

**DYNAMICS OF LARGE SCALE 3-DIMENSIONAL  
CIRCULATION OF THE INDIAN OCEAN**

Thesis submitted to  
**Goa University**  
for the Degree of

*Doctor of Philosophy*  
*in*  
*Marine Sciences*

by

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**June 2005**

**To my parents .....**

## STATEMENT

As required under the University ordinance 0.19.8.(vi), I state that this thesis entitled *Dynamics of large scale 3-dimensional circulation of the Indian Ocean* is my original contribution and it has not been submitted on any previous occasion.

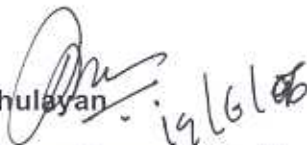
The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

  
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June 2005

## CERTIFICATE

This is to certify that the thesis entitled **Dynamics of large scale 3-dimensional circulation of the Indian Ocean** being submitted by (Ms). Swapna P for the award of the degree of Doctor of Philosophy, is a record of the original bona fide research work carried out by her. She has worked under my guidance and supervision and has fulfilled the requirements for the submission of the thesis. The results presented in this thesis have not been submitted in part or full to any other university or institute for the award of any degree, diploma, associateship, fellowship or other similar titles.

  
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## **Abstract**

The Indian Ocean possesses some unique characteristics because of the peculiar geological and geographical settings. Unlike the Atlantic and Pacific Oceans, the Indian Ocean is bounded by the Asiatic continents to the north and does not extend to the cold climatic regions of the northern hemisphere. Such a geographical situation causes asymmetry in its structure and circulation. The land masses of Asia also have profound influence on the meteorology and oceanography of this region. The land-ocean contrast generates seasonally, reversing winds, the monsoons, over the northern Indian Ocean, which in turn, reverse the oceanic circulation over its northern part. Another outgrowth of the geographical and climatological settings is the formation of high salinity waters in the Arabian Sea, Red Sea and Persian Gulf. The Indian Ocean has no polar or subpolar northern region, resulting in a net southward heat export across the equator.

The 3-d circulation of the Indian Ocean is very complex and is controlled by both local and remote forcing because of the peculiar geographical and climatic settings of Indian Ocean. The most important local forcing that control the circulation are the surface wind, the internal density field and the processes of advection and diffusion. Strong and variable winds force the ocean locally and they excite large scale waves such as Rossby and Kelvin waves which travel long distances to affect the ocean remotely. The circulation is also affected by forcing that occurred elsewhere during the previous season or months. Identification of these forcing functions that control the variability of circulation at different time and space scales and simulation of circulation should be the main objective of any modeling study. Purely observational studies cannot obtain information on the variability of circulation on such larger space and time scales. To determine the physical and dynamical mechanisms underlying the variability of circulation in the Indian Ocean, ocean circulation models such

as diagnostic, semi-diagnostic and prognostic models are the best for the study of circulation in the Indian Ocean.

There have been many studies, both observational and modeling, on the circulation and water mass characteristics in the tropical Indian Ocean. All these studies were focused on the theoretical or modeling aspects of a peculiar current or on a peculiar basin of the Indian Ocean such as Arabian Sea and or Bay of Bengal. Practically all the modeling studies were concentrated on the application of reduced gravity models of varying complexity or prognostic models based on idealized forcing functions. The existing numerical models of Indian Ocean also do not incorporate all site specific forcing functions such as fresh water fluxes and river discharge into the coastal area. It is, therefore necessary to develop 3-dimensional models of circulation that span the entire area of Indian Ocean. The system of currents in the Indian Ocean are interdependent, and the analysis and interpretation of currents in the Indian Ocean area should be carried out in an integrated manner to identify correctly the forcing functions that control the large scale circulation in the Indian Ocean.

One of the main objective of this thesis is to adapt and configure a fully non-linear, primitive equation type, sigma co-ordinate 3-dimensional circulation model for the entire Indian Ocean area which can be run on diagnostic, semi-diagnostic and prognostic modes. Such a model could identify both the local and remote forcing of the Indian Ocean circulation. The other objectives of the thesis are the following:

- (i) To study the steady state 3-dimensional circulation of Indian Ocean based on semi-diagnostic calculation
- (ii) To simulate the climatic 3-dimensional circulation of Indian Ocean using the state of art sigma co-ordinate model.



- (iii) To study the sensitivity of Indian Ocean circulation to different wind fields
  
- (iv) To compare the model results with available information on currents and hydrography of Indian Ocean and to bring out the relative roles of local and remote forcing on the general circulation of Indian Ocean.

A brief outline of the thesis is as follows: Besides this introductory chapter, the thesis contains five other chapters. In Chapter-II, the formulation of numerical models and its forcing parameters are described. The main objective of this chapter is to adapt and configure a 33-level state of art sigma co-ordinate ocean model that can be run on diagnostic, semi-diagnostic and prognostic modes for the Indian Ocean area to study the dynamics of large scale circulation of the tropical Indian Ocean. The numerical models used in the present thesis has been originally developed by Alexeev and Zalesny (1993) at the Institute of Numerical Mathematics, Russian Academy of Sciences, Moscow, and the same has been subsequently modified by Zalesny and Galkin (1996) and Bagno et al. (1996a, 1996b). The governing equations of the ocean general circulation model are the primitive equations of motions in spherical co-ordinates, with hydrostatic, Boussinesq and rigid lid approximations. The details of the model equations in z co-ordinate, its boundary and initial conditions are given both in z co-ordinate system and the sigma co-ordinate system.

Chapter-III addresses the problem of understanding the relative roles of steady local forcings of wind and internal density field in driving the circulation of the Indian Ocean using a semi-diagnostic model. Sarkisyan and Demin (1983), for the first time, developed a new technique called semi-diagnostic technique, to calculate the steady state 3-dimensional circulation. The numerical solution procedure of the semi-diagnostic models is described in this chapter. Accordingly, the primitive equation type, sigma co-ordinate, 3-dimensional model, developed at the Institute of

Numerical Mathematics, Russia, has been adapted and configured to the Indian Ocean area between the latitudes  $36^{\circ}$  S to  $29.5^{\circ}$  N and longitudes  $22^{\circ}$  E to  $142^{\circ}$  E. The model was forced with NCEP/NC AR wind field at the surface and Levitus temperature-salinity (Levitus, 1994) at various levels. The computed mean currents of the Indian Ocean at selected depths (upto 300 m) for the months of January, April, July and October, representing the four seasons of the year are presented in this chapter. The spatial variability of mean currents in the upper layers of the Arabian Sea, Bay of Bengal, equatorial and subtropical Indian Ocean were presented under separate headings. The semi-diagnostic model has been successful in reproducing all the permanent current systems in the Indian Ocean including the undercurrents over the entire annual cycle.

The time dependant evolution of circulation at various levels in the Indian Ocean and its underlying mechanisms are poorly understood. Better understanding of the dynamics can be achieved only by using the state of art simulation models. The unsteady time-varying circulation is controlled by both the local forcing and the remote forcing by long waves. The main goal of chapter-IV is to adapt and configure a state of art simulation model of circulation to the Indian Ocean area to study the large scale 3-dimensional circulation and to understand the dynamical mechanisms which are responsible for the observed circulation.

The governing equations of the state of art ocean general circulation model are the primitive equations of motion in spherical sigma co-ordinate with hydrostatic, Boussinesq and rigid lid approximations. The entire system of equations except the equation for the integral stream function were solved by the method of splitting. The stream function equation was solved by the method of successive approximation. The NCEP data on wind stress, heat and fresh water fluxes were used to drive the model.

The state of art simulation model results were compared with results from Simple Ocean Data Assimilation Model (SODA) to validate the model. The

circulation obtained from the simulation model are of agreement with the SODA results and also with available observations. All the current systems in the Indian Ocean were well reproduced by the model including the undercurrents and gyres. The volume transport for major currents were computed and compared with transport estimates available in the literature. The volume transport was also found to be comparable with the existing estimates for different currents. The dynamics of each of the current system were explained by comparing the state of art simulation model results with semi-diagnostic (adaptation) model results.

Results of ocean circulation models vary depending on its dynamics, spatial resolution, numerical scheme, the parameterization of the physical processes and the surface forcing parameters of which the later, the surface forcing parameters, have the most significant effects on model results. But changing the forcing parameters and coefficients, a good insight into the dynamics of circulation can be obtained. Winds derived from numerical models of atmospheric circulation are not very reliable for the near equatorial regions because of the breakdown of the assumption of geostrophy in those large scale models. Actual observed winds through remote sensing technique would give more reliable information on the windstress field at the equatorial and near equatorial regions. In this chapter, one sensitivity experiment is carried out with the wind field derived from Quikscat scatterometer. The response of the tropical Indian Ocean to NCEP reanalysis winds and the scatterometer winds is presented. The monthly mean response of the model to two wind datasets were compared for mass transport stream function, surface velocities and the surface temperature for the month of January, July, April and October representing the four seasons.

The model driven with scatterometer wind reproduced the circulation features in the equatorial Indian Ocean more realistically than the NCEP forcing. The current systems in equatorial regions were intensified by

25 cm/sec during April and October when the model was driven with Quikscat wind forcing. It has been observed that the simulation model response to the Quikscat winds is dynamically and thermodynamically consistent with the differences in the mean wind field. The sensitivity experiment revealed that the surface circulation was mainly controlled by the wind stress forcing and the thermodynamic forcing played a minor role at the upper levels.

Chapter-VI is devoted to the general conclusions on the entire thesis.

