THERMOCLINE VARIABILITY IN THE ARABIAN SEA AND ITS EFFECTS ON ACOUSTIC PROPAGATION

Thesis submitted in partial fulfilment of the requirements
for the degree of **Doctor of Philosophy**
in Physical Oceanography

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CERTIFICATE

This is to certify that this thesis on **Thermocline variability in the Arabian Sea and its effects on acoustic propagation** is an authentic record of research work carried out by Mr K G Radhakrishnan, under our supervision and guidance at the Naval Physical and Oceanographic Laboratory, Cochin 682 021 for the Ph.D degree of the Cochin University of Science and technology and no part of it has previously formed the basis for the award of any other degree in any other University.

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CONTENTS

PREFACE

Typical vertical profiles of temperature consist of a near surface well mixed layer, layer of strong vertical gradient followed by a weak gradient layer. The area of large vertical gradients in temperature is refered to as thermocline which is ubiquitous in the Arabian Sea. The thermocline structure in the Arabian Sea exhibits large spatial and temporal variations in association with the seasonally reversing monsoon winds and currents, upwelling and sinking, eddies and fronts, etc. The influence of these factors on the thermocline structure have not been adequately described. In the thesis attempts have been made to study the spatial and temporal variations of thermocline structure in the Arabian Sea.

Speed of sound in sea water depends on various oceanographic parameters such as temperature, salinity and pressure (depth). The horizontal and vertical gradients of these parameters result in the variation of sound speed structure and hence its propagation. The effect of salinity variations on sound speed is considerably less than the temperature variations. The role of thermocline variability on the acoustic propagation is not clearly understood for the Arabian Sea. In this thesis attempts have also been made to study influences of thermocline structure on acoustic propagation. The thesis contains six chapters. A brief outline of the work carried out in each chapter is given below.

In the introductory chapter the description of the area of study (Arabian Sea) and various factors affecting thermocline variability are discussed. As these variabilities and their influence on propagation in the Arabian Sea are not understood well, attempts are made to highlight this aspect. In addition to this the previous works relevant to the present study are reviewed.

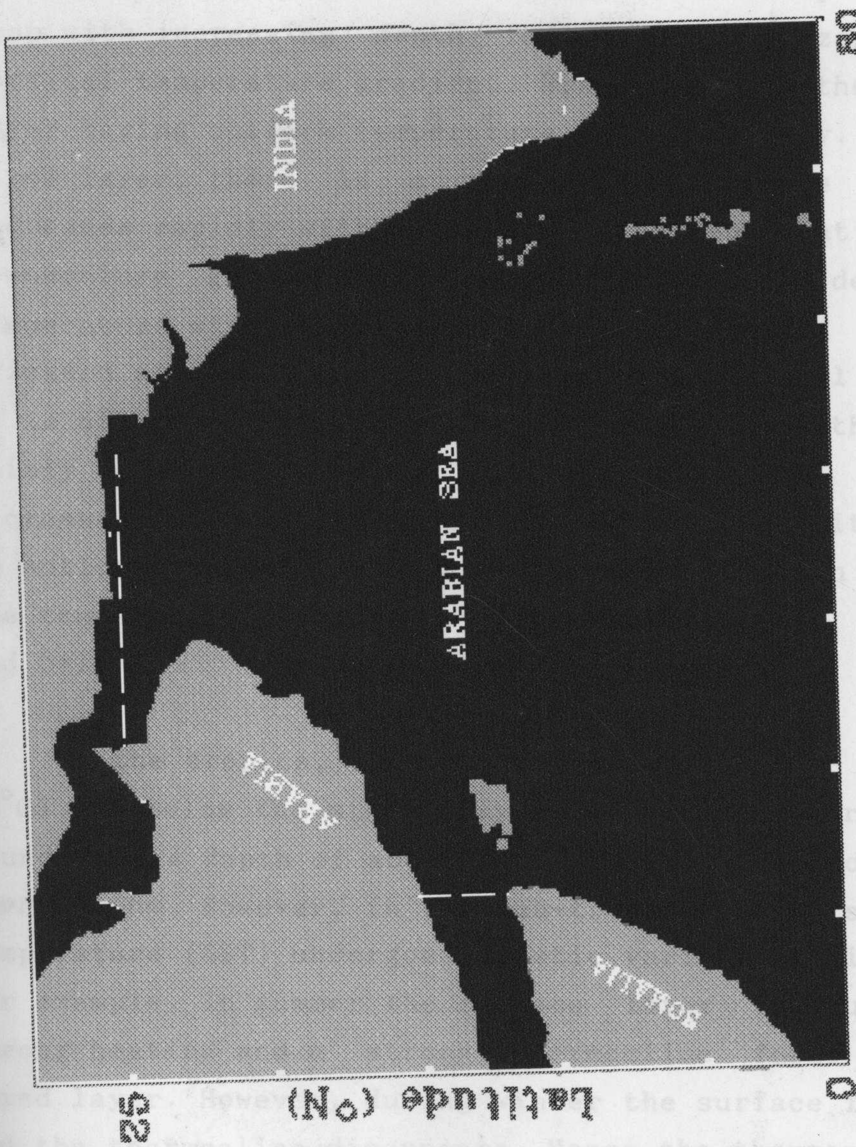
In chapter II climatology of the thermocline characteristics such as top, thickness, average temperature, gradient, etc. are described utilising an extensive data base. The preparation of this data base compiled from different sources is described. The variations of thermocline structure in the Arabian Sea on an annual cycle is analysed and interpreted.

Climatic mean study indicated that the processes controlling the thermocline dynamics are different for the coastal and open ocean areas. In chapter III regions off west coast of India are identified to investigate this aspect. The monthly cross shelf variations of thermocline characteristics at the selected locations in this region are studied based on a unique data set.

The short term variability of the thermocline characteristics at the selected locations based on time series data are studied in chapter IV. The role of dynamic stability on mixing characteristics in the thermocline is highlighted. The thermocline oscillations and their different harmonics are identified to study their influence on the acoustic propagation.

After establishing various factors causing thermocline variability the acoustic propagation aspects are studied in the Vth chapter. A range-dependent parabolic equation model is used to simulate the propagation conditions. Case studies for internal waves, eddy and typical thermocline structures identified at different locations are made to highlight their role on sound transmission.

The major findings and their importance are summarised in the last chapter along with the future outlook.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CHAPTER I

INTRODUCTION

1.1 THERMAL STRUCTURE IN THE OCEAN

In the ocean, a typical temperature profile consists of a surface well mixed layer, a layer of sharp temperature drop with increasing depth followed by a zone of weak vertical temperature gradient. Mixed layer is the turbulent layer having uniform temperature and salinity. Below the mixed layer, there is a zone in which the temperature decreases rapidly with depth and the depth at which the temperature gradient is maximum (rate of decrease of temperature with increase of depth) is called *thermocline* (Pickard and Emery, 1982). However in the actual observation it is often difficult to determine this depth precisely mainly because there is a zone in which temperature decreases rapidly with increasing depth. Hence it is easier to notice a thermocline zone as a range of depth over which the temperature gradient is large compared with that above and below.

In the tropics, usually the sea surface is warm (28°-$32^{\circ}C$) and below the mixed layer a strong thermocline is found upto a depth of about 200m. This is called the *main thermocline*. However, in the sub-tropics, the sea surface temperature (SST) undergoes drastic variations with season. For example, in summer the surface layer is subjected to strong heating and a strong thermocline forms below the mixed layer. However, during winter the surface layers cools and the thermocline disappears. Hence the thermocline during summer is called *seasonal thermocline*. In the polar regions,

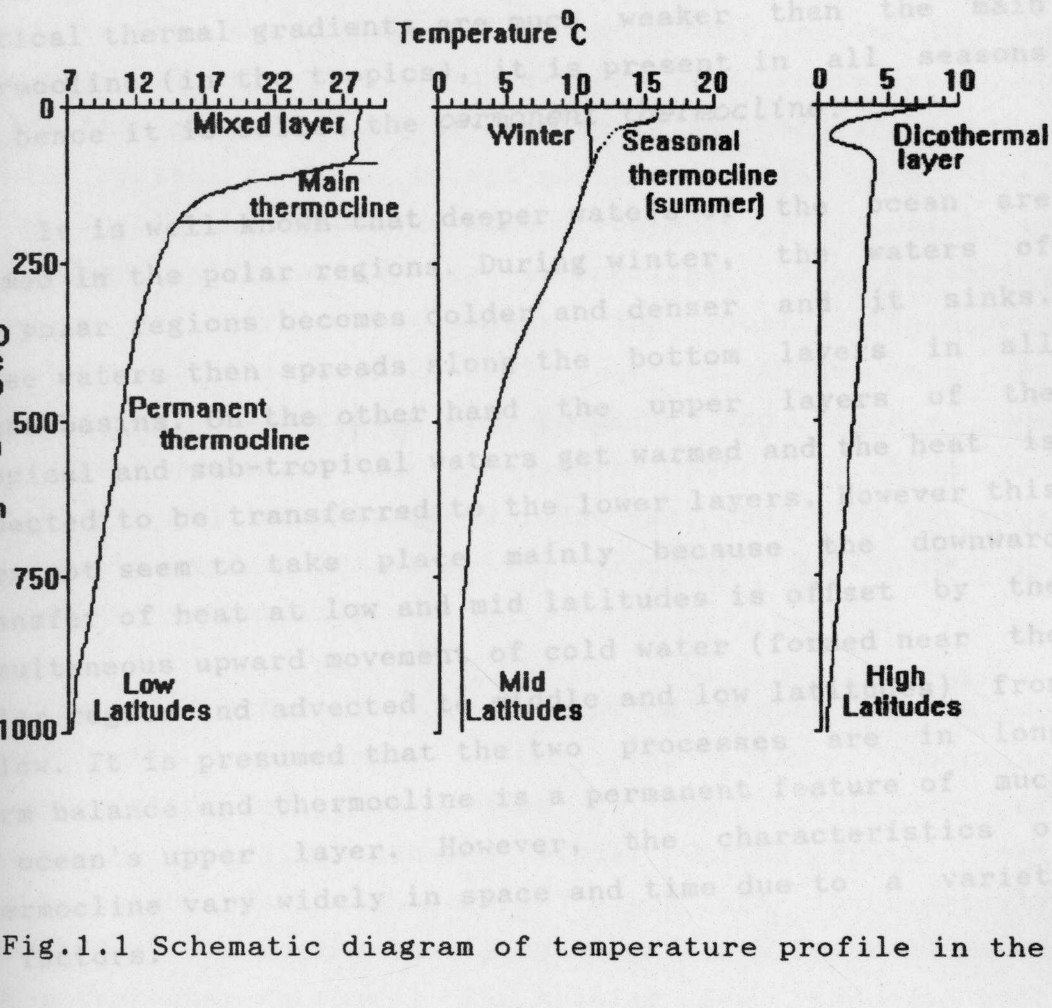

Fig.1.1 Schematic diagram of temperature profile in the Ocean

practically there is no thermocline and in winter the surface layers are colder than the underlying water. However with the advent of summer, the surface layers get heated and a zone of cold water is formed at about 50-100m depth called the *dicothermal layer* (Fig.1.1).

