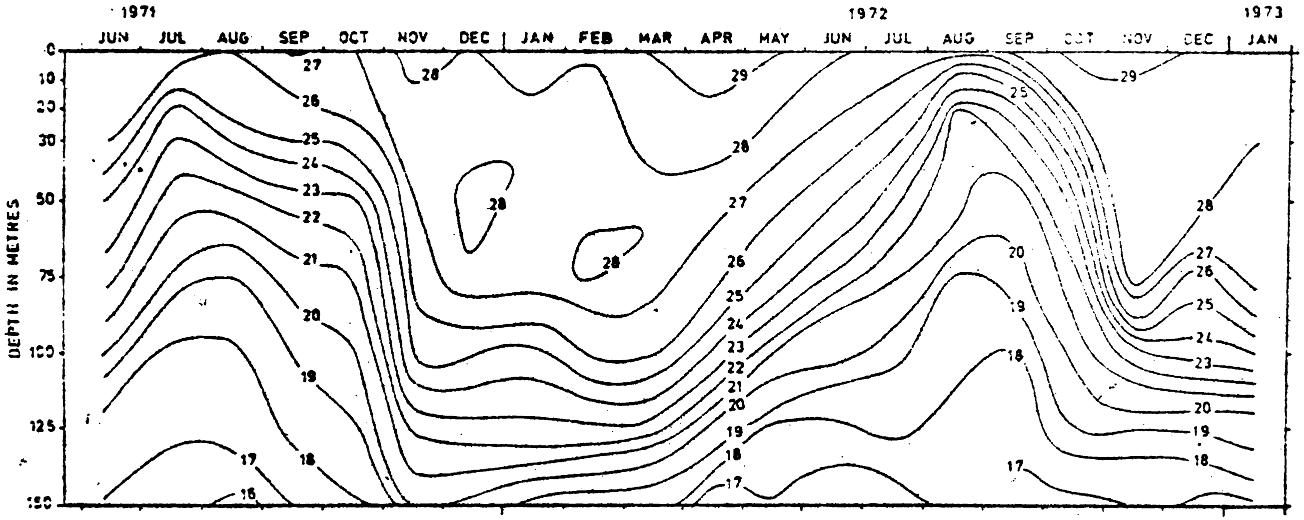


Fig. 23. Isopleth showing the seasonal fluctuations in the mean temperatures in the section off Cochin.

(From Anon., 1973)

density is also observed. The isotherms in the middle and lower thermocline are pushed up from February to March.

2.3. Time series of temperature during 1971-1972:

The time series section off Cochin is presented in Fig.23. The figure is reproduced from Anon. (1973). In subsurface layers, a lowering of temperature or upward displacement of isotherms starts from February to March. The temperature at all depths shows a minimum during July in 1971, whereas in 1972 the minimum temperatures are attained in August. The surface temperature begins to fall from June. In 1971 a sudden increase of temperature at all depths occurs between October and November while the increase is gradual in 1972. There is not much variation in the thermal field during the period December to February and the temperature in the surface layers is uniformly high.

2.4. Vertical sections of temperature and σ_t off Kasaragod:

The section off Kasaragod was covered in 1974 as a part of the Pelagic Fishery Survey. Oceanographic data were collected in seven series - January, March, May, July, August, November and December (Figs.24-30). The stations were occupied at intervals of about 10 miles in the continental shelf region and about 25 miles beyond the shelf. The figures are reproduced from Anon. (1976).

2.4.1. January

The isotherms and isopycnals run almost parallel to the surface from offshore to onshore, but near the coast a slight downward sloping is observed which indicates a weak northerly current (Fig.24). The depth of thermocline is about 80 m, and the surface temperatures are above 28°C. The pycnocline is well developed in the depth range of 40-100 m which suggests strong stratification. The low density water in the surface layers indicates the presence of low salinity water in this region.

2.4.2. March

A strong baroclinic field is observed during this month (Fig.25). The isotherms and isopycnals show upsloping towards the coast indicating a southerly flow between stations I and IV, but further offshore the flow is still northerly. The surface layers are warmer than in January, but the depth of mixed layer is reduced considerably, especially near the coast. The density increases from January to March while temperature decreases at all depths except in the upper layers. The isopycnals show a slight downward tilting towards the coast indicating a weak northerly countercurrent below 150 m.

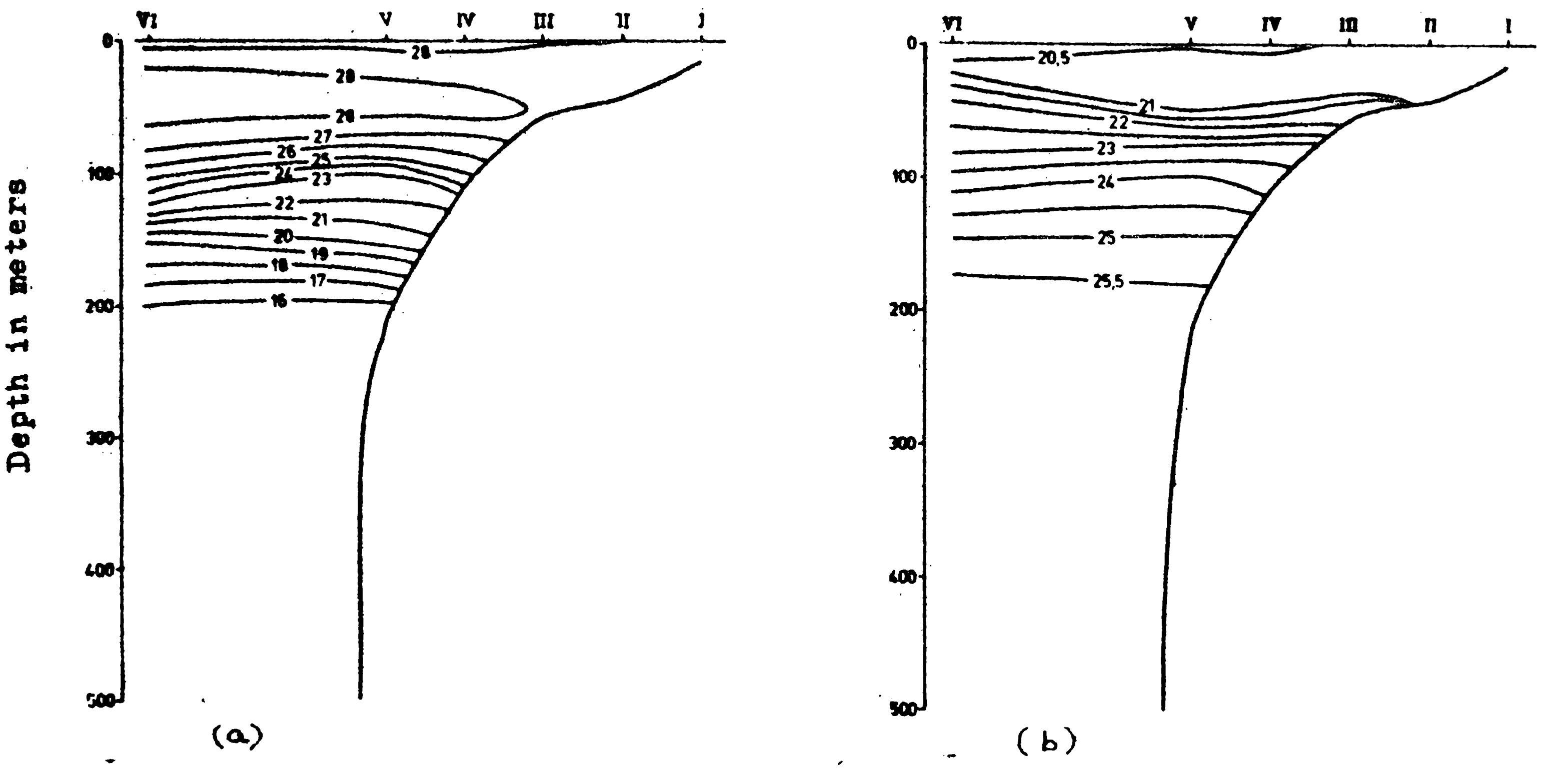


Fig.24. Vertical sections of (a) Temperature (^{o}C) and (b) σ_t (g/l) off Kasaragod, January 19, 1974 (from Anon., 1976).

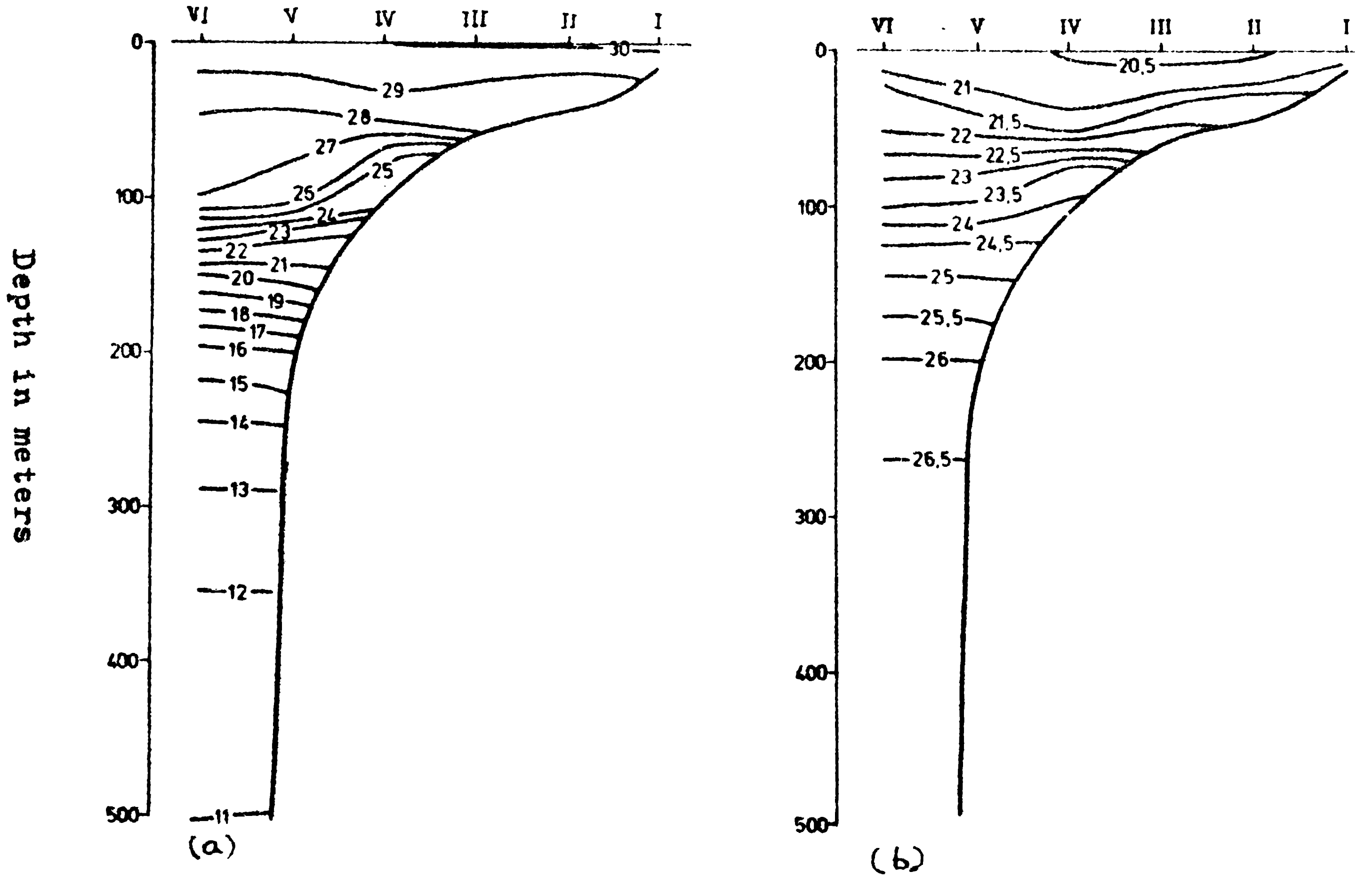


Fig.25. Vertical Sections of (a) Temperature (^{o}C) and (b) σ_t (g/1) off Kasaragod, March 14, 1974 (from Anon., 1976).

2.4.3. May

The coastal current from the surface to about 90 m is southerly (Fig.26). The tilting of isopycnals on the shelf area is approximately the same as in March, but a general upward displacement of isopycnals above 150 m is observed. The mixed layer is shallow in nearshore regions, but the depth of mixed layer gradually increases towards offshore. The surface temperature is still relatively high, about 29-30°C. The downward slope of isopycnals at the edge of the continental shelf indicates a northerly current below 100 m.

2.4.4. July

The temperature of the surface layer decreases considerably to about 27°C both in the nearshore and offshore regions (Fig.27). Near the coast, the thermocline and pycnocline are found close to the surface. The depth of mixed layer gradually increases offshore. The upward tilting of isotherms and isopycnals towards the coast in the upper layers suggests a southerly current. Further upward displacement of isotherms and isopycnals are evident above 200 m during the period May to July. A narrow countercurrent below 80 m in the continental slope region is again indicated.

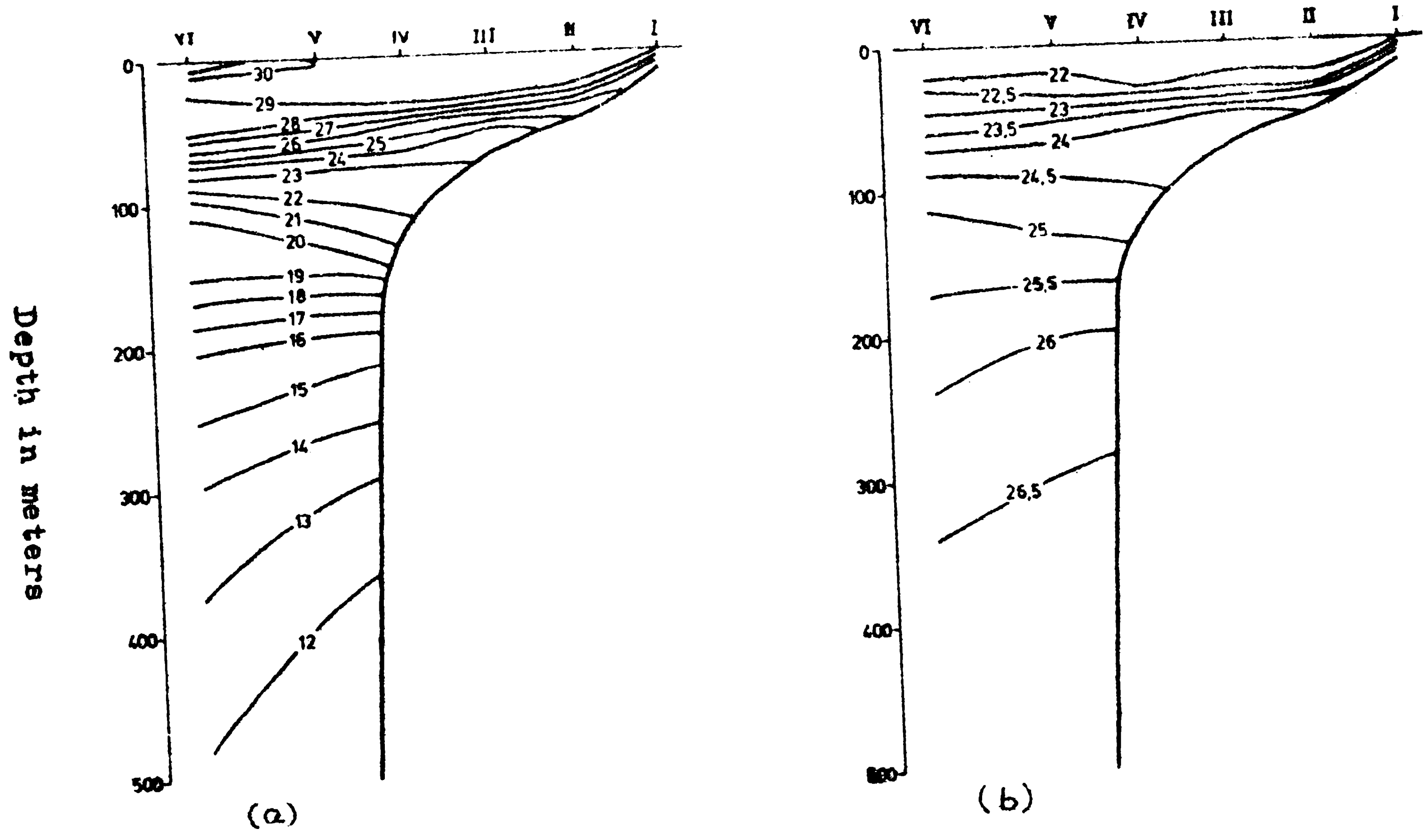


Fig.26. Vertical Sections of (a) Temperature (^{o}C) and (b) σ_t (g/l) off Kasaragod, May 15, 1974 (from Anon., 1976).

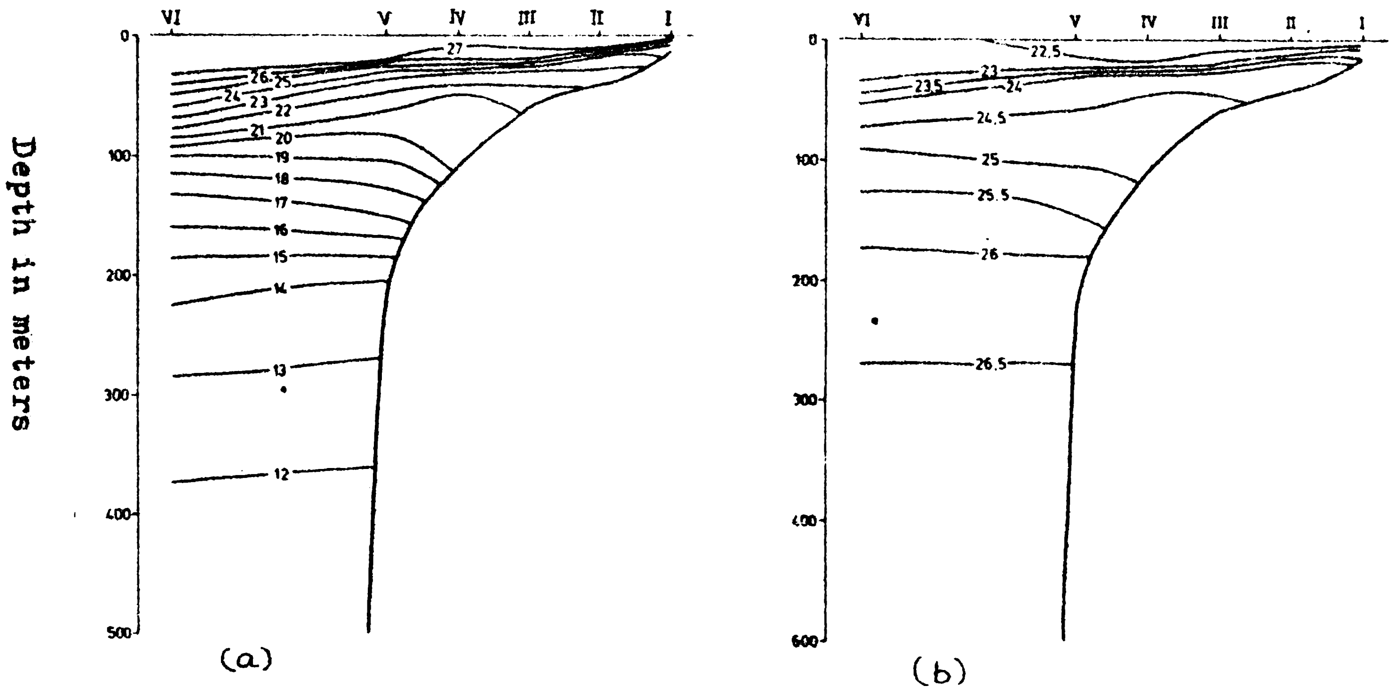


Fig.27. Vertical Sections of (a) Temperature (°C) and (b) σ_t (g/l) off Kasaragod, July 14, 1974 (from Anon., 1976).

2.4.5. August

The surface temperature further decreases to about 26^{o}C in the continental shelf (Fig.28). Near the coast the thermocline and pycnocline are observed at the surface. The surface flow is southerly. Further upward displacement of isotherms and isopycnals are evident between July and August. A countercurrent along the continental slope is also indicated, but unlike in July it is found as a deep reaching flow.

2.4.6. November

The upsloping of isotherms and isopycnals is more marked than in August, indicating a stronger southerly current between stations I and IV, but further offshore the flow is weak northerly (Fig.29). A slight increase in temperature and a decrease in density are observed at all levels above 150 m. In the nearshore regions the surface temperature is about 26^{o}C and increases with distance from the coast. The countercurrent at the shelf edge is evident, but it is not so strong as in August.

2.4.7. December

A dramatic change occurs between November and December (Fig.30). The isotherms and isopycnals slope down towards the coast indicating a northerly current.

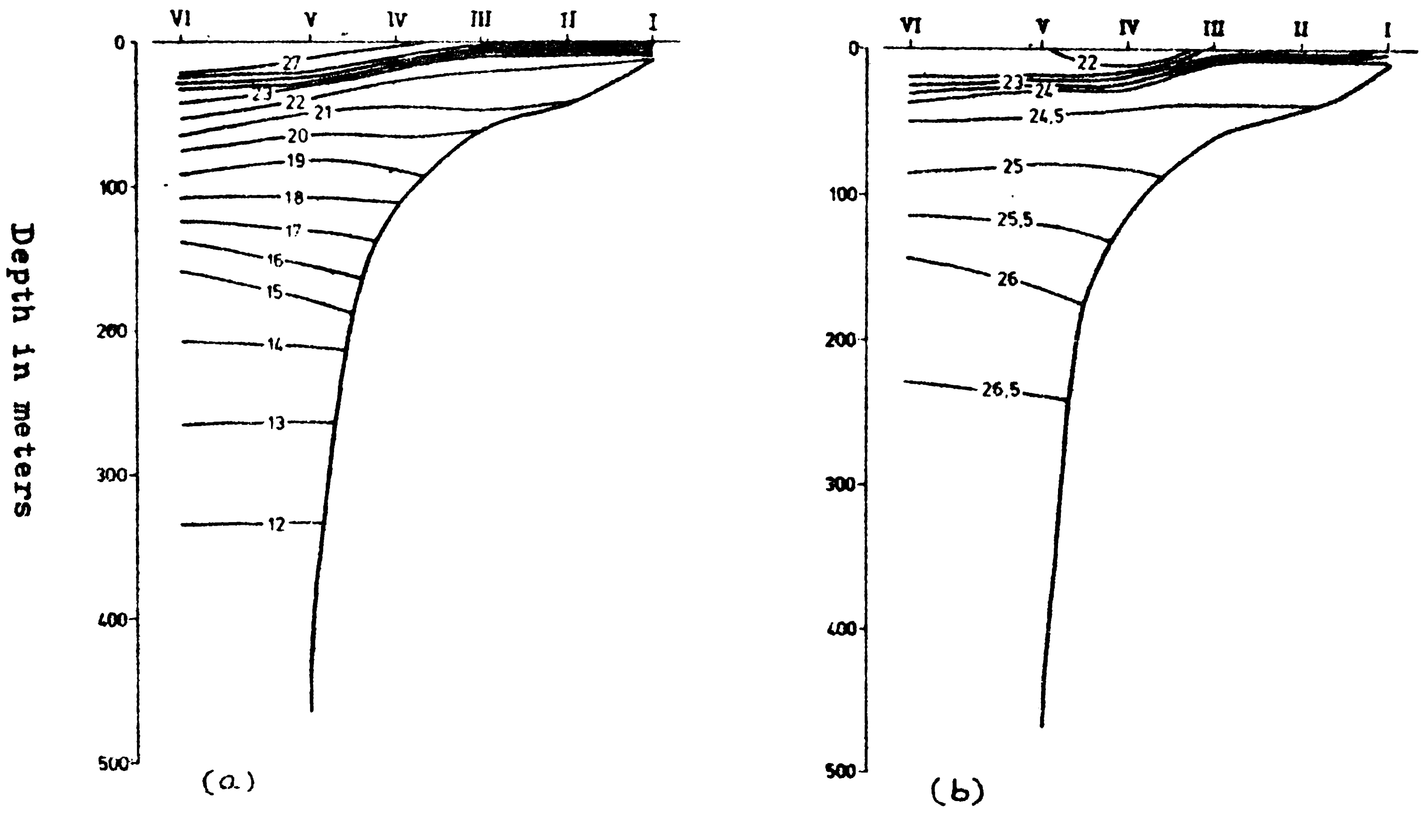


Fig.28. Vertical Sections of (a) Temperature (^{o}C) and (b) σ_t (g/l) off Kasaragod, August 25, 1974 (from Anon., 1976).

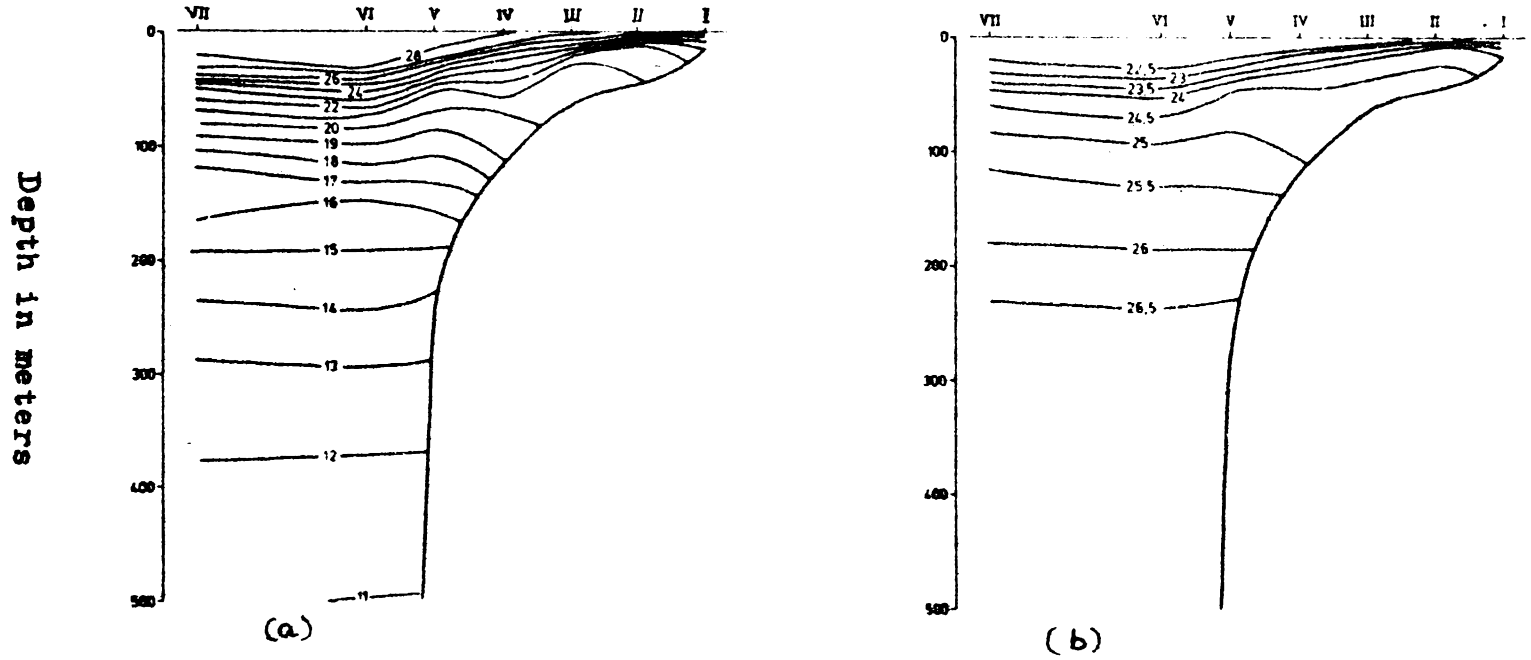


Fig.29. Vertical Sections of (a) Temperature (°C) and (b) σ_t (g/l) off Kasaragod, November 6, 1974 (from Anon., 1976).