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### **1.1 Introduction**

The Indian Ocean is the smallest and the least explored ocean of the world. It occupies approximately 20% of the world ocean ( $73.6 \times 10^6$  sq. Km). The Indian Ocean is bounded to the north by Iran, Pakistan, India and Bangladesh; to the west by Africa and Arabia; to the east by Australia, the Sunda Islands of Indonesia and Malayan Peninsula, Myanmar (Burma) and Thailand; to the south by the Antarctic continent. The Indian Ocean connects to the Atlantic Ocean near the southern tip of South Africa; it connects to the Pacific Ocean through the straits and marginal seas, such as Sunda straits, the Timor and Java Seas and the Great Australian Bight. The Indian subcontinent divides the northern Indian Ocean into two smaller basins, the Arabian Sea to the west and the Bay of Bengal to the east. Two Mediterranean seas, the Persian Gulf and Red Sea, join the Arabian Sea. The chain of Andaman and Nicobar islands separate the Andaman Sea from the Bay of Bengal. A hydro-chemical front located along  $10^{\circ}\text{S}$  (Wyrtki, 1973b) is generally taken as the boundary between the south and north Indian Oceans. Wind reversals due to the monsoons are seen primarily to the north of this latitude.

The Indian Ocean possesses some unique characteristics because of its peculiar geological and geographical settings. Unlike the Atlantic and Pacific Oceans, the Indian Ocean is bounded by the Asian continent to the north and does not extend to the cold climate regions of the northern hemisphere. Such a geographical situation causes asymmetry in its structure and circulation. The land mass of Asia also have profound influences on the oceanography and meteorology of this region. The land-ocean contrast forces seasonally reversing winds, the monsoons, over the northern Indian Ocean, which in turn reverse the oceanic circulation over its northern part. The monsoon winds blow south westerly during the summer season and northeasterly during the winter season. Associated

with the seasonally changing circulation are the various upwelling areas, which operate only during one season, in contrast to all other major upwelling areas in the world. Because the monsoon winds are asymmetrical about the equator, the current systems in the Indian Ocean are not symmetrical about the equator. The asymmetrical wind distribution generates convergence in the equatorial Indian Ocean. In other world oceans, divergence is observed near the equatorial regions. Another outgrowth of the geographical and climatological settings is the formation of high salinity waters in the Arabian Sea, Red Sea and Persian Gulf. These water masses form a high salinity layer in the Arabian Sea and effect the circulation in the intermediate depth drastically by preventing water of the southern hemisphere from penetrating into the northern Indian Ocean. Another outgrowth of the peculiar geographical and climatological settings is the equatorward heat flux in the north Indian Ocean. The Indian Ocean has no polar or subpolar northern region, resulting in a net southward heat export across the equator.

Geologically, the Indian Ocean is unique among the other oceans of the world with the presence of several submarine plateaus, aseismic ridges and hotspots. Recent studies have revealed that the Indian Ocean floor is characterized by seismically active mid-ocean ridge system which marks the major boundaries separating the major plates. The northern branch of this ridge system includes east-west trending Sheba Ridge, the northwest – southeast trending Carlsberg Ridge between the Owen Fracture zone and the equator. The N-S trending central Indian Indian Ridge (CIR) connects the southern end of the Carlsberg Ridge near the equator to the Rodrigues Triple Junction (RTJ). At the RTJ, the central Indian Ridge joins the other two branches, ie, the southwest Indian Ridge (SWIR) and the Southeast Indian Ridge (SEIR). Apart from active mid-ocean ridge system, the Indian Ocean floor is also characterized by the large shallow areas scattered all over the ocean variously termed, according to their overall morphology as banks, plateaus, aseismic ridges, seamount chain

and rises. Many of these features trend in a northsouth direction, and together with the active ridges and surrounding continents, the Indian Ocean is divided into a number of ocean basins. One of the outgrowths of these peculiar geological features is that the Indian Ocean has deep northward western boundary current.

## **1.2 Main features of Indian Ocean circulation**

The surface circulation in the Indian Ocean is controlled by monsoons in the tropics upto 10°S latitude and the southern hemisphere subtropical gyre at latitudes farther south. The surface circulation system north of about 10°S undergoes drastic seasonal changes under the influence of the seasonally reversing wind system. During the winter monsoon season, northeast trade winds brings cool, dry continental air, while during the summer monsoon season, the strong southwest wind brings humid maritime air into the northern Indian Ocean. In response to these wind systems, the surface circulation undergoes seasonal changes. (Cutler and Swallow , 1984; Hastenrath, 1989; Hastenrath and Griescher, 1991; Wyrki, 1971). The seasonal changes of the winds south of 10°S are smaller than to the north, and therefore, the variability of the ocean circulation in the southern part of the Indian Ocean is also smaller.

### **Surface circulation during the northeast monsoon season (December-March)**

The seasonal reversals of the surface wind field over the tropical Indian Ocean are more dramatic than in the other regions of low latitudes, and these reversals have profound effects on the upper hydrospheric structure and seasonal variations of surface current system (Hastenrath and Grieschar, 1991). The northeast monsoon starts in December and reaches its maximum strength during January-March. The wind direction is from northeast north of the equator, northerly at the equator and northwesterly to the south of it. In response to the prevailing winds, the

surface circulation over the tropical Indian Ocean undergoes substantial changes. The surface wind field provides the major mechanical forcing for the basin wide upper ocean circulation.

The current patterns in the tropical Indian Ocean during winter can be characterized as two counter rotating gyres extending across the entire basin. The southern gyre rotates clockwise and is bounded on the south by the South Equatorial current (SEC) and on the north by the Equatorial Counter Current (ECC). The axis of this gyre appear at about 10°S across the basin. The SEC extends from 20°S to 10°S, while the ECC is observed between 10°S and equator. The north Equatorial Current (NEC) represents the northern boundary of the counter clockwise rotating northern gyre. This gyre is bounded on the south by the ECC. The axis of this gyre is located approximately on the equator. Both gyres are closed on the west by the boundary currents along the African coast, namely, the East African Coastal Current (EACC) and the Somali Current (SC). The SEC feeds the EACC, which separate from the boundaries south of the equator. The SC is fed by the retroflexion of NEC at the coast and exhibited continuous southward flow along the boundary from about 8°N to 3°S. As a further extension of SEC, there are two southward flowing boundary currents, namely, the Mozambique Current (MZC) and the East Madagascar Current (EMC), (Swallow et al., 1988; Schott et al., 1988). In the northern Arabian Sea, the circulation is not well defined during this season. One branch of NEC circulates around the islands of Laccadives and flows along the west coast of India as West India Coastal Current (WICC). A prominent feature of circulation in the Bay of Bengal is the East India Coastal Current (EICC), which reverses direction twice a year (Shetye et al., 1993). Signatures of northward EICC first appear during February. By March, the current is seen along the entire east coast; ship drift data suggest that the EICC is part of an anticyclonic gyre, which is present in the bay during February-May and is best developed during March-April.



### **Surface circulation during pre-monsoon season (April-May)**

In April-May, during the transition period between northeast and southwest monsoon seasons, the winds north of the equator get weakened and moderate eastward winds blow along the equator. An anticyclonic wind gyre is found over the Bay of Bengal, broadly overlying the anticyclonic ocean gyre.

The most dramatic circulation feature in the spring season is the development of intense eastward Equatorial Jet (EJ) driven by the semiannual eastward winds. The EJ's occur in a narrow band, trapped within 2°-3° of equator, mostly in the central and eastern parts with a speed of nearly 1.5m/sec during May. At the western boundary of the Indian Ocean, the Somali Current flows southwestward and meets northward flowing EACC near the equator. In early May, the Somali Current responds rapidly to the onset of local southwesterly winds, reverses its direction and flows northward as continuation of EACC near the equator. There are hardly any changes in the current pattern in the southern tropical Indian Ocean.

### **Surface circulation during the southwest monsoon season (June – September)**

During the southwest monsoon season (June- September), the southeast trades of the southern hemisphere crosses the equator, change direction and sweeps as southwesterlies over the entire north Indian Ocean. The surface circulation south of the monsoon regime, ie, 10°S does not show much seasonal variability. The SEC and EACC feed the northward flowing Somali Current. The Somali Current crosses the equator, and a part turns offshore at about 4°N, flows southward and recirculates across the equator as the Southern Gyre (SG). With the onset of strong

southwest monsoon winds in June a strong anticyclonic gyre, called the 'Great Whirl' develops in the north between 4°N and 10°N. A third Gyre, the 'Socotra Eddy' is also observed in many summer monsoons northeast of Socotra. In August-September, the southern cold wedge propagates northward along the coast and meets with the northern one and the Somali Current appears as a continuous current from the equator up to 10°N.

In the Arabian Sea, the Somali Current feeds the eastward flowing low latitude monsoon current known as the Southwest Monsoon Current (SMC). The equatorward flowing WICC joins SMC and much of the SMC turns northward into the Bay of Bengal, flowing around the cyclonic Sri Lanka dome as EICC. In the northern Bay of Bengal, north of 15°N, the eastward currents which are already set during April -May last until August.

### **Surface circulation during the post monsoon season (October-November)**

October-November corresponds to the second transition period between the end of southwest and the beginning of northeast monsoon. At the equator, moderate eastward winds blow in strength slightly higher than the premonsoon season and the wind vanishes north of the equator. The equatorial circulation is dominated by eastward Equatorial Jet (EJ) with in 2°-3° of the equator with strength higher than the premonsoon EJ's. The strong Somali Current observed during southwest monsoon season decreases strength and continues to flow northward. In the Bay of Bengal and Arabian Sea, anticyclonic gyre is still apparent in monthly current plots. The EACC flows northeastward along the east African coast. There are no changes in the circulation pattern in the southern tropical Indian Ocean.