In the tropics and sub-tropics between about 200 and 1000m the temperature decreases with depth. Though the vertical thermal gradients are much weaker than the main thermocline (in the tropics), it is present in all seasons and hence it is called the *permanent thermocline*.

It is well known that deeper waters of the ocean are formed in the polar regions. During winter, the waters of the polar regions becomes colder and denser and it sinks. These waters then spreads along the bottom layers in all ocean basins. On the other hand the upper layers of the tropical and sub-tropical waters get warmed and the heat is expected to be transferred to the lower layers. However this does not seem to take place mainly because the downward transfer of heat at low and mid latitudes is offset by the simultaneous upward movement of cold water (formed near the polar region and advected to middle and low latitudes) from below. It is presumed that the two processes are in long term balance and thermocline is a permanent feature of much of ocean's upper layer. However, the characteristics of thermocline vary widely in space and time due to a variety of factors.

1.2 THERMOCLINE STUDIES IN THE ARABIAN SEA

Arabian Sea is the northwest part of the tropical Indian Ocean with land boundaries in the west, north and east. The domain of study extends from the equator to 25°N and 45°E to 80°E excluding the marginal seas, Red Sea and Persian Gulf.

In tropics, Arabian Sea is a region where the main thermocline is a ubiquitous feature. The sea surface temperature exceeds 29°C during pre-monsoon (Hastenrath and Lamb,1979) in the entire Arabian Sea while it cools significantly to about 23-24°C in the northern Arabian Sea during winter. The winter cooling and summer heating in the northern Arabian Sea causes drastic variations in thermocline characteristics. However in the central Arabian Sea and coastal regions, except northern Arabian Sea, most of the cooling occur during Summer (Colborn,1975) which in turn drastically alter the thermocline characteristics compared to pre-monsoon months. The most significant variations of thermocline from June to August are the shoaling of thermocline off Somalia and Arabia and concomitant deepening in the south central Arabian Sea (Hastenrath and Greischar,1989). However, they have not made attempts to explain the physical processes governing the thermocline variability.

The Arabian Sea is a region of a number of unique oceanographic phenomena. One of the important characteristics of this region is the occurrence of seasonally reversing monsoon winds. During south west monsoon season (June to September) winds are southwesterly which reverse to northeasterly during north east monsoon season (November-February). The Arabian Sea responds both thermodynamically and dynamically to the reversals of winds. Some of the major oceanographic features observed are summer and winter cooling, strong upwelling and sinking, undercurrents, watermass intrusions, meso-scale eddies (clockwise and anticlockwise), and internal waves. All these features are known to influence the ocean thermal structure in spatial and temporal domains (Colborn,1975; Duing and Leetmaa,1980; Schott,1983; Rao et al.,1989).

Associated with onset and progress of the summer monsoon large cooling of the surface layer take place mainly due to evaporative cooling and off shore spreading of cold upwelled water (Krishnamurti,1981; Duing and Leetmaa, 1980). As a result thermocline is encountered at deeper depths except near the coast where it shoals. During the monsoon season entrainment of cold waters from the thermocline into the mixed layer due to wind, wave and buoyancy mixing results in the erosion of the top layers of thermocline (Murthy et al.,1983; Ramesh Babu and Sastry,1984). The deepening of thermocline is mostly attributed to the mixing in the upper layers caused by wind wave action and convective over turning by buoyancy flux, convergence due to clockwise surface wind stress curl and enhanced vertical shear in the horizontal flow. (Wyrkti,1971; Colborn,1975; Rao et al.,1976; Sastry and Ramesh Babu,1979; Robinson et al.,1979 ; Rao,1987; Rao and Mathew 1990).

Vertical motions in the sea also influence thermocline characteristics. The thermocline shoals and sometimes even surfaces during the periods of upwelling (divergence) while it deepens during the periods of convergence (sinking). The process of upwelling commences in the early part of summer monsoon while sinking occur mostly in winter. The effect of the latter process is manifested as the deepening of thermocline. Moreover, the thermocline gradient also gets affected by these vertical motions. During the periods of upwelling, usually a undercurrent is noticed in the lower thermocline (counter to surface flow) which drastically alters the thermocline gradient in the lower thermocline. In the Arabian Sea, the prominent regions of upwelling and sinking are off Somalia (Bruce,1974; Schott,1983) off Arabia (Bruce,1974; Smith and Bottero,1977; Swallow,1984; Elliot and Savidge,1990; Bauer et al.,1991; Brock et al.,1991) and off the westcoast of India (Sharma,1968; Banse,1968; Wyrtki,1973).

A common feature of upwelling system is the presence of an undercurrent flowing opposite to the surface current (Yoshida and Mao,1957). The region of undercurrent are marked by isotherm downsloping in the subsurface levels and upsloping of isotherms in the surface levels towards the coast. The undercurrent is northward flowing (along west coast of continents) strong currents (≅ 2 Knots) usually found at the continental shelf break associated with coastal upwelling (Hart and Currie,1960). The undercurrents get weaker from south to north along the west coast of India, and ceases to be noticed at about 20°N (Shetye et al.,1990). This undercurrent carries low saline waters from southwestern Bay of Bengal/Equatorial Indian Ocean origin. Studies of Antony (1990), Mohan Kumar et al.,(1995) and Hareesh kumar and Mohan kumar (1995) have clearly established the presence of northward undercurrent along the southwest coast of India. This current is responsible for strong shear leading to mixing in the lower thermocline. This results in the spreading of isotherms in the lower thermocline (reduction of thermocline gradient). They are also responsible for the formation of fine scale structure (step and inversion) in the thermocline (Hareesh kumar et al.,1995). The equatorial undercurrent with its core about 50-100m depth causes spreading of thermocline (Sharma,1968).

The formation, interaction and advection of different watermasses can also cause variations in the thermocline characteristics. The intrusion of warm/cold water into the thermocline causes warming/cooling of the thermocline in that area. The Arabian Sea high salinity watermass is formed in the northern Arabian Sea and spreads southward in the upper thermocline zone (Rochford,1964; Wyrtki,1971). At the source region it has a temperature of about 30°C and salinty 36.5 PSU. The Persian Gulf watermass (temperature 27°C and salinity 39.5 PSU at the source) enters the northern Arabian Sea and spreads in the lower thermocline zone (Rochford,1964; Wyrtki,1971). The Red Sea watermass (temperature 20°C and salinity 39.7 PSU at source) is mostly found below the main thermocline (Wyrtki,1971; Brock et al.,1992). Further, the low saline Bay of Bengal/Equatorial Indian Ocean watermass (temperature 28°C and salinity 32.5 PSU at source) also enters the Arabian Sea (Darbyshire,1967; Pankajakshnan and Ramaraju,1987) but its influence is mostly limited to the mixed layer. During southwest monsoon the saline waters of pacific ocean origin enters the western Arabian Sea along with the Somali current (Swallow et al.,1983).

Ocean currents and their associated field of pressure, temperature and density vary in both time and space throughout the ocean. The variability is distributed unevenly with dominant spatial scales in the range of tens to hundreds of kilometers and temporal scales in the range of weeks to months. The meandering and filmenting of intense current systems, semi-attached and cast-off ring currents, advective vortices extending throughout the entire water column, lens vortices, planetary waves, topographic waves and wakes etc., are commonly referred to the generic term *eddies* (Robinson,1983). A knowledge of the actual description of ocean currents and their evolution in time on eddy scales is of considerable interest for practical purposes.

Arabian Sea is well known for its rich eddy structures (Duing,1972). They are zones of large horizontal and vertical temperature variability. In associate with these features one can expect large changes in the thermocline characteristics (Duing 1972; Swallow,1983). They are classified as cold core and warm core eddies depending on their core temperatures. In contrast to weak thermocline gradients at the core, sharp thermocline are observed at the peripheries of both cold core and warm core eddies. During the early stages of southwest monsoon, two clockwise eddies form off the Somalia coast (Swallow et al.,1983). By July-August, the eddy in the southern region move towards north and merge with the northern eddy (Swallow et al.,1983). However, in some years, both the eddies keep their identity till the end of southwest monsoon (Schott,1983). Das et al.,(1980) resolved eddies based on the hydrographic survey in the northern Arabian Sea in February and March-April 1974. They found eddies of about 200km diameter. Bruce et al.,(1980) reported a warm-core eddy to the northeast of Socotra having approximately 500km diameter based on three synoptic XBT (eXpendable Bathy Thermogaph) sections in June 1978. Studies based on the hydrographic sections covered by ATLANTIS II in 1964-65 and other drifter trajectories revealed that eddies are likely to be found anywhere in the Arabian Sea, with horizontal dimensions in the range 200-500km, vertical extent of some hundreds of meters, and typical surface currents of 20-30cm s^{-1} (Swallow, 1983).

Internal waves are sub-surface waves which propagate along the interface separating fluid layers of different densities within the sea. They may be generated by the flow of deep ocean currents over topographical features such as seamounts or the edge of the continental shelf break, the moving low atmospheric pressure systems and related short period variations in the wind stress and non-linear transfer of energy from surface waves, etc. Internal waves owe their existance to the density gradient and the gravitational restoring force. The frequency spectra of internal wave are bounded by the inertial frequency (Sin ϕ/12) and Brunt-Vaisala frequency,

$$N = \sqrt{-g\left[\frac{1}{\rho}\frac{\partial\rho}{\partial z} + \frac{g}{C^2}\right]} \text{ rad s}^{-1}$$

where, ϕ : latitude, g : acceleration due to gravity, C : speed of sound, ρ : density, ∂z and $\partial\rho$ are the depth difference and corresponding density difference.