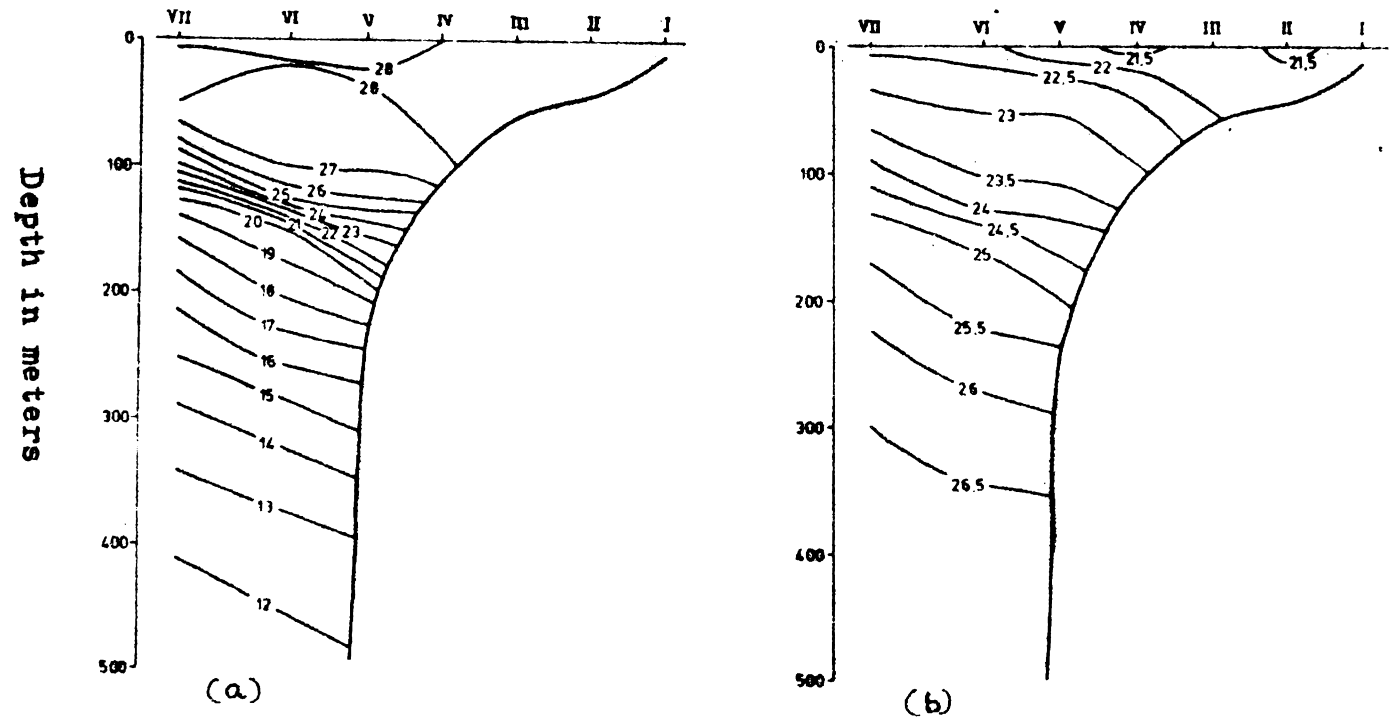


Fig.30. Vertical Sections of (a) Temperature (^{o}C) and (b) σ_t (g/l) off Kasaragod, December 11, 1974 (from Anon., 1976).

Unlike the southerly flow during the previous month, the northerly current is wide and deep reaching. The surface temperature is above 28°C and the mixed layer is deeper than 100 m. There is a general decrease in density and an increase in temperature at all depths down to 300 m.

2.5. Vertical sections of temperature off Karwar:

Oceanographic data collected from October 1971 to December 1972 during the Pelagic Fishery Survey are used for the present study (Figs.31-33). The figures are reproduced from Anon. (1973). Most of the investigations are confined to the continental shelf and the outermost station is about 50 miles offshore. The distance between two stations is about 10 miles. Only vertical sections of temperature are presented.

2.5.1. October

The thermocline is found almost at the surface in the continental shelf region (Fig.31a). The surface temperature is about 25°C near the coast and it increases to 27°C at a distance of 10 miles offshore. The surface current is weak southerly between stations I and IV, but turns to strong southerly further offshore. The isotherms slope down towards the coast below 50 m, indicating a northerly current.

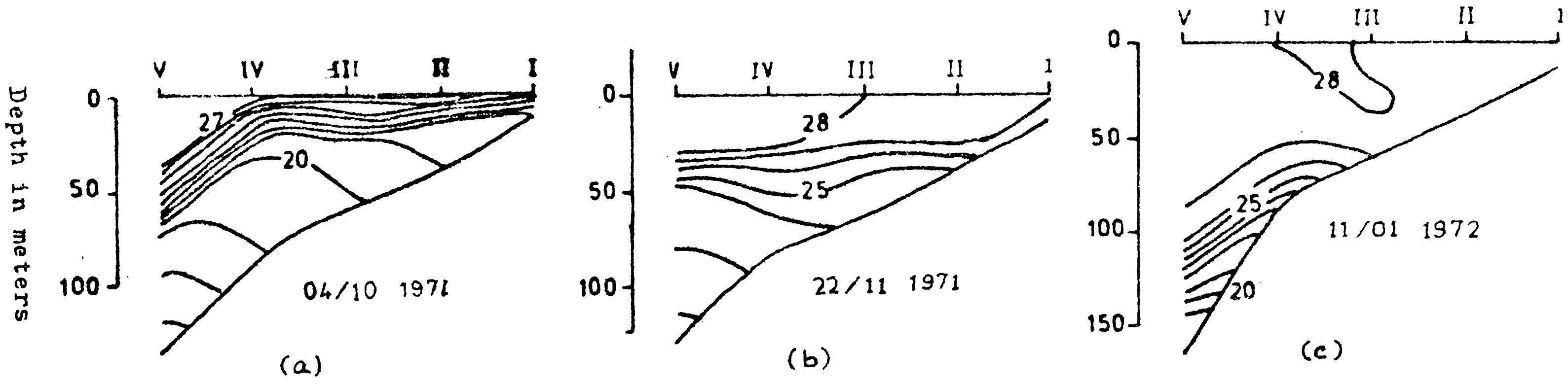


Fig.31. Vertical Sections of Temperature (^{o}C) off Karwar

(a) October (b) November and (c) January

(from Anon., 1973)

2.5.2. November

The surface temperature increases to above 28°C (Fig.31b). There is a considerable increase in temperature at all depths between October and November. The 22°C isotherm which is observed at about 20 m in October is displaced to about 110 m in a span of 49 days. Except in the upper 30 m, the isotherms show a downward tilt towards the coast.

2.5.3. January

The temperature in the surface layers ranges from 27-28°C (Fig.31c). Between stations I and IV the isotherms slope down towards the coast indicating a northerly flow, but further offshore the flow is southerly.

2.5.4. March

The mixed layer deepens from January to March to below 100 m (Fig.32a). The surface temperature is above 30°C near the coast, but decreases to 29°C in the offshore.

2.5.5. April

The isotherms slope up towards the coast indicating a southerly current (Fig.32b). The surface temperature continues to be above 29°C, but the depth of mixed layer decreases to about 70 m. There is a general

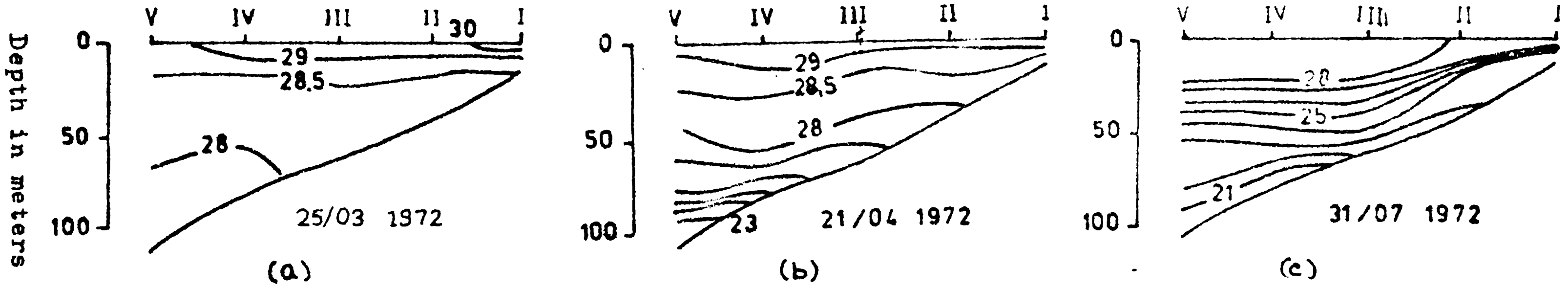


Fig.32. Vertical Sections of Temperature (°C) off Karwar
(a) March (b) April and (c) July (from Anon., 1973).

decrease of temperature between 70 and 100 m from March to April, though no significant changes are observed in the surface layers.

2.5.6. July

The thermocline is observed just below the surface in the nearshore regions (Fig.32c). The surface temperature is about 27°C near the coast and increases offshore. The isotherms slope up towards the coast indicating a southerly current in the upper 100 m. Considerable upward displacement of isotherms are evident from April to July.

2.5.7. August

By the end of August further decrease in temperature above 100 m is noticed except at the surface compared to July (Fig.33a). The surface flow continues to be southerly and there is slight indications of a subsurface countercurrent below 60 m.

2.5.8. October

The surface temperature is above 29°C near the coast and a slight increase in temperature at all depths is evident from August to October (Fig.33b). At the edge of the continental shelf a strong thermocline is noted between 30 and 50 m.

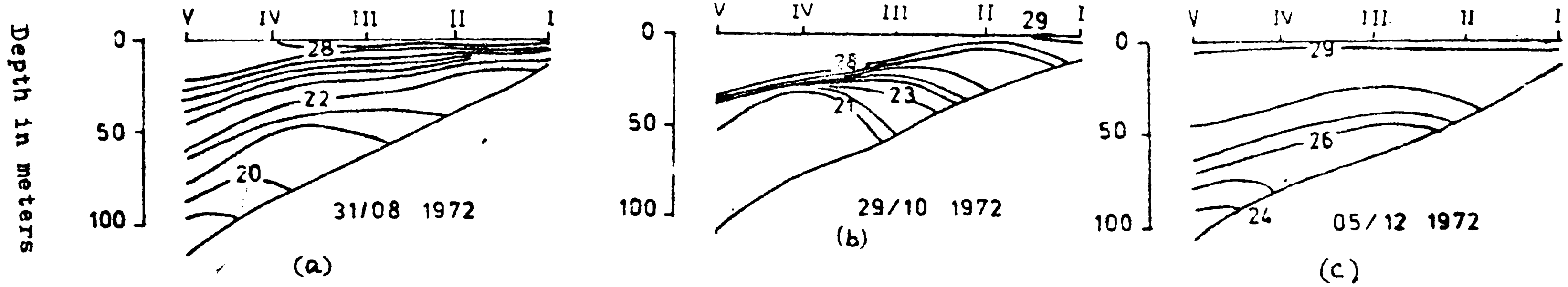


Fig.33. Vertical Sections of Temperature (°C) off Karwar

(a) August (b) October and (c) December

(from Anon., 1973)

2.5.9. December

The temperature increases considerably in the upper 100 m from October to December (Fig.33c). The surface temperature is above 29°C. At the edge of the continental shelf the depth of mixed layer is about 80 m.

2.6. Vertical sections of temperature off Ratnagiri:

The vertical temperature sections off Ratnagiri are reproduced from Anon. (1973). The observations were made in February and August (Fig.34).

2.6.1. February

During this month the surface temperatures are above 27°C in the nearshore regions and the depth of mixed layer is about 90 m (Fig.34a). The flow between the the Angria bank and the coast is not clear but further offshore the orientation of isotherms indicates a northerly flow.

2.6.2. August

The conditions during this month show some significant differences from those in the southern regions (Fig.34b). The surface temperature is well above 28°C in nearshore and offshore regions. The depth of thermocline is about 40 m in nearshore regions and it increases towards offshore. The upsloping of isotherms towards the coast

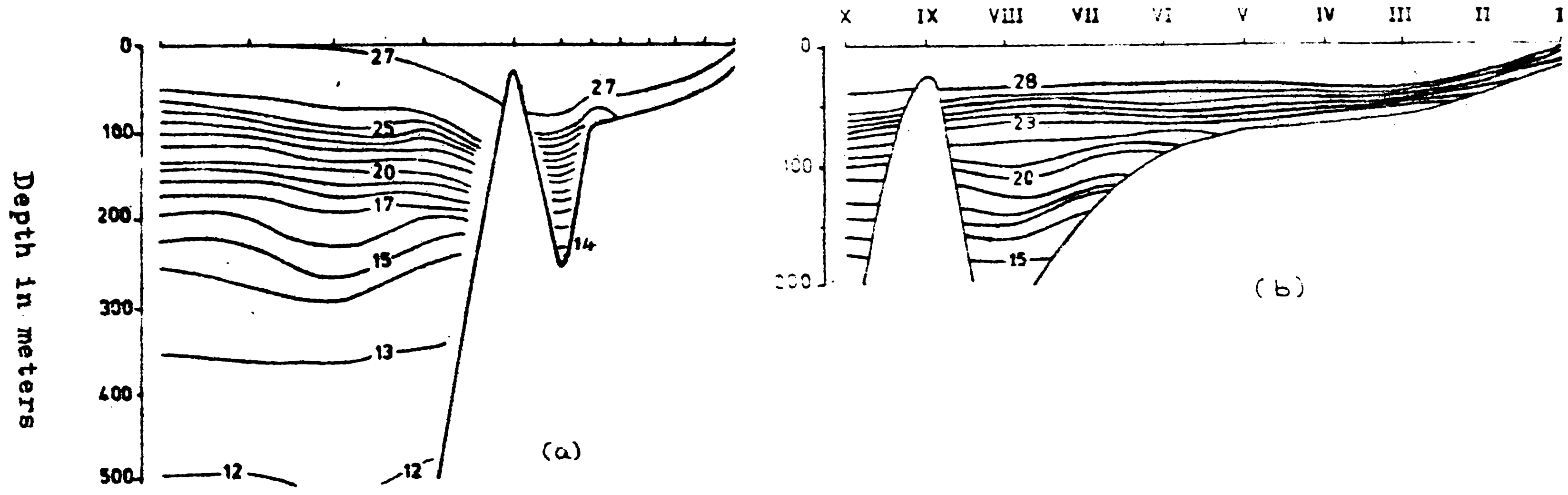


Fig.34. Vertical Sections of Temperature (^{o}C) off Ratnagiri (a) February and (b) August (from Anon., 1973).

suggests a southerly current. Upward displacement of isotherms are evident during the period February to August. The 23°C isotherm which is observed below 100 m in February is found at about 50 m in August in the nearshore regions.

Temperature and density fields off the east coast of India

Oceanographic investigations are not continuous and they are scarce off the east coast compared to those off the west coast of India. The available data are mainly confined to two places - off Waltair (17°44'N) and off Madras (13°08'N) (Figs.35-43). Further, the observations were conducted in different years, which is a limitation for a detailed discussion and to draw inferences.

2.7. Vertical sections of temperature and σ_t off Waltair:

The sections off Waltair were covered during January, March, April, July and October. For March and October only vertical sections of σ_t are presented (from LaFond and LaFond, 1968).

2.7.1. January

The observations off Waltair were taken in late January (Fig.35). The surface temperature is slightly

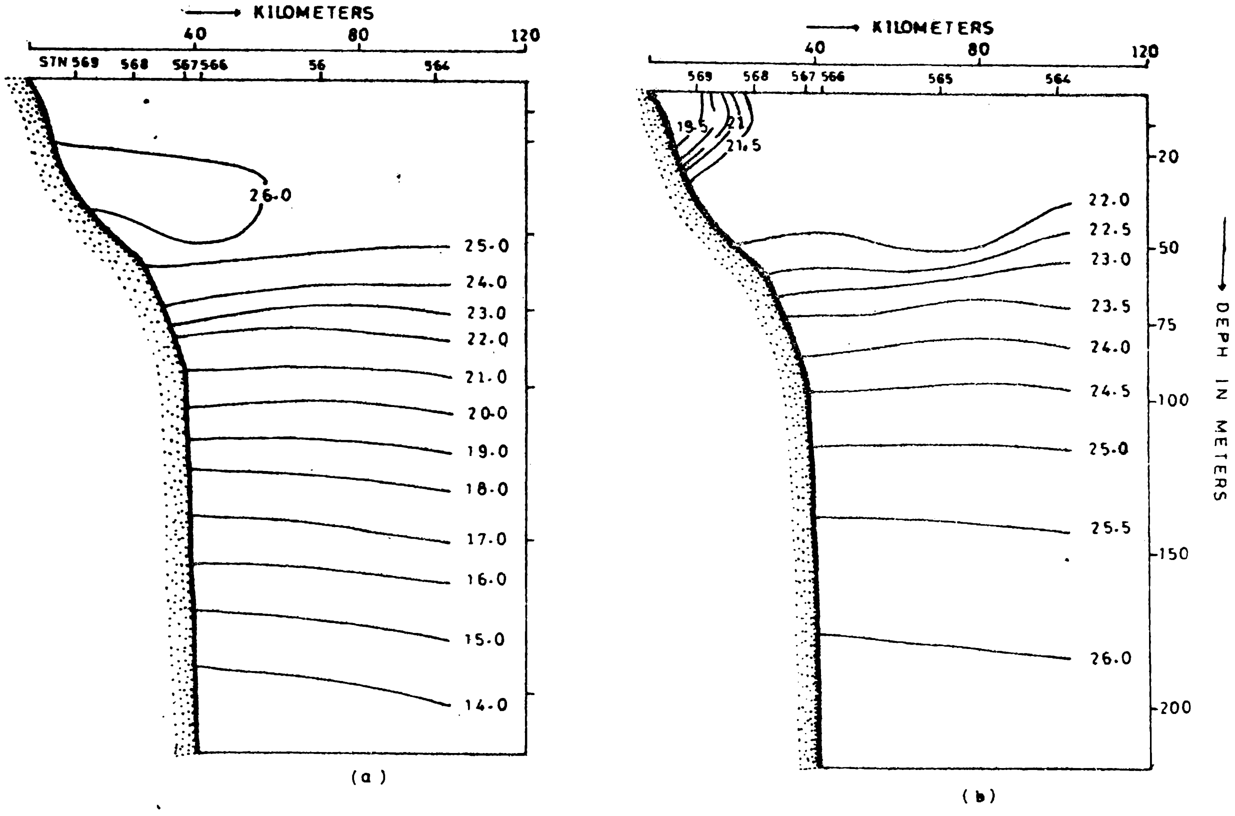


Fig.35. Vertical Sections of (a) Temperature (°C) and (b) σ_t (g/l) off Waltair January 21-22, 1965.

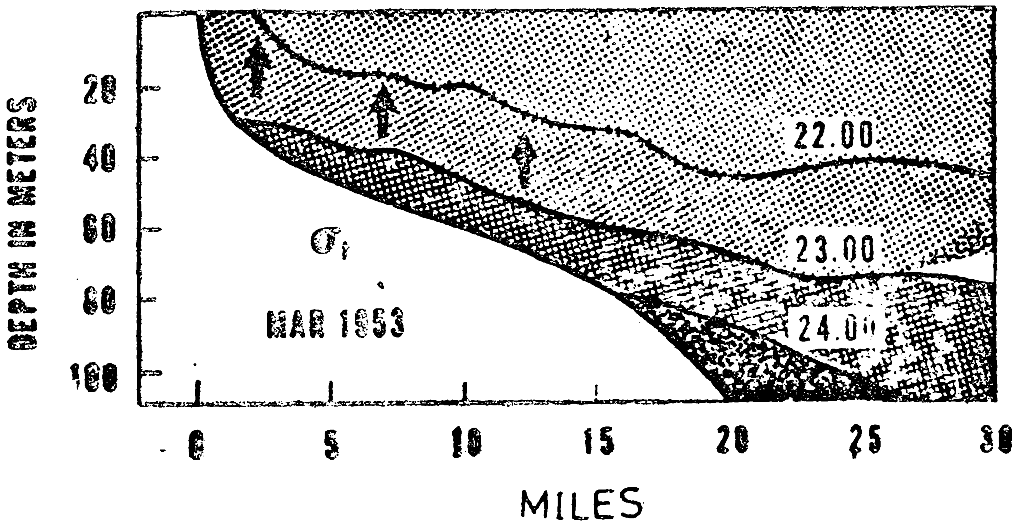
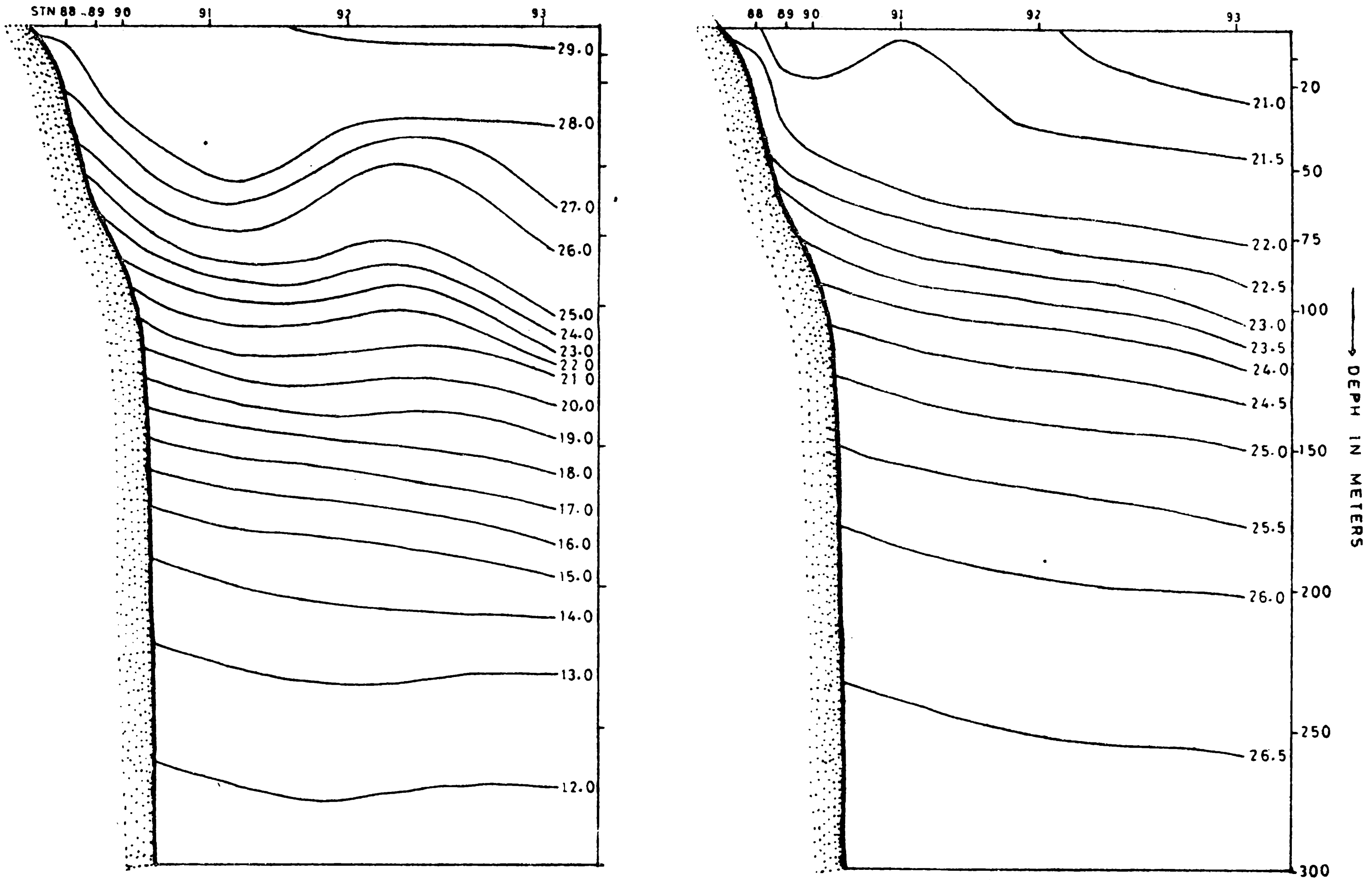


Fig.36. Vertical Section of σ_t (g/l) off Waltair for March (from LaFond and LaFond, 1968).



(a) (b)

FIG. 37. VERTICAL SECTIONS OF (a) TEMPERATURE (°C) AND (b) σ_t (g/l) OFF WALTAIR, APRIL 28, 1963.

above 25°C and the mixed layer is about 75 m deep. A temperature inversion is observed near the coast between 20 and 60 m. The isotherms and isopycnals below 50 m, run nearly parallel to the surface. Very near the coast, the surface density is very low.

2.7.2. March

The figure is reproduced from LaFond and LaFond (1968). The density field shows clear upsloping towards the coast indicating a fairly strong northerly flow (Fig.36). There is an increase in density at all depths above 100 m from January to March and this increase is more conspicuous in nearshore regions. The 22.0 g/l isopycnal outcrops into the naviface. At about 30 miles from the coast the increase in density from January to March is much less.

2.7.3. April

The surface temperature near the coast has increased to 28°C and still higher values are observed further offshore (Fig.37). The upsloping of isotherms and isopycnals continues in April also. The depth of mixed layer is about 50 m in nearshore regions and it increases offshore. There is a slight decrease in density at all depths between March and April.

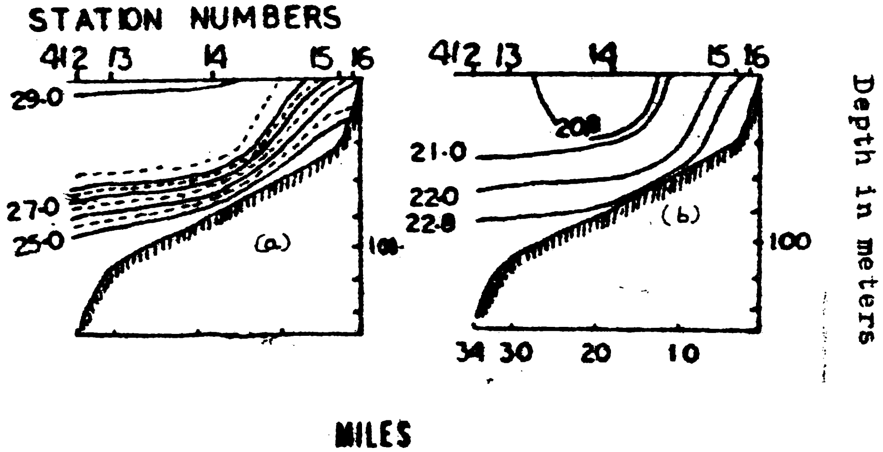


Fig.38. Vertical Sections of (a) Temperature (°C) and (b) σ_t (g.
off Waltair for July (from Murthy and Varadachari, 1968

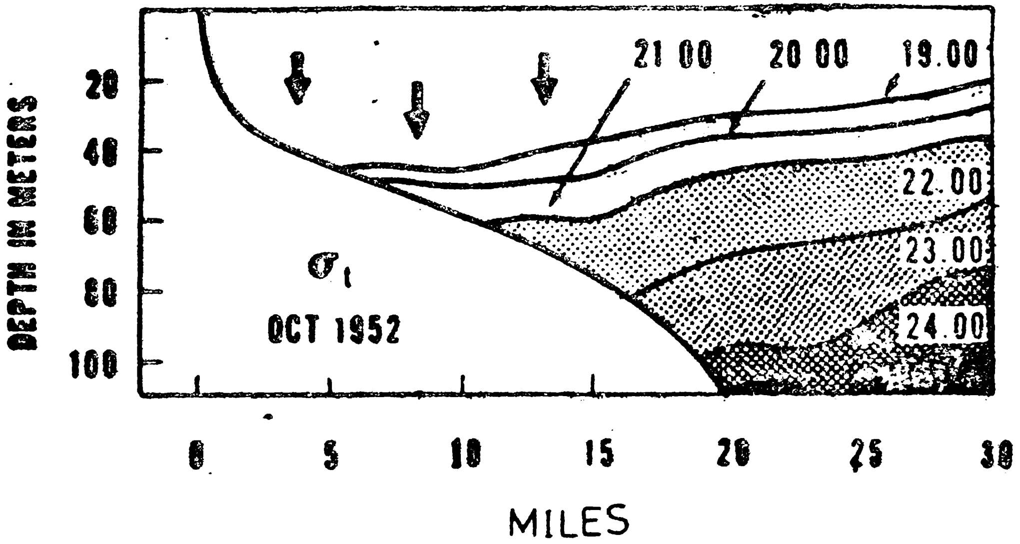


Fig.39. Vertical Section of σ_t (g/l) off Waltair for October (from LaFond and LaFond, 1968).

2.7.4. July

The figures are reproduced from Murthy and Varadachari (1968). In early July the surface temperature is about 26°C near the coast and increases to about 28°C at 10 miles offshore (Fig.38). The 22.0 g/l isopycnal outcrops into the naviface. The isotherms and isopycnals are pushed up from April to July. The upsloping of isotherms and isopycnals towards the coast suggests a northerly current.

2.7.5. October

The figure is reproduced from LaFond and LaFond (1968). The isopycnals slope down towards the coast indicating a southerly current (Fig.39). The density of the surface layers is low especially in the nearshore regions. Considerable downward movement of isopycnals is evident during the period July to October.

2.8. Seasonal variation of temperature and σ_t at different depths off Waltair

The curves used here are reproduced from Varadachari (1963) (Fig.40). The surface temperature is highest during September-October and again in April-May. The lowest surface temperatures are observed during December-January. At 125 m, the temperature begins to decrease from December and reaches a minimum in March.