### **1.2.1 Observational background**

During the past 40 years, a number of observational studies on the dynamic and thermodynamic processes of the Indian Ocean have been carried out. The 'Danish Arabia ,Felix Expedition' (1761-1767) to Arabia is considered as the first scientific survey undertaken in the Indian Ocean. But a comprehensive survey of the circulation in the Indian Ocean was carried out during the International Indian Ocean Expedition (IIOE) during 1959-1965. A large number of oceanographic expeditions were carried out by number of countries during this period, which gave information on basic physical properties including circulation and water masses of the Indian Ocean. These led to a number of publications, but most of them are concentrated on the Somali Current region.

Using IIOE data, Rochford (1964) studied the salinity distribution and discussed the variable flow patterns in the Indian Ocean. Warren et al., (1966) have discussed the characteristics of water masses and flow patterns in the Somali basins.

The first major description of the currents of the Indian Ocean appeared soon after the IIOE (Duing,1970; Wyrcki,1971,1973b). Based on the hydrographic data Wyrcki (1971) prepared an oceanographic atlas of the Indian Ocean, which is still considered to be one of the outstanding works on oceanography of the Indian Ocean. The other atlas of surface currents in the Indian ocean is based on the historical ship drift data ( KNMI, 1952, Mariano, 1995, Cutler and Swallow,1984. The monthly charts presented in the KNMI atlas are based on very limited data sets and it could not show strong currents such as Equatorial Jets in the Indian Ocean. Cutler and swallow (1984) compiled the surface currents of the Indian Ocean on 10-day averaged periods with a space resolution of 1° quadrangle of latitude and longitude. The shipdrift data collected between 1854 and 1974 have been used for the preparation of these charts. Mariano (1995) prepared surface current data using ship-drifts estimates made by merchant and

military ships. The temporal resolution of the data is monthly and horizontal resolution is 1° in longitude and latitude.

After IIOE, India and erstwhile Soviet Union conducted two Indo-Soviet Monsoon Experiments (ISMEX) in 1973 and 1977 respectively during which vast amount of meteorological and oceanographic data were collected from the northwestern Indian Ocean including the Arabian Sea. The next intensive study was the Indian Ocean Experiment (INDEX) during the first GARP Global Experiment (FGGE), which investigated the summer monsoon response of the Somali Current. Subsequently, during the International Monsoon Experiment (MONEX) in 1979, Russian Vessels along with the Indian research vessel 'Gaveshini' collected data on currents and hydrography at selected stations in the Indian Ocean.

In the following decade, only a few bilateral or individual studies were carried out in the Indian Ocean. These studies included the high-resolution 32°S sector of Toole and Warren (1993), studies of Somali current regime (Swallow et al., 1988, 1991; Schott et al., 1988, 1990) regional studies of Indian coastal currents (Shetye et al., 1990, 1991a) and the West Australian boundary circulation (Smith et al., 1991). Considerable additional data were also obtained from Expendable Bathymetry (XBT) surveys from volunteer ships, GEOSAT satellite altimetry and surface drifter studies (Molinari et al., 1990). The next intensive survey of the Indian Ocean was conducted during the World Ocean Circulation Experiment (WOCE), in 1995 – 1996. During the WOCE period, good quality data sets on hydrographic properties and various tracers were obtained. In addition, deep float and surface drifter deployments, moored arrays, repeat XBT schemes and high precision TOPEX/POSEIDON(T/P) altimetry operational since 1993, provided new insights into the variability of circulation in the Indian Ocean and its relations to forcing fields. In the northern Arabian Sea, a large observational programme with in the contexts of the Joint Global Ocean

Flux Study (JGOFS) was carried out during 1994-1996. Recently, Indian Ocean Experiment (INDOEX,1998) and Bay of Bengal Monsoon Experiment (BOBMEX,1999), Arabian Sea Monsoon Experiment (ARMEX,2002) were carried out which concentrated on oceanic as well as atmospheric parameters over the Indian Ocean.

#### **1.2.1.1 Arabian Sea Circulation**

The Arabian Sea is one of the few tropical basins that has limited northern extent and is forced by the seasonally reversing monsoon winds. These winds regulate various physical processes including the upper ocean circulation in the Arabian Sea. The most prominent and the best documented variations of upper ocean circulation can be seen off the coast of Somali.

#### **The Somali Current**

The Somali Current is the western boundary current of Indian Ocean with a volume transport comparable to that of the Gulf Stream and reverses in an annual cycle in response to the changes between the northeast and southwest monsoon seasons. It flows northeastward during the summer and southwestward in the winter. At its peak, during the southwest monsoon season, surface currents with magnitudes ranging from 3 to 4m/s have been reported, and its volume transport has been estimated to be 70 million tons per second.

The first survey of the circulation of the Somali Current was carried out by Swallow and Bruce (1966) during the IIOE period. From the hydrographic measurements of Somali Current between equator and 12°N, during the southwest monsoon of 1970, Bruce (1973) identified two upwelling areas off Somalia, each being associated with a branch of the current that turned eastward offshore. More evidence for the existence of a two-gyre circulation pattern was provided by measurements during 1975-1978 with

XBT's from tankers running from the Persian Gulf to South Africa (Bruce, 1979).

Observational studies by Bruce (1979) showed that a large eddy first formed in the Somali region approximately between 4°N and 12°N during late May or early June. Bruce called it as the 'Prime eddy' because it appears to be first formed in the region upon the commencement of the southwest monsoon. Prime eddy was considerably larger and more energetic than the other eddies formed during the season and it has been observed to remain in this location at least for 3 months after the cessation of the southwest monsoon. A smaller eddy associated with the Prime eddy was observed each years (1975-76) off Socotra between 12°N and 15°N. Also during another year (1976), a southern eddy was observed south of about 5°N and adjacent to the southern boundary of the prime eddy to the east of African coast. Observations indicate that northeastward flowing Somali Current is clearly part of the eddy field.

Brown et al., (1980) used SST data from ships and satellites to study the Somali eddy during the southwest monsoon of 1979. They observed large areas of cold waters along the Somali Coast between 5°N and 10°N during June and July. The cold waters associated with the northern and southern eddy systems could be traced several hundred kilometers off shore. By late August, the cold wedge at 5°N translated north eastward up to 10°N with a speed of 15 to 30 m/sec indicating a coalescence of the systems.

Using historical data on surface currents and SST from 1900 to 1973, Swallow and Fieux (1982) studied the circulation pattern in the Somali basin. In most of the years sampled, the Somali Current system contained two clockwise gyres, one south of 5°N, the other between 5°N and 10°N for at least part of June. They have presented evidence suggesting that the southern gyre appeared within a week or two of the onset of local south-westerly winds and that the northern gyre was well developed within

two weeks of the appearance of the strong southwesterly wind off northeastern Somalia.

Swallow et al., (1983) described the development of near surface circulation in the Somali basin during 1979 and explained its evolution in relation to wind field and to the equatorial current system. In the Somali basin during southwest monsoon, the low salinity water (salinity<35.1 ppt) from the SEC mixes with the high salinity (salinity>35.3ppt) surface waters of the Arabian Sea. Some aspects of the redistribution and modification of these water masses are described in the above paper.

During the late summer monsoon, after the collapse of the two gyre system, the Somali Current flowed as a continuous current carrying low salinity waters from south of equator to 10°N latitude. Synoptic observations made by Schott and Fieux (1985) in the Somali Current region showed that a continuous current does not exist before the onset of northeast monsoon. Instead, cross-equatorial flows with low surface salinity were joined to turn offshore south of 2°N, and between 6°N and 11°N, large anticyclonic gyre with high surface salinity were observed.

Quadfasel and Schott (1983) carried out current meter measurement near 5°N off Somali coast for a period of 2 and half years and reported the existence of permanent southward subsurface current in the depth range of 150 to 600 m with a near speed of 15 cm/sec. They have estimated the annual mean southward transport of Somali Current to be around  $5 \times 10^6$  m<sup>3</sup>/sec.

Using shipboard current profile, Leetma (1982) measured the transport in the Somali Current system during March-July 1979 in the top 100m. He found that just south of the equator the transport is east-west, had transport of  $10-15 \times 10^6$  m<sup>3</sup>/sec and is not significantly influenced by monsoon onset.

Moored current meter measurements carried out by Schott (1986) in the Somali Current for approximately one year revealed that the vertical current structure of the Somali Current is different during part of the year from that previously perceived from measurements in the boundary current away from the equator. He found that the southward Somali Current during the winter monsoon season only extends down to less than 150m and northward flow occurred below, down to 400m, followed again by southward flow underneath.

Using moored current measurements during October 1984-86 across the Somali Current on equator (Schott et al., 1990) studied the seasonal circulation changes of the entire Somali Current system between 4°S and 12°N. He found that current structure during the summer monsoon season is similar to western boundary current, while the profile in winter consist of a thin surface layer of southward flow, a northward undercurrent between 120m and 400m depth and below that a reverse flow again to southward. He has computed the summer mean transport close to zero and the annual mean transport in the upper 500m is 10Sv northward.

Fisher et al., (1996) carried out Conductivity-Temperature-Depth (CTD) / Acoustic Doppler Current Profiler (ADCP) surveys in the Somali Socotra region to investigate currents and transports associated with the Great Whirl and Socotra circulation. They found that the monsoon circulation was confined to the upper 300m depth, with intense surface currents up to 2.2m/s and 1.4 m/sec in the Great Whirl and Socotra Gyre regions respectively have been observed.

Moored array observation during WOCE 1995-96 and shipboard sections of winter 1997/98 conducted off the south of Socotra and Socotra passage by Schott and Fisher (2000) showed that the northern Somali Current during that time was characterized by an inflow from the east,



causing a divergence at the coast somewhere near 6-8°N, with northward surface flow north of these latitudes and equatorward flow south of them. The northward surface flow passes through the Socotra passage, but also veers eastward along the southern banks off Socotra. The westward upper layer inflow into the Somali Current system north of 7°N during the winter monsoon is also confirmed by XBT analysis of Donguy and Meyers (1995).