Several studies were carried out to understand the characteristics of the internal waves and its causative factors (Varkey,1980; Charyulu et al.,1994; Murthy et al.,1992; Murthy and James,1995). In the coastal waters off Cochin Rao et al.,(1995) reported the presence of internal waves throughout the water column with its maximum amplitude (20 to 30m) in the pycnocline. During the summer monsoon season, Murthy et al.,(1992) observed high frequency internal waves with significant spectral peacks at 0.5 to 2 cycles/hour in the deep waters off Ratnagiri and Karwar. Recently Murthy and Ananth (1994) reported diurnal activity of internal waves with intense activity during night. One of the notable results is that the local winds are not responsible for the generation of internal waves. Based on current measurements made in the coastal waters off Bombay, Varkey (1980) reported the presence of internal tides (12 hrs). Similar observations were also reported by Shenoi and Antony (1991).

1.2.1 IMPORTANCE OF THERMOCLINE STUDIES

The thermocline studies have got a wide variety of applications in the field of fisheries, underwater surveillance, Ocean Thermal Energy Conversion, Ocean Engineering, etc. In the present study major focus has been given to understand the thermocline characteristics with special emphasis on acoustic propagation in the Arabian Sea. The speed of sound in sea water is an oceanographic variable that determines the behaviour of sound propagation in the ocean. Sound speed varies as a function of water temperature, salinity and pressure (or depth). The speed of sound in the sea water increases with an increase in any of the above three parameters. Since temperature variations are rapid in the thermocline regions, the associated sound propagation is also expected to have large variability in this zone. The thermocline characteristics which influence acoustic propagation have not been adequately studied well for the Arabian Sea. Typical parameters which are commonly used to describe thermocline characteristics are top, thickness, gradient and oscillations in the thermocline (internal waves). All these parameters are known to have impact on the sound propagation.

Top of the thermocline generally coincides with the bottom of the surface mixed layer, the depth at which temperature is 1°C lower than at the surface (Wyrtki, 1971; Colborn, 1975; Robinson et al., 1979; Hastenrath and Merle, 1987). Hence, the factors which control the mixed layer can also be used to explain the variability of the thermocline top. After careful scrutiny top of thermocline is defined as the depth at which the vertical temperature gradient is more than 0.04 $^{\circ}C\ m^{-1}$ for the present study.

Thickness of the thermocline is the vertical separation between top and bottom of the thermocline (Colborn, 1975; Hasternrath and Greischar, 1989). Several authors have given criteria to define the bottom of the thermocline. According to Wyrtki (1964) it is the depth at which the vertical temperature gradient drops to 0.03$^{\circ}C\ m^{-1}$. Defant (1936) for his study in Atlantic Ocean and Colborn (1975) after studying several gradient limits for the Indian ocean prescribed 0.02$^{\circ}C\ m^{-1}$ as the lower boundary criterion. In a recent study, Hastenrath and Merle (1987) suggested it as the level from which downward temperature decreases by less than 2°C over an interval of 50m. After analysing the data set of Arabian Sea, a gradient criterion of 0.04$^{\circ}C\ m^{-1}$ drop in temperature is found more suitable for defining the lower boundary of thermocline in the Arabian Sea. This criterion is followed for the present study.

Thermocline gradient is the ratio of temperature difference between top and bottom of the thermocline over its thickness (Hastenrath and Greischar, 1989). In the present study it is computed by taking the temperature differences between two successive layers of 10m each which was then averaged over the entire thermocline.

1.3 OCEAN ACOUSTICS

Sound is the only form of energy which propagates to very long ranges within the volume of the oceans. This is due to the fact that low frequency is less attenuated and travel more distances. Research and exploratory activities on underwater life and other resources, communication, sea bottom mapping, remote control and monitoring of underwater equipment etc. utilise sound energy. Ocean acoustics has developed into a multi-disciplinary branch of science as there are several commercial and military applications of underwater sound.

Speed of sound and transmission loss are two most important acoustic parameters of the ocean medium. Sound speed in sea water increases with increase in temperature, salinity and pressure (depth). It is possible to calculate sound speed using the equation of state of sea water (Fofonoff and Millard, 1984). But the relations involved are cumbersome and computations are time consuming. Hence empirical relations are used for the calculation of sound speed (Wilson,1960; Del Grosso and Mader,1972; Del Grosso,1974; Medwin,1975; Chen and Millero,1977; Mackenzie,1981). Direct measurements of sound speed are also possible with commercially available velocimeters. Sound speed is given by (Mackenzie,1981)

$$C = 1448.96 + 4.591T - 5.304 \times 10^{-2} T^2 + 2.374 \times 10^{-4} T^3 + 1.340(S-35) + 1.630 \times 10^{-2} D + 1.675 \times 10^{-7} D^2 - 1.025 \times 10^{-2} T(S-35) - 7.139 \times 10^{-13} TD^3$$

Where C is the sound speed ($m\ s^{-1}$), T is the temperature ($^{\circ}C$), S is the salinity (PSU), and D is the depth (m). This equation is followed for sound speed computations in the present study.

Vertical variations in sound speed in the ocean are in general much larger than horizontal variations. This vertical variation in sound speed (sound speed profile) results in refraction of sound energy as it propagates in the medium resulting in various propagation characteristics.

Propagation of sound in the sea over long ranges is always by some form of ducted or guided propagation in which maximum energy is confined within the boundaries of the duct. These ducts are called sound channels, or wave guides in general. The deep sound channel (DSC), the surface duct, and the shallow water channel are the important types of wave guides that exist in the ocean. Phenomena associated with long range sound propagation in deep waters are discussed by many authors (Urick,1983; 1982; Brekhovskikh and Lysanov,1982). Lens-like action of the water column causes the formation of zonal patterns of energy distribution with high and low intensity areas. These are associated with the existence of convergence zones and shadow zones.

Transmission loss is a measure of sound intensity available at a point relative to the intensity at the source. It is represented in decibels (dB). There are two components for transmission loss viz., spreading loss and attenuation. Spreading loss is related to geometrical focusing and de-focusing of energy as it travels away from the source. Attenuation has two components: volume absorption and loss due to boundary interactions. Volume absorption involves the conversion of elastic energy into heat and represents a true loss of the energy to the medium. The processes leading to absorption are viscosity and molecular relaxation processes involving magnesium sulphate and boric acid (Urick,1982). The boundary interaction losses are surface- and bottom-scattering losses and reflection loss at the bottom. Other mechanisms determining transmission loss are volume scattering by inhomogeneities, diffraction, and leakage out of sound channels.

There are different methods for studying the propagation characteristics. Analysis of field experimental data help to reveal propagation features under various environmental conditions. Though expensive and difficult to conduct, experiments at sea provide realistic data. Theoretical studies and mathematical models of sound propagation help in interpreting and predicting propagation features observed in the environment. A range of mathematical methods exist for propagation modeling. There are simple analytical models and complex numerical models. Prediction of expected propagation conditions are useful in the planning of many underwater and related activities. They are used in purely research oriented work, in commercial applications, and in military requirements.

The theoretical basis underlying all mathematical models of acoustic propagation is the wave equation. Mathematical models of sound propagation can be conveniently grouped into two types: range-independent and range-dependent. In range-independent models a simplified mathematical model of the environment is used for obtaining a relatively quick estimate of transmission loss. Examples of such simplifying assumptions are constant water depth, range-independent sound speed profile etc. In range-dependent models, variations in water depth and sound speed profiles with range are also taken into account and hence are more general and realistic. But the computational efforts are phenomenally large compared to range-independent models. Most common range-independent models are usually based on either ray theory or normal mode theory (Urick,1983). If the environment varies both in range and depth, the wave equation is to be solved numerically. The

Parabolic Equation (PE-IFD) model (Lee and McDaniel,1988) is an example.

1.3.1 OCEANIC INHOMOGENEITIES AND ACOUSTICS

In reality, the ocean is an extremely complex and variable medium. In such a complex environment more complex models of propagation incorporating statistical characteristics of the variations might be necessary to obtain reliable predictions of the sound field. Ocean currents, internal waves and small-scale turbulence perturb the horizontally stratified character of the sound speed and cause spatial and temporal fluctuations in sound propagation. Boundaries of large currents, such as the Gulf stream and Kuroshio, represent frontal zones separating watermasses with essentially different characteristics. Within these frontal zones, temperature, salinity, density and sound speed suffer strong variations and hence the acoustic propagation (Levenson and Doblar,1976). Large eddies in the ocean are mostly observed near intense frontal currents. The parameters of synoptic eddies vary over rather wide range. The diameter of an eddy ranges from 25 to 500km. Analysis of propagation studies through a cyclonic gulf stream eddy revealed considerable variations in the propagation conditions (Vastano and Owens, 1973). Considerable fluctuations of the intensity and phase of sound waves arise in the presence of internal waves (Stanford,1974). We know that such characteristics of the ocean water as salinity, temperature, density, and current velocity do not vary smoothly with depth, but in discontinuous fashion. Such fine layered structure leads to multipath of sound transmission and hence cause additional fluctuations of phase and amplitude to the sound signal (Stanford,1974). Thicknesses of these layers typically vary from tens of centimetres to tens of metres.

Propagation of sound in the ocean is usually accompanied by the fluctuation in the amplitude and phase of the transmitted signal. The fluctuations are manifestations of not only the changing patterns of interaction with the bottom and surface, but also of the propagation of the energy through time-varying inhomogeneities in the ocean medium. Internal wave-induced variability has been found to be a very significant source of sound intensity fluctuation and has received considerable attention. There are several studies to predict the influence of internal wave field on acoustic transmission (De Saubies, 1976, 1978; Munk and Zachariasen, 1976; Flatte and Tappert, 1975; Flatte' et.al., 1979; Colosi et al., 1994). Most of the work on this subject deals with deep ocean environments. In the shallow water the modelling of internal wave fields runs out to be inappropriate, partly due to the strong influence of the atmosphere (wind stress) and the fact that the waveguide properties of these environments are considerably different from those of the deep ocean (Ali,1993). Using ray theoretical transmission loss computations and observed internal wave data, a transmission loss contrast of 22-30 dB are reported by several authors (Lee ,1961; Baxter and Orr,1982; Murthy and Murthy, 1986). Porter, et al., (1974), Pinkel and Sherman (1991) and Rubenstein and Brill (1991) studied sound speed fluctuations and corresponding spectrum of internal wave field. They simulated transmission loss data in these environments and compared them with experimental data.

The temperature fluctuations caused by eddies significantly alter the sound speed in the ocean, producing a transient range-dependent acoustic environment; the direct effect of the Doppler shifting by currents could also be of some relevance. On the other hand, the alterations of sound propagation by eddy currents can be used to infer the distribution of the currents themselves if travel times and something about the structure of the temperature field are known. This is the basis of the acoustic tomography technique.