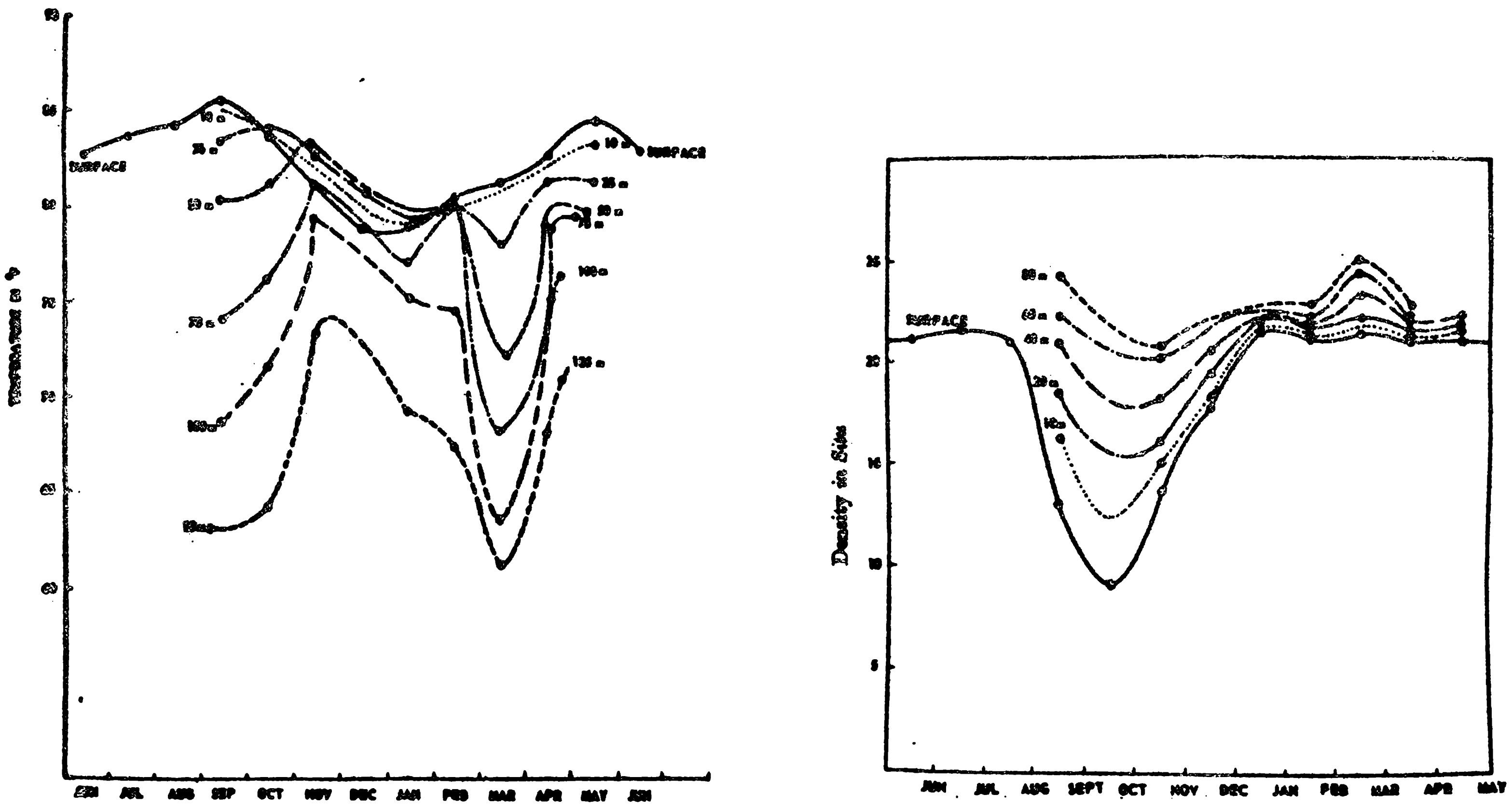


Fig.40. Seasonal variations of (a) Temperature (^{o}F) and (b) σ_t (g/l) at different depths of Waltair (from Varadachari, 1963).

But at 75 and 50 m the variation of temperature is not continuous till February. The temperature at these depths decreases sharply from February to March. After March, the temperature increases till May. For June, July and August no data is available, but during September the temperature shows a secondary minimum at all depths except at the surface. This indicates that the temperature decreases at subsurface depths sometime during June to August. From September onwards, the temperature increases between 25 and 125 m and reaches a peak in November. During October - February the temperature in the upper 50 m exceeds that at the surface, while the temperature at 75 m exceeds that at the surface between October and November.

The density field also shows large seasonal variation and it is maximum at the surface. The surface density is the least in September-October and maximum during January-August. The density variation at subsurface layers is less and it mainly depends on the temperature structure unlike in the surface layer. The density at 80 m depth is high in March and again in September, while it is the least in November, and again in April-May.

2.9. Vertical sections of temperature and σ_t off Madras:

The sections off Madras were covered during January, April, May and June. Due to the unavailability of data for the northeast monsoon, it could not be presented.

2.9.1. January

The surface temperature is about 26°C which is higher than that off Waltair for this month (Fig.41). The depth of mixed layer is about 85 m in nearshore regions. The isotherms and isopycnals show upsloping towards the coast in the nearshore regions indicating a weak northerly flow, but further offshore the flow is southerly.

2.9.2. April

The isotherms and isopycnals slope up towards the coast indicating a northerly current. The surface temperature is fairly high - about 28°C in nearshore and increases offshore (Fig.42). Near the coast, the thermocline is observed below 50 m. The density increases at all depths from January to April and this increase is more prominent in the nearshore regions.

2.9.3. May

The surface temperature is above 28°C in nearshore regions and increases to 29°C at about 25 km from the coast (Fig.43). The isotherms and isopycnals slope up towards the coast indicating a northerly current. The mixed layer is about 50 m deep near the coast, but at about 50km from the

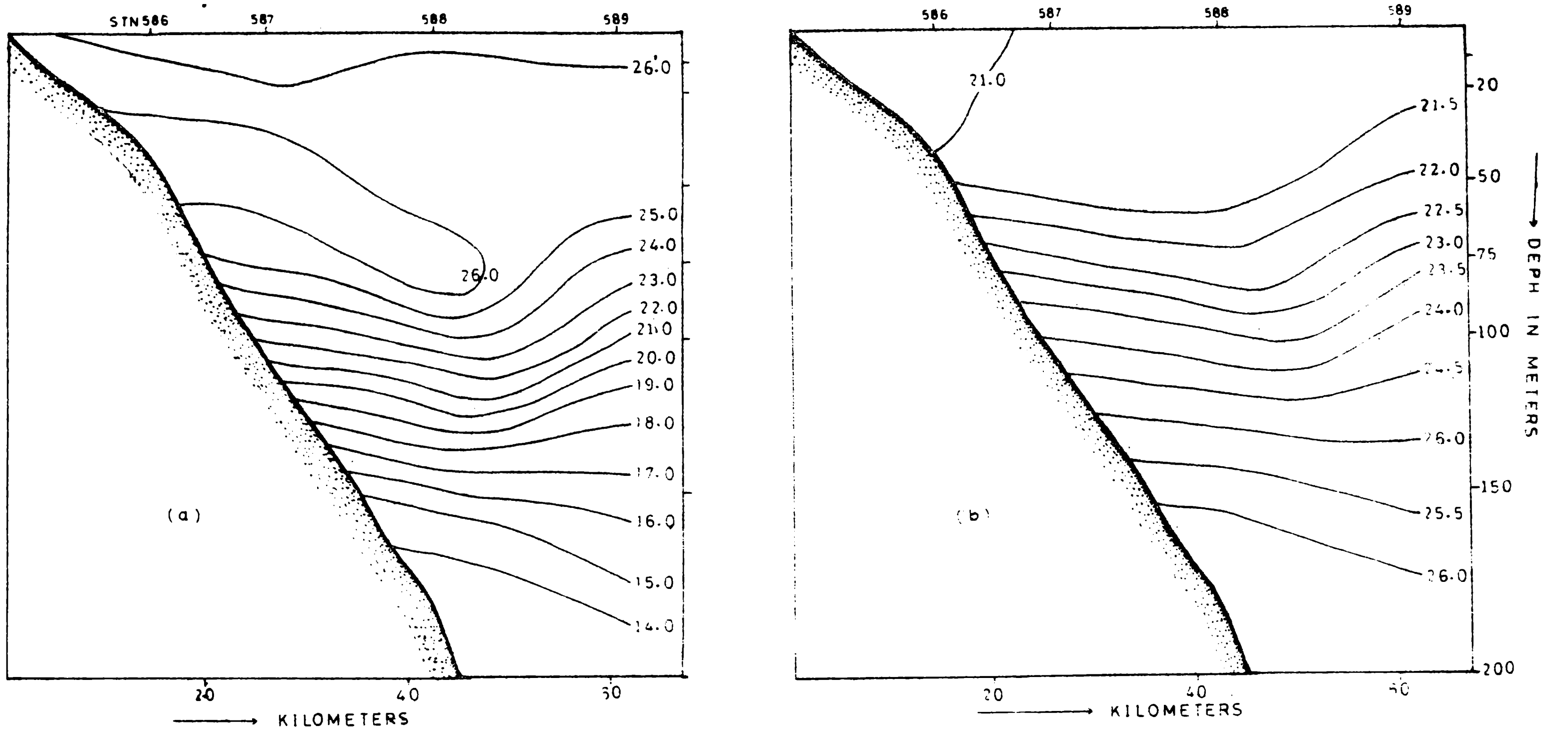


Fig.46 Vertical Sections of (a) Temperature (°C) and (b) σ_t (g/l) off Madras. January 31- February 1, 1965.

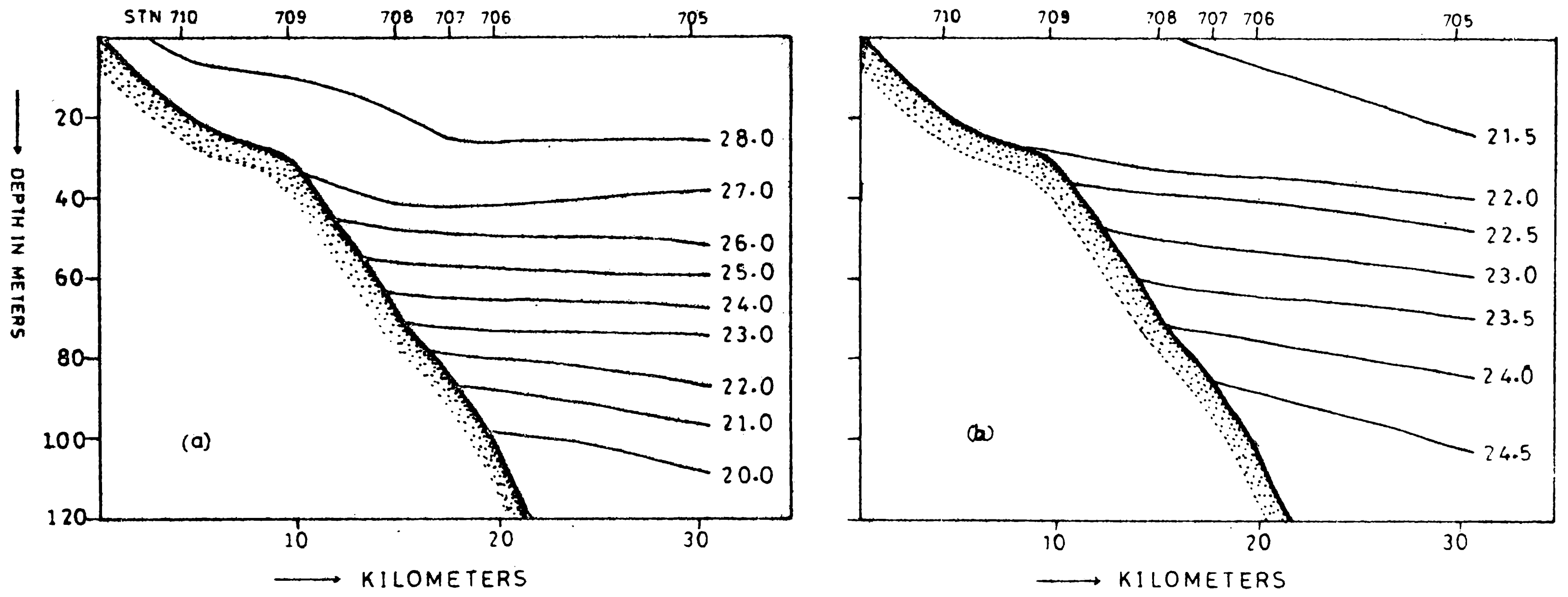


Fig. 42. Vertical Sections of (a) Temperature (°C) and (b) σ_t (g/l) off Madras, April 7-8, 1965.

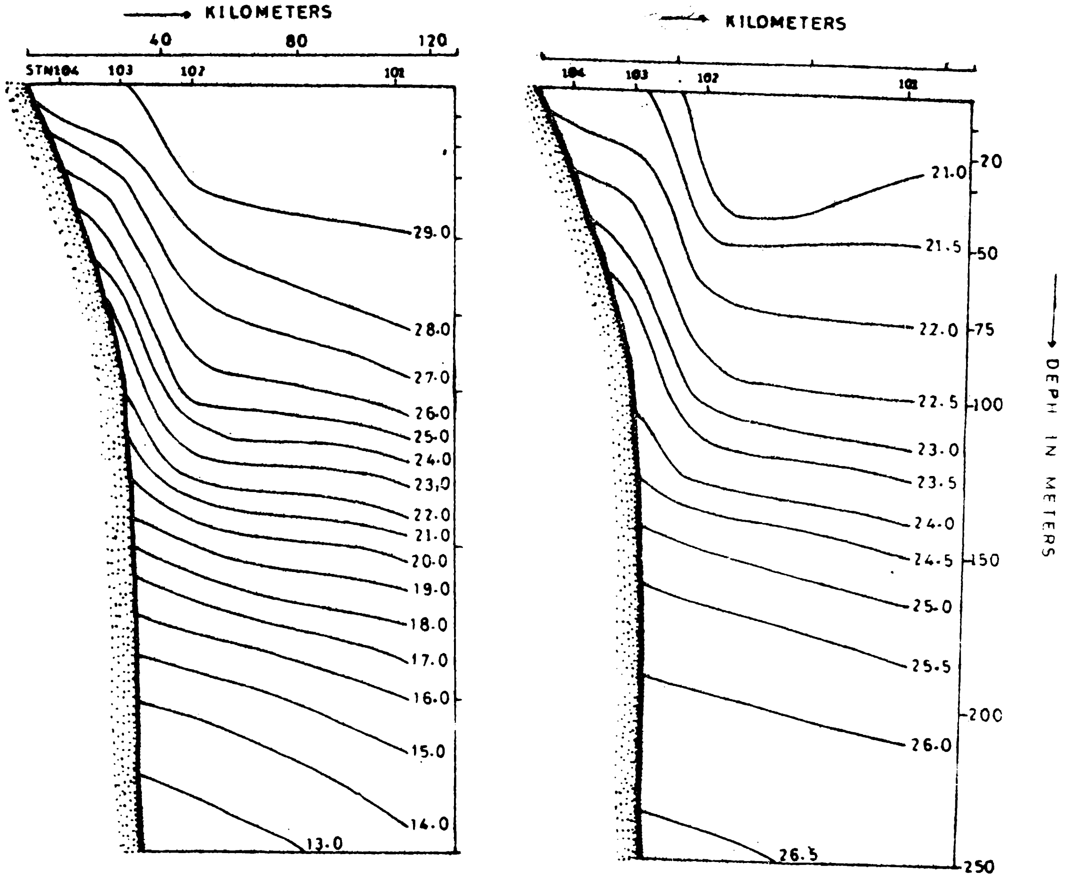


Fig.43. Vertical Sections of (a) Temperature (°C) and (b) σ_t (g/l) off Madras, May 3. 1963.

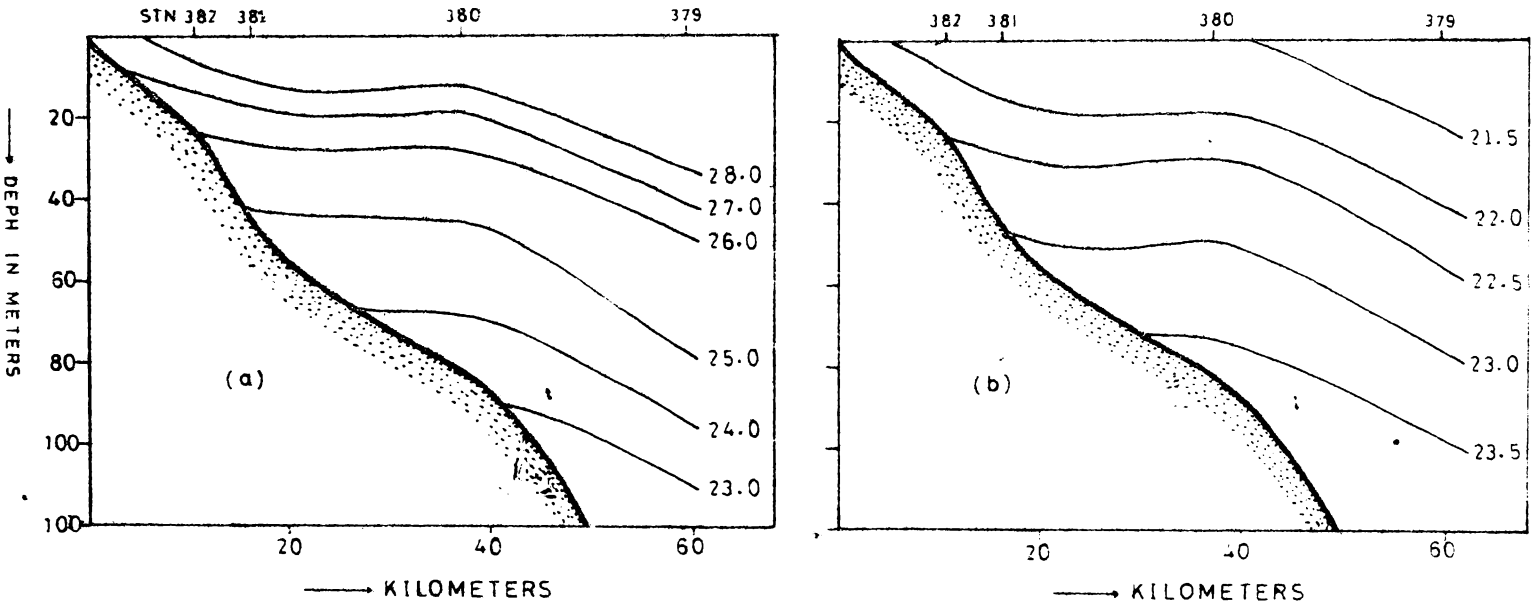


Fig.44. Vertical Sections of (a) Temperature (°C) and (b) σ_t (g/l)

off Madras, June 20-23, 1963

coast the depth of mixed layer increases to about 100 m. A slight decrease of density is observed at all depths except in the surface layers from April to May. There are no indications of a subsurface countercurrent down to a depth of 250 m. It is interesting to note that the upsloping of isopycnals is marked only upto a distance of about 40 km from the coast.

2.9.4. June

The upsloping of isotherms and isopycnals continues in this month also (Fig.44). The density field does not show much variation from that of May. The surface temperature is about 28°C near the coast and slightly increases offshore.

CHAPTER III

SURFACE VERGENCE, WINDSTRESS AND SEA LEVEL VARIATIONS

3.1. VERGENCE FIELD OF SURFACE CURRENTS OFF THE EAST AND WEST COASTS OF INDIA.

Vertical motions in the ocean are closely associated with divergence and convergence of surface currents usually induced by wind. Regions of divergence are defined as those where surface waters of the ocean flow away from each other, so that waters from subsurface depths rise as a feature of upwelling (Sverdrup et al., 1942). Conversely regions of convergence are areas where surface waters meet and sink. The areas of surface divergence are generally productive of plankton, while regions of convergence are relatively barren of plankton.

As already mentioned, the results obtained here do not represent a synoptic picture, but only an average over a few hundred kilometers and there are some limitations to this method very near the coast. Further there are some limitations in the basic data also. However, the surface divergence gives a qualitative understanding of the processes-upwelling and sinking.

The vergence field of the surface waters off the east and west coasts of India are presented for different months of the year (Figs.45-50). Areas of divergence are dotted in the figures while the areas of convergence are left blank. The isolines of convergence and divergence are drawn at an interval of 5 units (1 unit = 5×10^{-8} sec^{-1}). Vergence field with values exceeding 20 units are termed as strong, 10-20 units as moderately strong and less than 10 units as weak.

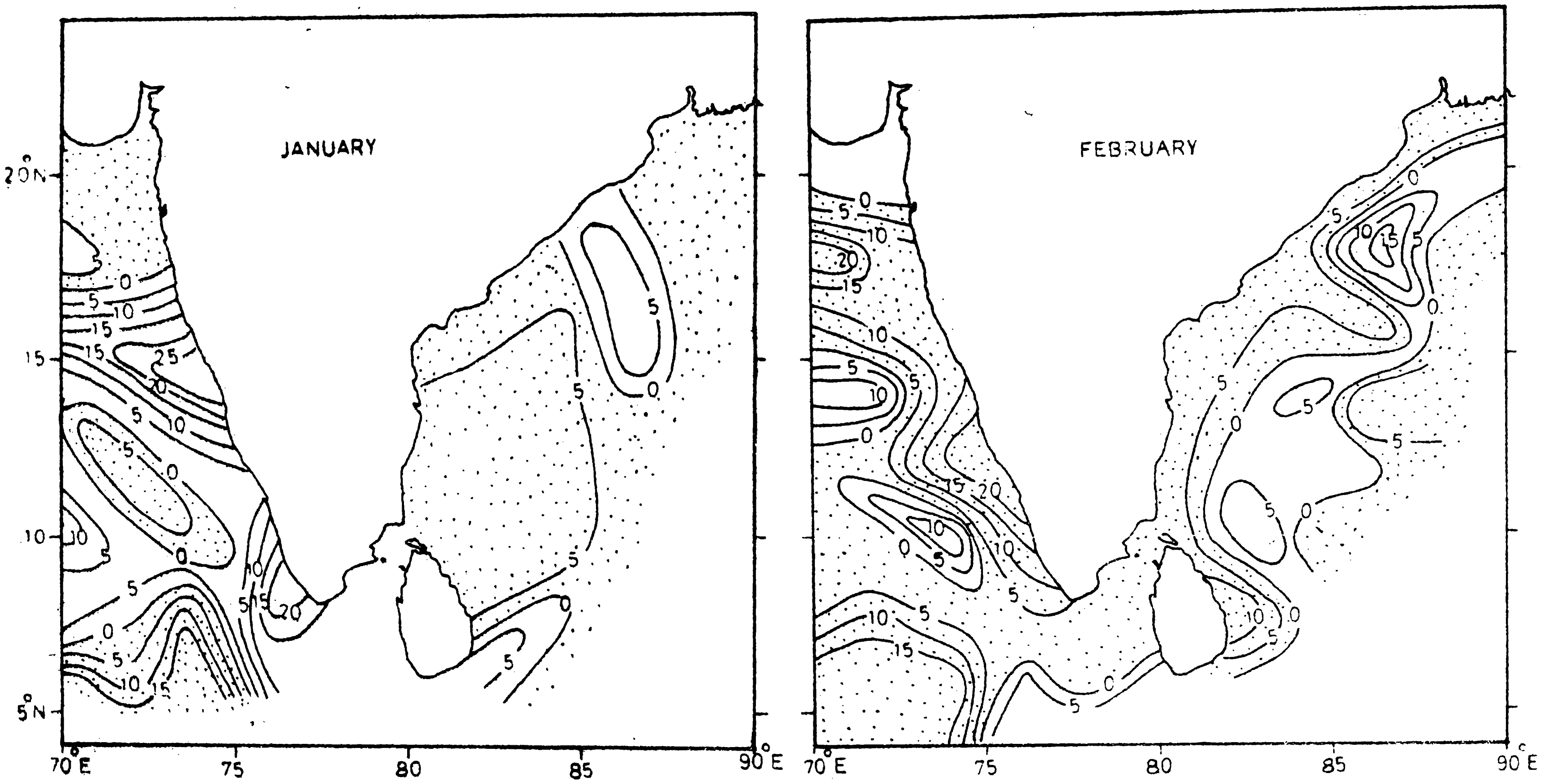
3.1.1. January

During this month convergence prevails off the west coast of India, except in the northern region where weak divergence is noticed (Fig.45a). Strong convergence is observed between 13°00'N and 15°00'N and in the region south of Quilon. In offshore regions,cells of both convergence and divergence are noted alternately.

In general, the field of divergence is predominant off the east coast of India.

3.1.2. February

By the month of February the convergence off the west coast of India is replaced by divergence (Fig.45b). However, in the region north of 17°00'N divergence is replaced by convergence. The divergence is strong between 10°00'N and 13°00'N. February is the month of reversal of surface currents off the west coast of India. It should be noted that the surface currents are highly variable in this month and the constancy of the current



(a) (b)

FIG.45. VERGENCE FIELD OF SURFACE CURRENTS 1 UNIT=5×10^{-8} SEC^{-1}.

is less than 50%. In these circumstances the absolute values of the vergence field obtained for this month may not be very representative.

Divergence continues to prevail off the east coast of India. The vergence field, in general, is weak. In offshore regions moderately strong convergence is noticed.

3.1.3. March

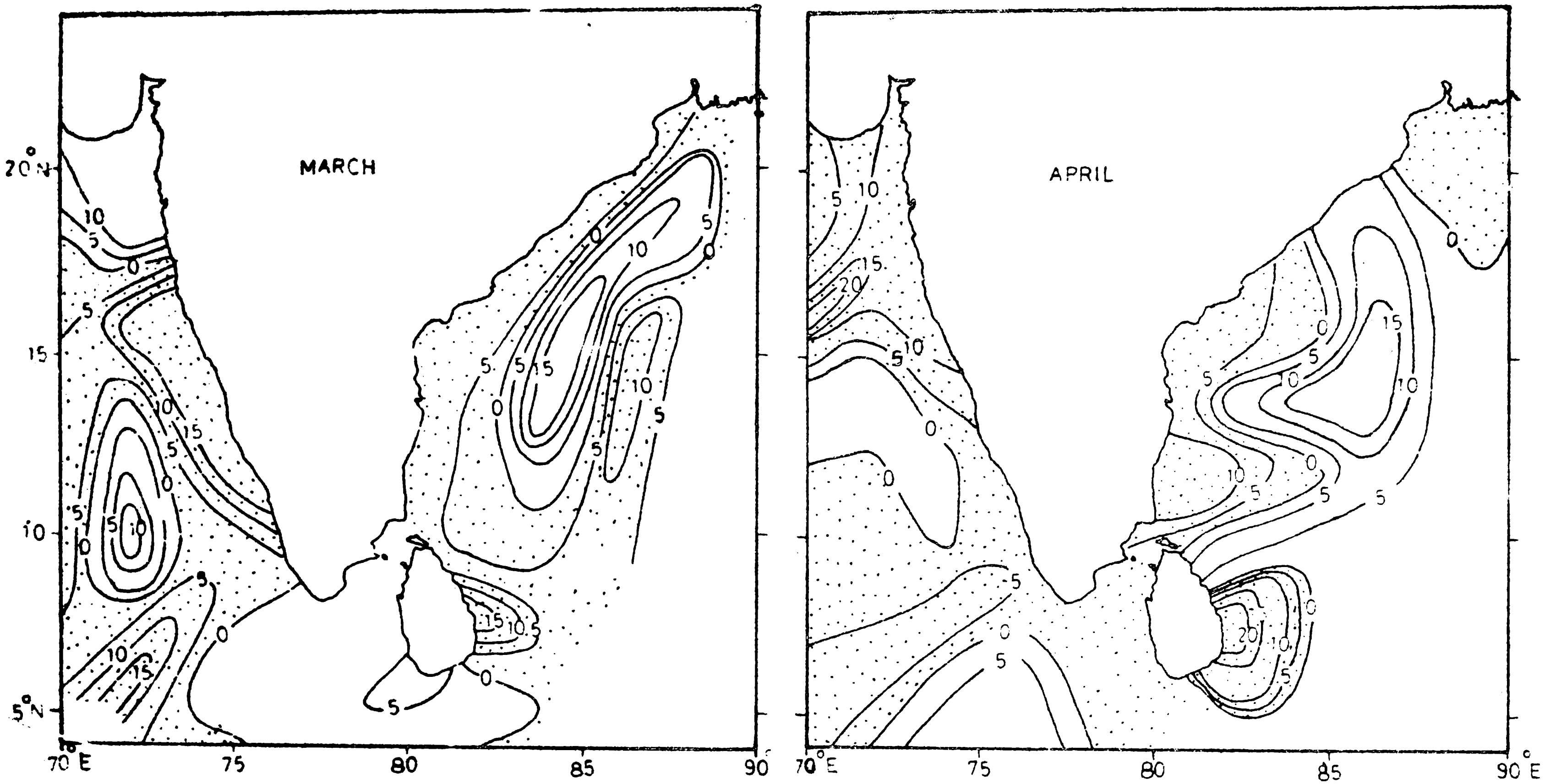
Divergence continues to prevail off the central and southern west coast of India (Fig.46a). The vergence field is moderately strong between Cochin and Karwar. South of Cochin weak divergence is found. However, moderately strong convergence is observed north of 16°00'N.

Weak divergence continues off the east coast of India. In offshore regions moderately strong convergence is observed.

3.1.4. April

By this month the entire west coast of India is under the influence of divergence (Fig.46b). Moderately strong divergence is indicated north of 16°00'N.

Off the east coast,divergence is observed in the region south of 18°00'N. A weak cell of convergence is noticed off the Orissa coast.



(a) (b)

FIG.46. VERGENCE FIELD OF SURFACE CURRENTS 1 UNIT = 5×10^{-8} SEC^{-1}.

3.1.5. May

Divergence continues to prevail off the entire west coast of India (Fig.47a). Between Karwar and Cochin moderately strong divergence is observed. However, in the northern and southern regions divergence is relatively weak.

Convergence dominates off the east coast except in the region south of Madras. Moderately strong convergence is noted off the Andhra and Orissa coasts.