The depth of the monsoon response of the Somali Current was studied by many authors. Schott and Quadfasel (1982), from the moored observations of 1979, showed that the response to a sudden onset was seen down to 200m. From the moored array studies, Dengler et al., (2002) concluded that the depth of monsoon response of the Great Whirl was less than 1500 m.

Three Somali undercurrents have been observed at different locations and at various times during the year. In April to early June, a southward undercurrent develops just beneath the northward surface flow in a depth range from about 100m to 300m. Leetma et al., (1982) has estimated the maximum instantaneous speed of this undercurrent to be 60cm/s. Studies of Quadfasel and Schott (1983) and Schott and Quadfasel (1982) showed that this undercurrent had a maximum monthly averaged speed of 20 cm/s.

The second undercurrent was observed during fall and winter flowing southward underneath the northward flowing branch of Somali Current in the 8-12°N latitude band (Quadfasel and Schott,1983). Moored array observations during WOCE 1995-96' and shipboard sections of winter of 1997/98' of Schott and Fisher (2000) confirmed the presence of this undercurrent. They measured southward velocities of about 30cm/s below 100m in the passage between Socotra and the mainland in January 1998.

A third cross-equatorial northward undercurrent was observed during the winter season in a depth range from 150-400m. Studies of Schott et al., (1990) showed that the transport of this northward undercurrent almost balances the southward surface flow of the Somali current.

### **Monsoon Currents**

The zonal monsoon circulation between Sri Lanka and equator is a crucial link for the exchange of water between the Arabian Sea and the Bay of Bengal. The ship drift observations (Cutler and Swallow, 1984) show that this circulation reverses with monsoon, flows eastward as southwest monsoon current (SMC) from June to September and westward as the Northeast Monsoon Current (NMC) from December to March.

### **Southwest Monsoon Current (SMC)**

The Southwest Monsoon Current (SMC) flows eastward south of India, turns around Sri Lanka and enters into Bay of Bengal. In the surface drifter data of Shenoi et al., (1999), a part of SMC appears to flow southeastward and crosses

the equator near Sumatra. The hydrographic data of Unnikrishnan et al., (2001) also show that the SMC between 80°E-88°E flows close to the equator and even to its south. The SMC transports high salinity water (Arabian Sea High Salinity Water) into the Bay of Bengal. (Murthy et al., 1992b, Gopalakrishna et al., (1996).

The first direct measurement of the seasonal variation of monsoon currents were carried out by Schott et al., (1994). The moored and shipboard ADCP measurements revealed that the strength of SMC decayed very quickly with depth, and its transport had to be determined either by extrapolating ADCP and current meters observations to the surface or by using seasonal mean ship drift currents as surface values. Based on shear extrapolation, the eastward SMC transport between 4-6°N

was estimated to be 8.4 Sv with 70% in the top 100m. The current and transport also exhibited strong intraseasonal variability in the shipboard measurements of August 1993, the eastward core of SMC was observed near 4°N and was separated from the eastward equatorial flow by a zone of weak currents. Another interesting feature observed was the presence of a narrow westward current just south of Sri Lanka from 5.5°N to 6°N. The low salinities near the Sri Lanka coast clearly indicates that it originates in the Bay of Bengal.

The intrusion of SMC into the Bay of Bengal was studied by Vinayachandran et al., (1999a) using XBT observations along the shipping route between Sri Lanka and Malacca strait and T/P analysis and an OGCM. The intrusion first appeared as broad northward shallow flow in the central part of Bay of Bengal and intensified and became narrow as the season advanced. They have estimated the mean seasonal (May-September) transport of SMC into the Bay of Bengal to be 10 Sv.

### **Northeast Monsoon Current (NMC)**

The climatological surface current maps derived from historical ship drifts (Cutler and Swallow, 1984; Rao et al., 1989) show a westward flow south of Sri Lanka during the winter monsoon, partly continuing westward at low latitude and partly flowing around Laccadive High into the west India coastal current. This current is referred to as the Northeast Monsoon Current (NMC). The NMC transports low salinity waters of the Bay of Bengal into the eastern Arabian Sea and flows along the Indian west coast as the WICC (Bruce et al., 1994, Han et al., 1999, Shenoi et al., 1999, Shankar and Shetye, 1997).

Using Moored and shipboard ADCP measurements, Schott et al., (1994) estimated the transport of NMC to be 12 Sv in early 1991 and 10Sv in early 1992.

The large scale circulation at the end of 1994-95 winter monsoon was surveyed by Hacker et al., (1998). From their upper layer ADCP vector distribution they concluded that the NMC was fed by waters from the near equatorial regions.

### **West India Coastal Current**

The west coast of India forms the eastern boundary of the Arabian Sea basin. A striking feature along the west coast of India is the shallowing of the thermocline and the development of an equatorward surface current and a weak poleward current during spring. Ship-drift observations show that the southward flow appears along the west coast of Indian in March, reaches peak strength in July and vanishes by October (Cutler and Swallow, 1984; Shetye and Shenoi, 1988). This current is known as the West India Coastal Current.

Using data collected during the 1960's and 1970's, Dabyshire (1967), Banse (1968) and Johannessen et al (1981) have described seasonal characteristics of water masses and circulation along the west coast of India. These studies showed that the southwest (northeast) monsoon is a time of upwelling (downwelling), with the WICC flowing equatorward (poleward). These authors identified local winds as the important forcing mechanism of the WICC. During 1971-75 about two hundred sections were made on the shelf from Ratnagiri to Tuticorin under the auspices of the UNDP/FAC Polagu Fishery Project . The area was surveyed 7-8 times a year. Using these data Johannessen et al., (1981) noted that upsloping along the coast started in the month of March or April and the seasonal variation was repetitive from year to year. They noted that though the wind is an important driving force from February onwards, the upwelling is not only associated with the local wind, but also with more large scale monsoonal condition which drive the anticyclonic Arabian Sea monsoon gyre.

Shetye and Shenoi (1988) compared the annual cycles of longshore components of windstress and ship-drift along the coast. They noted that during the Southwest monsoon both are in the same direction and this was interpreted to imply that local winds drive the surface circulation.

Utilising hydrographic data for several months along 15°N in the eastern Arabian Sea, Antony (1990) observed a northward flowing undercurrent at the time of upwelling along the west coast of India. They noticed an upward tilt of isotherms towards the coast from April till September, indicating the poleward undercurrent.

Studies of Shetye et al., (1990) along the coastal region off western India during June-August 1987 confirms the presence of the undercurrent. They have computed the dynamic topography relative to 1000db at various locations along the coast and pointed out that, during the southwest monsoon, there is an equatorward coastal current and poleward undercurrent with its core at 150 m or below. The T-S analysis showed that the undercurrent carried low salinity waters of southwestern Bay of Bengal.

Using hydrographic data collected during the northeast monsoon season along the western coast of India, Shetye et al., (1991a) described the poleward surface current and a southward moving undercurrent along the west coast of India. They concluded that it is the alongshore pressure gradient which drives the currents along the west coast of India during northeast monsoon season, where as currents are driven by winds during the southwest monsoon season.

Direct velocity measurements from shipboard ADCP and geostrophic computations were used by Stramma et al., (1996) to investigate the flow fields and the transports off the southwest coast of India east of 68°E and 8°N during the southwest monsoon season in August 1993. At the time of

the survey, the winds were weak and northerly off the shelf edge. They found a northward surface current against the prevailing winds at a speed of 40cm/s and a poleward undercurrent with its core at 100m depth. The total transport was estimated to be 4.7 Sv from surface to 300m. Watermass properties indicated that waters at the shelf edge was a mixture of low salinity water of the Bay of Bengal around Sri Lanka and high salinity waters of the Arabian Sea.

Bruce (1994), using hydrography and satellite altimetry sea level observations, discovered the presence of an anticyclonic eddy in the upper 300-400m of the eastern Arabian Sea during the northeast monsoon period (December-April). They called it the 'Laccadive Eddy' (LH). Its center is located at 10°N , 70°E to the west of the north south Laccadive Island chain. It grows rapidly from late November to late December at 10°N and then propagated westward in January and died in the mid basin. The LH appeared as the mirror like counterpart to the 'Great Whirl' found off the Somali Coast during the southwest monsoon season. Surveys and satellite altimetry measurements together with high resolution numerical simulation by Bruce et al., (1998) indicated that LH is comprised of multiple eddies. They hypothesized that in addition to local and remote seasonal forcing, the Laccadive High region is influenced by an intra seasonal signal that originates in the Bay of Bengal.

The northern Arabian Sea was extensively studied as part of the JGOFS (Joint Global Ocean Flux Studies) during 1994-1996. The observations consisted of repeated ship sections normal to the Oman coast, of special frontal surveys and satellite SST and altimetry. The AVHRR (Advanced Very High Resolution Radiometer) observations and ADCP survey by Bohm et al., (1999) identified the existence of a northeastward coastal jet along the south coast of Oman in early May and persisting throughout the summer monsoon. It was called the Ras Al Hadd Jet as it flowed past Ras

Al HJadd at the southeast corner of Oman. Its maximum velocity was 1m/s and maximum transport was estimated to be 2-8 Sv in September.

Shi et al., (1999) determined time series of the alongshore flow from a combination of Topex/Poisedon altimetry, JGOFS hydrography and Ekman transports for 1993-1995 in the northern Arabian Sea and found that the maximum eastward flow occurred earlier in monsoon and decreased strength from about 10Sv in 1993 to about 2 Sv in 1995 in correspondence to a decrease in monsoonal wind forcing between these years. The main reason for this northeastward flow was due to onshore pressure gradient established by the upwelling which reduces sea level near the coast by 30 cm.