Hamilton (1974) is considered to be the first to encounter the manifestation of this variability, eddy, during the experiment on long range propagation of sound along two paths (Antigue-Eluethra, Antigue-Bermuda) in the Sargasso sea. Clark and Kronengold (1974) carried out detailed experiments to study the fluctuations of amplitude and phase of an acoustic signal at short and long ranges across the Florida Strait and along the Eluethra-Bermuda route, respectively. Both these studies were accounted for by the fact that the sound paths intersected various synoptic-scale inhomogeneities of the oceanic structure. There are several experimental studies across the Gulf Stream eddy (Weinberg and Zabalgogeazcoa, 1977 ; Beckerle et al., 1980).

The effect of an eddy manifests itself not only in local changes of amplitude and phase of a sound signal but also in displacements of the boundaries of convergence zones and acoustic shadow zones as a whole. The convergence zones correspond to the areas of substantial concentration of sound energy related to the arrival of one or several sound rays at each point of such a zone; in the shadow zones there are no rays or intensities of the signals arriving along them are small. In the recent study through the Gulf Stream eddy Mellberg et al.,(1990) observed a change of more than 5dB in sound intensity level and a shift of 10km in the location of first convergence zone in a time varying acoustic field..

Any eddy is a distribution of not only the sound speed field but also of currents. These currents can either accelerate or decelerate the propagation of a sound signal. Moreover, the length of the sound path and its orientation relative to the eddy are important for the propagation of sound. Attempts were made by Henrick (1980) and Itzikowitz et al.,(1982) to consider all these effects jointly on sound propagation. Several theoretical and experimental studies (Munk,1980; Weinberg and Clark,1980; Baer,1981) have been made to understand the horizontal (lateral) refraction of sound rays produced by oceanic eddies.

Oceanic microstructure induced variability has been found to be a very significant source of sound intensity fluctuations and has received considerable attention in these years (Melberg and Johannessen,1973;Lysanov and plotkin,1987; Potter,1991). Shulkin et al.,(1979) observed a fluctuation of acoustic intensity of the order of 5-10dB at a range of 210m for a high frequency(60kHz) sound source. Including the effect of oceanic microstructure to a model for predicting internal wave fluctuations Ewart (1980) observed a very good agreement between model simulations and the experimental results. However, in a study by Unni and Kaufman (1980) pointed out that the presence of microstructure adds little to the phase fluctuations.

Even though the importance of the oceanographic features on acoustic propagation has been realised, systematic studies addressing this aspect are rather few for the Indian Ocean. Prasanna Kumar et al.,(1992) have analysed the sound speed structure and propagation characteristics of a cold core eddy in the Bay of Bengal. They noticed a travel time delay of the order of 200 milliseconds for an acoustic ray passing through the eddy. Ramana Murty et al.,(1993) studied acoustic characteristics of the Bay of Bengal waters. Eigen rays, rays connecting the source and receiver, are identified in the deep sound channel and their turning depth, path length, travel time etc. were computed in the study. They also studied intensity fluctuation along the eigen rays due to both refraction and volume absorption by the medium. Prasanna kumar et al.,(1994) also carried out similar work in Bay of Bengal. In their study, a climatological mean sound speed profile was developed after analysing hydrographic data collected from this area. This climatological profile was used for studying the acoustic characteristics. Somayajulu et al.,(1994), based on acoustic simulation studies in the Arabian Sea, attributed the fluctuations in the travel time of the eigen rays in the deep sound channel to the sound speed fluctuations in this region.

1.4 OBJECTIVES OF THE STUDY

The variability of thermocline characteristics has profound influence on underwater acoustic propagation. As the thermocline characteristics affect the transmission of sound enormously, apriori knowledge of its characteristics is very essential for the conduct of ocean acoustics studies. The review of available literature clearly points out that studies are rather fragmentary as far as the distribution of thermocline characteristics and acoustic propagation aspects in the Arabian Sea are concerned.

The prime objective of this study is to identify the generic features of thermocline variability and to highlight different oceanographic aspects causing this variability. After having identified the features, temporal and spatial distribution of the thermocline characteristics on a basin scale is studied in detail. This gives an idea of the thermocline structure viz. topography, gradient and thickness. It is worth mentioning here that the analysis were carried out with extensive data bases to bring out salient features observed in the thermocline.

The role of thermocline features on acoustic propagation is not studied well for the Arabian Sea. This problem can be addressed in two ways viz. experimental studies at sea and mathematical modeling. Logistics involved in the planning and conduct of experimental studies are enormous especially for range dependent scenario. The advantage of using theoretical models is that with the available environmental information a realistic assessment of propagation can be attained. Keeping these aspects in the background, in the present study an attempt has also been made to study the propagation under different oceanic conditions.

The unique nature of the Arabian Sea is discussed highlighting various oceanographic features controlling the thermocline characteristics in the introductory chapter. In addition to this all the previous works pertaining to the thermocline variability are reviewed.

In the next chapter to bring out the oceanographic features, which cannot be identified by synoptic observations at a particular location, climatological aspects of the thermocline characteristics for the entire Arabain Sea is studied. This was carried out utilising an extensive temperature data base. The variations in the thermocline structure in the Arabian Sea on an annual cycle is analysed and interpreted. This study showed that the thermocline characteristics for the deep and coastal waters are distinct.

In the third chapter thermocline characteristics for the coastal waters are exclusively studied focusing west coast of India. This study has shown the importance of onshore/offshore processes in controlling the thermocline characteristics. To investigate this aspect thermocline characteristics are studied based on a unique data set.

To identify the oscillations in the thermocline, mainly caused by internal waves, its characteristics at the selected locations based on time series data are presented in chapter 4. The role of dynamic stability on mixing characteristics in the thermocline is highlighted. The thermocline oscillations and their different harmonics are identified.

After establishing various factors causing thermocline variability the acoustic propagation aspects are studied. A range-dependent parabolic equation model is used to simulate the propagation conditions. Case studies for internal waves, eddy and typical thermocline structures identified at different locations are made to highlight their role on sound transmission.

The major findings and their importance are summarised in the last chapter of the thesis.

CHAPTER II

THERMOCLINE CLIMATOLOGY OF THE ARABIAN SEA

2.1 INTRODUCTION

Studies on thermohaline variability of the Arabian Sea received considerable momentum after the International Indian Ocean Expedition (IIOE). Based on these data sets, watermass structure in the Arabian Sea was analysed by Rochford (1964), Gallaghar (1966), Darbyshire (1967), Wyrtki (1971), Sastry and D'Souza (1971,72) and Sharma (1976). However, most of the studies on thermal structure were limited to either selected locations or seasons (Colon,1964; Warren et al.,1966; Taft and Knauss,1967; Banse,1968; Saha,1974). Colborn (1975) made a climatological study of the Indian Ocean thermal structure utilising all available data till then. The data sets collected during other observational programs, particularly MONSOON-77, INDEX-79 and MONEX-79 have considerably improved our understanding of the thermal structure variability on synoptic time scales. These experiments were also confined to certain locations in the Arabian Sea during pre-monsoon or monsoon seasons (Quadfasel and Schott,1982; Swallow et al.,1983; Schott,1983; Rao et al.,1990).

Climatological studies of thermocline variability in the Arabian Sea have not received much attention till recently. In most of the earlier studies importance is given to address the variability of surface mixed layer characteristics (Molinary,1986(a,b); Rao et al.,1989; McCreary and Kundu,1989). More recently, Brock et al.,(1991)

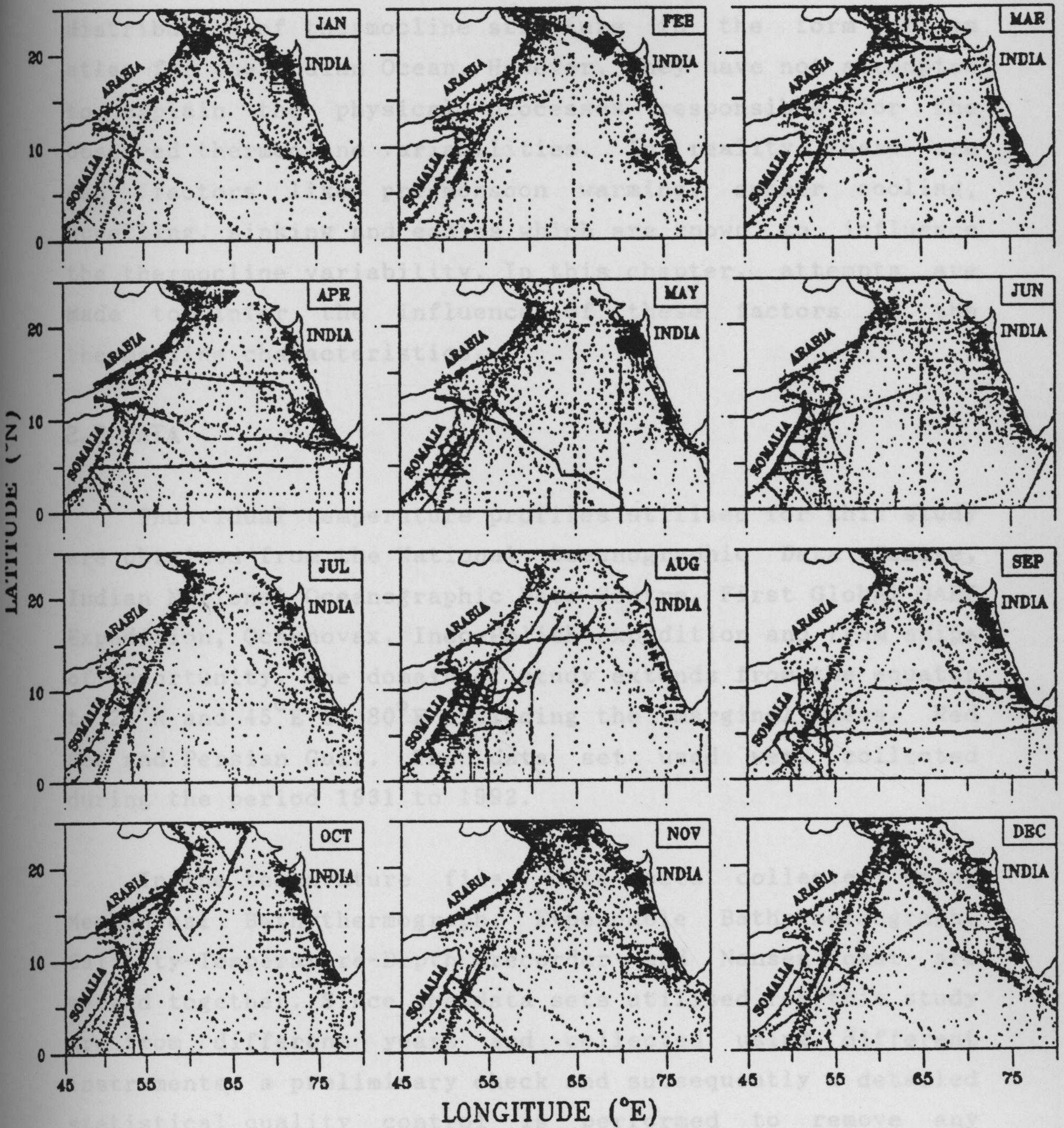

Fig. 2.1 Distribution of temperature data (dots corresponding to vertical profiles)

made a detailed study on watermass structure off the Arabia coast in the upper 500m during summer monsoon. In a recent work, Hastenrath and Greischar (1989) presented the climatic distribution of thermocline structure in the form of an atlas for the Indian Ocean. However, they have not attempted to explain the physical processes responsible for the observed thermocline variabilities. In reality there are many factors like pre-monsoon warming, summer cooling, upwelling, sinking and eddies which are known to influence the thermocline variability. In this chapter, attempts are made to infer the influence of these factors on the thermocline characteristics.