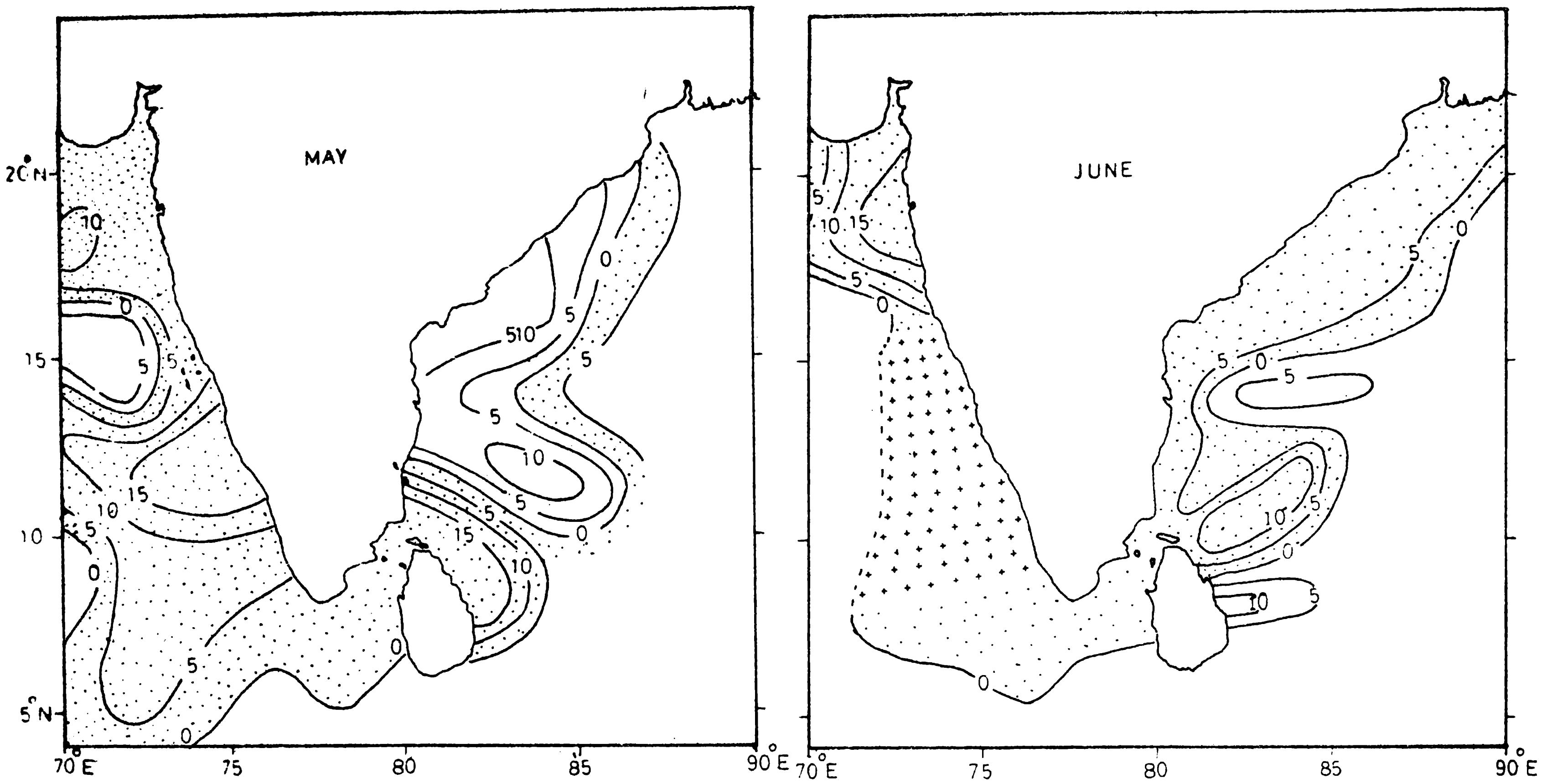
3.1.6. June

Due to paucity of data the vergence field south of 16°00'N could not be drawn off the west coast of India (Fig.47b). North of 16°00'N moderately strong divergence prevails.

The convergence off the east coast has been again replaced by divergence by June. The divergence is moderately strong off the Andhra and Orissa coasts. In other regions the vergence field is weak.

3.1.7. July

In the regions north of 15°00'N divergence continues to prevail (Fig.48a). South of 15°00'N no conclusion can be drawn due to the unavailability of data.



(a) (b)

FIG.47. VERGENCE FIELD OF SURFACE CURRENTS 1 UNIT= 5×10^{-8} SEC^{-1}.

(•••• REGIONS OF INADEQUATE DATA)

Off the east coast of India the vergence field shows alternate cells of divergence and convergence, but off Madras, Northern Andhra and Orissa coasts divergence continues to prevail.

3.1.8. August

Moderately strong divergence is observed off the Maharashtra coast (Fig.48b). South of Mangalore, moderately strong convergence is noticed.

Off the east coast mainly convergence dominates except off the Orissa coast where weak divergence is noted.

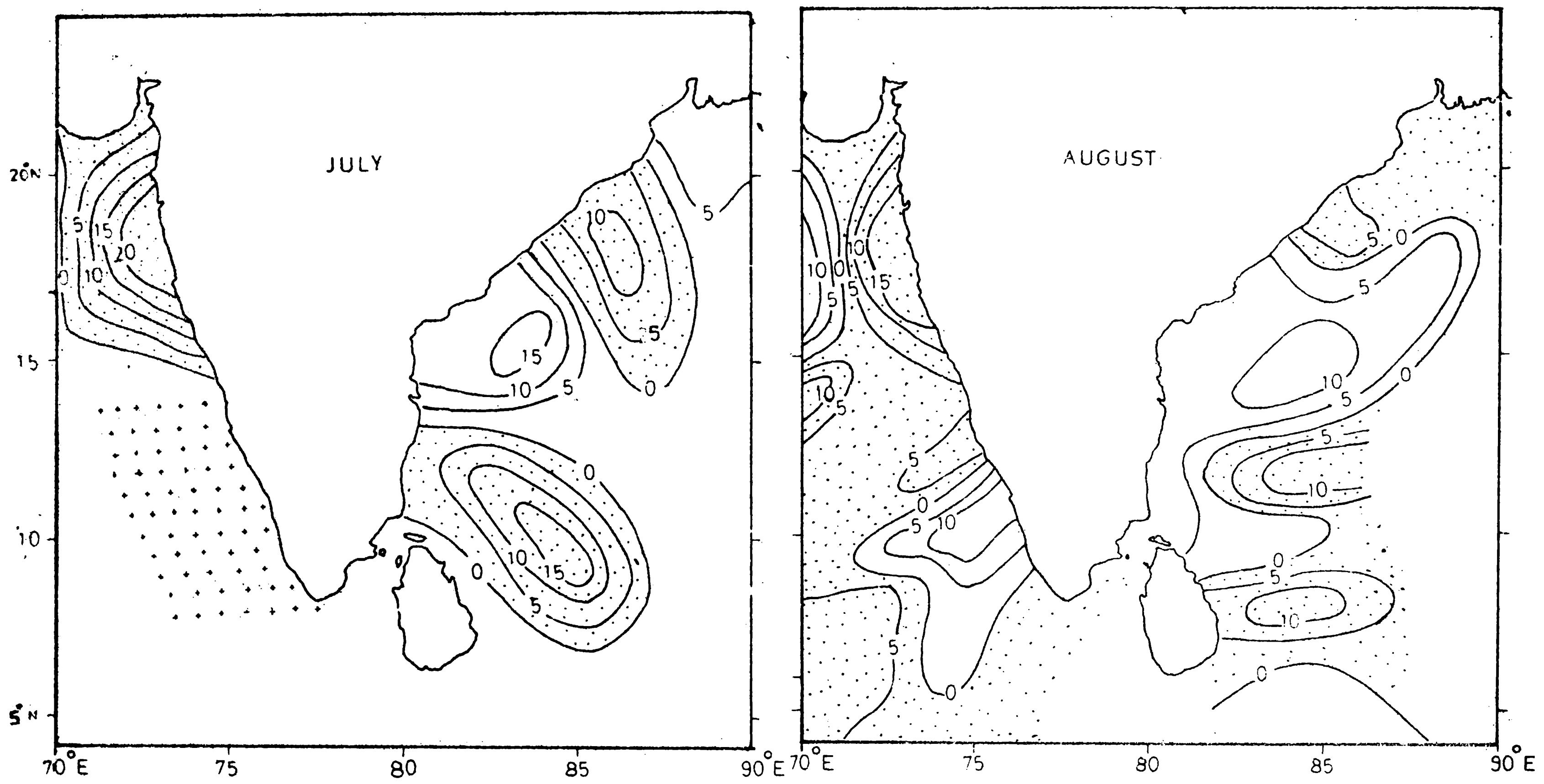
3.1.9. September

Off the west coast the convergence field has extended to further north upto 16°00'N (Fig.49a). The convergence is moderately strong between Cochin and Karwar. However, north of 16°00'N divergence continues to prevail.

Mainly convergence is observed off the east coast of India, except in the region south of Madras. However, compared to the west coast the vergence field is weak here.

3.1.10. October

By this month the entire west coast of India is under the influence of convergence (Fig.49b). October



(a) (b)

FIG.48. VERGENCE FIELD OF SURFACE CURRENTS 1 UNIT=5×10^{-8} SEC^{-1}.

(···· REGIONS OF INADEQUATE DATA)

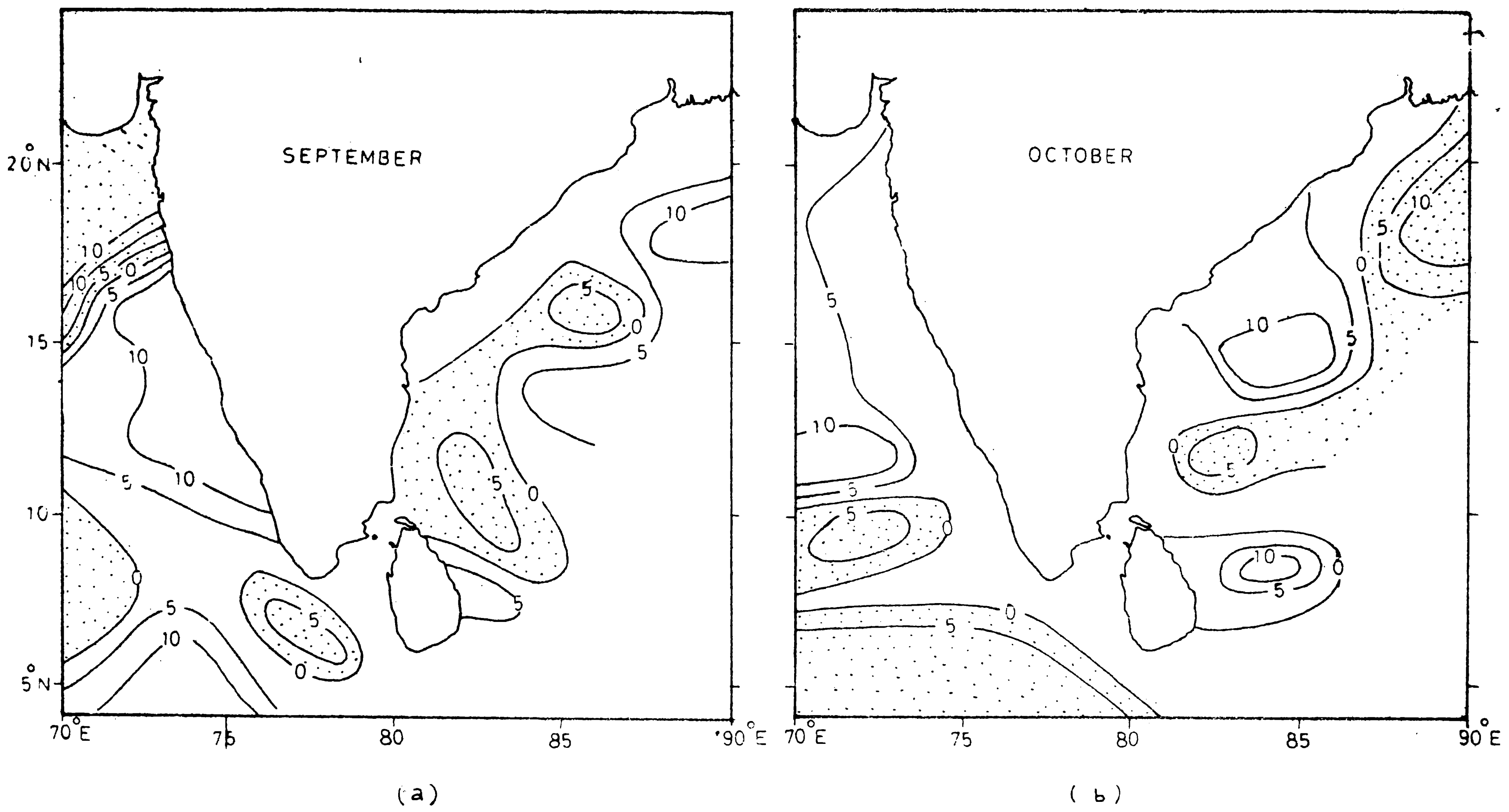


FIG. 49. VERGENCE FIELD OF SURFACE CURRENTS 1 UNIT= 5×10^{-8} SEC^{-1}.

is the month of reversal of surface currents to northerly. The currents are generally weak and variable and so the field of vergence also is weak.

Weak convergence continues to prevail off the entire east coast of India.

3.1.11. November

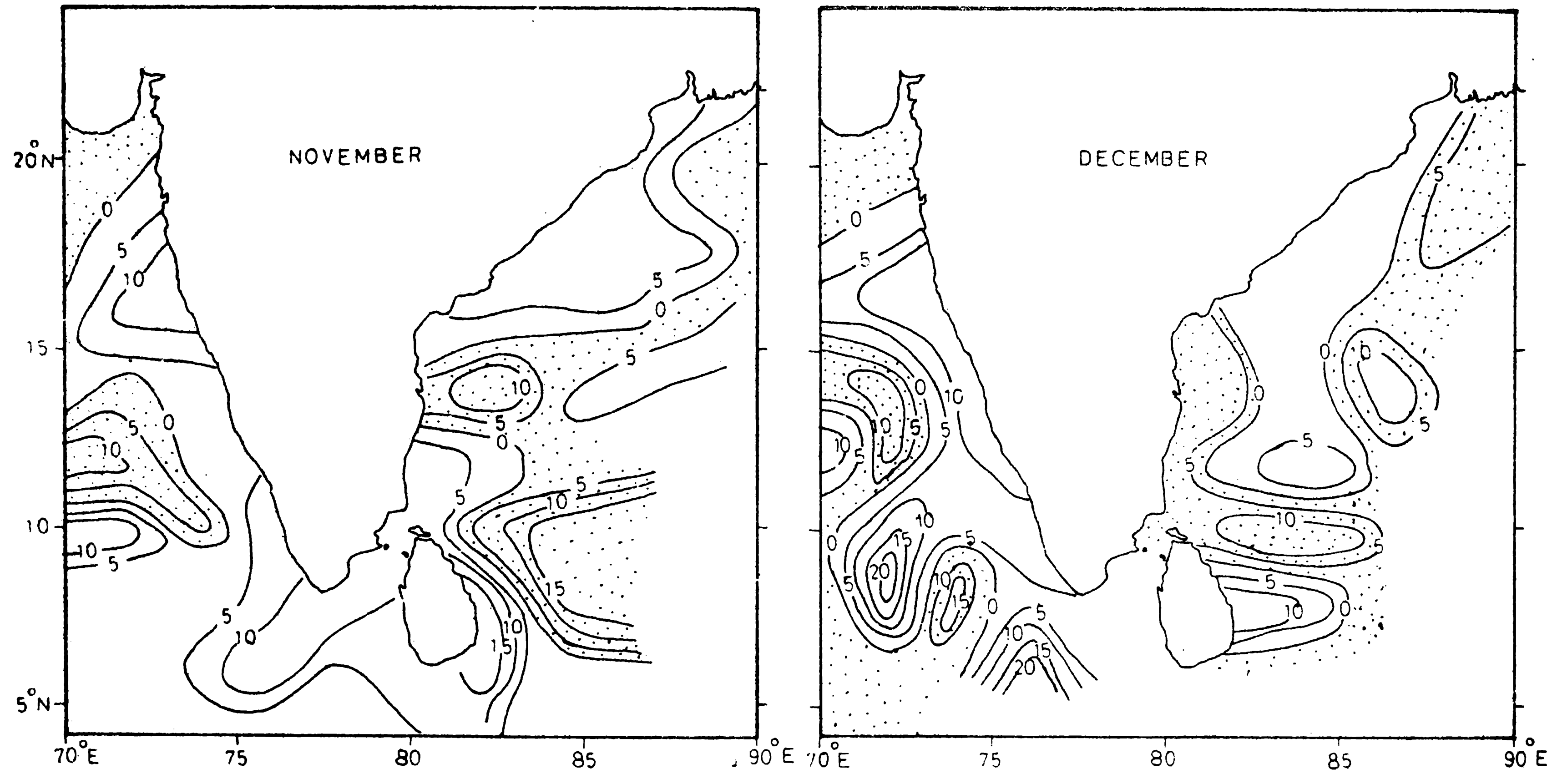
There is no significant change in the nature of the vergence field off the west coast of India to that in October (Fig.50a). The convergence is moderately strong off the Maharashtra coast, while in other regions weak divergence is observed.

Weak convergence continues to prevail off the east coast. However, a cell of strong divergence is found north of Madras, but its reliability is doubtful as it may be the result of the limitation of the data used.

3.1.12. December

Except in the northern regions off Maharashtra convergence continues off the west coast (Fig.50b). The convergence is weak in the southern regions, but between 12°00'N and 17°00'N it is moderately strong.

Off the entire Andhra coast weak convergence continues to prevail in December also.



(a) (b)

FIG. 50. VERGENCE FIELD OF SURFACE CURRENTS 1 UNIT = 5×10^{-8} SEC^{-1}.

Summarising the results it could be inferred that generally divergence prevail off the west coast of India from February to August and convergence during the rest of the year. But a closer examination indicates that off the Kerala coast convergence starts slightly earlier, in August. The northwestern part also exhibits some peculiarities. Off northern Maharashtra, divergence starts in April and continues upto September. There are some doubts regarding the presence of divergence in that region in December-January. Both divergence and convergence are strongest between Cochin and Karwar. The occurrence of divergence is mainly found during the period of southerly currents, barring September, while convergence is observed during the period of northerly currents.

Off the east coast also the vergence field changes seasonally. Divergence prevails from January to April and again in June. The vergence field shows cells of convergence and divergence in July. Convergence is observed in May and again during August to December. In general, the vergence field in this region is much weaker than that off the west coast.

3.2. WINDSTRESS

The resolved windstress components parallel and normal to the average trend of the coastline off Cochin, Karwar and Bombay on the west coast and off Madras and Waltair on the east coast are presented for different months (Fig.51-53). Off the west coast equatorward and offshore components and off the east coast the poleward and offshore components are favourable for upwelling.

3.2.1. Windstress off Cochin

Throughout the year, the windstress component parallel to the coast in the equatorward direction is present (Fig.51a). But the magnitude of this component is negligibly small from October to February. From March onwards, the equatorward component of windstress increases and by April it reaches a value of 0.07 dynes cm^{-2}. A slight decrease is observed in May. There is a sudden increase in June upto values over 0.12 dynes cm^{-2} and maximum values are reached in July. A slight decrease is noted in August and by September this windstress component decreases considerably.

The offshore component of windstress is present from November to March. But its magnitude is too small. The onshore component of wind stress is present from

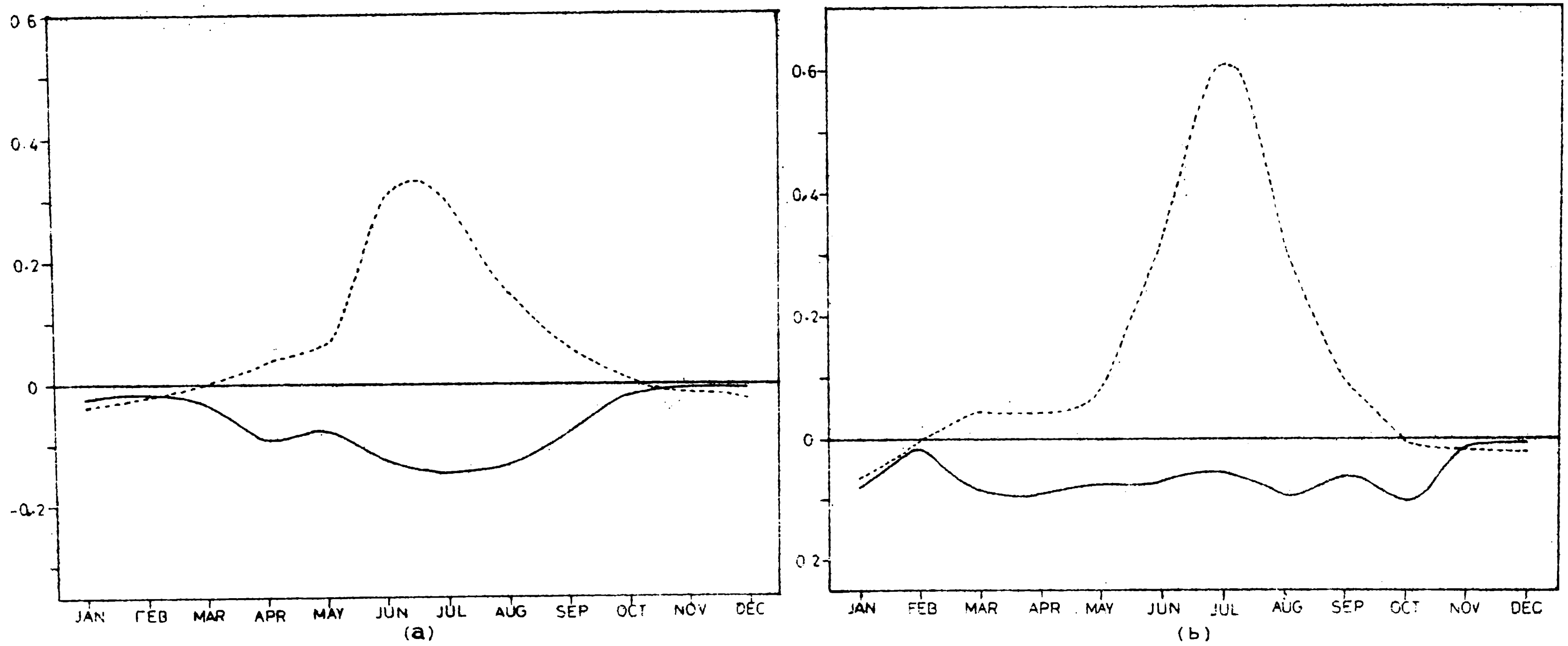


FIG. 51. MONTHLY CHANGES IN MEAN WINDSTRESS COMPONENTS (a) OFF COCHIN AND (b) OFF KARWAR [-----, WINDSTRESS COMPONT TO AVERAGE COASTLINE (+) VALUE ONSHORE (−) VALUE OFFSHORE AND ——, WINDSTRESS COMPONENT TO AVERAGE COASTLINE (+) VALUE POLEWARD (−) VALUE EQUATORWARD]

April to October. From May onwards, the onshore component increases to values over 0.3 dynes cm^{-2} in June-July. From August, the onshore component decreases suddenly.

3.2.2. Windstress of Karwar

Off Karwar also the equatorward component of windstress is present throughout the year (Fig.51b). From November to February, the values are negligibly small. From March, the windstress component increases and reaches values about 0.1 dynes cm^{-2} in August-October. After October the values decrease sharply. Compared to that off Cochin, this component is slightly less off Karwar.

The offshore component of windstress is present from October to January. Except for January the values are negligibly small. The onshore components are present from March to September. This windstress component increases suddenly in June and reaches a peak value over 0.6 dynes cm^{-2} in July. After July, it decreases sharply. The onshore components are strongèr off Karwar than that off Cochin.

3.2.3. Windstress off Bombay

The wind distribution off Bombay shows some considerable variation from that off Cochin and Karwar (Fig.52). The equatorward component of windstress is

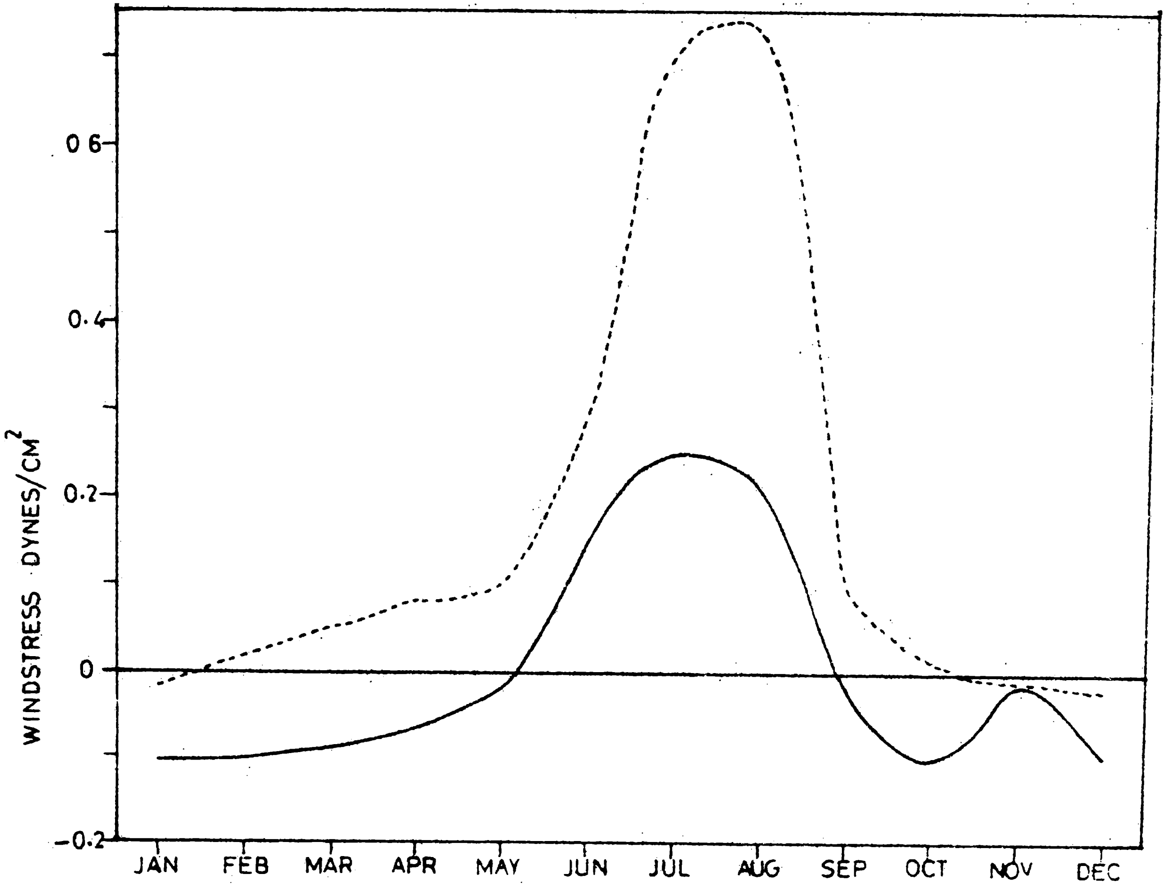


FIG.52. MONTHLY CHANGES IN MEAN WINDSTRESS COMPONENTS OFF BOMBAY

[----, WINDSTRESS COMPONENTS TO AVERAGE COASTLINE (+) VALUE ONSHORE (−) VALUE OFFSHORE; AND ——, WINDSTRESS COMPONENT (+) VALUE POLEWARD, (−) VALUE EQUATORWARD.

present from September to May, but it is insignificant except during October and from December to March. Unlike in the southern regions, during June-August there is a poleward component of windstress which is favourable for sinking and it reaches a peak in July-August with values over .2 dynes cm^{-2}.

The offshore component of windstress is present from October to January, but it is insignificant. The onshore component is present from February to September. It acquires appreciable values during July-August with values over 0.7 dynes cm^{-2}. From September the value of the onshore component decreases.

3.2.4. Windstress off Waltair

The poleward component of windstress parallel to the coast is present from March to September (Fig.53a). But except for the period April to August the values are small. High values over 0.7 dynes cm^{-2} are observed during the peak of the southwest monsoon (June, July, August). The equatorward component of windstress is observed from October to February with maximum values in November-December.