The interior of the Arabian Sea is filled with mesoscale eddies. They have been observed in repeated ADCP survey by along lines normal to the Arabian coast by Flagg and Kim (1988).

The relation between LH/LL and the interior Arabian Sea was studied by Brandt et al., (2002) and stramma et al., (2002). They analyzed the WOCE ship section along 8°N during summer and winter monsoons in conjunction with T/P altimetry. They concluded that much of the seasonal variability in the stratification and meridional circulation could be explained by the propagation of the rossby waves from the west coast.

#### **1.2.1.2 Bay of Bengal circulation**

The Bay of Bengal is the northeastern arm of the Indian Ocean. The Arabian Sea, the northwestern arm of the Indian Ocean, is completely separated from the Bay of Bengal by the Peninsular India. Though the Bay of Bengal and Arabian Sea are located in the same latitudinal belt and are influenced by monsoons, there are remarkable differences between those two basins. Unlike the Arabian Sea, a large quantity of fresh water enters the Bay of Bengal through river discharge and rainfall. Hence the

surface waters in the Bay has low salinity and the stratification in the upper layers is often dominated by salinity gradients. The width of the Bay of Bengal is less than the Arabian Sea and the coastline is about 1.5 times shorter than that of Arabian Sea. These dimensions are relevant for the propagation of rossby and coastal kelvin waves in the two basins. The sea surface temperature of Bay of Bengal is greater than 28°C which is favorable for the genesis of synoptic scale disturbances such as low, depression and cyclogenesis. On the other hand, Arabian Sea is too cold over most of the year to generate such disturbances.

The winds over the Bay of Bengal are southwesterly during May-September and northeasterly during November-January. The transition from SW to NE winds takes place during October and reverse transition takes place during February-April. The wind possesses strong anticyclonic curl in the southern Bay during February-April and strong cyclonic curl in the southern bay during the northeast monsoon season. In response to the winds, circulation in the Bay exhibits a seasonal cycle which is reflected in the surface currents and hydrography.

Observations in the Bay started in the 19<sup>th</sup> century with the expedition of the NOVARA (1857-1859) and VALDIVIA (1898-1899). The data collected during the cruises of RMIS INVESTIGATOR were analyzed and documented by Sewell in various reports of Memoirs of the Asiatic Society of Bengal (Sewell, 1929). During IIOE, many cruises were conducted in the Bay of Bengal and the availability of the data increased tremendously. The voluminous data collected for the Indian Ocean during IIOE were analyzed and presented in the form of an atlas by Wyrтки (1971).

Other sources of data in the Bay of Bengal are the atlases (KNMI,1952; Deutsches Hydrographisches Institut, 1960; Cutler and Swallow, 1984) which give the surface currents of the Indian ocean. Among these, the Cutler and Swallow, 1984 atlas is particularly useful to study Bay of Bengal



circulation because of the data coverage over a long period and better spatial resolution. Current meter observations are scarce in the Bay of Bengal. The longest current meter record is for a period of 14 days by Rao et al., (1991). Legeckis (1987) used satellite imagery for identifying western boundary current in the Bay of Bengal and satellite tracked drifting buoys provide information on Bay of Bengal circulation (Molinari et al., 1990).

The surface circulation in the interior of the Bay of Bengal is best organized during the transition period from NE to SW monsoon during Feb-May. Ship drift (Cutler and Swallow, 1984; Duing 1970), satellite tracked drifting buoys (Molinari et al., 1990) and dynamic topography computed from climatological temperature and salinity (Shetye et al., 1993) all suggest the presence of an anticyclonic gyre during this period. The EICC flowing poleward forms the western boundary of this basin-wide anticyclonic gyre. EICC reverses direction twice a year, flowing northeastward from February to September with a strong peak in March-April and southwestward from October to January with a strong peak in November.

Earlier hydrographic surveys which revealed the existence of EICC include the studies of La Ford 1957, and Scherbinin (1979).

With the onset of the SW monsoon, the anticyclonic gyre breaks up. During the SW monsoon ship drifts suggest southwestward flow in the southern and northern parts of the bay with northward flow in between (Duing, 1970; Cutler and Swallow, 1984).

Using the hydrographic data collected in the western Bay of Bengal during April-September 1978, Gopalakrishna and Sastry (1985) pointed out that the flow in the northwestern Bay of Bengal is directed equatorward and

strong upwelling takes place in the southern regions off the east coast of India.

A hydrographic survey carried out by Shetye et al., (1991a) during the SW monsoon of 1989 shows that during SW monsoon season, active upwelling takes place along the eastern coast, with near surface isotherms and isopycnals tilting upward from depths of about 80m within 40Km of the coast and deeper ones sloping downwards suggesting a southward undercurrent. In the northern Bay of Bengal flow is equatorward with the freshwater plume from Ganges and Brahmaputra moving southward against local winds and were located just outside the upwelling band.

Studies of Babu et al., (1991) using CTD data collected in the northwestern Bay of Bengal during July 1984 revealed the existence of a cold core subsurface eddy centered at  $17^{\circ}40' N$  and  $85^{\circ}19'E$  between 50 and 300 db. The flow along the northern Bay was southward due to the influx of freshwater and windstress curl, and in the southwestern bay the flow was northward due to the local winds. They proposed that the eddy was generated due to the baroclinic instability at the interface of these two opposing boundary currents along the western Bay of Bengal.

Using ship drift currents and surface geostrophic flows derived from Topex/Poseidon, Eugeneheer and Quadfasel (2000) showed that at the height of summer monsoon there was a western boundary confluence near  $10^{\circ}N$  with the EICC flowing northward to the north of  $10^{\circ}N$  and southward south of it. Studies of Vinayachandran et al., (1999) showed that this confluence is mainly due to the Southwest Monsoon Current that circulates cyclonically about the Sri Lanka Dome at about  $6^{\circ}N$ .

Murthy et al., (1992a) studied the circulation pattern along the northwestern Bay of Bengal during the withdrawal phase of summer monsoon of 1983. The study revealed that local winds induced upwelling

and that observed near surface salinity near the coast was an indicator of the Ekman processes of upwelling.

Murthy et al., (1992b) studied the effects of freshwater flux, the wind forcing and Indian Ocean monsoon drift currents on the property distribution and the circulation in the Bay of Bengal during southwest monsoon season. They found that the northern freshwater influenced region is characterized by cyclonic circulation and the southern region is thermohaline driven. These studies also suggest the propagation of long period planetary waves from the southeastern bay towards the southern bay.

In the open bay ship drifts suggest northeastward current, which is the continuation of the Southwest Monsoon Current. The intrusion of SMC into Bay of Bengal is revealed by the studies of Vinayachandran et al., (1999, 1998).

Vinayachandran and Yamagata (1998) used the results from an OGCM to study the response of the oceanic region surrounding Sri Lanka to the monsoonal winds. They found that during the southwest monsoon season, a cold dome developed east of Sri Lanka which they called the Sri Lanka Dome (SLD). SLD is formed mainly due to the cyclonic curl in wind stress. The SLD decays after September and cold dome called Bay of Bengal Dome developed north of Sri Lanka. The source of cold water of the Bay of Bengal Dome was traced back to the SLD and upwelling zone along east coast of India.

During the northeast monsoon season, ship drifts show an equatorward current along the western boundary of the Bay of Bengal (Cutler and Swallow, 1984).

Suryanarayana et al., (1993) investigated the circulation in the Bay of Bengal during October-December of 1983. During late October, the monsoon current fed into the north flowing eastern boundary current of Bay of Bengal. The surface circulation relative to 1000db level surface indicates a northward flowing eastern boundary current north of 8°N and a cyclonic gyre to the west of it.

The circulation features of the western Bay of Bengal during the northeast monsoon was studied by Shetye et al., (1996) using the hydrographic data collected during December 1991. They could locate low salinity plume along the eastern coast of India and equatorward flowing EICC. They calculated the transport of EICC north of 13°N with reference to 1000db level to be 7.1Sv. The EICC flow southward along the east coast of India and its southern part, south of 13°N, a northwestward flow from the offshore meeting with the coastal current was observed

Using hydrographic data collected during March-April 1991, Shetye et al., (1991a) showed that the presence of poleward current along the western boundary of the bay north of 10°N carrying warmer waters of southern origin. They proposed that this poleward current is the western boundary current of the seasonal anticyclonic subtropical gyre which forms in the Bay of Bengal during January and best developed during March-April and decays in June.

### **1.2.1.3 Equatorial and southern subtropical Indian Ocean**

#### **Equatorial Indian Ocean**

The equatorial Indian Ocean is driven by the wind field which is unique in the sense that its annual mean is weak and westerly and its annual cycle has strong semiannual component. Due to this unique wind field the equatorial current in the Indian Ocean are different from the other oceans. Ship-drift climatology indicates that the surface currents in the equator

reverse direction four times a year, flowing westward during winter, weakly westward in the central and western ocean during summer and strongly eastward during spring and fall. The eastward currents were first pointed out by Wyrtki (1973) and they are known as Wyrtki Jets (WJs) or Equatorial Jets (EJs). They appear as a narrow band, trapped in the equatorial wave guide within 2-3° of the equator mostly in the central and eastern regions and disappears in the western part where the currents have strong meridional component. The ship-drift climatology indicates roughly the same strength for the two jets, with the October – November one slightly stronger (1 m/s) than the April-May one (0.90 m/s).