2.2 DATA

Individual temperature profiles utilised for this study are obtained from the National Oceanographic Data Centre, Indian National Oceanographic Data Centre, First Global GARP Expedition, Oceanovax, Indo-Polish expedition and from ships of opportunity. The domain of study extends from the equator to 25°N and 45°E to 80°E excluding the marginal seas, Red Sea and Persian Gulf. The data set used were collected during the period 1931 to 1992.

In the temperature file, data sets collected using Mechanical Bathythermograph, Expendable Bathythermograph, Salinity-Temperature-Depth recorder and Nansen cast are merged together. Since the data sets utilised for this study are from different years and collected using different instruments, a preliminary check and subsequently a detailed statistical quality control is performed to remove any spurious data. The details of the quality control procedures used are discussed below.

As a first step, locations, date, and ship codes of all stations are checked to eliminate duplicate data. Then the data which are grossly in error is eliminated by range checking. Various range criteria are used for temperature at different depth levels following Levitus (1982). Further, each temperature profile is checked for inversion. Except in selected areas like the vicinity of Red Sea and Persian Gulf, profiles having thermal inversion greater than 1°C are eliminated. Then the vertical profiles of temperature are interpolated using Lagrangian interpolation scheme to obtain values at every 10m depth. Following Levitus (1982) statistical check is performed to eliminate erroneous data for each 2°x2° grid. By this process, 7237 spurious data profiles were eliminated. After the quality control, temperature data sets contain 47,695 profiles. Station locations of these temperature profiles for each month are presented in Fig.(2.1). Finally, monthly mean profiles of temperature for each 2°x2° grids were computed.

2.3 MONTHLY THERMOCLINE CHARACTERISTICS

To study the basin scale variability of the thermocline characteristics in the Arabian Sea and the factors influencing its variability, monthly evolution of top, thickness, average temperature and gradient of the thermocline are described in the following sections.

2.3.1 TOP OF THE THERMOCLINE

Top of the thermocline is computed for each 2° X 2° grid and its monthly distribution is presented in Fig.(2.2). During December - February, the circulation pattern in the Arabian Sea is anticlockwise (KNMI,1952). This gyre causes the redistribution of thermal field resulting in sinking

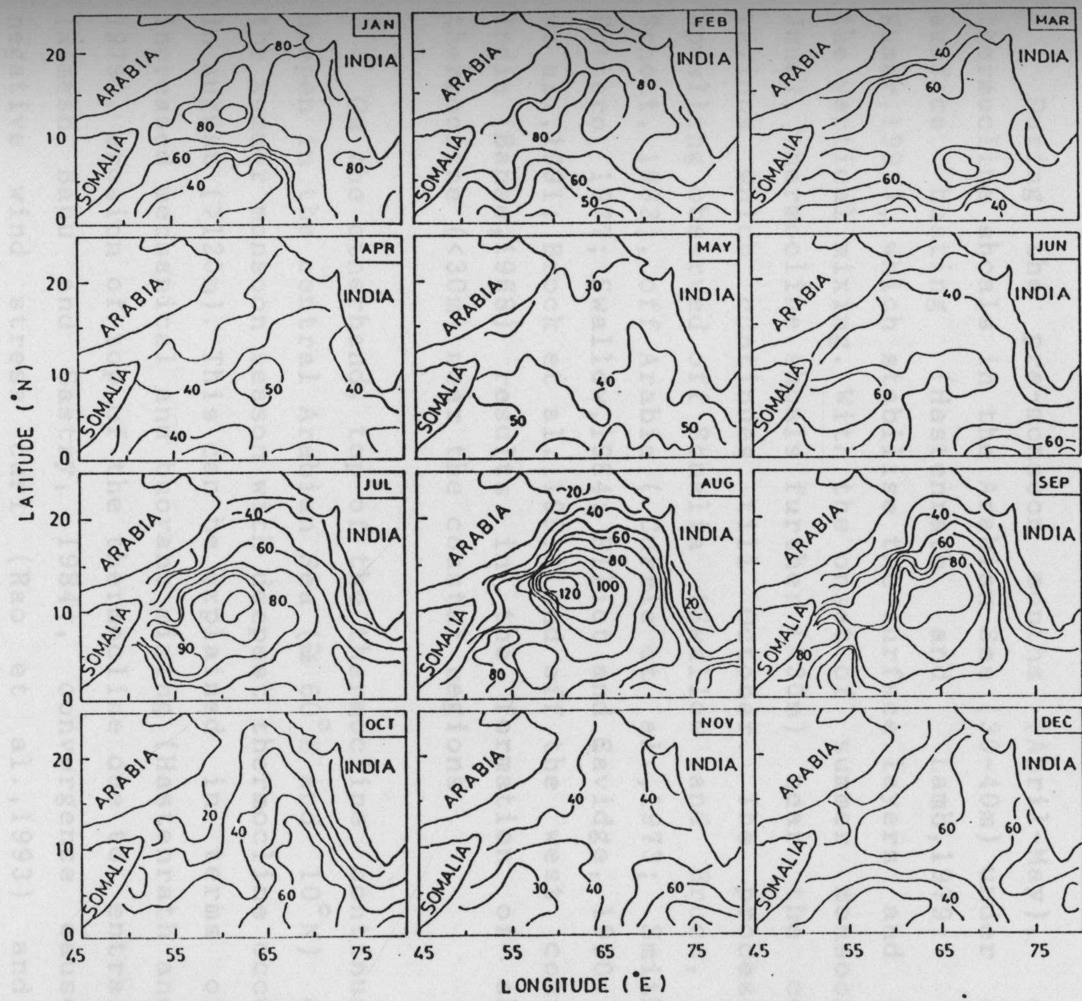

Fig. 2.2 Monthly distribution of the thermocline top (m)

(convergence) near the coastal regions and divergence in the central Arabian Sea. Hence, the thermocline is found to be deep (>70m) all along the coastal region during this period while it is shallow (<50m) near the equator. In the nothern Arabian Sea (north of 20°N) drastic net heat loss (Hastenrath and Lamb,1979), enhanced the vertical mixing and thereby deepened the thermocline to over 80m.

During the pre-monsoon months (April-May), entire thermocline shoals in the Arabian Sea (30-40m) under strong surface heating (Hastenrath and Lamb,1979; Mohan Kumar,1991), which stabilise the surface layers and reduce the vertical mixing. With the onset of summer monsoon (by June), thermocline shoals further (<30m) near the coastal regions which continues till October. The process of upwelling observed off Somalia (Swallow and Bruce, 1966; Schott, 1983), off Arabia (Currie et al.,1973; Smith and Bottero, 1977; Swallow,1984; Elliot and Savidge, 1990; Bauer et al.,1991; Brock et al.,1991) and off the west coast of India (Banse,1968) results in the formation of shallow thermocline (<30m) near the coastal regions.

On the otherhand, top of the thermocline continues to deepen in the central Arabian Sea (≅ 60°E and 10°N) during the summer monsoon season with deepest thermocline occurring in August (>120m). This can be explained in terms of the increased mechanical and buoyant mixing (Hastenrath and Lamb 1979), erosion of top of the thermocline due to entrainment (Ramesh Babu and Sastry, 1984), convergence caused by negative wind stress curl (Rao et al.,1993) and the clockwise gyre in the Arabian Sea. One of the major findings of this analysis is that strong spatial variability is noticed during July-September in the entire Arabian Sea. This suggests the importance of two physical processes, viz.

upwelling near the coasts and sinking in the central Arabian Sea in controlling the top of the thermocline. Top of the thermocline exhibits minimum variability in the entire Arabian Sea during pre-monsoon months (April-May) and post-monsoon period (November), suggesting weak dynamic processes.

2.3.2 THERMOCLINE THICKNESS

The monthly distribution of the thermocline thickness presented in Fig.(2.3) also reveals marked variations across the Arabian Sea. One of the notable findings is the occurrence of thin thermocline (< 40m) in the northern Arabian Sea (north of 20°N) throughout the year. The thin thermocline in the northern Arabian Sea is caused by a variety factors. The northern Arabian Sea is the source region of Arabian Sea High Salinity Watermass(ASHSW). This watermass at the source region has a salinity about 36.5 PSU and temperature about 30°C (Brock et al.,1992) which sinks and occupies the mid-thermocline region as it advects southward (Rochford,1964). The Persian Gulf water which enters the nothern Arabian Sea has a core depth of about 200m in the northern Arabian Sea (Fig.2.3a). This watermass has a temperature of about 27°c and salinity about 39.5 PSU at the source region (Brock et al.,1992). Between these two high saline waters, there is a relatively low salinity zone. The Persian Gulf watermass is denser than the ASHSW and hence the latter occupies a deeper (200m) depth (Fig.2.3a). Since the diffusion of temperature is much greater than that of salinity (Pond and Pickard,1983), near the core of Persian Gulf watermass the layer between these two watermasses are warmed much faster than it gains salinity. This reduces the thermocline gradient (Fig.2.3a) and hence reduction in the thickness of the thermocline.