The offshore component of windstress is present only from June to October with values over 0.2 dynes cm^{-2}

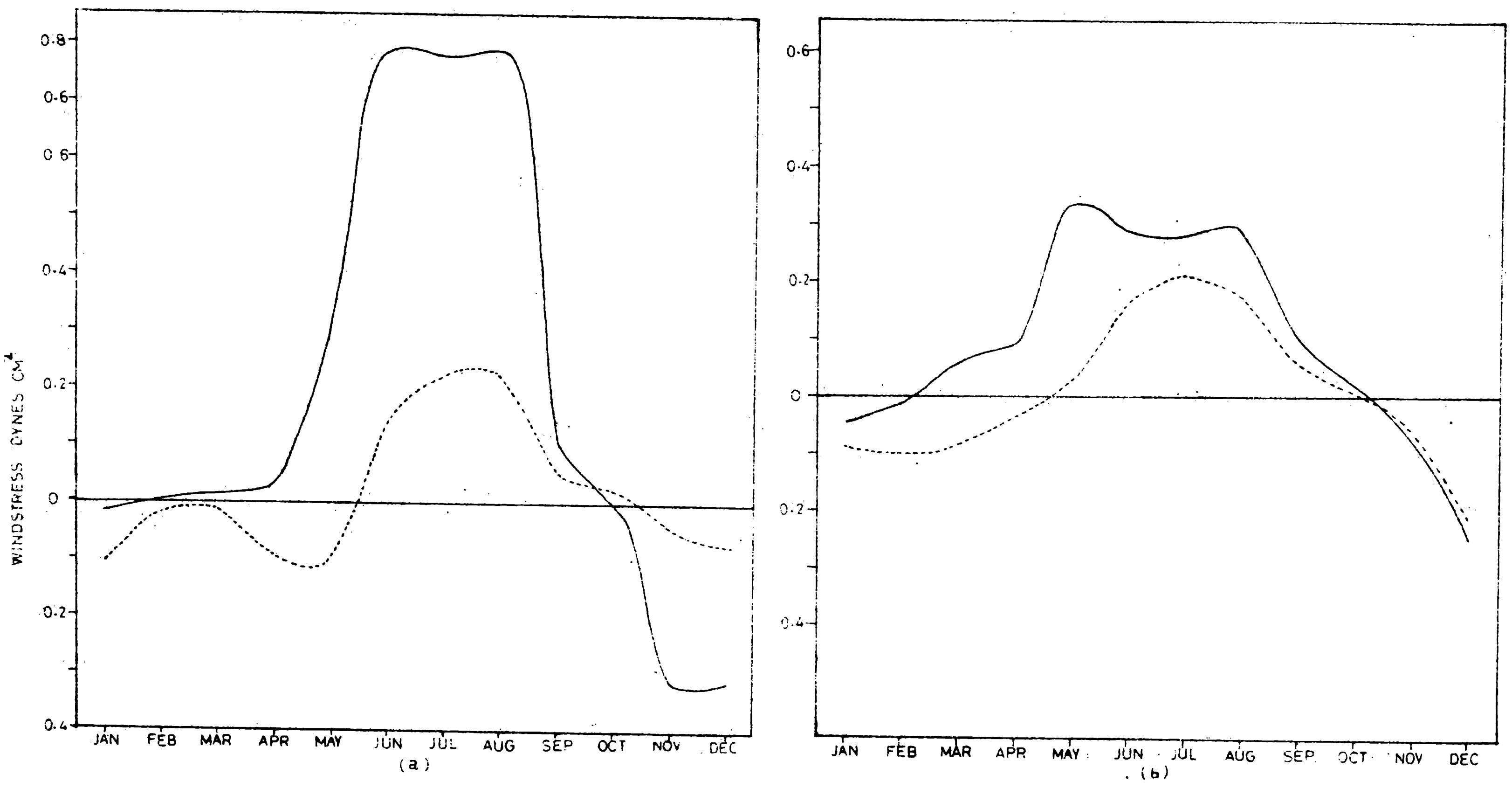


FIG.53. MONTHLY CHANGES IN MEAN WINDSTRESS COMPONENTS (a) OFF WALTAIR AND (b) OFF MADRAS
[------, WINDSTRESS COMPONT TO AVERAGE COASTLINE (+) VALUE ONSHORE (−) VALUE OFFSHORE
AND ——, WINDSTRESS COMPONENT TO AVERAGE COASTLINE (+) VALUE POLEWARD (−) VALUE EQUATORWARD]

during July-August. The onshore component is observed from November to May, but values over.1 dynes cm^{-2} are observed only in January and again in May.

3.2.5. Windstress off Madras

The poleward component of windstress parallel to the coast is present from March to October (Fig.53b). From March onwards the value of this component increases to about 0.33 dynes cm^{-2} by May. During the period June to August, the poleward component does not show much variation. After August, the poleward component of windstress decreases rapidly. The equatorward component of windstress is present from November to February, but except for December the values are very small.

The onshore component of windstress is found from November to April and fairly high values over 0.1 dynes cm^{-2} between December and March. From May onwards the offshore component is present with high values over 0.2 dynes cm^{-2} till August. Weak offshore component is present during September.

3.3. SEA LEVEL VARIATIONS

Monthly changes in sea level at Cochin and Marmugao on the west coast and at Madras and Visakhapatnam on the east coast are presented (Figs.54–55).

Sea level undergoes seasonal as well as annual variations. In the present study the latter is ignored, and the picture presented are monthly averages of a few years.

A number of factors affect mean sea level such as atmospheric pressure, vertical motions, evaporation, rainfall, surface heating and cooling etc. Of these, the effects of atmospheric pressure, vertical motions and freshwater discharge are the most important, though, other factors also have significant effects in certain localities. If the effects of atmospheric pressure and rainfall on mean sea level are known, vertical motions can be inferred qualitatively from the sea level variations. The effect of upwelling is that the sea level is lowered with upwelling, whereas sea level increases with sinking. In order to infer upwelling from sea level variations one should consider the increase or decrease instead of the maximum or minimum values.

3.3.1. Sea level variations off Cochin

The sea level off Cochin starts decreasing from

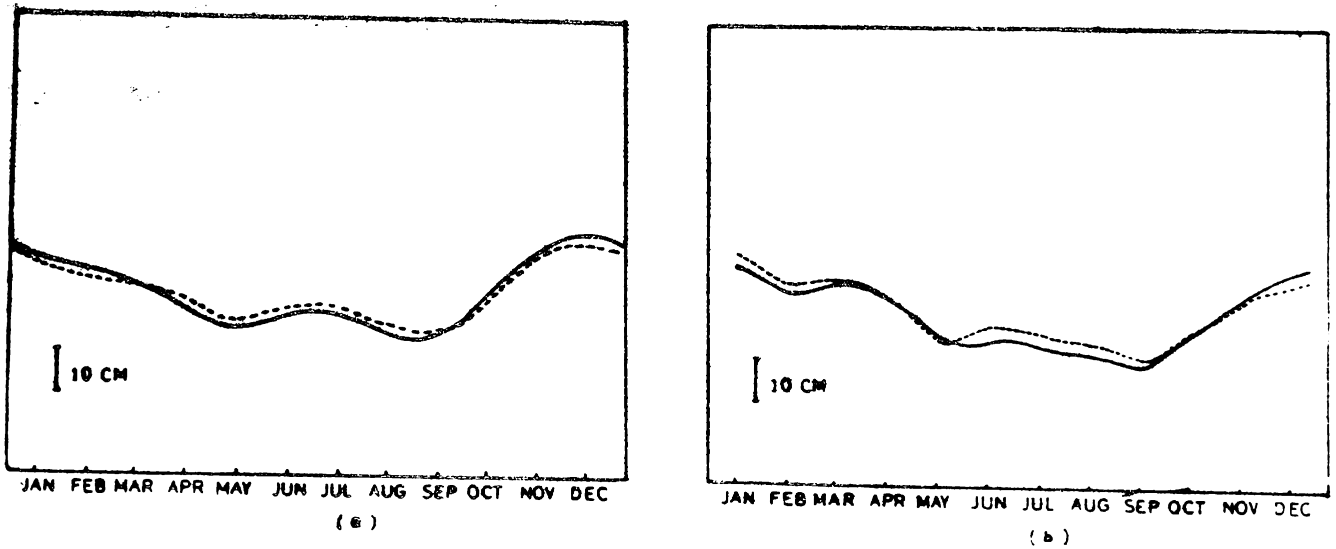
January-February till May. In June a slight increase is observed. The sea level again decreases and a minimum is observed in August. The sea level increases from September.

The slight decrease in sea level during January-February can be due to winter cooling. However, from February to May, sea level decreases gradually, despite intense solar heating. This is possibly due to upwelling. The increase in sea level in June is the result of sudden increase in freshwater discharge due to southwest monsoon rains. However, the sea level again lowers though there is large volumes of freshwater discharge during July-August. The lowest sea level in August possibly represent the period of maximum effect of upwelling. The increase in sea level from September may be due to sinking.

3.3.2. Sea level variations of Murmugao

Off Marmugao, the sea level begins to decrease from March till May. A slight increase occurs in June, but it again decreases from July to September. The sea level increases from October.

The meteorological conditions in Cochin and Marmugao do not show much variations. The sea level variation suggests a possible later commencement of upwelling off Marmugao. The annual minimum in sea level occurs in September, one month later than that off Cochin.



(a)

(b)

Fig 54. Monthly charges in mean sea level (a) at Cochin (from Banse, 1968) and (b) at Murmugao (date from Kesavadas, 1977). (........., Actual observations and ——, former corrected for the effect of air pressure).

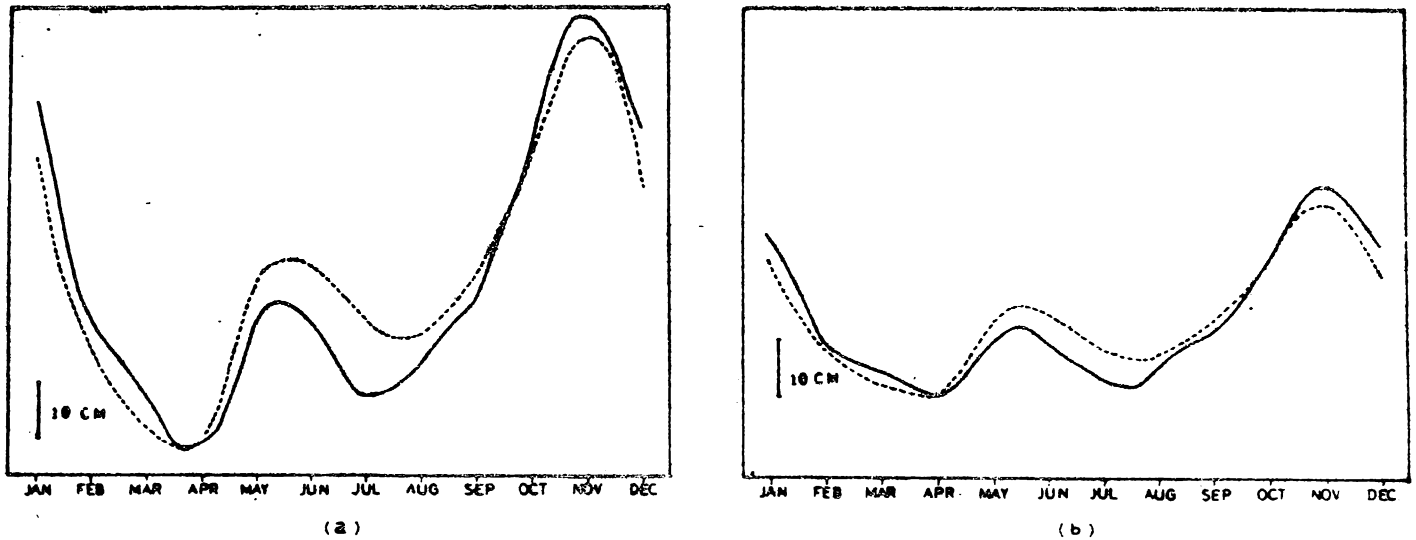
3.3.3. Sea level variations off Visakhapatnam

Off Visakhapatnam, the sea level decreases from November-December and a minimum is reached in March-April (Fig.55a). In May the sea level increases and from June another decrease is observed. A secondary minimum occurs in July. From September, the sea level increases sharply. The annual range in observed sea level is about 51 cm.

The decrease in sea level in December-January can be the result of a number of factors, such as winter cooling, reduction in river run off or upwelling. However, from February onwards the incoming solar radiation increases and the minimum in April can be mainly due to upwelling. The intense solar heating can be the reason for slight increase in sea level during May. The secondary minimum in July also may be the result of upwelling. From September, the sea level increases possibly due to sinking and increased freshwater influx.

3.3.4. Sea level variations off Madras

The sea level off Madras begins to decrease from December till April (Fig.55b). After April, the sea level slightly increases till May and another decrease is observed from June and a secondary minimum occurs in July-August. The sea level increases from September and the



(a)

(b)

FIG.55.MONTHLY CHANGES IN MEAN SEALEVEL (a) AT VISAKHAPATNAM AND (b) AT MADRAS [-----, ACTUAL OBSERVATIONTIONS AND ——, FORMER CORRECTED FOR THE EFFECT OF AIR PRESSURE. DATA FROM RAMANADHAM AND VARADARAJULU, 1964. AND VARADARAJULU AND DHANALAKSHMI, 1975.]

highest sea level is reached by November. The annual range of sea level off Madras is about 34 cm.

The factors affecting sea level off Visakhapatnam and off Madras are almost similar. Off Visakhapatnam, the primary minimum and secondary minimum in sea level occur slightly earlier than that off Madras.

CHAPTER IV

UPWELLING OFF THE WEST COAST OF INDIA

Since the physical characteristics of the waters change markedly due to upwelling, the time variation of these parameters can be used to infer upwelling. Many factors associated with thermal and density structure such as the time variation of a particular isotherm or isopycnal, the inclination of the thermocline or pycnocline towards the coast, the offshore-onshore gradient of temperature or density at a constant depth etc. can be used to study upwelling. Further, the surface vergence and sea level variations give qualitative inferences on the vertical motions.

The temperature and density fields off the west coast of India show large seasonal variations, at the surface as well as in subsurface layers. A lowering of temperature and an increase in density below 75 m starts during January-February off Quilon, whereas no noticeable change is observed in the surface layers (Figs.9 and 10). The decrease in temperature and increase in density at subsurface levels continue even after February and its influence gradually extends to the surface layers. The depth of mixed layer gradually decreases and the decrease is more prominent in nearshore regions. The temperature at 150 m begins to decrease from February to March off Cochin (Figs.21 and 22). The observations off Karwar are confined to the upper 100 m where the temperature begins to decrease from March to April (Figs.32a and 32b).

Several factors such as the variation in the amount of solar radiation that is directly absorbed at different depths, the effect of heat conduction, internal waves and vertical motions affect the temperature structure at subsurface depths. The incoming solar radiation off the west coast of India increases from February till May and so the continued decrease of temperature at subsurface depths during this period does not seem to be the result of decrease in the amount of incoming solar radiation. Further, the variations in density and temperature due to the effect of heat conduction or internal waves may not continue for a very long period as observed off the west coast of India. So the continued decrease of temperature and increase of density from February are due to upwelling. Hence, upwelling in deeper layers commences from February off Cochin. The sea level variations and the presence of divergence off the west coast of India from February also support this view.

The upward movement of isotherms and isopycnals in deeper layers seems to start slightly earlier in the south and gradually extends to north as evidenced from the sections off Quilon, Cochin and Karwar (Figs.9 and 10; 21 and 22; 32a and 32b). The sea level off Cochin begins to decrease during January-February, while that off Mormugao begins to decrease during March-April (Fig.54) which also give an indication that upwelling starts earlier in the southern regions.

The upward movement of isotherms and isopycnals continues to take place from February off Cochin. A sudden decrease of surface temperature is noticed in early June off Quilon and Cochin. In fact, the surface temperature decreases from 30-31°C in early May to 25-26°C in early June in the nearshore regions (Figs.3 and 4; 12 and 13). The decrease of surface temperature is maximum near the coast and less in offshore regions. This sudden lowering of surface temperature marks the arrival of cold, upwelled water from thermocline region. The 23.0 g/l isopycnal is observed very near the surface in early June (Figs.4 and 13). The decrease of temperature at all depths continues till July off Quilon and till August off Cochin. A corresponding increase in density is also observed in the same period except in the upper 10 m in the nearshore regions, where a decrease is noticed (Figs.5,14 and 15). The surface waters off the west coast of India are considerably diluted during this period due to southwest monsoon rains and river discharge, and this low salinity water is the reason for the decrease in density in the surface layers.

The thermocline is observed at the surface in the nearshore regions off Quilon, Cochin and Kasaragod during July-August (Figs.5 and 6; 14 and 15; 27 and 28). Off Cochin and Quilon, several of the isotherms outcrop into the naviface. The temperature and density fields suggest that in 1964 the maximum effects of upwelling are felt in July off Quilon and in August off Cochin. The time series section of temperature off Cochin shows the lowest temperature at all depths during July in 1971 and during August in 1972 (Fig.23). The maximum effects of upwelling occur only after the deepest possible water reaches the surface. Continuous upward movement of isopycnals stops by the end of July or early August (except in the upper 10 m) off Cochin and a steady state is reached for a while. The annual minimum in sea level off Cochin during August gives an indication that on a climatological basis the maximum effects of upwelling occur during August in this region (Fig.54a). Combining thermal and density structure, and sea level variation, it can be inferred that upwelling off Cochin continues till late July or early August. The vertical sections of temperature off Kasaragod in August and off Karwar in early October (Figs.28 and 31) suggest that upwelling continues for a longer time in the northern regions compared to that off Cochin. This is further supported by the sea level off Marmugao which shows an annual minimum during September. In these regions upwelling continues till the end of August or early September.

The vertical temperature section off Ratnagiri during early August differs very much from that of the southern regions during this month (Fig.34b). The isotherms show upsloping towards the coast indicating a southerly current. But even in nearshore regions the thermocline is about 40 m deep and the surface temperatures are above 28°C. Observations during the Pelagic Fisheries Survey also indicate less upwelling off Ratnagiri compared to that in the regions south of Karwar (Anon., 1980). Further inferences on the vertical motions in the region north of Ratnagiri can be obtained from early works.

Observations of temperature and salinity were made in late March and April 1962 between Ratnagiri and Veravel (Patil et al., 1964). These sections showed marked temperature gradients at the surface but water of 25°C was found only at 75–100 m. There was a slight upsloping of isotherms and isopycnals noticeable off Bombay and further north, and it marks the beginning of upwelling of deep water (Banse, 1968). Rising of isotherms and isopycnals off Goa starts earlier to June, however it seems that upsloping off Bombay starts only by June (Banse, 1972).

In September 1962, the 25°C isotherm was observed on the outer shelf off Bombay at about 20 m, below the shallow thermocline and the 23°C isotherm at about 50 m (Edelman, 1965). Upsloping of isotherms during the post monsoon period, before the onset of northeast monsoon was reported from the northern region (Banse, 1968). Near Bombay, water of 24°C occurred under much warmer surface water at 22 m depth in late October to early November 1958 (Carruthers et al., 1959). The vertical uplift of the 23°C isotherm in the eastern Arabian Sea indicates an uplift of 75 m between summer monsoon and post monsoon seasons, although as a rule it is more likely to be 50 m (Banse, 1968). Jayaraman and Gogate (1957), Carruthers et al. (1959), Neyman (1964) and Gallagher (1966) suggested upwelling in the northeastern Arabian Sea during northeast monsoon. However, Banse (1968) concludes that there is neither regular upwelling reaching the surface in November and December nor there is evidence of cool deep water reaching the surface in January or February.

It seems that upwelling in the region north of Ratnagiri is less intense during southwest monsoon compared to the southern regions. However, unlike in the southern regions, upwelling continues even after the southwest monsoon and the maximum effects of upwelling occur during post monsoon season and it continues till the northeast monsoon is well established, or sometimes even for a longer time.

The wind system off the west coast of India changes seasonally. During southwest monsoon, the winds on coastal stations south of Karwar are predominantly northerly or northwesterly, due to the influence of the Western Ghats. The winds averaged for each 2^{o} latitude-longitude quadrangle adjacent to land from Trivandrum to Karwar are westerly or slightly northwesterly during southwest monsoon (Anon., 1952). The coast is oriented in a north-northwest to south-southeast direction. So there is always a wind component parallel to the coast in an equatorward direction which is favourable for upwelling during southwest monsoon. Apart from local wind, the prevailing current system also has considerable influence on upwelling off the west coast of India.

The equatorward component of windstress parallel to the coast is present throughout the year off Cochin (Fig.51a). But the windstress is too weak to produce any significant vertical motion from October to February. From February, the coastal current along the west coast of India begins to flow towards south (Anon., 1952). Upward movement in deeper layers starts just before the reversal of surface current to southerly as is evident from Figs 21 and 22. The mass readjustment for the southerly flow starts before the current reversal and it is the reason for upward displacement in deeper layers before current reversal. A southerly current with vertical shear along the west coasts of continents is favourable for upwelling (Varadachari, 1961). The offshore Ekman transport due to the wind and the reversal of the current to southerly are responsible for the commencement of upwelling from February. The coastal current gathers speed in May (Anon., 1952), while the wind speed increases suddenly by June. The onshore and equatorward component of windstress increase and there is a considerable strengthening of the southerly current which is not exactly wind driven, but the coastal configuration forces the current to flow towards south. The onshore component of windstress act against upwelling, but theoretical works by Yoshida (1958b) indicate that the effect of windstress perpendicular to the coast on upwelling is usually very less compared to the windstress parallel to the coast. The accelerated coastal current which requires more denser water near the coast and the equatorward component of windstress favour upwelling from June and by July the wind and current attain maximum speed, and upward movement of isotherms and isopycnals continue till then. There is a slight decrease in wind and current speed in August, but more or less a steady state is maintained. By September both the wind and current speeds decrease considerably, and a general decrease in surface layer density is observed in nearshore regions which is mainly due to the mass re-adjustment in the density field for a weaker southerly flow. The effect of windstress is negligible from October.

The equatorward component of windstress off Karwar is significantly high till October (Fig.51b). That may be the reason for the longer duration and later cessation of upwelling in this region. The onshore component of windstress is very strong during July which can have an adverse effect on upwelling.

The winds during southwest monsoon are essentially southwesterly in the region off Ratnagiri and further north. These winds are favourable for sinking. Off Bombay, the equatorward component of windstress parallel to the coast is absent during southwest monsoon and instead a poleward component is present (Fig.52). However, owing to the coastal configuration the currents are southerly, which require denser water near the coast. The upsloping of isotherms and isopycnals are evident but there is no evidence of cold water reaching the surface during southwest monsoon. Upwelling near the coast continues till geostrophic balance of the current is established though the winds are unfavourable. The unfavourable winds during southwest monsoon seem to be the main reason for lesser upwelling of Ratnagiri and further north during this period. However, by September-October the winds become favourable for upwelling. The maximum effects of upwelling in this region occur during post monsoon or early northeast monsoon periods.

So it can be concluded that the commencement of upwelling off the southwest coast of India is caused mainly by the prevailing wind system, but only with the reversal of coastal current to southerly. The current begins to flow towards south slightly earlier in the southern regions as evident from the Dutch Atlas (Anon., 1952) and this is mainly the reason for the earlier commencement of upwelling in the southern regions. During the early part of southwest monsoon, the accelerated southerly current and the equatorward component of windstress favour upwelling in the region south of Karwar. With the decreasing speed of wind and current, further upward movement of isotherms and isopycnals ceases by the end of July or early August off Cochin. However with favourable winds, upwelling continues for a longer time off Karwar. Upwelling during southwest monsoon is dependent on the velocity of wind and coastal current. The effects of upwelling need not depend on the velocity of wind at that locality alone, because the velocity of the coastal current is dependent on wind strength over large areas. The lesser upwelling off Ratnagiri and further north is due to unfavourable winds, though the current is favourable for upwelling. The individual effects of windstress and coastal current on upwelling are difficult to estimate with the available data. However, the lesser upwelling off Ratnagiri and further north during southwest monsoon, where the winds are totally unfavourable for upwelling suggests that the equatorward component of windstress parallel to the coast has a significant effect on upwelling in the region south of Karwar during southwest monsoon.

Towards the end of the southwest monsoon the oceanographical conditions off Cochin and Quilon change. In September, the isopycnals show slight upsloping towards the coast indicating a weak southerly flow and the depth of the mixed layer increases from that of the previous month (Figs.7,16). However, substantial decrease in temperature and increase in density at all depths are observed off Cochin and Quilon from September to October which suggests upward movement during this period (Figs.7 and 8; 16 and 17). The time series section of temperature in 1971 gave a slight indication of a lowering of surface layer temperature from September to October, but there were no such indications in 1972. In 1971 and 1972 the observations were made in the last week of October, and probably by that time the conditions might have been changed. The observations in Cochin harbour during 1962 by Ramamirtham and Jayaraman (1963) indicate the lowest temperature in early August and again in October. The time series sections of temperature and density based on a decade's data by Sharma (1968) show a decrease in temperature and increase in density at all depths from September to October. The occurrence of this phenomenon every year is not clear, mainly because of its short duration and lack of observations at that time. However, the present study and those by Sharma (1968), Ramamirtham and Jayaraman (1963), suggest that this phenomenon has been observed in many years. The windstress component parallel to the coast in the equatorward direction shows a decreasing trend after August and this decrease is very rapid during September-October (Fig.51c). The wind observations at Cochin for 1964 did not indicate any deviation from that of the average conditions for September and October. These factors suggest that the upward movement observed from September to October is not due to wind, but due to a probable cause of oceanic origin. Theoretical studies by Yoshida (1967) indicate that the free baroclinic motion contains an internal Kelvin wave and the wave has significant amplitudes if its speed is close to that of wind variations, otherwise it decays due to intense boundary mixing. Whenever there is a resonance between the baroclinic waves and the existing wind speed, the poleward propagating baroclinic waves produce localised upwelling even in the absence of strong wind field (Yoshida, 1967). Perhaps, the poleward propagating baroclinic waves are responsible for an induced upwelling from September to October. It has been observed that the sudden onset of upwelling in the Gulf of Guinea is caused by coastally propagating baroclinic waves (Houghton, 1976; Houghton and Beer, 1976; Clarke, 1979).

The temperature and density fields change dramatically from October to November off Cochin (Figs.17 and 18). The thermocline which is observed almost at the surface in October has receded to below 100 m by November. The coastal current changes its direction to northerly during this period. The downward displacement of isotherms and isopycnals from October is due to sinking. However, slight upward movement of isotherms and isopycnals are evident from November to December in 1963 (Figs.18 and 19), while the sections for January and February show downward movement of isotherms and isopycnals (Figs.21 and 22). The time series section of temperature shows no variation from November 1971 to February 1972, whereas a slight upward movement of isotherms are evident from November to December in 1972 (Fig.23). Neither the vertical sections nor the time series sections give any evidence of continuous downward displacements of isotherms after November. The slight upward and downward displacement of isotherms and isopycnals within the deep mixed layer seem to be associated with fluctuations in current speed.

The effect of windstress on vertical circulation is negligible along the west coast of India from October to February. The surface current along the west coast of India is northerly from November to January (Anon., 1952; Varadachari and Sharma, 1967). The wind during this period is northerly or northeasterly but it is too weak. The surface current flows towards north because of the boundary effects, though the wind system off the west coast of India is not favourable for a northerly current from November to January. The reversal of the coastal current from southerly to northerly takes place in October-November. A northerly current along the west coast is favourable for sinking (Varadachari, 1961), and it is the northerly current that induces sinking off the west coast of India. The current reverses its direction slightly earlier in the south (Anon., 1952) thereby inducing sinking earlier in the southern regions.

Approximate velocity of vertical motions can be obtained from the time variation of isotherms or isopycnals. Assuming alongshore invariance of density field and no mixing across isopycnals an estimate of vertical velocities are made from the vertical movement of the 23.5 g/l isopycnal. From February to April the upward displacement of the 23.5 g/l isopycnal gives a velocity of upwelling of about 2×10^{-4} cm sec^{-1} off Cochin. The velocity of upwelling increases to 7×10^{-4} cm sec^{-1} from April to May.

Maximum velocities of upwelling are observed between May and June with values over 1.6×10^{-3} cm sec^{-1}. This value is comparable to the velocity of upwelling reported for the Gulf of Guinea (Ingham, 1970). However, compared to major upwelling regions, the velocity of upwelling off the southwest coast of India is less, since very high vertical velocities are observed in many upwelling regions - 5×10^{-3} cm sec^{-1} off San Juan in the Peru Current upwelling (Zuta et al., 1978), 7×10^{-3} cm sec^{-1} off Oregon (Smith et al., 1966) and even upto 10^{-1} cm sec^{-1} in the Canary Current upwelling region (Barton et al., 1977). But in these regions these high velocities persist for only a few days. Off the west coast of India the process of upwelling is gradual and the upward movement continues for a longer duration, and it takes about three to four months for the water of the thermocline region to reach the surface. The velocity of upwelling off Kasaragod and Karwar also seems to be similar to that off Cochin, though the upward displacement of 23.5 g/l isopycnal give lesser values due to lack of continuous observations. As in other upwelling regions,the velocity of upwelling decreases offshore in the region of study. Off Quilon and Cochin, the 23.5 g/l isopycnal does not show any upward movement in the nearshore regions after June, obviously due to the presence of low salinity water in the surface layers. However, upward movement continues even after June as evidenced by the relative positions of the 24.0 g/l and 25.0 g/l isopycnals (Figs.4 and 5; 13 and 14).

The velocity of upwelling from September to October is high off Cochin and Quilon. The 23.5 g/l isopycnal off Quilon shows a velocity of 2.3×10^{-3} cm sec^{-1} which is much greater than the velocity of upwelling from May to June. High velocity of upwelling is also observed off Cochin during this period where the 25.0 g/l isopycnal indicate velocities upto 2.5×10^{-3} cm sec^{-1}.

Compared to upwelling sinking is a very quick process in the region of study. The 23.5 g/l isopycnal indicates a velocity of sinking of 3.7×10^{-3} cm sec^{-1} from October to November off Cochin, which is about twice the velocity of upwelling during May-June. Values over 3×10^{-3} cm sec^{-1} are observed off Kasaragod from November to December. The high velocity of sinking is associated with the sudden reversal of coastal currents in this region. The reversal of the surface current is abrupt in this region, perhaps within a period of one month (Anon., 1976). The sudden reversal of the surface current from southerly to northerly in this area causes sudden downward displacement of isotherms and isopycnals.

The sea surface temperatures off Cochin are maximum during April-May, with values over 30°C (Figs.11 and

12). Sea surface temperatures above 30°C are observed off Kasaragod and Karwar also during March–April (Figs. 25,26 and 32). The incident solar radiation along the west coast of India is maximum from February to May and the high sea surface temperatures during this period are the result of intense solar heating. The lowest sea surface temperatures are observed during July–August, off Cochin and Quilon with values less than 24°C in the nearshore regions. This gives an annual variation of surface temperature of about 6–7°C, but this variation decreases with increasing distance from the coast. The annual surface temperature off Karwar ranges from 25° to 31°C. However, the annual variation is more pronounced at subsurface depths. At 100 m, the annual variation is about 9°C off Cochin, which is much greater than the annual variation at the surface.