The first direct current measurement carried out at the equator by Knox (1976) near Gan Island (73°10'E, 0°41'S) showed energetic eastward currents throughout the upper 100m mixed layer in phase with the zonal eastward component of local winds during this transition periods between the two monsoons. He found the fall Jet in 1973 to be stronger than either the preceding or following spring jets. The drifter climatology by Molinari et al., (1990) also shows the fall jet to be stronger than the spring jet.

Equatorial current observations in the western Indian Ocean in 1975 and 1976 were carried out by Leetma et al., (1980). During both the years, a strong undercurrent was present throughout the measurement period in the vicinity of the equator. A second region of eastward flow above the thermocline was observed at 3°S. During May and June the undercurrent moved southward and merged with the southern region of the eastward flow.

Hydrographic survey made by Erikson (1979) in the equatorial section revealed high zonal pressure gradient in the near surface equatorial Indian Ocean. He pointed out that these high pressure gradients are due to intra-seasonal westerly winds prevailing at the equator. He suggested that

deep fluctuations in the dynamic height found in the Indian Ocean could be related to the easterly equatorial jets of the Indian Ocean.

Luyten and Swallow (1976) studied the equatorial current in the western Indian Ocean during spring and summer of 1979 as part of the Indian Ocean Experiment (INDEX). They found that the near surface equatorial circulation responded directly to the variations in the wind field.

Reverdin (1987) studied the climatological seasonal cycle of the upper equatorial Indian Ocean. He has evaluated the surface currents from ship-drifts and the temperature profile from BT, XBT and CTD surveys conducted as part of First GARP Global Experiments in 1979. Observations indicated intense variability of the equatorial currents near the surface and below the thermocline with a semiannual frequency. The eastward flowing undercurrent is detected in the thermocline during March and April.

Reverdin (1986), using the surface drifter data, estimated the near surface meridional convergence in eastward surface jets of equatorial Indian Ocean. They obtained a large convergence of currents at the surface than at deeper levels.

Clark and Liu (1993) investigated the seasonal sea level cycle at the eastern end of the equatorial Indian Ocean using tide gauge data. They found large difference between the annual and semiannual components. They concluded that the semi-annual component was largely a response for the reflection of equatorial Kelvin waves and that the annual cycle was determined by the alongshore monsoonal winds.

Visbeck and Schott (1992) carried out moored current meter measurements in the equatorial Somali current region and along the equator between 50°E and 60°E and these observations are compared

with a GFDL model to study the current variations in the western equatorial Indian Ocean.

The annual cycle and interannual variability of the equatorial currents were investigated by Reppin et al., (1999) as part of the World Ocean Circulation Experiment (WOCE) . The current meter array was deployed along 80°30'E between 4°5'S and 5°N from July 1993 to September 1994. They found that the Equatorial Jet was showing large seasonal asymmetry with a monthly mean eastward transport of 3.5Sv in November 1993 and 5Sv in May 1994. The equatorial undercurrent was observed to have a maximum transport 17Sv in March to April 1994 and more than 10Sv in August 1994. They concluded that the interannual variability of Equatorial Jet in the observations and ship-drift data was due to the variability of the zonal winds and southern oscillation index.

Observations carried out by Sprintall et al., (2000) within the Indonesian exit passages and internal seas showed that arrival and passage of semi-annual Kelvin waves. They suggested that these semi-annual Kelvin waves were remotely forced by westerly wind bursts that occurred in the first week of May 1997 in the equatorial Indian Ocean during the transition from northeast to southwest monsoon.

Hydrographic data analysis along the cross equatorial sections of 80°E, 84°E and 88°E by Unnikrishnan et al., (2001) during the southwest monsoon period of 1994 revealed thermocline variability and anomalous current structure in the upper ocean. An equatorial undercurrent with a transport of 5 Sv towards east was present between 2°N and 1°S.

### **Equatorial Undercurrent (EUC)**

In the Indian Ocean, an eastward Equatorial Undercurrent exists only during the NE monsoon season. It was during the IIOE period, EUC was first observed and was documented by Traft (1967) at several positions

along the equator between 53°E and 91°E during the months of March and April 1963 with speeds up to 0.8m/s. But it was not detected during the Sw monsoon of 1962. Swallow (1967) reported the existence of a shallow EUC in March 1964, but by April the surface flow reversed and the EUC vanished. Then Knox (1976) reported an EUC at Gan Island (73°E) in March 1973 with velocities up to 1m/s, but no such EUC occurred in spring of 1974. Leetma and Stommel (1980) confirmed the existence of the EUC in NE monsoon of 1975 and 1976. Both these observational periods, EUC was found from January to June at 55° 30'E with observed speeds reaching 0.8m/s in February and March. They also reported a meandering of the EUC in which its core was at times displaced by more than 100Km south of the equator.

A number of cross equatorial ADCP sections were carried out in the 50-60°E longitude band during the WOCE cruises of April to September, 1995. In April 1995, the 'Meteor' cruise found a well developed undercurrent at 57°E in the depth 200-500m. In June, the flow at the undercurrent level reversed, and by August, all currents above 200m were directed westward on the equator (Schott et al., 1997; Walter 1997).

Reppin et al., (1999) carried out moored ADCP observations from the region south of Sri Lanka from June 1993 to August 1994. The monthly mean zonal velocities for the upper 150m of these observations showed that EUC existed in the depth range 50-150m from February to May 1994. It disappeared in June, but contrary to earlier assumptions about the extent of the EUC, it reappeared again in August with less transport and at a shallower depth.

### **Southern Subtropical Indian Ocean**

The circulation of the southern Indian Ocean is not well understood due to paucity of hydrographic data. The dynamic topography of the Indian Ocean from the Atlas of Wyrski (1971) shows two persistent features for



the south Indian Ocean; a large, basin wide circulation and a well-developed subgyre west of the Madagascar Ridge.

Based on the hydrography, sea level data and ship-drifts currents available at the time, Wyrski (1961) developed composite seasonal circulation pattern for the seas within and neighboring the maritime continent. For the South Java Current, he estimated a maximum eastward transport of 4 Sv during late winter monsoon and weak westward flow during the summer monsoon.

Stramma (1992) investigated the distribution of the subtropical front in the southern Indian Ocean and the current associated with the front. A current band of increased zonal speed in the upper 1000m just north of the Subtropical Front (STF) in the west, north of south Africa was observed in the open Indian Ocean . He called it the Southern Indian Ocean Current (SIOC) which separates the southern limb of the subtropical gyre of Indian Ocean from the north band of Antarctic Circumpolar Current. The estimated volume transport of southern Indian Ocean Current near Africa was 60 Sv in the upper 100m and reached to 10.1 Sv near western Australia.

The first 18 months of the altimeters data from the Topex/Poseidon were analyzed by Park and Gamberovi (1995) to study the surface circulation of the southern Indian Ocean. The dynamic topography derived from the T/P were compared with the output of a fine resolution Antarctic model and the hydrographic data. The altimeter solution showed good agreement with the numerical solutions and indicated the presence of an anticyclonic subtropical gyre north of the Antarctic circumpolar current and two cyclonic subpolar gyres south of it.

From the quasi-synoptic hydrographic sections in the subtropical gyre of the southern Indian Ocean, Stramma et al., (1997) estimated the flow

fields of the subtropical gyre and found that most of the flow fields in the subtropical gyre recirculates in the western and central part of the basin. The mean transport in the upper 100m consists of eastward transport of 60 Sv SE of south Africa, out of which about 20 Sv recirculates in the southwest Indian subgyre between 40°E and 50°E. Another major diversion occurred northward between 60°E and 70°E and at 90°E, the remaining 20 Sv of the eastward flow splits up, 10Sv going north to join westward flow and only 10 Sv continue in the northeastward direction to move northward near Australia.

The Mozambique Basin is located in the southwestern Indian Ocean and the circulation consists of the Agulhas current flowing southwestward along the coast of south Africa and in the northern part, the East Madagascar current flowing southward along the east coast of Madagascar into the Agulhas current. Individual surveys over the past decades showed a complex structure of the flow pattern in the Mozambique channel with the presence of energetic partially bottom trapped eddies.

Grundhning (1988) using hydrographic data collected during 1981, identified the appearance of strong southwesterly flow of  $3 \times 10^6 \text{ m}^2/\text{s}$  at the Mozambique Ridge between March and April and an intense cyclonic eddy further south, east of the Ridge. They noted that between April and July the eddy had moved away and could not be located in July.

Grundhning et al., (1991) studied the circulation and watermass properties of the southwest Indian Ocean using ship derived hydrographic data during spring 1987 and Geosat Altimeters data. They could trace two intense cyclonic eddies of diameter 130 and 240 Km in the vicinity of Mozambique Ridge and Mozambique Basin. They found that the vicinity of the Madagascar Ridge seemed to represent a possible condition for equatorward transport of water extending from the mid thermocline to

1800db and originating from higher latitude. The passage of north Atlantic Deep water was constrained by the bottom topography south of the Madagascar Ridge, and this led to a reduction of its salinity and oxygen concentration.

de Ruijter et al., (2002) suggested from T/P altimeter analysis that one of the mechanisms of Mozambique channel throughflow could be by anticyclonic eddies that are triggered at the northern edge of the channel by Rossby waves arriving from the east. After passing through the channel, these eddies presumably even affect the Agulhas retroflection and associated eddy shedding into the Atlantic.

Early portrayals of the currents that feed the Agulhas current were based on the measurements of ship-drifts and SST (Moller 1929, Paech 1926, Miche elis 1923). They showed a simple and direct inflow into the northern Agulhas current from the South Equatorial Current, one via the Mozambique channel called Mozambique current, the other around the southern tip of Madagascar, called the East Madagascar Current. Studies of Saetra and Jorge De Silva (1984) suggested that the Mozambique current is not an upstream extension of the Agulhas Current, instead the circulation in the channel consists of a series recirculation cells.