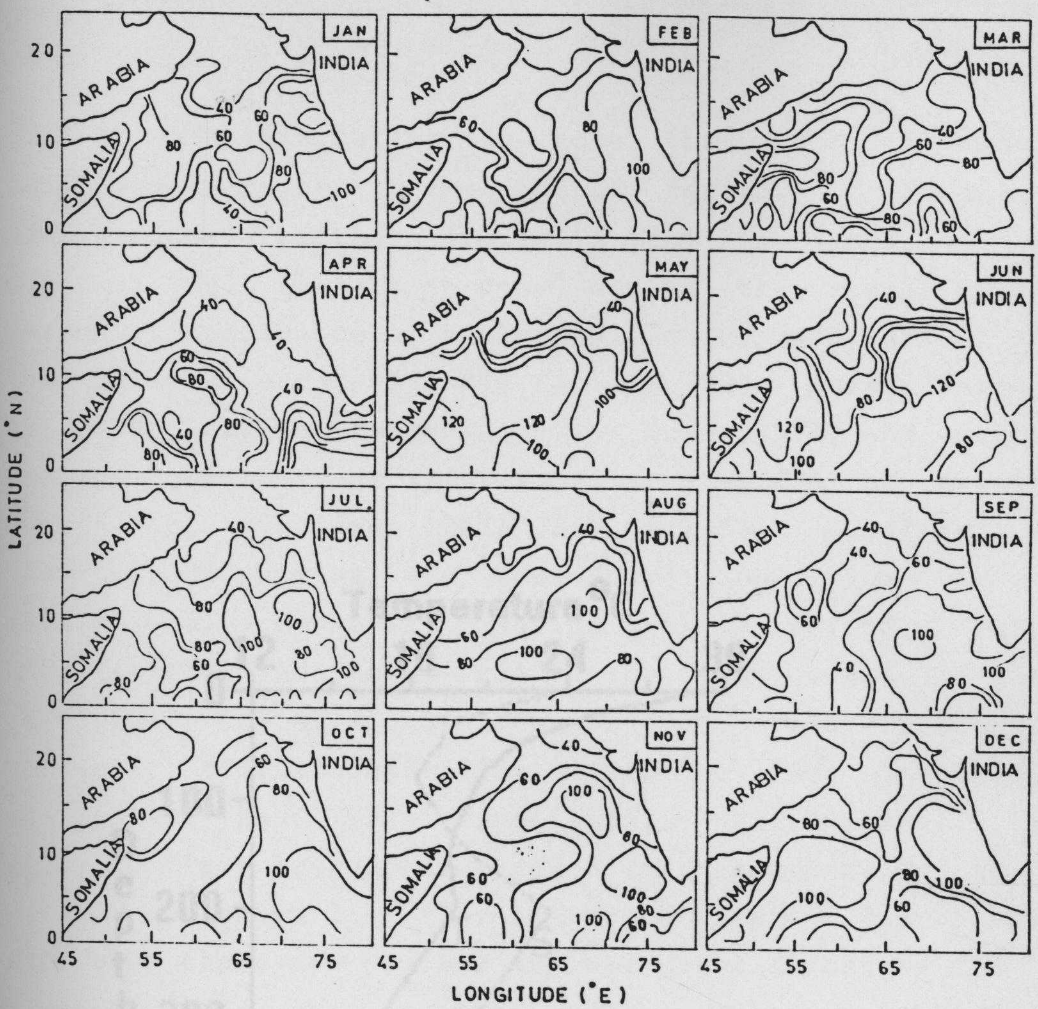

Fig. 2.3 Monthly distribution of the thermocline thickness (m)

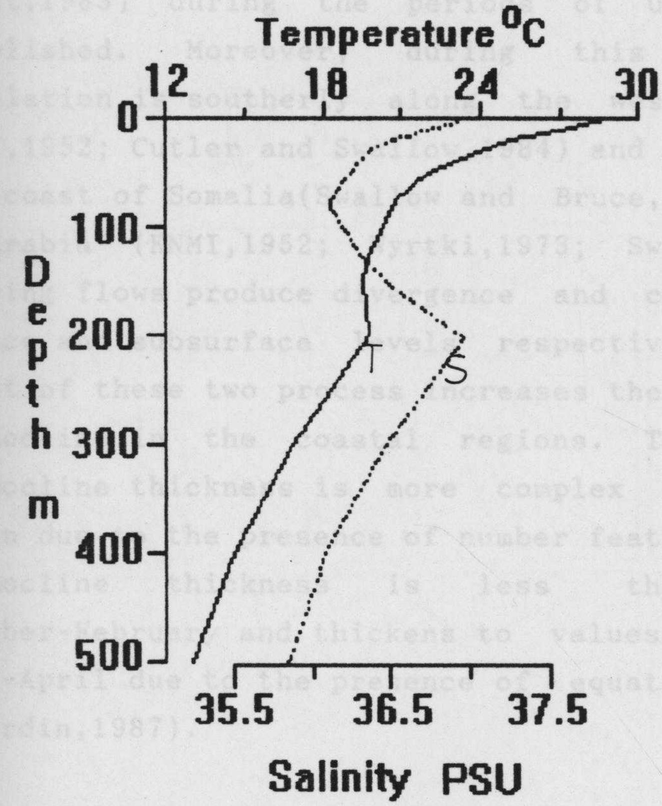

Fig.2.3a Typical temperature and salinity profile in the Northern Arabian Sea (22°22'N, 60°05'E)

Northern Arabian Sea (22°22'N, 60°05'E)

It is interesting to note that the thermocline thickness increases in the coastal regions of Somalia (≅ 120m in June), southern Arabia (≅ 100m in June) and west coast of India (≅ 120m in June) during the summer monsoon season. The presence of northward flowing undercurrent along the southwest coast of India (Antony,1990; Muralidharan et al., 1995; Hareesh Kumar and Mohan Kumar,1995) and southward flowing undercurrent off Somalia (Leetmaa et al.,1982; Schott and Quadfasel,1982; Schott,1983; Quadfasel and Schott,1983) during the periods of upwelling has been established. Moreover, during this period, surface circulation is southerly along the west coast of India (KNMI,1952; Cutler and Swallow,1984) and northerly along the east coast of Somalia(Swallow and Bruce,1966; Schott,1983) and Arabia (KNMI,1952; Wyrtki,1973; Swallow,1984). These opposing flows produce divergence and convergence in the surface and subsurface levels respectively. The combined effect of these two process increases the thickness of the thermocline in the coastal regions. The variability of thermocline thickness is more complex in the equatorial region due to the presence of number features. For instance, thermocline thickness is less than 60m during December-February and thickens to values over 80m during March-April due to the presence of equatorial undercurrent (Reverdin,1987).

2.3.3 AVERAGE TEMPERATURE IN THE THERMOCLINE

The annual variation of the average temperature in the thermocline (Fig.2.4) is found to vary between 19°C and 24°C. During the pre-monsoon months (April-May) and post-monsoon period (November), minimum variation is observed in the entire Arabian Sea (22° to 23°C and 20° to

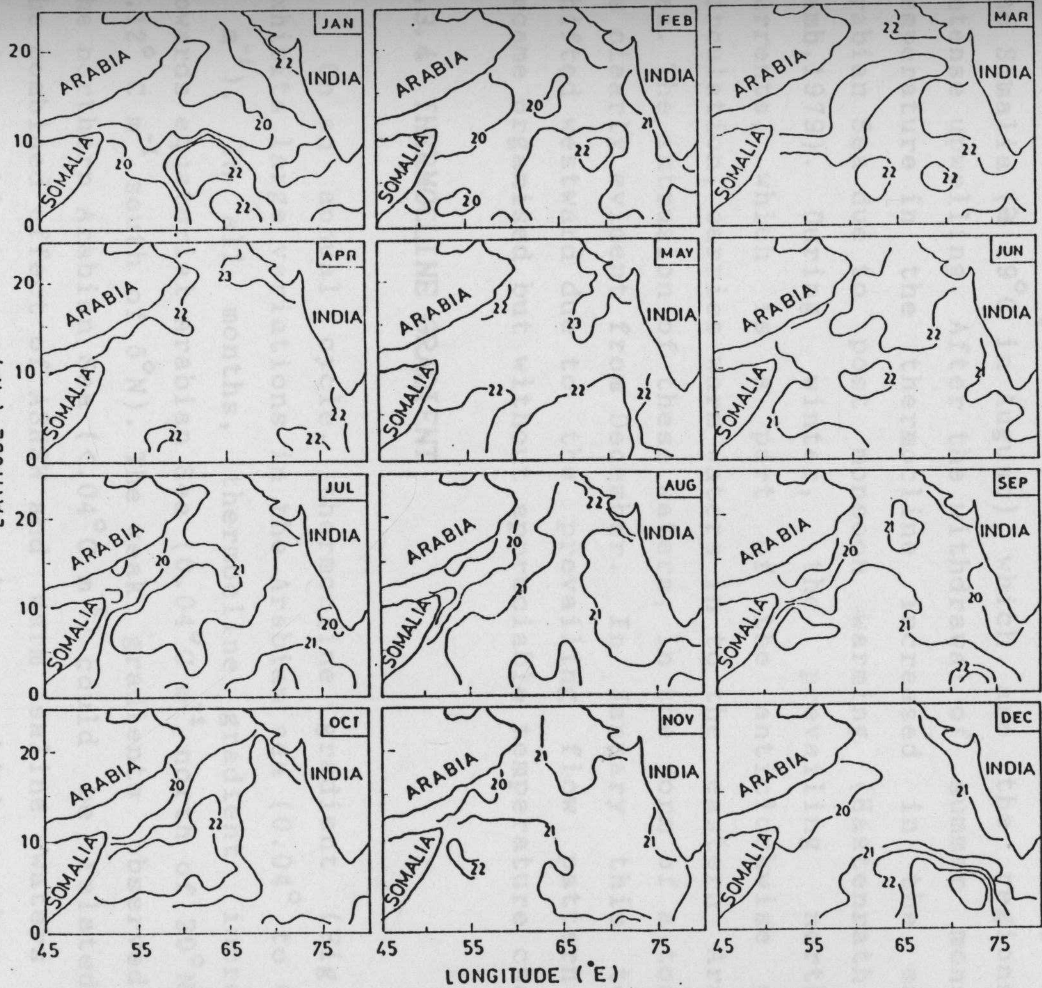

Fig. 2.4 Monthly distribution of the thermocline temperature (°C)

21°C respectively) suggesting weak dynamic processes. Comparatively large temperature during pre-monsoon season may be caused by oceanic heat gain (Hasternrath and Lamb 1979).

With the onset of summer monsoon, temperature in the entire Arabian Sea decreases. The minimum temperature is noticed in the coastal regions off the Southwest coast of India (≅ 20°C in September), Arabia (≅ 19°C in September) and Somalia (≅ 19°C in August), which are the regions of intense upwelling. After the withdrawal of summer monsoon, temperature in the thermocline increased in the entire Arabian Sea due to post monsoon warming (Hastenrath and Lamb,1979). During winter, the prevailing northerly currents, which is a part of the anticlockwise gyral circulation, carries warm waters in to the eastern Arabian Sea. The intrusion of these waters, in the form of a tongue, is clearly evident from December. In January this tongue shifted westward due to the prevailing flow pattern and became organised but without appreciable temperature change.