The incoming solar radiation along the southwest coast of India shows an annual minimum during southwest monsoon. The southwest monsoon period characterised by overcast skies considerably reduces the incoming solar radiation. The mean monthly air temperatures in the coastal stations between Trivandrum and Mangalore show an annual minimum during July–August (Anon., 1966). The monthly mean air temperatures at Fort Cochin are presented in Table 1.

Table 1. Average air temperature at Fort Cochin for the period 1931-1960.

	Temperature (°C)		Temperature (°C)
January	26.90	July	25.90
February	27.55	August	26.05
March	28.55	September	26.25
April	28.70	October	26.70
May	28.30	November	26.95
June	26.55	December	26.90

The sea surface temperature in the continental shelf off the south west coast of India is lowest during July-August. Sea surface temperature less than 23°C were recorded off the Kerala coast in many years. The data presented by Ramasastry and Myrland (1959) show temperature less than 23°C during September between Quilon and Alleppey. Observations of the sea surface temperature at Thumba (8°32'N) by Pillai and Narayanan (1974) show sea surface temperature in the range 22-24°C during July-August. Sea surface temperature in the range 22-24°C were recorded during southwest monsoon in the nearshore regions off Cape Comorin, off Quilon and off Cochin in many years and this is evident from the reports of Pelagic Fisheries Survey (Anon., 1980).

During July-August, 7/8 parts of the sky is covered by clouds off Cochin (Anon., 1966). The inner shelf region also is characterised by almost overcast skies during this period. There are some limitations in comparing a climatological air temperature data with a synoptic sea surface temperature data for the period July-August. A comparison of air temperature at coastal stations and sea surface temperature in the nearshore regions indicate that the sea surface is at least 2°C colder than the atmosphere during July-August. Other factors such as evaporation also reduces the sea surface temperature. The evaporation in the Arabian Sea also shows a maximum during southwest monsoon (Venkiteswaran, 1956; Jagannathan and Ramasastry, 1964), but the most intense evaporation takes place in the central Arabian Sea. There are only a few observations of sea surface temperature and air temperature taken simultaneously. The observations in the coastal waters at Thumba (8°32'N) during 1967-1970 show that the sea surface temperature is about 3°-4°C lower than air temperature during July-August (Pillai and Narayanan, 1974). The observations in the South Kanara region also indicate that sea surface temperature is below air temperature during August, whereas no observations are available for June-July (Benakappa et al., 1980). Earlier works by Ramamurthy (1963) in the North Kanara region also suggest that the sea surface temperature is less than air temperature during July-August, whereas sea surface temperature exceeds air temperature during the remainder of the year. Further, it is interesting to note that off Cape Comorin, sea surface temperatures as low as that of Quilon and Cochin were observed in many years and it is evident from the Pelagic Fishery Survey report (Anon., 1980), and the effects of clouds are less in the Cape region. The sea surface temperature is above 28°C off Ratnagiri during August, where cloudy conditions prevail but the effects of upwelling are less. Normally, the sea surface temperature is greater than air temperature (Sverdrup et al., 1942). The above mentioned factors give indications that the low sea surface temperature off the west coast of india during July-August may be due to the effect of upwelling and not the result of overcast skies or evaporation as pointed by Sharma (1978).

The 23.0 g/l isopycnal is observed very near the surface in the inshore regions off Quilon and Cochin during early June (Figs.4 and 13). By July, the 23.0 g/l isopycnal is slightly pushed down due to rains and freshwater influx, though the 24.0 g/l and 25.0 g/l isopycnals show upward movement from June to July. The time variation of the 23.0 g/l isopycnal indicate that water from about 90 m depth reaches the surface due to upwelling (Figs.21 and 13). The 23°C isotherm indicates an upward displacement of about 125 m during February to

August, but for the same period the 23.0 g/l isopycnal shows an uplift of only 190 m (Figs.21 and 15). After early June, further upward movement of the 23.0 g/l isopycnal is checked by the intense precipitation and river discharge. But upwelling continues even after June and the cold upwelled water undergoes mixing with the surface water which is considerably diluted by the rains and river discharge thereby the temperature is lowered, though there is a decrease in density in the upper 10 m. The effect of low salinity water is evident even at a distance of 40-50 km from the coast (Anon., 1976). This water checks any further increase in density in surface layers, but the temperature continues to decrease till July/August off Cochin. However, it is very difficult to make a quantitative account of the mixing of upwelled water and the low salinity water of the surface layers as pointed out by Banse (1968).

Year to year variations in the onset, duration and intensity of upwelling and sinking are evident. For studying such variations continuous observations are necessary. A general picture of year to year variations are well demonstrated in the time series section off Cochin during 1971-1972. Upwelling was stronger in 1971 and the effects persisted for a longer duration compared to that in 1972. In 1971 the lowest temperature at all depths occurred in July. Whereas in 1972 it is attained during August. Sharma (1966) reports similar variations in upwelling off Cochin during 1964 and 1965. It has been reported that the intensity of upwelling was exceptionally high in the region south of Kasaragod in 1977 compared to the preceding years (Anon., 1980). These year to year variations are caused by the variations in the causative factors. Fluctuations in the intensity of southwest monsoon cause changes in the effects, duration and cessation of upwelling.

The density structure at subsurface depths off Cochin, Quilon and Kasaragod clearly reveals the presence of a subsurface northerly current beneath the surface southerly flow during the period of upwelling. The flow is narrow and mainly confined to the continental slope region. In all regions, the density field suggests a weak northerly flow and its vertical extent is usually less than 50 m. This poleward flowing countercurrent is one of the indicators of upwelling (Yoshida and Tsuchiya, 1957). During the early stages of upwelling this countercurrent is observed at depths below 100-125 m, but in July-August it is observed below 70-80 m. A subsurface poleward flowing countercurrent is observed in all major upwelling regions such as the Peru current upwelling (Gunther, 1936; Wooster and Gilmartin, 1961), off California (Reid et al., 1958; Reid, 1962), and in the Benguela Current upwelling (Hart and Currie, 1960). Off California and Peru this poleward flowing countercurrent is narrow and weak. In the Peru Current upwelling region the poleward countercurrent has maximum velocity in the northern regions off Peru where speeds of 4–10 cm sec^{-1} are observed (Wooster and Gilmartin, 1961). Unfortunately, no direct current measurements are available at subsurface depths in the region of study and the limitations of the geostrophic approximation in shallow regions and the wide station spacing prevent any reasonable estimate of the velocity of the subsurface countercurrent.

The effects of upwelling are evident even beyond 100 km off the Kerala Coast during July–August (Figs.5,6, 14 and 28). Off Karwar also the effects of upwelling are evident upto 80 km from the coast upto which the observations are made (Figs.32c and 33a). This suggests that the width of the upwelling zone is fairly high off the west coast of India.

The oxygen content of the surface layers are near saturation during the period November to May in the region between Karwar and Cape Comorin (Anon., 1976,1980). However, oxygen depleted water of subsurface layers reaches the surface layers by the end of May or early June (Anon., 1973,1976,1980). Like the isotherms and isopycnals, the isolines of oxyty also show an upsloping towards the coast during the southwest monsoon period (Ramasastry and Myrland, 1959; Anon., 1973,1976; Ramamirtham and Rao, 1973). The oxygen content of sea water is not a conservative property and the oxygen content of the waters depend on many factors such as photosynthesis, decaying organisms, mixing and residence time of water etc., and certainly varies in space and time. Concentrations of oxygen below 0.25 ml/l are common on the shelf during southwest monsoon (Banse, 1968). In the nearshore regions off Karwar oxygen values less than 1.0 ml/l are observed just below the surface during July-August (Anon., 1976,1980). Off Quilon and Cape Comorin, the oxygen content of surface layers is not as low as in the regions north of Quilon and based on that it is concluded that upwelling is less intense in the region off Quilon and further south compared to that off Cochin and further north (Anon., 1976). But the present study does not suggest any significant difference in the intensity and effects of upwelling off Quilon and Cochin. Further in many years the velocity of upwelling calculated from the movement of the 23°C isotherm off Cape Comorin and Quilon are of the same magnitude to that off Cochin and Kasaragod, and in some years like 1977 very strong upwelling is indicated between Cochin and Cape Comorin (Anon., 1980). The higher oxygen content off Quilon and further south during southwest monsoon suggests that apart from upwelling other factors also might influence the oxygen distribution north of Quilon. Sharma (1978) points out that the strong stratification in the surface layers, greater flux of decaying organic matter and the frequent formation of mud banks are the reasons for the low oxygen content of the waters off the southwest coast of India during southwest monsoon. It is interesting to note that the mudbanks are mainly formed in the region north of Quilon (Damodaran and Hridayanathan, 1966). Further, the stratification caused by the freshwater influx is less in the region south of Quilon. So apart from upwelling, the influence of other deoxygenating factors are less of Quilon and further south and that may be the reason for comparatively higher oxygen content of the waters in that region during the southwest monsoon.

The salinity in the surface layer off the West Coast of India undergoes large scale seasonal fluctuations. The salinity distribution in this region is mainly controlled by two factors, the coastal current and freshwater influx. From November to January the coastal currents are towards north which bring water from the equatorial region. During this period the salinity at the surface is very low, and surface salinity as low as 30‰ is observed off the Kerala Coast (Darbyshire, 1967). The surface salinity was less than 32.6‰ off Kasaragod during January 1974 (Anon., 1976). Salinities below 33‰ were observed in January 1959 even beyond the continental slope (Banse, 1968). During this period the effect of river run off is very limited in this region. The low salinities are the result of the northerly coastal current which brings low salinity water from the Bay of Bengal which is considerably diluted by the northeast monsoon rains and also river discharge (Darbyshire, 1967). However, higher salinities are observed at subsurface depths during this period.

From February onwards the coastal current flows towards south off the west coast of India (Anon., 1952; Varadachari and Sharma, 1967). This current brings high salinity water from the northern Arabian Sea. The salinity in the surface layer increases from February till late May. Values over 34.5‰ - 35‰ are evident from the charts of Darbyshire (1967) and Anon. (1976). From June, the salinity in the surface layers decreases to values below 30‰ in nearshore regions because of the freshwater influx of southwest monsoon rains (Darbyshire, 1967; Anon., 1976). Therefore, during the period when upwelled water is at the surface the surface salinities are low, which would have been higher in the absence of heavy rains and river discharge.

As in all major upwelling regions, the upwelled water off the west coast of India is rich in nutrients. Off Calicut,phosphate values are maximum during July and they begin to decrease from September (Suryanarayana Rao 1956). Reddy and Sankaranarayanan (1968) reports marked seasonal variation in the nutrient content in the surface layers off the west coast of India. High nutrient content is observed in the surface layers during the monsoon period whereas it is very low during December. The phosphate content off Quilon is high ranging from 0.54 to 1.4 µg at/l during the southwest monsoon in the nearshore regions and towards the offshore regions it becomes lower. It is also observed that the concentrations of nutrients show a general decreasing trend from south to north (Reddy and Sankaranarayanan, 1968).

Since the effects of upwelling off the southwest coast of India are pronounced and even comparable to some of the major upwelling regions, high biological productivity can be expected in this region. The cold upwelled water of relatively low oxygen content and rich in nutrients promotes productivity. Off the west coast of India, upwelling brings about ideal conditions for the growth of phytoplankters, the primary synthesizers. The aquatic environment is conditioned like a culture medium for growth—a fall in temperature to optimum levels (from 31-32°C to 22-25°C), slight lowering of salinity from 35-36‰ to 30-32‰) and plentiful supply of nutrients (Subrahmanyan, 1959a). Various other factors also affect the primary productivity, such as insolation and turbidity of the water etc.

During southwest monsoon the waters off the west coast of India are cold, turbid, of low oxygen content and rich in nutrients. Further the incoming solar radiation is less due to cloudy conditions. But it has been pointed out by Steeman Neilson and Jenson (1957) that even if the solar radiation is reduced by 50%, the production per unit area would be about 80% to that of clear day. The primary productivity is considerably reduced only on dark cloudy days with intermittent rains and such days are few (Ramachandran Nair et al., 1973). In the nearshore regions of the west coast of India, (inside the 50 m zone) during southwest monsoon, the average primary productivity is estimated to be about 1.37 gCm^{-2} day^{-1} (Ramachandran Nair et al., 1973). The rate of primary productivity decreases offshore. However, in the nearshore regions values over 1.0 gCm^{-2} day^{-1} is commonly met with the production rates of lesser magnitudes is a rarity (Ramachandran Nair et al., 1973). This suggests that during this period the primary productivity rates are as high as that reported off Peru (Holmes et al., 1957) and off Oregon (Anderson, 1964). In all these regions productivity rates are generally higher than 1.0 gCm^{-2} day^{-1} during upwelling. Observations of Qasim et al. (1978) indicate that inside the 50 m zone of the continental shelf off the west coast of India primary productivity averaged 0.33 gCm^{-2} day^{-1} during March-April. This suggests a four times increase in primary productivity during southwest monsoon, despite a reduction in the incoming solar radiation. Off the west coast of India, the phytoplankton bloom occurs during July-August (Subrahmanyam, 1973). Observations in different years show remarkable consistency in the period of the phytoplankton bloom. The zooplankton bloom, generally, occurs by the end of the southwest monsoon mainly in August-September (Anon., 1976).

Earlier investigations by different workers differs in their views regarding the onset, duration and cessation of upwelling along the west coast of India. Ramasastry and Myrland (1959) concludes that upwelling off the southwest coast of India occurs during postmonsoon. From the analysis of temperature and oxygen in the nearshore regions off the southwest coast of India, Ramamirtham and Jayaraman (1960) inferred upwelling from late August to October. From the upsloping of isotherms towards the coast Banse (1959) indicates that upwelling off the southwest coast of India seems to last through the southwest monsoon. From observations in the nearshore regions off Karwar, Ramamurthy (1963) concludes that upwelling in 1956–1957 started in June-July. Off Karwar in July 1959 the surface temperature fell to 24.4°C indicating upwelling (Banse, 1968). Banse (1968) in a general way states that upwelling off the southwest coast of India starts with the onset of southwest monsoon. However, Ramamirtham and Jayaraman (1963) observed water colder than 27°C below 5 m in Cochin harbour in May 1962 and based on that Banse (1968) inferred that upwelling in 1962 must have commenced at that time. Based on similar observations of decrease in temperature in the surface layers from 30–31°C in April-May to 25–26°C towards the end of June in 1958 and first week of July in the harbour of Karwar, Banse (1968) points out that in some years upwelling starts much earlier to June unlike the earlier concepts that it starts in June-July.

From the analysis of a decades data Sharma (1968) concludes that upwelling off the southwest coast of India starts in February and continues upto July-August. Upwelling starts earlier in the south and gradually extends to north (Sharma, 1971,1978). The present study also gives almost similar results for the southwest coast of India. But upwelling continues for a longer period in the northern regions. During September-October a secondary period in upwelling is evident, though it continues only for a short duration. The difference in conclusions obtained by earlier workers are mainly due to inadequate data while some authors inferred upwelling only when there is a lowering of surface temperature. But the process of upwelling starts much earlier to the occurrence of low temperature at the surface.

Absence of wind induced upwelling during southwest monsoon has been indicated by several authors (Darbyshire, 1967; Banse, 1968; Sharma, 1968,1978). However, the winds have significant effect on upwelling in the region south of Karwar. The winds in the oceanic area adjacent to the coast are westerly or slightly northwesterly in the region south of Karwar during south-west monsoon. Due to the orientation of the coast, there is always a wind component parallel to the coast in the equatorward direction which is favourable for upwelling. However, the winds are southwesterly off Ratnagiri and further north, though the current is favourable for upwelling. The lesser upwelling in this region during southwest monsoon is due to unfavourable winds.

Ramamirtham and Jayaraman (1960) infers sinking off the southwest coast of India from November to January.

Sharma (1978) indicates sinking from September. The present study suggests that sinking off Cochin starts from October, but there are no indications of further continuous downward movement of isotherms or isopycnals after November.

From the time variation of the 23.0 g/l isopycnal Sharma (1978) infers that water from about 90 m depth reaches the surface due to upwelling. The vertical uplift of the 23.5 g/l isopycnal shows an uplift of about 90 m off Cochin in 1964. However, the 23°C isotherm indicates an upward movement of about 125 m during 1964, and this descrepancy is mainly due to the presence of low salinity water in the surface layers during southwest monsoon.

According to Sharma (1968,1978) the low sea surface temperature during July-August is the result of decrease in solar radiation because of overcast skies during active southwest monsoon. But the present study suggests that the sea surface temperature is lower than air temperature during southwest monsoon and the low sea surface temperatures are the result of upwelling.

CHAPTER V

SECTION I - UPWELLING OFF THE EAST COAST OF INDIA

The temperature and density fields off Waltair and Madras show significant seasonal variations. The data available are not adequate to describe all features associated with upwelling since the observations are neither continuous nor made in the same year. However, a comparison of temperature and density sections, sea level variation and surface vergence give a general picture regarding upwelling off the east coast of India.

Off Waltair, the sea surface temperature shows a minimum of about 25°C in January but in deeper layers a conspicuous minimum occurs during March (Fig.40). The low surface temperature in January is essentially due to winter cooling and the thermocline is about 75 m deep (Fig.35). During March-April, the isotherms and isopycnals slope up towards the coast and the surface and subsurface temperature is minimum closest to the coast and increases offshore (Figs.36 and 37). The time variation of temperature shows that the temperature at 125 m begins to decrease from December and continues upto March whereas at 75 m and 50 m the lowering of temperature occurs only during February to March (Fig.40). The sea level shows an annual minimum in March-April (Fig.55a). So it could be inferred that the lowering of temperature and increasing of density at all depths in March are due to the effect of upwelling.

Off Madras also considerable upward displacement of isotherms and isopycnals takes place from January to April (Figs.41 and 42). The sea level shows an annual minimum during April. This gives an indication that on an average the maximum effects of upwelling occur in April off Madras.

The wind averaged for each 2^{0} latitude-longitude quadrangle off Waltair becomes favourable for upwelling from March (Fig.53a). The wind data presented by LaFond (1954) indicate that the winds of Waltair begin to blow from south or southwest from February. The surface current in this area turns towards north from January (Anon., 1952). However, off Madras the current reverses to northerly only by February. A northerly current along the east coast is favourable for upwelling (Varadachari, 1961). Neither the wind nor the current are favourable for upwelling during December, but at 125 m depth the temperature lowers and density increases from December and it can be due to winter cooling which results in convective motion in deeper layers. Significant upward movement takes place from February to March when the wind also becomes favourable for upwelling. The vergence field off the east coast shows divergence from January. So it can be inferred that upwelling off Waltair commences from January with the reversal of the surface current which occurs ahead of the wind reversal. Upwelling off Madras seems to set-in only by February since the current in this region turns to ards north only from February.

The annual minimum in sea level during March-April off Visakhapatnam indicates that on a climatological point of view the maximum effectsof upwelling occur during this period. Off Madras, the maximum effects of upwelling occur during April as is evident from the sea level.

The wind stress parallel to the coast that favours upwelling increases from March off Waltair and Madras. However, further upward movement of isotherms and isopycnals are not observed during April-May.In fact, a downward movement is observed after March (Fig.44). During April-May the thermocline is more than 40 m deep even in nearshore regions (Figs.37,42 and 43). The sea level also shows an increase from April to May (Fig.55a). Though the winds off the east coast are favourable for great upwelling, the factors which act against upwelling dominate during April-May. During this period, the upwelled water is constantly heated in the surface layers. A decrease in current speed after March-April can be another factor that produces a decrease in density in nearshore regions. The deep mixed layer during this period can be the result of intense wind induced mixing. Off Madras also the sea level shows an increase from April to May (Fig.55b), suggesting similar changes as those off Waltair.

The time variation of temperature and density at different depths off Waltair indicate that the temperature at all depths decreases sometime after May, but before September (Fig.40). The vertical sections of temperature and σ_t indicate upward movement from April to July (Figs. 37 and 38). The sea level off Visakhapatnam shows a decrease from June and a secondary minimum is observed during July (Fig.55a). The vergence field shows divergence during June-July. The wind stress component parallel to the coast which induces upwelling shows a maximum during southwest monsoon (Fig.53a). The thermal and density variations, vergence field, sea level decrease and windstress conclusively suggest the occurrence of a secondary phase of upwelling during June-July. The sea level shows a slight increase from July to August. The secondary minimum in sea level off Visakhapatnam indicates that on a climatological basis the effects of this secondary upwelling is in July. Off Madras, the sea level shows a secondary minimum in July-August which suggest that the effects of the secondary upwelling occur in this month.

The density at all depths decreases considerably from July to October off Waltair (Figs.38 and 39). The time variation of temperature at different depths shows an increase from September whereas no data are available for August. The sea level increases sharply after August. Further the vergence field shows convergence from August. Combining all these factors it could be understood that sinking off Waltair starts in August. The northerly surface current off Waltair ceases sometime in August (Varadachari, 1961). The current reverses its direction by the end of August. A southerly current along the east coast is favourable for sinking (Varadachari, 1961). The maximum sea level in November suggests that the effects of sinking are conspicuous during this month. The sinking process off the east coast starts before the reversal of the wind as the winds become favourable for sinking only from October. The effects of sinking are further magnified by the heavy freshwater influx due to rains during September-October.

Off Madras, oceanographic data for subsurface depths could not be presented for August or northeast monsoon season due to paucity of data. However, from the sea level some inferences can be drawn. The sea level shows a secondary minimum during July-August and it increases after August (Fig.55b). This suggests that sinking off Madras starts after August, slightly later than that off Waltair.

The upward displacement of the 22.0 g/l isopycnal from late January to March off Waltair shows a velocity of upwelling of about $1x10^{-3}$ cm sec^{-1} for the nearshore regions. However, the velocity of upwelling rapidly decreases offshore. Off Madras, the velocity of upwelling is about $7x10^{-4}$ cm sec^{-1} from January to April. This indicates that the velocity of upwelling off the east coast is slightly less than that off the west coast and also continuous upward displacement lasts for a lesser period.

The relative positions of 22.0 g/l isopycnal during October, March and July off Waltair suggest that water from about 85 m reaches the surface due to upwelling (Figs.35,36 and 38). Off Madras, the 22.0 g/l isopycnal shows an uplift less than 70 m from January to April. Upwelling off Waltair seems to be more intense than that off Madras during spring and summer. The factors that cause upwelling are more favourable off Waltair compared to those off Madras. The windstress favourable for upwelling is much stronger off Waltair than that off Madras (Figs.53a,53b). The current off Waltair is stronger and steadier during southwest monsoon whereas off Madras it is highly variable and even southerly flow is indicated (Murthy and Varadachari, 1968). Further, off Waltair the winds blow at such an angle to the coast that it is favourable for intense upwelling (LaFond and LaFond, 1968).

The sections off Waltair and Madras for January, March, April and June-July (Figs.35,36,37,38,42,43 and 44) suggest that the effects of upwelling are confined to a distance less than about 25 km from the coast. There is a considerable increase in density in the nearshore regions off Waltair from January to March, but at a distance of 25 km from the coast 23.0 g/l isopycnal shows no significant upward movement during this period (Figs.35 and 36). Theoretically the width of the upwelling zone is much less for the east coast of continents compared to that for the west coast at that latitude (Yoshida, 1967). Practically the effects of upwelling off the east coast of India are mainly confined to the inner continental shelf region.

The orientation of isopycnals in the sections off Waltair in April clearly indicate that the current is northerly down to 300 m (Fig.37). The dynamical computations by Poornachandra Rao (1956) also indicate northerly flow down to 300 m off Visakhapatnam in March. The available data for the east coast do not suggest the possibility of a subsurface countercurrent down to 300 m. This means that the subsurface countercurrent associated with upwelling is possibly below 300 m or absent during upwelling. However, no conclusion can be drawn without a detailed investigation.

During April-May and June-July, the thermocline is observed at depths below 40-50 m even in the nearshore regions off Waltair and Madras (Figs.37,38,42 and 43). The depth of the mixed layer increases with distance from the coast. Off Waltair at about 30 miles from the coast the thermocline is about 100 m deep in July (Fig.38). The temperature at the surface and subsurface depths show offshore-onshore gradients, but the position of the thermocline when the effects of upwelling are expected, indicates some difference from that off the west coast. Due to upwelling, water from the thermocline is not reaching the surface though the surface temperature is the least near the coast and increases offshore. A mixed layer of more than 40 m deep makes the effects of upwelling less significant compared to many other regions of upwelling.

The surface waters off Waltair are warm in summer and early fall, and colder in winter (LaFond, 1958b). The annual surface temperature ranges from 25°C to 29°C. Data presented by LaFond (1958b) indicate an annual variation of about 3°C off Madras with higher values in summer and fall and lower values during winter. Off Waltair, the surface temperature drops slightly in the nearshore regions due to upwelling during March–April and June–July, which would have been still higher in the absence of upwelling because of intense solar heating during spring and summer.

The oxygen content off the east coast of India changes seasonally. Off Waltair, the oxygen content at the surface ranges between 2.37 and 4.95 ml/l with higher values in October and lower values during February–May (Ganapati and Sarma, 1958). When the upwelled water is at the surface layers during March–April the oxygen content of the surface layers also shows higher values which are quite unusual for an upwelling region. It can be partly due to photosynthetic activity, but another reason is that water from oxygen minimum layer may not be reaching the surface layers. It is observed that during April–May the oxygen minimum layer is well below 50 m even in nearshore regions and in all stations near the coast the oxygen is higher down to the bottom (Jayaraman, 1965).

The salinity in the surface layer off Waltair undergoes large annual variation with maximum values during March–May and minimum in October–November (LaFond, 1958b). The annual range is about 10‰ for the inshore region which is very high compared to other regions at similar latitudes. The surface salinity falls below 25‰ during October-November due to heavy run off and southerly currents which bring low salinity water from the northern regions. Off the east coast of India surface salinity increases due to upwelling and it is very evident from the upsloping of isohalines during February-March from the sections of LaFond (1957).

Off Waltair, significant increase in the nutrient content occurs during February-March (LaFond, 1957). Observations of Ganapati et al. (1956) indicate no significant variations in the phosphate content at the surface throughout the year. However, at subsurface depths during March-April values over 1.52 µg at/l were observed and the silicates also show a peak in March (Ganapati et al. 1956). Ganapati and Sarma (1958) reports maximum phosphate content in the surface layers during January-February. Though there are evidences of an increase in nutrient content during February-March in the nearshore regions, the period of occurrence of maximum phosphate vary from year to year, as evidenced from the works of LaFond (1957), Ganapati et al. (1956), Ganapati and Sarma (1958), Mojumdar (1967).

Primary productivity measurements in the Bay of Bengal were less until recently. The average primary production in the Bay of Bengal during April-May 1957, April-May 1963 and March-April 1975 were 0.60, 0.82, and 0.18 gCm^{-2} day^{-1} for the inshore regions which indicate fairly high values except during 1975, while in August-September 1978 primary productivity was 1.28 gCm^{-2} day^{-1} for the inshore regions (Bhattathiri et al., 1980). During this period the production for 1978 was much higher compared to 1976 and 1977 (Bhattathiri et al. 1980). The greater productivity during this period can be due to the effect of upwelling. Off Waltair the phytoplankton bloom is observed in March/April (Ganapati and Rao, 1958). However, data for different years off the east coast show different periods of plankton bloom as is evident from Subrahmanyam (1973). The magnitude of the standing crop off the east coast is much less compared to that off the west coast for almost all the months. Similarly, the fishery resources off the east coast of India are less compared to those off the west coast of India (Panikkar and Jayaraman, 1966; Ramachandran Nair et al., 1973).

Upwelling has been indicated by LaFond (1954) along the east coast of India during March-April. The lowering of sea surface temperature in August along the east coast prompted LaFond (1958b) to infer the possibility of a secondary period in upwelling. Theoretical study by

Varadachari (1961) indicates the occurrence of upwelling from January to July and sinking from August to December along the east coast of India. Murthy and Varadachari (1968) indicates upwelling during premonsoon and monsoon periods along the east coast with intense upwelling off Waltair than that off Madras and Karaikal. The present study does not indicate the occurrence of continuous upward movement of isotherms and isopycnals from January to July off Waltair. Upward displacement of isotherms and isopycnals are evident from January to March and again during June-July off Waltair. During April-May the isotherms and isopycnals are pushed down mainly due to intense solar heating and a possible decrease in current speed, though the wind and current are favourable for further upwelling during April-May.

Jayaraman (1965) doubts the large scale upwelling off the east coast of India and claims there is no evidence of marked upwelling along the east coasts of continents in the Northern Hemisphere - with the exception of the Somali-Arabian coasts. The arguments are mainly based on the oxygen content and position of thermocline from the available data off the east coast. The present study also suggests that the process and effects of upwelling off the east coast differ considerably from those off the west coast, and these are briefly dealt in Section II.

SECTION II - UPWELLING OFF THE EAST COAST OF INDIA - A COMPARISON WITH THE WEST COAST

The analysis of temperature and density structure, surface vergence, windstress and sea level conclusively prove the occurrence of upwelling and sinking along the east and west coasts of India. However, the process and effects of upwelling and sinking in these regions show some significant differences, and some of the most striking features are mentioned here.

Off the west coast of India, the commencement of upwelling is due to the northerly winds, but it starts only with the reversal of the current towards south, whereas off the east coast, upwelling starts when the current begins to flow towards north, though the winds are unfavourable at that time.