Lutjeharms et al., (1981) and Lutjeharms (1988) showed that there was no connection between the east Madagascar current and the Agulhas current, except in a sporadic way by filaments and eddies. Studies of Harris (1972) using hydrographic data suggested that about 35 Sv of Agulhas current comes from East Madagascar current, 10 Sv comes through the Mozambique channel and 27 Sv is recycled in a southwest Indian Ocean subgyre. Fu (1986), using an inverse method solution for six hydrographic sections in the Indian Ocean indicated a southward transport of 6 Sv through the Mozambique channel.

The South Equatorial Current (SEC) appears as a band of westward flow between 10°S and 20°S in the ship-drifts (Cutler and Swallow, 1984) and also in drifter tracking (Shenoi et al., 1999). The surface current charts of Schott (1983) show the northern branch of SEC in the Indian Ocean passing around the northern extremity of Madagascar and continuing westward to the coast of Africa near 11°S. There it splits into the north going EACC and a branch flowing south into the Mozambique channel to join the Agulhas current. The SEC also bifurcates along the coast of Madagascar near 17°S, generating the Northeast Madagascar Current (NEMC) to the north and the South East Madagascar Current (SEMC) to the south, which flows southward to join the Agulhas current.

The EACC runs northward throughout the year between latitudes 11°S and 3°S with surface speed exceeding 1m/s in northern summer. The volume transport of the EACC has been computed by Swallow et al., (1991). They estimated the mean transport of EACC at 5 sections between 4-5 °S to be 19.9 Sv northward in the upper 500db. Between 500db and 1000db, the transport was estimated to be weak of the order of 1 Sv. They found that above 300db, most of the water from the northern branch of SEC goes into the EACC and below that goes into the Mozambique channel. During winter, the EACC meets the Somali Current to form Equatorial Counter Current (ECC) with an eastward transport of 22Sv, and in the northern summer EACC merges with the Somali Current. Studies of Duing and Schott (1978) using subsurface mooring in the Somali Current region during January-July of 1976, showed that the northward EACC and the southward Somali Current causes a confluence at 2-3°S and then flows eastward as ECC. The hydrographic section of Swallow et al., (1991) also showed the eastward flowing ECC during the winter season. They estimated the volume transport of ECC to be 22 Sv in the upper 300db. In the monthly drifter maps of Shenoi et al., (1999), the ECC is best developed in February when it forms a continuous band across the Indian Ocean.

## **Leeuwin Current**

The Leeuwin current flows southward along the Australian coast against the prevailing winds. It is about 50 m wide, extends to a depth of 250 m and has a mean speed of about 30 cm/s with a seasonal maxima of 60 cm/s. The direct observation of the Leeuwin current did not take place until 1970's, when an investigation was commissioned into the life cycle of the Western Rock Lobster. Cresswell et al., (1980) using the hydrographic data collected off Australia during 1974-76 and satellite tracked buoys described the flow pattern of the Leeuwin current.

Shipboard observations by Thompson (1984) identified poleward surface current along the west Australian shelf from 22°S to 28°S . The surface current was fresh, warm, low dissolved oxygen concentration and high in nutrients. Below the surface poleward flow, equatorward undercurrent was observed which was saline, high in oxygen concentration and low in nutrients. He pointed out that the winter cooling of the mixed layer allow the surface geopotential gradient to overcome the windsstress to drive the Leeuwian current against the local winds.

Godfrey and Ridgeway (1985) determined the annual mean and seasonal variability of the southward pressure gradient that existed between the warm and fresh Indonesian throughflow waters and cooler and saline water off the southwest Australia. They found that there was a southward pressure gradient throughout the year that reached a maximum amplitude in May/June, when Leeuwin Current is the strongest.

The first large scale study of the Leeuwin current was undertaken during the Leeuwin Current Interdisciplinary Experiment (LUCIE). From the Current meter and CTD measurement of LUCIE, Smith et al. (1991) observed strong poleward flow between the surface and 250m within 100Km of the shelf edge with a poleward transport of 5 Sv except for January. A narrow equatorward undercurrent was also observed between

250m and 450m along the continental slope. They pointed out that the Leeuwin current depends on the alongshore pressure gradient of the eastern Indian Ocean and the seasonal variation in the strength of the current is due to the variation in windstress and not due to the alongshore pressure gradient.

Hollway (1995) described the Leeuwin Current from shipboard ADCP and moored current meter observations made during May June of 1993. The Leeuwin current was characterized by a broad (250Km), deep(440m), weak (0.2m/s) poleward flow with a transport of 4 Sv. An undercurrent of magnitude similar to poleward transport was also observed.

Using Topex/Poseidon Altimeter data for 3 years during 1993-1995, Morrow and Birol (1998) studied the seasonal and interannual variability in the southeastern Indian Ocean. The T/P data confirmed the presence of the alongshore pressure gradient maxima in May which act as the principal forcing mechanism for the Leeuwin Current that moves poleward against the prevailing equatorial winds. They also obtained a secondary peak in pressure gradient in November which was not observed in the climatological data.

### **Indonesian throughflow**

Currents flowing along the eastern boundary of the Indian Ocean are markedly different from those found in the eastern Pacific and Atlantic. The Indonesian Archipelago consisting of about 13700 islands separate the seas of the southwest Pacific from the equatorial Indian Ocean. These islands form a 'leaky boundary' through which Pacific Ocean waters pass into the Indian Ocean.

Fieux et al., (1994,1996) carried out the first modern shipboard section observations across the exit region between Australia and Bali and reported a throughflow transport of  $18.6 \text{ Sv} \pm 7 \text{ Sv}$  from a ship section

taken in August 1989. They also found negative transports of nearly  $-2.6 \pm 7$  Sv from a similar section in March 1992.

Meyers et al., (1995) using XBT data from repeat sections with a mean T/S relation, determined a transport of 5 Sv in the upper 400m. He used 400m as the reference level for the calculation of the transport. when the reference level was extended to greater depths using climatological hydrography, the estimate increased to about 11 Sv.

Gordon and Susanto (1999) estimated a mean transport of about 5-15 Sv from annual means of moored current meter observations in the narrow Makassar strait. Little information was available on the deep structure from direct measurements.

## **1.2.2 Theoretical and modeling background**

Observational data sets, although large in size and complexity, can not provide a complete description of the large scale circulation. However, dynamical synthesis and interpretation of the data can be better achieved by theoretical and modeling studies. The numerical models are effective tools to describe quantitatively the dynamical behavior of the complex, non-linear and turbulent system of oceanic general circulation.

### **1.2.2.1 Arabian Sea circulation**

A number of modeling studies have been carried out on the northern Indian Ocean and most of them attempted to simulate the Somali Current response to the summer monsoon. Cox (1970) was the first to develop a large scale numerical model of the Indian Ocean, using an early version of the Bryan-Cox or Geophysical Fluid Dynamics Laboratory (GFDL) model. This three-dimensional model, with 7 levels in the vertical and driven by idealized wind stress and temperature -salinity data, could reproduce the reversal of the Somali Current and most of the other large-scale

circulation features of the region. The major limitation of the model were the lack of sufficient resolution, restrictive boundary condition of temperature and salinity and simplified treatment of vertical turbulent mixing. However, the model was generally successful in simulating the large scale features of the current and water masses of the Indian Ocean, especially in reproducing the Somali Current and its seasonal variation.

Lighthill (1969), using an analytical model, showed that a northward cross-equatorial Somali Current could be generated by westward propagating, long wavelength, equatorially trapped Rossby waves excited by the wind stress curl in the open ocean. After their arrival at the western boundary, the waves reflect into short wavelength rossby waves that superpose to form the western boundary current.

Cox (1976) used three dimensional numerical model to study and compare the two previously proposed theories for the development of Somali Current (SC). He found that non-linear horizontal shearing instabilities were able to produce eddies in the SC, similar to the observed two gyre system.

Cox (1979) developed a 3-dimensional numerical ocean model to study the transient response of the western boundary region of a tropical ocean to the sudden onset of winds parallel to the boundary. The behavior of resulting western boundary current eddies was studied as a function of various parameters of the model. Numerical results indicated that the alongshore movement of the eddies decreased and vanished when western boundary orientation were changed from northward to northeastward.

The northward migration of the Great Whirl was investigated by Hurlburt and Thompson (1976) using a two layer numerical model. They showed that non-linear eddies formed at the equator by an impulsively applied



wind stress could move northward along the coast as a result of advection effects.

Anderson and Moore (1979) considered the Somali Current to be a free inertial cross-equatorial jet remotely forced by the southern hemisphere trade winds and found reasonable separation latitude for the southern gyre of the Somali Current.

Lin and Hurlburt (1981) used a non-linear reduced-gravity model to simulate the salient features of the Somali Current system including its rapid response to the wind field. Model studies showed that the Somali Current responded very rapidly to the applied local wind forcing.

The influence of equatorially trapped waves on the Somali coast was presented by Cane and Gent (1981). They have developed a procedure for calculating effects of western boundaries of arbitrary geometry on low frequency equatorial waves.

Luther and O'Brien (1985) developed a wind-driven numerical model to investigate the seasonal cycle of currents in the Arabian Sea. This non-linear reduced gravity model includes a realistic bottom geometry and is forced by observed monthly mean winds. The model reproduced many of the observed features of the seasonal variation in the Somali Current such as the development and collapse of the two gyre system.

Mc Creary and Kundu (1985) used an analytical model to study the evolution of the vertical structure of the low latitude western boundary current such as Somali Current. The model was driven by the steady alongshore component of the wind and the dynamics of the model give importance to both vertical and horizontal mixing processes. Numerical experiments were conducted with and without the curl of the wind stress.