2.3.4 THERMOCLINE GRADIENT

On an annual cycle, thermocline gradient (Fig.2.5) exhibits large variations in the Arabian sea (0.04° to 0.14° C m^{-1}). In all months, thermocline gradient increased towards equatorial Arabian Sea (0.04°C m^{-1} north of 20°N to 0.12° C m^{-1} south of 5°N). The weak gradients observed in the northern Arabian Sea (<.04°C m^{-1}) could be related to the combined effect of ASHSW and warm saline waters from Persian Gulf into the thermocline, which makes the thermocline more diffused.Near the equator the thermocline gradients exceeds ≅0.1°C m^{-1} throughout the year. It is more during winter compared to summer off Somalia and southwest

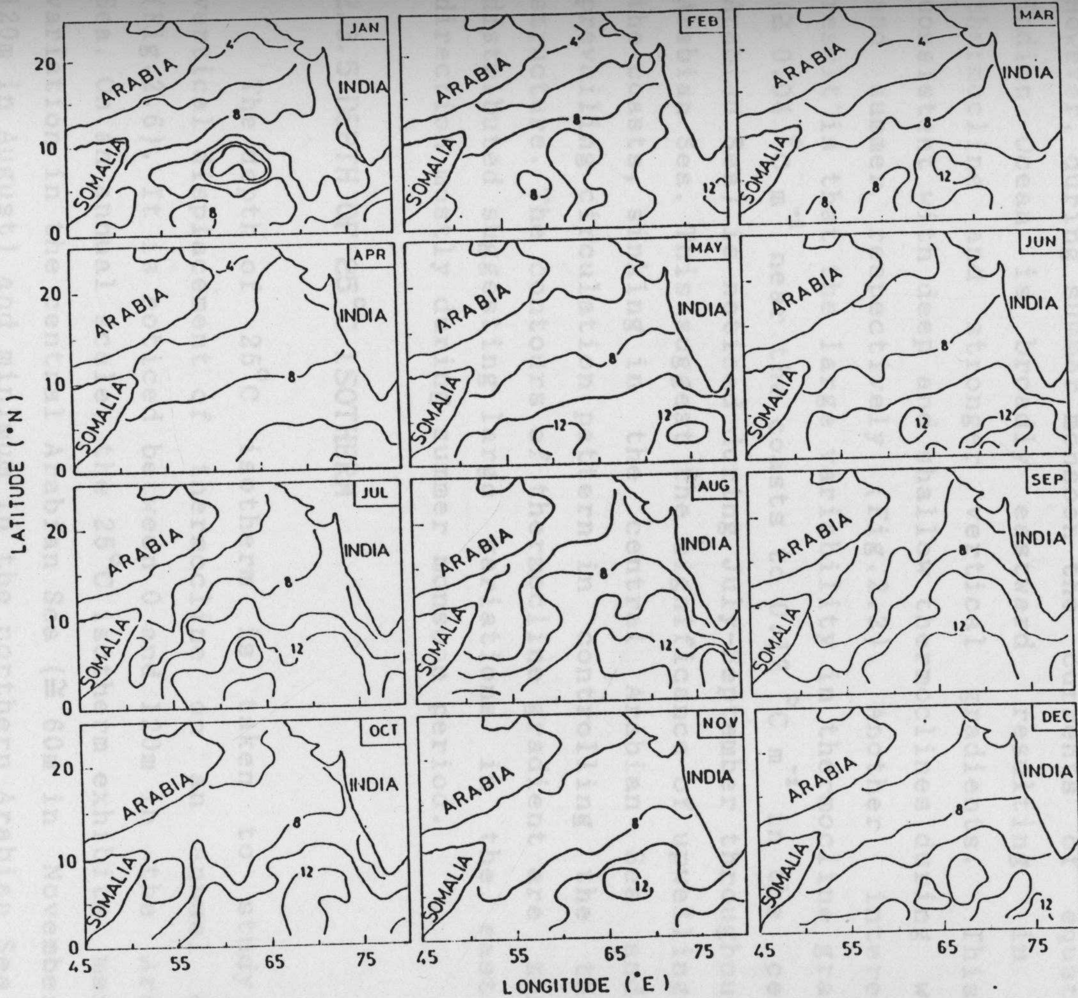

Fig. 2.5 Monthly distribution of the thermocline gradient ($\times 10^{-2}$ °C m^{-1})

coast of India. The presence of equatorial Indian Ocean / Bay of Bengal watermass over the ASHSW off the southwest coast of India is responsible for the large gradient. The relatively lower gradient in the equatorial Indian Ocean during the early part of the year (January to June) could be related to the spreading of thermocline associated with equatorial undercurrent (Montgomery and Stroup,1962). The equatorial undercurrent is found to be presented in Indian Ocean between January and June (Leetmaa and Stommel, 1980). However, during summer monsoon the currents of equatorial Indian Ocean is broadly eastward resulting in deep thermocline and stronger vertical gradients. This is consistent with deep and shallow thermoclines during winter and summer respectively (Fig.2.2). Another interesting result is that the large variability in thermocline gradient ($\cong$ 0.04 $^{\circ}C\ m^{-1}$ near the coasts to 0.12 $^{\circ}C\ m^{-1}$ in the central Arabian Sea) is noticed during July-September throughout the Arabian Sea. This suggest the significance of upwelling near the coasts, sinking in the central Arabian Sea and the prevailing circulation pattern in controlling the thermal structure. The contours of thermocline gradient are zonally distributed suggesting large variations in the east-west direction mostly during summer monsoon period.

2.3.5 DEPTH OF 25°C ISOTHERM

The depth of 25°C isotherm is taken to study the vertical displacement of thermocline on an annual cycle (Fig.2.6). It is noticed between 0 and 120m in the Arabian Sea. On an annual scale, the 25°C isotherm exhibits maximum variation in the central Arabian Sea ($\cong$ 60m in November to 120m in August) and minimum in the northern Arabian Sea (20m in March to 50m in December). The occurrence of this isotherm at shallower depths (0m) in the northern Arabian

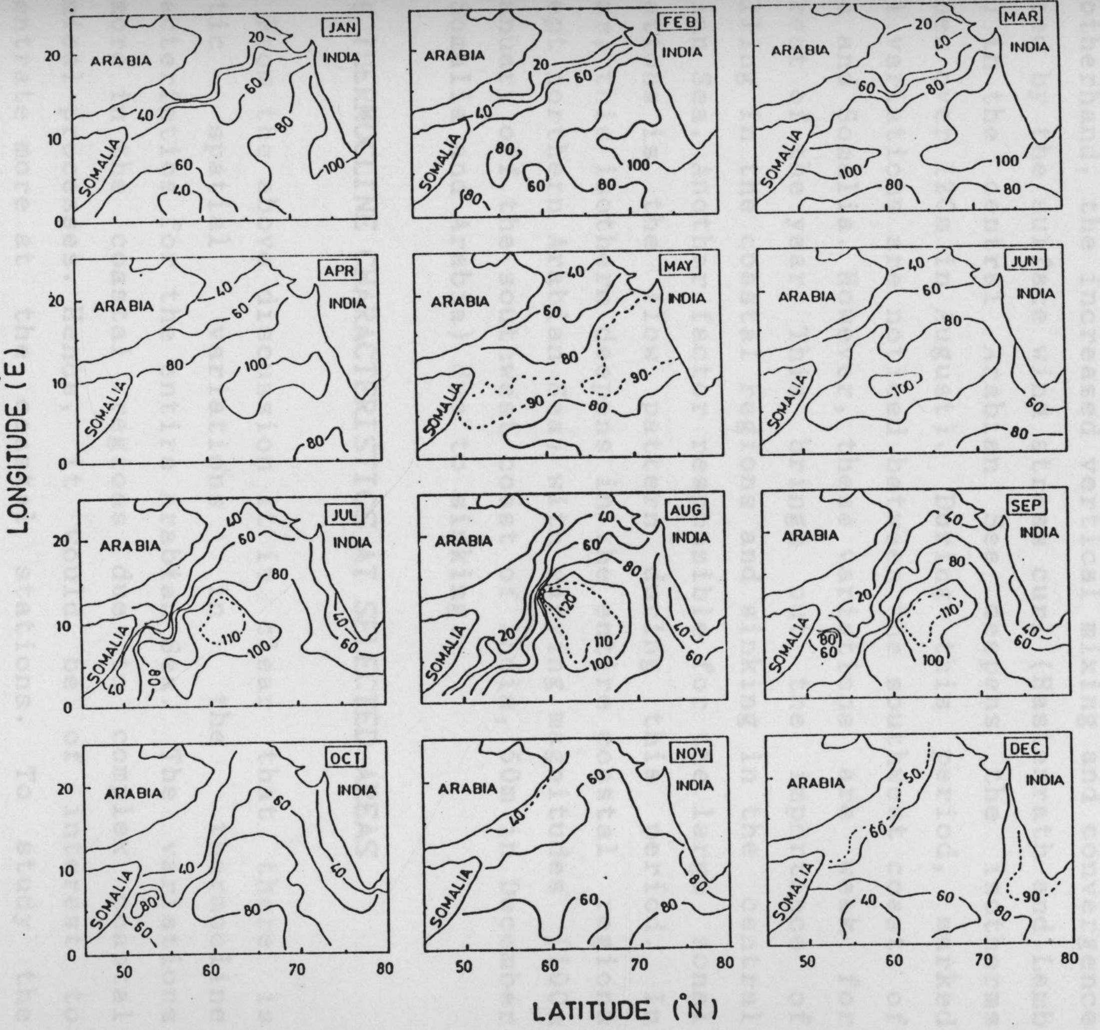

Fig. 2.6 Monthly distribution of depth of 25°C isotherm (m)

Sea (north of 20°N) is due to increased net heat loss (Hastenrath and Lamb,1979) which cools the upper layers of the water column. Just before the onset of monsoon (May) this isotherm is found between 40 and 90m. With the onset of summer monsoon, when there is intense upwelling in the coastal regions, it shoaled (< 40m in July off Cochin, < 20m in August off Arabia and < 20m in August off Somalia). On the otherhand, the increased vertical mixing and convergence induced by the surface wind stress curl (Hastenrath and Lamb 1979) in the central Arabian Sea deepens the isotherms (values over 120m in August). During this period, marked zonal variations are noticed between the southwest coast of India and Somalia. However, these variations are weak for the rest of the year. This brings out the importance of upwelling in the coastal regions and sinking in the central Arabian Sea. Another factor responsible for the large zonal variations is the flow pattern during this period. In winter, this isotherm deepens in the entire coastal regions (except northern Arabian Sea) with varying magnitudes (100m in January off the southwest coast of India, 50m in December off Somalia and Arabia) due to sinking.