When the effects of upwelling are maximum the thermocline reaches the surface and even outcrops into the naviface in the nearshore regions off the west coast of India. There is considerable fall in surface temperature near the coast. The surface temperature off the east coast shows offshore-onshore gradients but there are no evidences of water from thermocline region reaching the surface in any season. The thermocline is below 40 m in all seasons off the east coast of India and there are no indications of water from thermocline reaching the surface. This makes the effects of upwelling less significant in this region.

Off the west coast, a secondary upwelling occurs during September-October which dees not seem to be associated with wind or current, but may be due to poleward propagating baroclinic waves. Off the east coast, a secondary period in upwelling occurs which is related to southwest monsoon winds.

Sinking off the west coast of India is due to the northerly coastal current and not due to the wind in these regions. Off the east coast, sinking starts when the current reverses its direction to southerly, but afterwards winds also favour sinking.

The effects of upwelling are evident off the west coast even beyond 100 km offshore. But off the east coast the effects of upwelling are limited to a very narrow region, possibly, less than 25 km from the coast.

During the period of upwelling, a subsurface poleward flowing countercurrent is evident below 80-100 m off the west coast of India. But off the east coast, such a countercurrent could not be traced even upto 300 m from the available data.

The sea surface temperature along the west coast ✓ shows an annual variation of 6-7°C, in the nearshore regions, and the lowest temperature occurs when the effects of upwelling are maximum. However, off Waltair, the annual variations of sea surface temperature is only 4°C and the lowest temperature occurs during winter and not due to the effect of upwelling.

Off the west coast of India, considerable fall in oxygen content in the layers just below the surface is observed when the upwelled water is in the surface layers. However, off the east coast, the surface layers are near saturation, when the effects of upwelling are expected to be maximum and the nearshore stations show oxygen saturation down to the bottom. Absence of oxygen depletion is also not common in upwelling regions, though low oxygen content need not be an essential feature associated with upwelling.

The salinity of the surface layers off the west coast is low when the upwelled water is in the surface layers. The salinity would have been much higher in the absence of southwest monsoon rains and river discharge. However, off the east coast salinity increases due to upwelling.

Considerable amounts of nutrients are brought to the surface layers due to upwelling and plankton bloom occurs during late southwest monsoon off the west coast of India. However, the high biological productivity off the east coast is confined to a narrow region close to the coast.

Regarding the extent (width of the upwelling zone), and associated physico-chemical and biological characteristics, upwelling off the west coast of India resembles some of the major upwelling regions along the west coasts of continents, though the intensity of upwelling is less. However, upwelling off the east coast of India differs much from that off the west coast regarding the extent, and associated physico-chemical and biological characteristics.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The Thesis is an outcome of some investigations carried out by the author on upwelling and sinking off the west and east coasts of India. The aim of the study is to find out the actual period and duration of upwelling and sinking, their driving mechanism, various associated features and the factors that affect these processes. It is achieved by analysing the temperature and density fields off the west and east coasts of India, and further conclusions are drawn from the vergence field of surface currents, windstress and sea level variations.

Vertical sections of temperature and σ_t are drawn off Quilon (8°50'N), off Cochin (10°00'N), off Kasaragod (12°31'N), off Karwar (14°47'N) and off Ratnagiri (16°59'N) along the west coast of India, and off Waltair (17°44'N) and off Madras (13°08'N) along the east coast of India. Further, a time series section of temperature off Cochin and time variation of temperature and density at different depths off Waltair are also utilised. The vergence field is evaluated by direct calculation from the surface current vectors available at a two-degree latitude-longitude quadrangle. Monthly mean windstress components parallel and perpendicular to the coast are computed off Cochin, Karwar and Bombay along the west coast and off Madras and Waltair along the east coast. The influence of windstress on vertical circulations are discussed. The monthly mean sea level at Cochin and Murmugao on the west coast and at Madras and Visakhapatnam on the east coast are presented and upwelling and sinking are inferred from the sea level variation.

The temperature and density structure off the Indian coasts undergo considerable seasonal variations at the surface and subsurface depths, with maximum changes in the nearshore regions, and these changes are mainly associated with upwelling and sinking although other factors are also responsible to a certain extent. The monthly mean sea level in the region of study also changes seasonally, which decreases with upwelling and increases with sinking. The vergence field, in general, shows divergence during upwelling and convergence during sinking, though some differences are there mainly due to the limitations in the method and the data used.

Upwelling off the west coast of India commences in deeper layers by February in the southern regions and slightly later, by March in the northern regions. The upwelled water from the thermocline region reaches the surface in the nearshore regions by early June.

Off the southwest coast of India, upwelling continues till July-August, but in the northern regions upwelling continues upto August-September. The maximum effects of upwelling are generally observed in August off Cochin, whereas in the northern regions and maximum effects of upwelling occur slightly later.

The commencement of upwelling from February off the southwest coast of India is due to the offshore transport of the wind, but it starts only with the reversal of current to southerly. Along the south west coast intense upwelling continues even during southwest monsoon. During this period there is a windstress component parallel to the coast in the equatorward direction in the region south of Karwar, which is favourable for upwelling. Upward displacement of isotherms and isopycnals continues till the wind and current acquire maximum speed i.e. till July-August off Cochin. However, upwelling continues and the effects persist for a slightly longer time off Karwar mainly due to more favourable winds towards the end of southwest monsoon.

Upwelling off Ratnagiri and further north differs from that in the southern regions. During southwest monsoon the effects of upwelling are less in this region compared to those in the region south of Karwar, and there is no significant lowering of surface temperature. The maximum effects of upwelling in this region occur during post monsoon season. The lesser intensity of upwelling in this region during southwest monsoon is due to unfavourable southwesterly winds. However, upwelling occurs due to the southerly coastal current during this period.

The isotherms and isopycnals in the continental shelf off Cochin and Quilon are displaced to deeper layers from August to September mainly due to a decrease in wind and current speed. But during September-October a sudden upward movement of isotherms and isopycnals are observed. This does not seem to be associated with wind or current, but seems to be associated with poleward propagating baroclinic waves which can produce localised upwelling without any significant wind at that locality if resonance occurs between these waves and the existing wind field.

Off Cochin, sinking starts during October-November. Off Karwar sinking seems to start slightly later. There are no evidences of continuous downward displacements of isotherms and isopycnals after November off Cochin. Sinking off the west coast of India is essentially due to the northerly coastal current and not due to the wind in this region. The slight upward and downward displacements of isotherms and isopycnals after November are associated with fluctuations in the velocity of the northerly current. In the northern regions sinking starts slightly later.

The velocity of upwelling off the west coast of India is much less especially in the initial stages. However, off Cochin, from May to June values upto 1.6×10^{-3} cm sec^{-1} are observed which is fairly high. From September to October the velocity of upwelling upto 2.5×10^{-3} cm sec^{-1} is observed. The velocity of upwelling off Kasaragod and Karwar also seems to be of similar magnitude as that off Cochin.

The intensity of sinking is very high compared to that of upwelling along the west coast of India. Off Cochin, from October to November the velocity of sinking is about 3.7×10^{-3} cm sec^{-1} which is twice the maximum observed velocity of upwelling in this region. High velocity of sinking is observed off Kasaragod also during November to December. The high velocity of sinking is the result of sudden reversal of the coastal current from southerly to northerly, which occurs within a period of about one month.

Off Cochin, the density variation suggests that water from about 90 m depth is reaching the surface due to upwelling. However the temperature variation indicates that water from about 125 m depth reaches the surface.

This discrepancy is due to the influence of heavy rains and river discharge. After June there is no further increase in density in the upper 10 m, though upwelling continues till July-August. The cold upwelled water mixes with the low salinity water in the surface layers and the temperature is lowered, though there is a decrease in density in the upper 10 m of the nearshore regions during this period.

The effects of upwelling are evident even at distances more than 100 km off the west coast of India. This indicates that the width of the upwelling zone in this region is fairly high, typical of upwelling in low latitudes.

Off the west coast of India, during the period of upwelling a subsurface countercurrent is evident below the surface southerly flow, usually at depths below 100 m but in the later stages of upwelling it is observed below 60-80 m. This northerly current is narrow and confined to the shelf-edge or continental slope region.

Year to year variations in the period and intensity of upwelling are evident off the west coast of India. Such variations are associated with variations in the causative factors.

The sea surface temperature off the west coast of India in the region south of Karwar shows an annual variation of 6–7°C in the nearshore regions. The maximum values over 30°C occur during March–April and early May, owing to intense solar heating. The minimum occurs in July–August off Quilon and Cochin and slightly later in the northern regions. During this period, surface temperature between 22°–24°C is observed in the nearshore regions in many years. The air temperature in the coastal stations also shows an annual minimum during this period due to cloudy conditions, but the sea surface temperatures are less than air temperature at least in the nearshore regions. The low sea surface temperature during this period is due to the effect of upwelling and not the result of a reduction in solar radiation.

In the region north of Cochin when the upwelled water is at the surface layers very low oxygen contents are observed just below the surface. Apart from upwelling, the stratification caused by run off, greater number of decaying organisms and the frequent formation of mud banks also reduce the oxygen content in the region north of Quilon. However, off Quilon and further south, the effects of run off and mud banks are less and comparatively higher oxygen contents are observed in this region.

Off the west coast of India, the salinity in the surface layer falls below 30‰ in the nearshore regions during southwest monsoon due to heavy rains and river discharge. Therefore, during the period when upwelled water is at the surface, salinity is low which would have been high in the absence of southwest monsoon rains. During the sinking also salinity in the surface layer is low since the northerly current brings low salinity water from Bay of Bengal.

Along the west coast of India substantial amounts of nutrients are brought to the surface layers due to upwelling and high productivity is observed. Data for different years show remarkable consistency in the period of plankton bloom, which reaches a peak in July–August off the Kerala coast.

Seasonal upwelling occurs off the east coast of India also. Off Waltair, upwelling starts in January while off Madras upwelling starts by February. The maximum effects of upwelling occur in March off Waltair and in April off Madras. However, there are no indications of water from thermocline region reaching the surface during this period.

Off the east coast, upwelling starts when the coastal current begins to flow towards north, though the winds are unfavourable for upwelling during this period. However, the velocity of upwelling increases when the winds also become favourable for upwelling by February-March off Waltair and slightly later off Madras.

The windstress favourable for upwelling increases after March off Waltair. However, no further upward displacement of isotherms and isopycnals are observed, instead a downward displacement is evident during April-May. This may be mainly the result of intense solar heating and a decrease in current speed. Off Madras also this feature is observed between April and May and it is amply reflected in the sea level which shows an increase in May.

A secondary period of upwelling occur during Southwest monsoon of the east coast of India. Upwelling off Waltair occur in June-July, while off Madras it seems to last until August. This is characterised by another decrease in sea level.

Off the east coast of India, sinking seems to start earlier in the north and later in the south. Off Waltair sinking starts in August whereas off Madras sinking starts slightly later. The maximum effects of sinking occur in November, during this month the sea level shows an annual maximum. Sinking off the east coast of India starts when the current reverses its direction to southerly, but from October the wind also favours sinking.

From late January to March the velocity of upwelling is about 1×10^{-3} cm sec^{-1} for the nearshore regions off Waltair. The velocity of upwelling off Madras is about 7×10^{-4} cm sec^{-1} from late January to April. In both the places the velocity of upwelling rapidly decreases offshore.

Off Waltair, the time variation of density suggests that water from about 80 m reaches the surface due to upwelling, whereas off Madras water from only about 70 m reaches the surface. The greater upwelling off Waltair is mainly due to stronger winds favourable for upwelling and stronger coastal currents. Further, the orientation of the coast also favours greater upwelling off Waltair compared to that off Madras.

Along the east coast during March-April and June-July period, the effects of upwelling are evident only in the nearshore regions, possibly upto a distance of 20-25 km from the coast. Further, the thermocline is more than 40 m deep in nearshore regions.

The available data for the east coast do not indicate the presence of a subsurface countercurrent down to a depth of 300 m during upwelling. There are indications that the subsurface countercurrent which is a conspicuous feature of eastern boundary current upwelling is absent or below 300 m off the east coast of India. However, no conclusion can be drawn in this regard till detailed observations are made available.

Off Waltair, the annual range of sea surface temperature is about 4°C while off Madras the annual range is about 3°C. The minimum values occur during winter and maximum values during summer and fall in both these places.

The oxygen contents in the surface layers off Waltair are maximum in spring and minimum during fall. The surface waters are near saturation when the effects of upwelling are maximum.

Salinity increases due to upwelling off the east coast of India. The salinity in the surface layers decreases considerably during the period of sinking mainly due to the southerly current and river discharge of northeast monsoon rains.

Due to upwelling, only the nearshore regions of the east coast are enriched by nutrients. The plankton bloom also is limited compared to that off the west coast. Observations in different years indicate different periods of nutrient enrichment and plankton bloom.

The present study suggests that regarding the extent and effects, upwelling off the west coast of India is comparable to that of some major upwelling regions, though not in the same class of Peru or Benguela Current upwelling. Upwelling off the east coast of India differs considerably in regard to extent and effects from that off the west coast and other upwelling regions. The influence of upwelling on fishery resources are very high off the west coast of India. Off the east coast also upwelling influences the fishery resources at least in the nearshore regions, though not as much as that off the west coast of India.

The author feels that the present study has greatly enhanced our knowledge on upwelling and sinking off the west and east coasts of India. Off the southwest coast of India two periods of upwelling are evident. The effect of winds on upwelling during southwest monsoon has been subjected to some controversy. The present study suggests that the winds are significantly favourable for upwelling in the region south of Karwar during this period. Upwelling during September-October does not seem to be due to wind or current, but can be the result of poleward propagating baroclinic waves. The present study also indicates that the intensity of sinking is very high, compared to the intensity of upwelling off the southwest coast of India. There are also indications that the low sea surface temperature during July-August is the result of upwelling and not the result of decrease in solar radiation or evaporation. The width of the upwelling zone also is high off the west coast of India. Considering various effects, upwelling off the west coast of India resembles some major upwelling regions, though the intensity of upwelling is less. Off the east coast also two periods of upwelling are evident, but the effects of upwelling in this region are much less compared to the west coast and many other upwelling regions.

A clear picture of the process and effects of upwelling during southwest monsoon off the west coast of India can be made only if there is simultaneous observations of wind, air temperature, oceanographic properties and direct current measurements at surface and subsurface levels at least for a few years. We have a few years oceanographic data but simultaneous meteorological observations and current measurements are too sparse to get a clear picture of the individual effects of wind and current on vertical circulations. The conditions that exists in September and October need special attention. Similar detailed studies are necessary for the east coast also where the available data indicate a lot of difference from major upwelling regions. Further, there can be some localised factors which need detailed investigation. Finally it is worthwhile to quote Defant (1961), there is no doubt that upwelling and sinking of oceanic waters is primarily connected with convergence and divergence regions, occurring at the sea surface. The cause of these divergences and convergences in most cases lies in the distribution of windstress exerted by the prevailing wind on the sea surface. A totally satisfying explanation of upwelling at continental coasts has not yet been given, and is probably not possible at all since the total process is composed of a number of substages each of which is always controlled by other factors.

REFERENCES

REFERENCES

Allen, J.S., 1973. Upwelling and coastal jets in a continuously stratified ocean. J. Phys. Oceanogr., 3: 245-257.

Anand, S.P., C.B. Murty, R. Jayaraman and B.M. Aggarwal, 1968. Distribution of temperature and oxygen in the Arabian Sea and Bay of Bengal during the monsoon season. Bull. natl. Inst. Sci. India, 38: 1-24.

Andrews, W.R.H. and L. Hutchings, 1980. Upwelling in the southern Benguela Current. Progr. Oceanogr., 9: 1-81.

Anderson, G.C., 1964. The seasonal and geographic distribution of primary productivity off the Washington and Oregon Coasts. Limnol. Oceanogr., 9: 284-302.

Anon., 1952. Koninklijk Nederlands Meteorologisch Instituut, Indische Oceaan Oceanographische on Meteorologische gegevens. 2nd Ed., Publ. No.135, 1: Text 31 pp, and 2: 24 Charts.

Anon., 1966. Climatological Tables of observations in India (1931-1960). India Meteorological Dept., 470 pp.

Anon., 1967. CMFRI Oceanographic Station List, Stn.No. 2000-3000, Vol.IV, 581-1005.

Anon., 1973. Hydrographic investigations - June 1971 to January 1973. Progress Report No.3. FAO, Rome, IND/69/593, 35 pp.

Anon., 1976. Physical Oceanography of the southwest coast of India based on the investigations of the UNDP/FAO Pelagic Fishery Project. *Progress Report No.16. FAO, Rome,* IND/69/593, 39 pp.

Anon., 1980. Oceanographic investigations along the southwest coast of India (1976-'78). A report prepared for Pelagic Fishery investigations on the Southwest Coast, phase II - Project. *FAO, Rome,* FI: DP/IND/75/038, 51 pp.

Arthur, R.S., 1965. On the calculation of vertical motion in eastern boundary currents from determination of horizontal motion. *J. Geophys. Res.*, 70: 2799-2804.

Austin, T.S., 1958. Variation with depth of oceanographic properties along the equator in the Pacific. *Trans. Am. Geophys. Un.*, 39: 1055-1063.

Austin, T.S. and M.O. Rinkel, 1958. Variations in upwelling in the equatorial Pacific. *Proc. Pacific Sci. Congr.*, 9th, Bankok, 16, Oceanography, 67-71.

Bakun, A., 1978. Guinea Current upwelling. *Nature*, 271: 147-150.

Balaramamurthy, C., 1957. Distribution of density and the associated currents at the sea surface in the Bay of Bengal. *Indian J. Meteor. and Geophys.*, 8: 88-98.

Bang, N.D. and W.R.H. Andrews., 1974. Direct current measurements of a shelf - edge frontal jet in the southern Benguela system. *J. mar. Res.*, 32: 405-417.

Banse, K., 1959. On upwelling and bottom trawling off the west coast of India. *J. mar. biol. Ass. India*, 1: 33-49.

Banse, K., 1960. Bemerkungen Zu meereskundlichen Beobachtunglu von der Ostkuste von Indien. Kieler Meeresforsch, 16: 214-220.

Banse, K., 1968. Hydrography of the Arabian Sea shelf of India and Pakistan and effects on demersal fishes. Deep Sea Res., 15: 45-79.

Banse, K., 1972. Upsloping of isotherms on the continental shelf off Goa and Bombay in June 1967. J. mar. biol. Ass. India, 14: 344-356.

Barnett, T.P., 1977. An attempt to verify some theories of 'El Nino'. J. Phys. Oceanogr., 7: 663-647.

Barton, E.D., A. Huyer and R.L. Smith, 1977. Temporal variations observed in the hydrographic regime near Cabo Corveiro in the North West African upwelling region, February to April 1974. Deep Sea Res., 24: 7-24.

Beers, J.R., M.R.Stevenson, R.W. Eppley and E.R.Brooks, 1971. Plankton populations and upwelling off the coast of Peru, June 1969. Fish. Bull., 69: 859-876.

Belevisch, R.R., 1966. A dynamic method for computing the vertical movements of water in the ocean. Okeanologia,U.S.S.R., 6: 1069-1073.

Benakappa, S., M.P.M. Reddy and V. Hariharan, 1980. Hydrographic conditions in the fishing grounds off Mukka - Kaup. South Kanara. Mahasagar, 13: 1-7.

Bhattathiri, P.M.A., V.P. Devassy and K. Radhakrishna, 1980. Primary production in the Bay of Bengal during southwest monsoon of 1978. Mahasagar, 13: 315-323.

Bjerknes, J., 1961. Survey of 'El Nino', 1957–1958 in its relation to tropical Pacific meteorology. *Bull. inter - Am. trop. Tuna Commn.*, 5: 3–62.

Bjerknes, J., 1966. 'El Nino' study based on analysis of Ocean surface temperatures 1935–'57. *Bull. inter - Am. trop. Tuna Commn.*, 12: 219–303.

Blackburn, M., 1962. An oceanographic study in the Gulf of Technantepec. *Spec. Scient. Rep. U.S. Fish. Wildl. Serv. Fish. No.* 404, 28 pp.

Blackburn, M., 1965. Oceanography and the ecology of Tunas. *Oceanogr. Mar. Biol. Ann. Rev.*, 3: 299–322.

*Bobzin, E., 1922. Vergleichende Betrachtung des Klimas und der Kalten Auftriebstromungen an der Sudevestafrikanischen und Sudarabischen Kuste. *Dtsch. Ubers. Met. Beob, Hft.* 23: 1–18.

Bogadanov, D.V., V.A. Sokolov and N.S. Khromov, 1968. Regions of high biological and fishing productivity in the Gulf of Mexico and Caribbean Sea. *Okeanologia, U.S.S.R.*, 8: 466–478.

Brocks, K. and L. Kugermeyer, 1972. The hydrodynamic roughness of the sea surface. In - *Studies Phys. Oceanogr.*, Ed. A.L. Gorden, 75–92.

Bruce, J.G., 1973. Large scale variations of Somali current during southwest monsoon 1970. *Deep Sea Res.*, 20: 837–846.

Bruce, J.G., 1974. Some details of upwelling off the Somali and Arabian Coasts. *J. mar. Res.*, 32: 419–422.

---

*Not referred in original.

Bruce, J.G., 1979. Eddies off the Somali Coast during the southwest monsoon. *J. Geophys. Res.*, 83: 7742-7748.

Buchan, A., 1895. Reports on oceanic circulation, based on the observations made on board H.M.S. Challenger and other observations. *Rep. Scient. Res. Voy. 'Challenger'* Physics and Chemistry, Part 8, Appendix,33pp.

Burt, W., H. Crew, N. Plutchak and J. Dammon, 1974. Diurnal variations of winds over an upwelling region off Oregon. *Bound. Lay. Meteor.*, 4: 35-45.

Calvert, S.E. and N.B. Price, 1971. Upwelling and nutrient regeneration in the Benguela Current, October 1968. *Deep Sea Res.*, 18: 505-523.

Carruthers, J.N., S.S. Gogate, J.R. Naidu and T. Leevastu, 1959. Shoreward upslope of the layer of minimum oxygen off Bombay: its influences on marine biology, especially fisheries. *Nature*, 183: 1084-87.

Caviedes, C.N., 1973. Secas and El Nino; two simultaneous climatic hazards in South America. *Proc. Assoc. Am. Geogr.* 5: 44-49.

Chidambaram, K. and M. Devidas Menon, 1945. The co-relation of west coast (Malabar and south Canara) fisheries with plankton and certain oceanographical factors. *Proc. Indian Acad. Sci.*, 22B: 355-367.

Clarke, A.J., 1979. On the generation of the seasonal coastal upwelling in the Gulf of Guinea. *J. Geophys. Res.*, 84: 3743-3751.

Cromwell, T., 1953. Circulation in a meridional plane in the central equatorial Pacific. *J. mar. Res.*, 12: 196-213.

Cromwell., 1958. Thermocline topography, horizontal currents and 'ridging' in the eastern tropical Pacific. Bull. inter - Am. Trop. Tuna Commn., 3: 135-164.

Currie, R.I., A.E. Fischer and P.M. Hargreaves, 1973. Arabian Sea upwelling. In - The Biology of the Indian Ocean. Ed. B. Zeitzchel and S.A. Gerlach: 37-53.

Cushing, D.H., 1971. Upwelling and the production of fish. In - Advances in Marine Biology. Ed. F.S. Russel and M. Yonge, 9: 255-334.

Damodaran, R. and C. Hridayanathan, 1966. Studies on the mud banks of the Kerala Coast. Bull. Dept. Mar. Sci. Univ. Cochin, 2: 61-68.

Darbyshire, M., 1967. The surface waters off the coast of Kerala, South west India. Deep Sea Res., 14: 295-320.

Deacon, G.E.R., 1963. The Southern Ocean. In - The Sea Vol.II. Ed. M.N. Hill, 281-296.

*Defant, A., 1936a. Das Kaltwasseran ftriebs gebiet vor der Kuste Sudwestafrikas in Landerkdl. Festrchr. Krebs, p. 52-56.

Defant, A., 1936b. Die Troposphase Dentscha Atlantische Edped. Meteor. 1925-27. Wiss. Erg. dt. VI, Teil. 1, 3. Lief. p. 289-411.

Defant, A., 1961. Physical Oceanography, Vol. I. Pergamon Press, New York, 729 pp.

*De Tessan, U., 1844. Voyage Autour du Monde sur la Fregate 'La venus Pendant les annees 1836-1839, Paris, 10 Vols.

---

*Not referred in original.

Dietrich, G., 1957. General Oceanography, Interscience Publishers, 588 pp.

Edelman, M.S., 1965. Brief characteristics of the water masses in the Gulf of Eden and the North Arabian Sea (In Russian). *Trudy VNIRO*, 57: 93–107.

Ekman, V.W., 1905. On the influence of earth's rotation on ocean currents. *Ark. f. Math. Astron. Och. Fysik.*, 2: 52 pp.

Emilsson, I., 1961. The shelf and coastal waters off southern Brazil. *Bolm. Inst. Oceanogr. S. Paulo*, 11: 101–102.

Evans, R.H. and O.B. Brown, 1981. Propagation of thermal fronts in the Somali Current System. *Deep Sea Res.*, 28: 521–527.

Forsbergh, E.D., 1963. Some relationships of meteorological, hydrographic and biological variables in the Gulf of Panama. *Bull. inter - Am. trop. Tuna Commn.*, 7: 109 pp.

Fukuoka, J., A. Bathster and F. Cergignon, 1964. An analysis of hydrographical conditions in the Caribean Sea (111) – especially about upwelling and sinking. In – *Studies on Oceanography*, Ed. A. Yoshida, Univ. of Tokyo, 145–149.

Fukuoka, J., 1965. Coastal upwelling near Venezuela (1) year to year change in upwelling. *Bol. Inst. Oceanogr. Univ. Oriente*, 4: 223–233.

Fukuoka, J., 1966. Coastal upwelling near Venezuela (2) certain periodicities of hydrographical conditions. *Bol. Inst. Oceanogr. Univ. Oriente*, 5: 84–95.

Gallagher, J.F., 1966. The variability of water masses in the Indian Ocean. *Publ. Nat. Oceanogr. Data Centre*, G-11: 1-74.

Ganapati, P.N. and V.S.R. Murthy, 1954. Salinity and temperature variations of the surface waters off Visakhapatnam Coast. *Andhra Univ. Mem. Oceanogr.*, 1: 125-142.

Ganapati, P.N. and D.V.Subba Rao, 1958. Quantitative study of plankton off Lawsons Bay, Waltair. *Proc. Indian Acad. Sci.*, 48B: 189-209.

Ganapati, P.N. and V. Sarma, 1958. Hydrography in relation to the production of plankton off Waltair Coast. *Andhra Univ. Mem. Oceanogr.*, 2: 168-192.

Ganapati, P.N., E.C. LaFond and P.V. Bhavanarayana, 1956. On the vertical distribution of chemical constituents in the shelf waters off Waltair. *Proc. Indian Acad. Sci.*, 33B: 68-72.

Garner, D.M., 1961. Hydrology of the NewZealand coastal waters, 1955. *Bull. N.Z. Dept. Scient. Ind. Res.*, No. 138, 84 pp.

Garvine, R.W., 1971. A simple model of coastal upwelling dynamics. *J. Phys. Oceanogr.*, 1: 169-179.

Garvine, R.W., 1974. Ocean interiors and coastal upwelling models. *J. Phys. Oceanogr.*, 4: 121-125.

George, P.C., 1953. The marine plankton of the coastal waters of Calicut with observations on the hydrological conditions. *J. Zool. Soc. India*, 5: 76-107.

Gill, A.E. and A.J. Clarke, 1974. Wind-induced upwelling, coastal currents and sea-level changes. *Deep Sea Res.*, 21: 325-346.

Green, C.K., 1944. Summer upwelling - northeast coast of Florida. *Science*, 100: 546-547.

Guillen, O., 1971. The 'El Nino' phenomenon in 1965, and its relation with the productivity in coastal Peruvian waters. In - *Fertility of the Sea*, 1: 187-196.

Gunther, E.R., 1936. A report on oceanographical investigations in the Peru Coastal Current. '*Discovery*' *Rep.*, 13: 107-276.

Hachey, H.B., 1937. Ekman's theory applied to water replacement on Scotian shelf. *Proc. Trans. Nova Scotian Inst. Sci.*, 19: 264-276.

Halpern, D., 1974. Summertime surface diurnal period winds measured over an upwelling region near the Oregon Coast. *J. Geophys. Res.*, 29: 2223-2230.

Halpern, D., 1976. Measurements of near-surface windstress over an upwelling region near the Oregon Coast. *J. Phys. Oceanogr.*, 6: 108-112.

Halpern, D., 1980. Vertical motion at the equator in the eastern Pacific (abstract). *EOS* 61: 998.

Halpern, D., R.L. Smith and E. Mittelstaedt, 1976. Cross-shelf circulation on the continental shelf off N.W. Africa during upwelling. *J. mar. Res.*, 35: 787-796.

Hamilton, P., and M. Rattray Jr., 1978. A numerical model of the depth dependent, wind driven upwelling circulation on the continental shelf. J. Phys. Oceanogr., 8: 437-457.

Hart, T.J. and R.I. Currie, 1960. The Benguela Current. 'Discovery' Rep., 31: 121-198.

Heath, R.A., 1972. Oceanic upwelling produced by northerly winds on the North Canterbury Coast. J. mar. Freshwat. Res., 6: 343-351.

Hidaka, K., 1954. A contribution to the theory of upwelling and coastal currents. Trans. Am. Geophys. Un., 35: 431-444.