2.3.6 THERMOCLINE CHARACTERISTICS AT SELECTED AREAS

From the above discussion it is clear that there is drastic spatial variations in the thermocline characteristics for the entire Arabian Sea. The variations are more in the coastal regions due to complex coastal dynamical processes. Hence, it would be of interest to concentrate more at the coastal stations. To study the thermocline behavior in the coastal and deep stations, typical areas were selected in the coastal belt and open ocean (Fig.2.7). The areas selected are: Area I (Cochin), Area II (Bombay), Area III (Karachi), Area IV (Arabia), Area

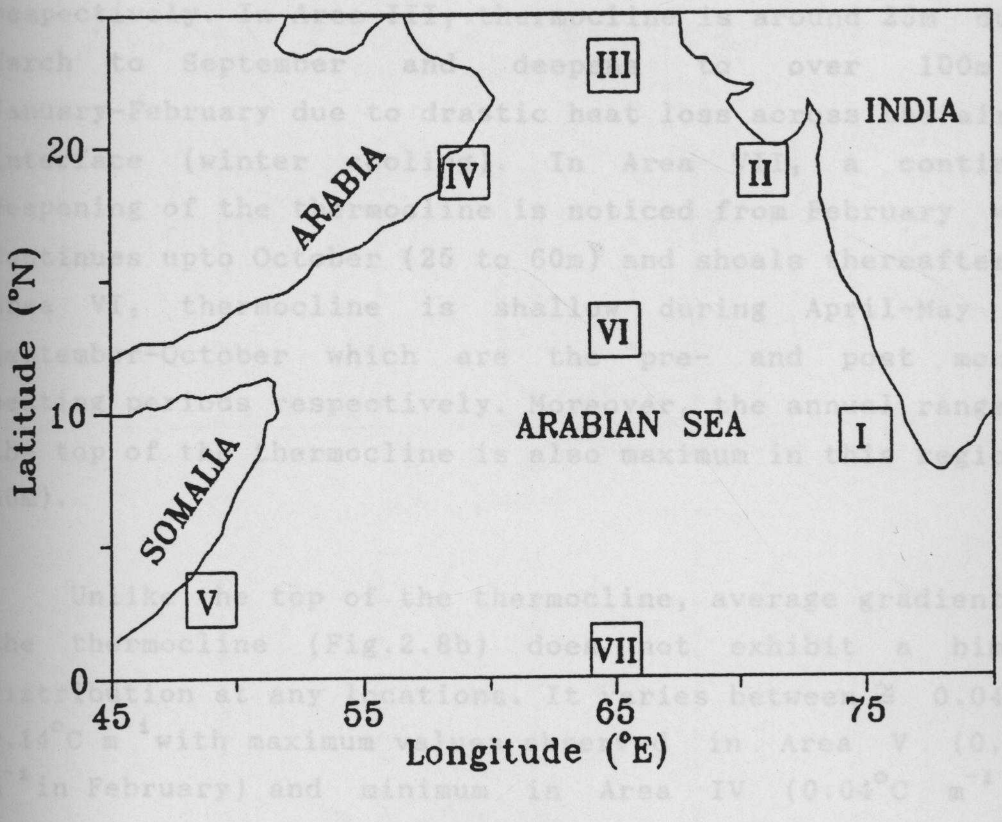

Fig. 2.7 Typical areas selected in deep and coastal waters

V (Somalia), Area VI (Central Arabian Sea) and Area VII (equatorial Arabian Sea).

The top of the thermocline (Fig.2.8a) exhibits a bi-modal distribution with a varying magnitude at all locations except in Areas III and VII. The thermocline is deepest (≅ 100m) in Areas II and III during January-February mainly due to winter cooling and sinking. On the otherhand, in Area VI the maximum depth is noticed during the summer monsoon season (>100m in August). Increased vertical mixing processes and convergence induced by the surface wind stress curl (Hastenrath and Lamb,1979) are the prime mechanisms responsible for the deeper thermocline in this region. In Areas I and IV, shallower thermocline is noticed during April-May (25m) and August-September (15m), which are the periods of pre-monsoon heating and coastal upwelling respectively. In Area III, thermocline is around 25m during March to September and deepens to over 100m in January-February due to drastic heat loss across the air-sea interface (winter cooling). In Area VII, a continuous deepening of the thermocline is noticed from February which continues upto October (25 to 60m) and shoals thereafter. In Area VI, thermocline is shallow during April-May and September-October which are the pre- and post monsoon heating periods respectively. Moreover, the annual range of the top of the thermocline is also maximum in this region (≅ 80m).

Unlike the top of the thermocline, average gradient in the thermocline (Fig.2.8b) does not exhibit a bimodal distribution at any locations. It varies between ≅ 0.04 to $0.14^{\circ}C\ m^{-1}$ with maximum values observed in Area V ($0.14^{\circ}C\ m^{-1}$ in February) and minimum in Area IV ($0.04^{\circ}C\ m^{-1}$ in August). In Areas III and IV, the thermocline gradient is

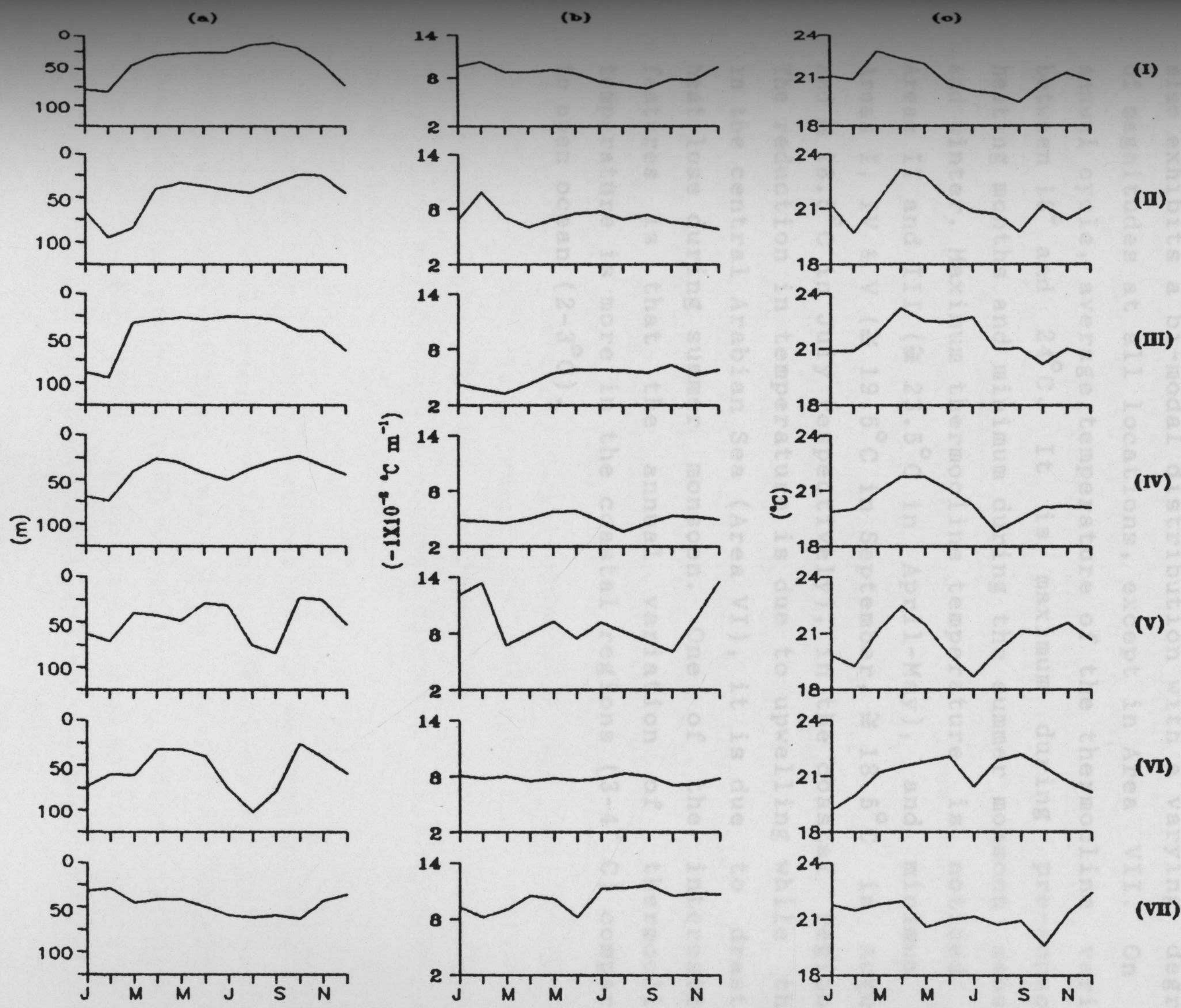

Fig. 2.8 Monthly distribution of (a) thermocline top (b) thermocline thickness (c) thermocline temperature at the selected locations.

weak (<0.05°C m^{-1}) during most part of the year. In the Area VI, the average gradient remains the same ≅ 0.08°C m^{-1} throughout the year. The maximum gradient fluctuation is observed in the Area V (0.08°C m^{-1}) while minimum variations are observed in Areas VI (<0.01°C m^{-1}), III (0.03°C m^{-1}), IV (0.02°C m^{-1}) and VI (<0.01°C m^{-1}).

The average temperature of the thermocline (Fig.2.8c) also exhibits a bi-modal distribution with a varying degree of magnitudes at all locations, except in Area VII. On an annual cycle, average temperature of the thermocline varies between 18° and 24°C. It is maximum during pre-monsoon heating months and minimum during the summer monsoon season and winter. Maximum thermocline temperature is noticed in Areas II and III (≅ 23.5°C in April-May), and minimum in Areas I, IV & V (≅ 19.5°C in September, ≅ 18.5°C in August and ≅ 18.5°C in July respectively), in the coastal regions. The reduction in temperature is due to upwelling while that in the central Arabian Sea (Area VI), it is due to drastic heat loss during summer monsoon. One of the interesting features is that the annual variation of thermocline temperature is more in the coastal regions (3-4° C) compared to open ocean (2-3°C).