Hidaka, K., 1958. Computation of windstresses over the oceans. Rec. Oceanogr. Wks. Japan, 4: 77-123.

Hidaka, K., 1960. On the equatorial upwelling. Mem. Kobe. Mar. Obs., 14:1-3.

Hidaka, K., 1961b. Equatorial upwelling and sinking in a zonal ocean with lateral mixing. Geophys. J. Roy. Astro. Soc., 4: 359-371.

Hidaka, K., 1965. Evidences of an intense upwelling at the equator. La. mar. Bull. Soc. Franco. Japan Oceanogr., 3: 1-8.

Hidaka, K., 1966. Non linear computation of the equatorial upwelling. J. Oceanogr. Soc. Japan, 22: 145-153.

Hidaka, K., 1968. Computation of upwelling and sinking from direct measurements of horizontal currents. J. Oceanogr. Soc. Japan, 24: 167-172.

Holmes, R.W., B. Schaefer and B.M. Shimada, 1957. Primary production, chlorophyl and zooplankton volumes in the tropical eastern Pacific. *Bull. inter - Am. trop. Tuna Commn.*, 2: 129-156.

Houghton, R.W., 1976. Circulation and hydrographic structure over the Ghana continental shelf during the 1974 upwelling. *J. Phys. Oceanogr.*, 6: 909-924.

Houghton, R.W. and T. Beer, 1976. Wave propagation during the Ghana upwelling. *J. Geophys. Res.*, 81: 4423-4429.

Hseuh, Y. and R.J. Kenney, 1972. Steady coastal upwelling in a continuously stratified ocean. *J. Phys. Oceanogr.*, 2: 27-33.

Hufford, G.L., 1974. On apparent upwelling in the southern Beaufort Sea. *J. Geophys. Res.*, 79: 1305-1306.

Hughes, P. and E.D. Barton, 1974. Stratification and water-mass structure in the upwelling area off North West Africa in April/May 1969. *Deep Sea Res.*, 21: 611-628.

Hulburt, E.M., 1966. The distribution of phytoplankton and its relationship to hydrography, between Southern New England and Venezuela. *J. mar. Res.*, 24: 67-81.

Hulburt, H.E. and J.D. Thompson, 1973. Coastal upwelling on a β-plane. *J. Phys. Oceanogr.*, 3: 16-32.

Huyer, A., 1976. A comparison of upwelling events in two locations: Oregon and N.W.Africa. *J. mar. Res.*, 34: 531-546.

Huyer, A., 1977. Seasonal variation in temperature, salinity and density over the continental shelf off Oregon. *Limnol. Oceanogr.*, 22: 442-453.

Huyer, A. and R.L. Smith, 1974. A surface ribbon of cool water over the continental shelf off Oregon. J. Phys. Oceanogr., 4: 381-391.

Huyer, A., R.D. Pillsbury and R.L. Smith, 1975b. Seasonal variation of alongshore velocity field over the continental shelf off Oregon. Limnol. Oceanogr., 20: 90-95.

Ichiye, T., 1966. Vertical currents in the equatorial Pacific Ocean. J. Oceanogr. Soc. Japan, 22: 274-284.

Ingham, M.C., 1970. Coastal upwelling in the northwestern Gulf of Guinea. Bull. Mar. Sci., 20: 2-34.

Jagannathan, P. and A.A. Ramasastry, 1964. Climatic changes in the Indian seas. J. Geophys. Res., 69: 215-221.

Jayaraman, R., 1965. Upwelling off the east coast of India. Curr. Sci., 4: 121-122.

Jayaraman, R. and S.S. Gogate, 1957. Salinity and temperature variations in the surface waters of the Arabian Sea off the Bombay and Saurashtra coasts. Proc. Indian Acad. Sci., 45B: 151-164.

Jayaraman, R., C.P. Ramamirtham and K.V. Sunderamam, 1959. The vertical distribution of dissolved oxygen in the deeper waters of the Arabian Sea in the neighbourhood of the Laccadives during the summer of 1959. J. mar. biol. Ass. India, 15: 206-211.

Jayaraman, R., R. Viswanathan and S.S. Gogate, 1961. Characteristics of sea water near the light house, Bombay. J. mar. biol. Ass. India, 3: 1-5.

Jones, P.G.W., 1971. The southern Benguela Current region in February, 1966. Part I. Chemical observations with particular reference to upwelling. *Deep Sea Res.*, 18: 193–208.

Jones, P.G.W., 1972. The variability of oceanographic observations off the coast of North West Africa. *Deep Sea Res.*, 19: 405–431.

Johnson, D.R., E.D. Barton, P. Hughes and C.N.K. Mooers, 1975. Circulation in the Canary Current upwelling region off Cabo Bajador in August 1972. *Deep Sea Res.*, 22: 547–578.

Johnson, D.R., T. Fonseca and H. Sieven, 1980. Upwelling in the Humboldt coastal current near Valparaiso, Chile. *J. mar. Res.*, 38: 1–16.

Kesavadas, V., 1979. Seasonal variation in mean sea level at Mormugao, west coast of India. *Mahasagar*, 12: 59–67.

Khromov, N.S., 1965b. On the quantitative distribution of plankton in the New Caribean Sea in the Gulf of Mexico. *Trudy VNIRO*, 57: 381–389.

Kindle, J.C. and J.J.O'Brien, 1974. On upwelling along a zonally oriented coastline. *J. Phys. Oceanogr.*, 4: 125–130.

Knauss, J.A., 1963. Equatorial currents. *Trans. Am. Geophys. Un.*, 44: 477–478.

LaFond, E.C., 1954. On upwelling and sinking off the east coast of India. *Andhra Univ. Mem. Oceanogr.*, 1: 117–121.

LaFond, E.C., 1957. Oceanographic studies in the Bay of Bengal. *Proc. Indian Acad. Sci.*, 46B: 1–46.

LaFond, E.C., 1958a. On the circulation of the surface layers off the east coast of India. *Andhra Univ. Mem. Oceanogr.*, 2: 1-11.

LaFond, E.C., 1958b. Seasonal cycle of sea surface temperature and salinity along the east coast of India. *Andhra Univ. Mem. Oceanogr.*, 2: 12-21.

LaFond, E.C. and P.V. Bhavanarayana, 1957. On the replenishment of some plant nutrients during the upwelling period on the east coast of India. *Indian J. Fish.*, 4: 75-79.

LaFond, E.C. and C. Borreswara Rao, 1955. Vertical temperature structure off the east coast of India. *Def. Sci. Org. Pub.* No. 4155, 1-89.

LaFond, E.C. and K.G. LaFond, 1968. Studies on oceanic circulation in the Bay of Bengal. *Bull. natl. Inst. Sci. India*, 38: 164-183.

*Lane, R.K., 1965b. Climate and heat exchange in the oceanic region adjacent to Oregon. Ph.D. Thesis, *Oregon State University*, 115 pp.

Lathifa, P.N. and A.V.S. Murthy, 1978. Studies on upwelling along the west coast of India using geopotential anomaly. *Indian J. mar. Sci.*, 7: 219-223.

Longard, J.R. and R.E. Banks, 1952. Wind induced vertical movement of the water on an open coast. *Trans. Am. Geophys. Un.*, 33: 377-380.

Lynn, R.J., 1967. Seasonal variation of temperature and salinity at 10 meters in the California Current. *Rep. Calif. coop. Ocean. Fish. Invest.*, 11: 157-186.

---

*Not referred in original.

Mashahida, T., 1972. Brief analysis of upwelling phenomena near the eastern coast of Taiwan. Acta Oceanogr. Taiwanica, 2: 25-30.

Mc Ewan, G.F., 1912. The distribution of ocean temperatures along the west coast of North America deduced from Ekman's theory of upwelling of cold water from adjacent ocean depths. Int. Revueges. Hydrobiol. Hydrogr., 5: 243-286.

Moeda, S., R. Kishimotâ, 1970. Upwelling off the coast of Peru. J. Oceanogr. Soc. Japan, 26: 300-309.

Mojumdar, P., 1967. Observations on the hydrological conditions of the surface waters of Waltair (Bay of Bengal) during 1964-66. J. mar. biol. Ass. India, 9: 164-172.

Mooers, C.N.K., C.A. Collins and R.L. Smith, 1976. The dynamic structure of the Frontal zone in the coastal upwelling region off Oregon. J. Phys. Oceanogr., 6: 2-21.

Murthy, C.S. and V.V.R.Varadachari, 1968. Upwelling along the east coast of India. Bull. natl. Inst. Sci. India, 38: 80-86.

Murthy, A.S.N., M.G.S.Rao and G.S.Sharma, 1982. Current structure in the upper layers of the Arabian Sea during southwest monsoon. Indian J. mar. Sci., 11; 1-6.

Narayanan, V. and R. Padmanabha Pillai, 1974. Analysis of sea-surface temperature at an equatorial coastal station. J. mar. biol. Ass. India, 16: 169-174.

Neuman, G., 1960. Evidences of an Equatorial Undercurrent in the Atlantic Ocean. *Deep Sea Res.*, 6: 328-334.

Neyman, V.G., 1964. Factors conditioning the oxygen minimum in the subsurface waters of the Arabian Sea. *Dept. Oceanogr. Univ. Washington*, Seattle, 1-3: mimeo.

Niebauer, H.J., T. Green and R.A. Razotzkia, 1977. Coastal upwelling and/downwelling cycles in southern Lake Superior. *J. Phys. Oceanogr.*, 7: 918-927.

Noble, A., 1968. Studies on sea water off the North Canara coast. *J. mar. biol. Ass. India*, 10: 197-227.

Paffley, M.B. and J.J. O'Brien, 1976. A three dimensional simulation of coastal upwelling off Oregon. *J. Phys. Oceanogr.*, 6: 164-180.

Patil, M.R., C.P. Ramamirtham, P.U. Varma, C.P. Nair and P. Myrland, 1964. Hydrography of the west coast of India during the pre-monsoon period of the year 1962. Part I - shelf water of Maharastra and South West Saurashtra coasts. *J. mar. biol. Ass. India*, 6: 151-166.

Panikkar, N.K. and R. Jayaraman, 1966. Biological and oceanographic differences between Arabian Sea and Bay of Bengal. *Proc. Indian Acad. Sci.*, 14B: 231-240.

Patullo, J.G., 1963. Seasonal changes in sea level. In - *The Sea* Vol. II. Ed. M.N. Hill, 485-496.

Patullo, J.G., W. Munk., W. Revelle and E. Strong, 1955. The seasonal oscillation in sea level. *J. mar. Res.*, 14: 88-155.

Peaulosky, J., 1974a. Longshore currents and the onset of upwelling over bottom slope. *J. Phys. Oceanogr.*, 4: 310-320.

Pedulosky, J., 1974b. Longshore currents, upwelling and bottom topography. *J. Phys. Oceanogr.*, 4: 300–320.

Pedulosky, J., 1978a. An inertial model of steady coastal upwelling. *J. Phys. Oceanogr.*, 8: 171–177.

Pedulosky, J., 1978b. A non linear model of the onset of upwelling. *J. Phys. Oceanogr.*, 8: 178–187.

Philander, S.G.H., 1979. Upwelling in the Gulf of Guinea. *J. mar. Res.*, 37: 23–33.

Poornachandra Rao, C., 1956. Currents off Visakhapatnam. *Indian J. Met. Geophys.*, 7: 377–379.

Posner, G., 1957. The Peru Current. *Bull. Bingham Oceanogr. Coll.*, 16: 106–155.

*Puff, A., 1890. Das Kalte Auftriebwasser an Ostseite des Nordatl. und an der Westssite des Nordindischen Ozeans. Dissertation, *Univ. Marbury*, 99 pp.

Purushan, K.S. and T.S.S.Rao, 1974. Studies on upwelling off the southwest coast of India. *Indian J. mar. Sci.*, 3: 81–83.

Qasim, S.Z., M.V.M. Wafar, Sumitra Vijayaraghavan, Joseph, P. Royan and L. Krishnakumari, 1978. Biological productivity of the coastal waters of India – from Dabhol to Tuticorin. *Indian J. mar. Sci.*, 7: 84–93.

Raghuprasad, R., 1957. Seasonal variation in the surface temperature of sea water at Mandapam from January 1950 to December 1954. *Indian J. Fish.*, 4: 20–31.

---

*Not referred in original.

Ramachandran Nair, P.V., Sydney Samuel, K.J.Joseph and V.K.Balachandran, 1973. Primary production and potential fishery resources in the seas around India. Proc. Symp. Living Resources of the Seas around India. Sp. Publ. C.M.F.R.I., 184-198.

Ramamirtham, C.P. and R. Jayaraman, 1960. Hydrographic features of the continental shelf waters off Cochin during the years 1958-59. J. mar. biol. Ass. India, 2: 155-168.

Ramamirtham, C.P. and R. Jayaraman, 1963. Some aspects of the hydrographical conditions of the backwaters around Wellington Island (Cochin). J. mar. biol. Ass. India, 5: 170-177.

Ramamirtham, C.P. and M.R. Patil, 1965. Hydrography of the west coast of India during the pre-monsoon period of the year 1962, Part 2: In and offshore waters of the Konkan and Malabar coasts. J. mar. biol. Ass. India, 7: 150-168.

Ramamirtham, C.P. and D.S.Rao, 1973. On upwelling along the west coast of India. J. mar. biol. Ass. India, 15: 306-317.

Ramamurthy, S., 1963. Studies on the hydrological factors in the North Kanara coastal waters. Indian J. Fish., 10: 75-93.

Ramanadham, R. and R. Varadarajulu, 1964. Fluctuations in the monthly mean sea level at Visakhapatnam as related to the dynamics of the atmosphere over the western Bay of Bengal. Indian Journal of Pure and Applied Physics, 2: 228-231.

Ramasastry, A.A., 1959. Water masses and the frequency of sea water characteristics in the upper layers of the Southeastern Arabian Sea. J. mar. biol. Ass. India, 1: 233–246.

Ramasastry, A.A.,1963. Surface water characteristics in the Bay of Bengal off Madras. Indian J. Met. Geophys., 14: 464–469.

Ramasastry, A.A. and C. Balaramamurthy, 1957. Thermal field and oceanic circulation along the east coast of India. Proc. Indian Acad. Sci., 46B: 293–323.

Ramasastry, A.A. and P. Myrland, 1959. Distribution of sea temperature, salinity and density in the Arabian Sea along the south Malabar Coast (South India) during the post monsoon season. Indian J. Fish., 6: 223–255.

Rao, L.V.G., T. Cherian, K.K. Varma and V.V.R.Varadachari, 1974. Hydrographical feature of the inner shelf waters along the central west coast of India during winter, spring and summer. Mahasagar, 7: 15–26.

Reddy, C.V.G. and V.N. Sankaranarayanan, 1968. Distribution of nutrients in the shelf waters of the Arabian Sea along the west coast of India. Bull. natl. Inst. Sci. India, 38: 206–220.

Reid, J.L., 1962. Measurements of the California Countercurrent at a depth of 250 meters. J. mar. Res., 20: 134–137.

Reid, J.L., G.I. Roden and J.G. Wyllie, 1958. Studies of the California Current System. Rep. Calif. coop. Ocean. Fish. Invest., 28–57.

Richards, F.A., 1960. Some chemical and hydrographic observations along the north coast of South Africa. 1. Cabo Tres Puntas to Curacao including the Cariaco Trench and the Gulf of Cariaco. *Deep Sea Res.*,7: 163-182.

Roden, G.I., 1961. On the wind driven circulation in the Gulf of Tehuantepec and its effect upon surface temperatures. *Geophysica International*, 1: 55-72.

Roden, G.I., 1962. Oceanographical aspects of the eastern equatorial Pacific. *Geophysica International*, 2: 77-92.

Roden, G.I., 1972. Large scale upwelling off northwestern Mexico. *J. Phys. Oceanogr.*, 2: 184-189.

Royal Society, 1965. International Indian Ocean Expedition *R.R.S. Discovery Cruise 3. Cruise Report*, 55 pp.

Ryshkov, G., 1959. Calculation of the development of upwelling in a deep sea. *Akad. Neuk. USSR Investica. Ser. Geofia*, 9: 1432-1433.

Saito, Y., 1956. Theory of the transient state concerning upwelling and coastal current. *Trans. Am. Geophys. Un.*, 37: 38-42.

Sankaranarayanan, V.N.,and S.Z. Qasim, 1968. The influence of some hydrographical factors on the fisheries of Cochin area. *Bull. natl. Inst. Sci. India*, 38: 846-853.

Sastry, J.S. and R.S. D'Souza, 1972. Upwelling and upward mixing in the Arabian Sea. *Indian J. mar. Sci.*, 2: 17-27.

Schaefer, M.B., T.M. Bishop and G.V.Howard, 1958. Some aspects of upwelling in the Gulf of Panama. *Bull. inter - Am. trop. Tuna Commn.*, 3: 79-132.

Schell, I.I., 1970. Variability and persistence in the Benguela Current and upwelling off Southwest Africa. *J. Geophys. Res.*, 75: 5225-5241.

*Schott, G., 1931. Der Peru-strom und Seinenordlicheu Nachbargebiete in normaler und anomalar Ausbildung. *Ann. Hydrog. mar. Met.*, 59: 161-169; 200-213; 240-252.

*Schott, G., 1933. Auftriebwasser an den australischen West kusten. Ja and Nein. *Ann. Hydrog. mar. Met.*, 61: 225-233.

Sewell, R.B.S., 1929. Geographic and Oceanographic research in Indian waters. Pt. 5, temperature and salinity of surface waters of the Bay of Bengal and Andaman sea. *Mem. Asiat. Soc. Bengal*, 9: 133-205.

Shannon, L.V., 1964. Hydrology of the south and west coasts of South Africa. *Investl. Rep. Div. Fish. Un. S. Afr.*, 58: 1-62.

Sharma, G.S., 1966. Thermocline as an indicator of upwelling. *J. mar. biol. Ass. India*, 8: 8-19.

Sharma, G.S., 1968a. Seasonal variation of some hydrographic properties of the shelf waters off the west coast of India. *Bull. natl. Inst. Sci. India*, 38: 263-276.

Sharma, G.S., 1968b. Some inferences on the Equatorial Undercurrent in the Indian Ocean based on the physical properties of the waters. *J. mar. biol. Ass. India*, 10: 224-236.

Sharma, G.S., 1971. Studies on divergence of the surface waters in the North Indian Ocean. *Ph.D. Thesis, Andhra University, Waltair*, 102 pp.

---

*Not referred in original.

Sharma, G.S. 1976. Water characteristics and current structure at 65^{o}E during the southwest monsoon. *J. Oceanogr. Soc. Japan*, 32: 284-296.

Sharma, G.S., 1978. Upwelling off the south west coast of India. *Indian J. mar. Sci.*, 7: 209-218.

Sharma, G.S., R. Narendran Nair and Basil Mathew, 1982. Current structure in the intertropical Indian Ocean. during north east monsoon. *Indian J. mar. Sci.*, 11: 7-14.

Sherman, L., 1952. A note on the vector operations and co-ordinate systems. *Q. J. Roy. Met. Soc.* 28: 633-634.

*Smith, R.L., 1964. An investigation of upwelling along the Oregon Coast, *Ph.D. Thesis, Oregon State University*, 83 pp.

Smith, R.L., 1968. Upwelling. *Oceanogr. Mar. Biol. Ann. Rev.*, 6: 11-46.

Smith, R.L., 1974. A description of current, wind and sea level variations during coastal upwelling off the Oregon Coast, July-Aug. 1972. *J. Geophys. Res.*, 79: 435-443.

Smith, R.L., 1978b. Poleward propagating perturbations in currents and sea level variations along the Peru Coast. *J. Geophys. Res.*, 83: 6083-6092.

Smith, R.L. and J.S. Bottero, 1977. On upwelling in the Arabian Sea. In - *A Voyage of Discovery*: 291-304.

---

*Not referred in original.

Smith, R.L., C.N.K. Moers and D.B. Enfield, 1971. Mesoscale studies of the physical oceanography in two coastal upwelling regions: Oregon and Peru. In - *Fertility of the sea*, 2: 513-535.

Smith, R.L., J.G. Patullo and R.K. Lane, 1966. An investigation in the early stage of upwelling along the Oregon Coast. *J. Geophys. Res.*, 71: 1135-1140.

Steemann Nielsen, E. and E.A.Jensen, 1957. Primary oceanic production. *Galathea Rep.*, 1: 49-136.

Stefansson, U. and F.A. Richards, 1964. Distribution of dissolved oxygen, density and nutrients off the Washington and Oregon Coasts. *Deep Sea Res.*, 11: 355-380.

Stommel, H. and W.S. Wooster, 1965. Reconnaissance of the Somali Current during the southwest monsoon. *Proc. Indian natl. Acad. Sci.*, 54: 8-13.

Subrahmanyan, R., 1959a. Studies on the phytoplankton of the west coast of India. Part I. *Proc. Indian Acad. Sci.*, 50B: 113-187.

Subrahmanyan, R., 1973. Hydrography and plankton as indicators of marine resources. *Proc. Symp. on living resources of the seas around India. Sp. Publ. C.M.F.R.I.*, 199-228.

Subrahmanyan, R. and A.H.Viswanatha Sarma, 1965. Studies on the phytoplankton of the west coast of India. Part 4. Magnitude of the standing crop for 1955-1962, with observations on nanoplankton and its significance to fisheries. *J. mar. biol. Ass. India*, 7: 406-419.

Suryanarayana Rao, S.V., 1957. Preliminary observations on the total phosphorus content of the inshore waters of the Malabar Coast of Calicut. Proc. Indian Acad. Sci., 45B: 77-85.

Sverdrup, H.U., 1938. On the process of upwelling. J. mar. Res., 1: 155-164.

Sverdrup, H.U. and R.H. Fleming, 1941. The waters off the coast of southern California, March to July, 1937. Bull. Scripps. Instn. Oceanogr., 4: 261-378.

Sverdrup, H.U., M.W. Johnson and R.H. Fleming, 1942. The Oceans, their Physics, Chemistry and general biology. Prentece - Hall, New York, 1087 pp.

Swallow, J.C., 1964. Equatorial Undercurrent in the western Indian Ocean. Nature, 204: 436-437.

Swallow, J.C. and J.G. Bruce, 1966. Current measurements off the Somali Coast during the southwest monsoon of 1964. Deep Sea Res., 13: 861-888.

Taft, B.A. and J.A. Knauss, 1967. The Equatorial Undercurrent of the Indian Ocean as observed by the Lusiad Expedition. Bull. Scripps Instn. Oceanogr., 9:126 pp.

Thompson, J.D., 1978. Role of mixing in the dynamics of upwelling systems. In - Upwelling Ecosystems. Ed. R. Boje and M. Tomczak, 203-222.

*Thorade, H., 1909. Uber die Kalifornische Meeresstrong. Annln Hydrogr. Berl., 37: 17-34; 63-76.

---

*Not referred in original.

Thrailkill, J.R., 1956. Relative areal zooplankton abundance off the Pacific Coast. *Spec. Scient. Rep. U.S. Fish. Wildl. Serv.* (Fisheries), No. 188, 85 pp.

Thrailkill, J.R., 1957. Zooplankton volumes off the Pacific Coast, 1956. *Spec. Scient. Rep. U.S. Fish. Wildl. Serv.* (Fisheries), No. 232, 55 pp.

Thrailkill, J.R., 1959. Zooplankton volumes off the Pacific Coast, 1957. *Spec. Scient. Rep. U.S.Fish. Wildl. Serv.* (Fisheries), No. 326; 57 pp.

Thrailkill, J.R., 1961. Zooplankton volumes off the Pacific Coast, 1958. *Spec. Scient. Rep. U.S. Fish. Wildl. Serv.* (Fisheries), No. 374, 70 pp.

Thrailkill, J.R., 1963. Zooplankton volumes off the Pacific Coast, 1959. *Spec. Scient. Rep. U.S. Fish. Wildl. Serv.* (Fisheries), No. 414, 77 pp.

Tomczak, M. Jr., 1977. Continuous measurement of near surface temperature and salinity in the N.W. African upwelling region between Canary Islands and Capvert during the winter of 1971-72. *Deep Sea Res.*, 24: 1103-1120.

Varma, P.U. and C.V.G. Reddy, 1959. Seasonal variations of the hydrological factors of the Madras coastal waters. *Indian J. Fish.*, 6: 298-305.

Varadachari, V.V.R., 1956. Thermal structure of upwelling in spring off the coast of Waltair. *Proc. Oceanogr. Seminar and Symposium at Andhra University*, Central Board of Geophysics, 1-2.

*Varadachari, V.V.R., 1958. On some meteorological and oceanographic studies of coastal waters off Waltair in relation to upwelling and sinking. *Andhra Univ.* D.Sc. Thesis (unpublished).

---

*Not referred in original.

Varadachari, V.V.R., 1961. On the process of upwelling and sinking on the east coast of India. Osmania Univ. Press, Hyderabad, Mahadevan Shastyabdapurti Vol., 159-162.

Varadachari, V.V.R., 1963. Seasonal variation of some physical features of the coastal waters off Waltair. Def. Sci. J., 10: 147-152.

Varadachari, V.V.R. and G.S.Sharma, 1967. Circulation of the surface waters in the North Indian Ocean. J. India Geophys. Un., 4: 61-73.

Varadarajulu, R. and S. Dhanalakshmi, 1975. Sea levels and waves along the Madras Coast. Indian J. mar. Sci., 4: 115-123.

Venkiteswaran, S.V., 1956. On evaporation from the Indian Oceans. Indian J. Met. Geophys., 7: 265-284.

Warren, B.A., H. Stommel and J.C. Swallow, 1966. Water masses and patterns of flow in the Somali basin during the southwest monsoon of 1964. Deep Sea Res., 13: 825-860.

Wells, H.W. and I.E. Gray, 1960. Summer upwelling off the northeast coast of North Carolina. Limnol. Oceanogr., 5: 108-109.

*Witte, E., 1880. 'Das Emporquellen von Kaltem Wasser an meridionalen Kusten, Ann. Hydrogr. Berlin, 8: 192-193.

Wooster, W.S., 1960. 'El Nino'. Rep. Calif. coop. Ocean. Fish. Invest., 7: 43-45.

---

*Not referred in original.

Wooster, W.S., 1978. Upwelling research and ocean affairs. In - *Upwelling Ecosystems*, Ed. R. Boje and M. Tomczak, 291-300.

Wooster, W.S. and T. Cromwell, 1958. An oceanographic description of the eastern tropical Pacific. *Bull. Scripps. Instn. Oceanogr.*, 7: 169-282.

Wooster, W.S. and M. Gilmartin, 1961. The Peru-Chile Undercurrent. *J. mar. Res.*, 19: 97-112.

Wooster, W.S. and O. Guillen, 1974. Characteristics of 'El Nino' in 1972. *J. mar. Res.*, 32: 387-404.

Wooster, W.S. and J.H. Jones, 1970. California Undercurrent off Northern Baja California. *J. mar. Res.*, 28: 235-267.

Wooster, W.S. and J.L. Reid, 1963. Eastern boundary currents. In - *The Sea*, Vol. II. Ed. M.N. Hill, 253-280.

Wooster, W.S., A. Bakun and D.R. McLain, 1976. The seasonal upwelling cycle along the eastern boundary current of the North Atlantic. *J. mar. Res.*, 34: 131-141.

Wyrtki, K., 1962. The upwelling in the region between Java and Australia during the south-east monsoon, *Australian J. mar. Freshwat. Res.*, 13: 217-225.

Wyrtki, K., 1963. The horizontal and vertical field of motion in the Peru Current. *Bull. Scripps Instn. Oceanogr.*, 8: 313-346.

Wyrtki, K., 1964b. Upwelling in the Costa Rica Dome. *Fish. Bull.*, 63: 355-372.

Wyrtki, K., 1966. Oceanography of the eastern equatorial Pacific Ocean. *Oceanogr. Mar. Biol. Ann. Rev.*, 4: 33-68.

Wyrtki, K., 1975. El Nino, the dynamic response of the equatorial Pacific Ocean to atmospheric forcing. *J. Phys. Oceanogr.*, 5: 572-584.

Wyrtki, K., 1981. An estimation of equatorial upwelling in the Pacific. *J. Phys. Oceanogr.*, 11: 1205-1214.

Yoshida, K., 1955a. Coastal upwelling off the California Coast. *Rec. Oceanogr. Wks. Japan*, 2: 8-20.

Yoshida, K., 1958b. A study on upwelling. *Rec. Oceanogr. Wks. Japan*, 4: 186-192.

Yoshida, K., 1958b. Coastal upwelling, coastal currents and their variations. *Rec. Oceanogr. Wks. Japan*, Special Number, 85-89.

Yoshida, K., 1959. A theory of the Cromwell Current (The Equatorial Undercurrent) and of the equatorial upwelling - An interpretation in a similarity to a coastal circulation. *J. Oceanogr. Soc. Japan*, 15: 159-170.

Yoshida, K., 1967. Circulation in the eastern tropical oceans with special reference to upwelling and undercurrents. *Japan J. Geophys.*, 4: 1-75.

Yoshida, K., 1981. The coastal undercurrent - a role of longshore scales in coastal upwelling dynamics. *Prog. Oceanogr.*, 9: 83-131.

Yoshida, K. and M. Tsuchiya, 1957. Northward flow in lower layers as an indicator of coastal upwelling. Rec. Oceanogr. Wks. Japan, 4: 14-22.

Zuta, S., T. Rivera and A. Bustamante, 1978. Hydrologic aspects of the main upwelling areas off Peru. In - Upwelling Ecosystems. Ed. R. Boje and M. Tomczak, 235-256.

- G 3200 -