Simmons et al., (1988) verified the numerical model of the Arabian Sea. An evaluation of the predictive capability of the upper layer circulation model of the northwest Indian Ocean has been presented in this study. The model is a non-linear reduced gravity model incorporating realistic basin geometry. Ship-observed winds for 1985 were used to force the model and to generate the resultant dynamic response. The model results for the fall of 1985 were compared with U.S. Navy bathythermograph and NOAA satellite data collected during Aug-Nov 1985. The model was only moderately successful in reproducing the structure of large, homogenous pool of water located off the Arabian Peninsula in September.

Mc Creary and Kundu (1988) investigated the dynamics of Somali Current system during the sw monsoon using a 2 1/2 layer numerical model that includes the entrainment of cool water in to the upper layer. Solutions are forced by a variety of simple wind stress fields in the ocean basin with western boundaries oriented either meridionally or at 45° angle. Numerical experiments were conducted to investigate the dynamics behind the generation and coalescence of the eddies in the somali region. The model failed to reproduce a southward coastal undercurrent suggesting that some important processes are neglected in the model.

Kindle and Thompson (1989) examined the circulation of the western Indian Ocean using a reduced gravity model with one active layer and realistic basin geometry for the entire Indian Ocean north of 30°S. The Hellerman and Roseinstein (1983) monthly mean wind stress climatology was used to force the model. The numerical simulations reproduced the observed 26 day oscillations along the equator and the 50 day oscillations between the equator and Madagascar.

Anderson et al., (1991) used a sixteen level GCM to study the dynamics of the Somali Current during the SW monsoon season. Solutions were found for a number of model geometries and wind forcing patterns. The GCM

did not reproduce cold wedge observed in SST at 4°N although a current separation did develop there.

Jensen (1991) used a four layer model to study the seasonal cycle in the Somali current system. The results suggested that the baroclinic instability could generate the Great Whirl in early June. There was good agreement between the observed undercurrent and the simulations in the model. Remote winds were suggested to control the intermediate flow along the Somali coast.

Visbeck and Schott (1992) compared the seasonal cycles found in the moored current meter measurements in the equatorial Somali Current region between 50°E and 60°E with multi-layer GFDL model for the tropical Indian Ocean. The objectives of the study were to analyze the seasonal cycle in the western Indian Ocean along the equator and in particular its interaction with the western boundary and to test the hypothesis that the mid-depth variations of the equatorial Somali current are at least partly related to remote forcing over the equatorial interior.

Mc Creary et al., (1993) used a 21/2 layer thermodynamic numerical model to study the Indian Ocean circulation. Monthly climatological data including air temperature and specific humidity were used to force the model. The model SST was used to determine the sensible and latent heats fluxes. Their main objective were to study the relative importance of remote versus local forcing, the thermodynamic processes and the development of meridional circulation cells. They found that the currents along the western coast of India were strongly affected by the remote forcing from Bay of Bengal through out the year. They suggested that model Somali undercurrent flowing from 5°N during spring was remotely forced by Rossby waves radiating off the west coast of India and the seasonal Somali undercurrent in the fall between 11°N and 3°N was forced by winds during the previous southwest monsoon season.

Schott and Fisher (2000) compared the winter monsoon circulation of the high resolution POCM simulation with their observation. The model could reproduce the northern undercurrent including its supply route from the east and through socotra passage.

Esenkov and Olson (2002) used an eddy resolving open boundary version of the MICOM (Miami Isopycnal Co-ordinate Ocean Model) to investigate the subsurface circulation and watermasses in the western Arabian Sea. The model subsurface circulation and transport were in good agreement with the observations near the equator.

A three-dimensional diagnostic model has been developed by Bahulayan and Shaji (1996) to compute the monthly mean circulation and sea surface topography in the western tropical Indian Ocean north of 20°S and west of 80°E. The model has 18 levels in the vertical with a maximum depth of 900m, resolution of 1° in the latitude and longitude directions and is forced by climatological monthly mean wind, temperature and salinity data. This model reproduced successfully the sea surface topography and its associated circulation for all months. Due to the absence of seasonal variability in the wind field, the computed sea surface topography pattern in the southern tropical Indian Ocean south of 10°S do not show much monthly variability.

Bahulayan et al., (1997) and Shaji et al., (1997) adapted semi-diagnostic model to the western tropical Indian Ocean to study the steady state circulation.

### **Monsoon Currents**

The physics of the monsoon currents were investigated by the studies of Mc Creary et al., (1993) and Vinayachandran et al., (1998, 1999). The numerical solutions of MC Creary et al., (1993) reproduced the SMC as a strong eastward current south of India and flows across the southern Bay

of Bengal. The SMC is locally forced by the wind curl pattern south of India and is remotely forced from the equator by a packet of reflected Rossby waves in the central Bay of Bengal.

Vinayachandran et al., (1998) used an Indo-Pacific model adapted from the GFDL model of Cox (1984) to study the monsoon response of the sea around Sri Lanka. In the model simulations, the SMC extends to the equator in the south, merging with the equatorial jet and to the eastern boundary in the east. East of Sri Lanka, the SMC branches into two, one branch turns northward to enter into the Bay during the entire season and the other continues eastward. Their model results showed good agreement with the ship-drift and the geostrophic flow field. They concluded that the spring WJ excites equatorial Kelvin wave and a part of which propagate along the periphery of the bay as a coastal Kelvin wave.

Vinayachandran et al., (1999) used GFDL Modular Ocean Model to study the intrusion of the SMC into the Bay of Bengal. The model was forced with FSU winds and Hellerman winds to the south of 30°S. The model reproduced an anti cyclonic eddy to the east of Sri Lanka Dome and SMC flow into the east of Sri Lanka. The core of Sri Lanka was weaker in the model when compared with the results from XBT data. The model results demonstrated that SMC east of Sri Lanka was forced both by Ekman pumping in the bay and the Rossby wave radiation associated with the spring WJ in the equatorial Indian Ocean.

Shankar et al., (2002) used an OGCM to simulate the monsoon currents and a 1 1/2 layer reduced gravity model to investigate the processes that force these currents. Numerical experiments showed that the dynamics of the north Indian Ocean on seasonal time scales can be explained by linear wave theory. The circulation is controlled by both local forcing and remote forcing, whose signals are carried by equatorial and coastal waves and also the local Ekman drift.

Several models obtained westward undercurrent beneath the SMC consistent with the observations. Potembra et al., (1991) using 3 1/2 layer model obtained a annual harmonic of 6 Sv transport for the monsoon currents south of Sri Lanka in their top layer and a strong semi annual harmonic in their undercurrent layer.

Numerical solution of Mc Creary et al., (1993) shows that currents along the west coast of India are strongly affected by remote forcing from the Bay of Bengal throughout the year. From April through October, the surface current was southward and a northward coastal current was also reproduced in the model. From October through February, the surface current was northward with a southward undercurrent.

Shankar and Shetye (1997) investigated the dynamics of the high and low in sea surface topography off the southwest India using an analytical model. They concluded that the high and low are generated due to the non-linearity. They are caused by westward propagating Rossby wave radiated by Kelvin wave propagating poleward along the western margin of the Indian subcontinent.

Salvekar et al., (2000) used a 2 1/2 layer thermodynamic numerical ocean model to simulate the SST and currents in the north Indian Ocean during the onset phase of the monsoon from 1994 to 1996. Daily SSM/I winds and NCEP heat fluxes were used to drive the model. The maximum variability in the simulated SST was found along the Somali and Indian coasts and equatorial region.

#### **1.2.2.2 Bay of Bengal circulation**

The Bay of Bengal is poorly represented in coarse resolution OGCMs as the Bay occupies only a small fraction of the total area of the world oceans. The modeling studies in the Indian Ocean were mainly concentrated on the Somali Current and the equatorial Indian Ocean.

There have been efforts to simulate the Bay of Bengal circulation using barotropic models. Bahulayan and Varadachari (1986) used a barotropic model of the Bay of Bengal for the simulation of the wind-driven circulation in the Bay of Bengal. A constant southwesterly wind with a speed of 10m/sec was applied for 100 hrs to simulate the wind-driven circulation. The simulated flow was poleward along the western boundary and equatorward along the eastern boundary.

Bahulayen and Unnikrishnan (1992) used the same model to study the depth averaged circulation of Bay during the northeast and southwest monsoons, driven by observed climatological winds. This study showed a poleward western boundary current during the southwest monsoon and an equatorward western boundary current during the northeast monsoon. They suggested that these currents are driven by alongshore winds.

Rao et al., (1992) examined the circulation around the Indian Peninsula using a barotropic model driven by climatological winds. Dube et al., (1998) developed an oceanic climatological circulation model for the Bay of Bengal. In this paper, special emphasis was given to the southern open boundary conditions for the model, and sensitivity experiments have been performed with different open boundary conditions.

Jensen et al., (1991) forced a 3-dimensional model of a section of the western bay with constant (5 m/s) southwesterly and northerly winds for a maximum period of 7 days. They suggested that local southwest (northeast) winds cause upwelling (downwelling) along the east coast of India.

Potemra et al., (1991) studied the seasonal circulation in the Bay of Bengal. A 3 1/2 layer model driven by climatological monthly mean winds is used to examine the dynamics of the region. This model accurately simulated currents with slight deviation from available observations.

Lisan Yu et al., (1991) used a reduced gravity model to explain the hypothesis that the remote forcing is one of the mechanism that determine the semi-annual reversal of upper ocean circulation in the Bay of Bengal. Three numerical experiments have been performed to compare the oceanic response to a remote forcing, a local forcing and a combined forcing. It is found that the long Rossby waves excited by the remotely forced Kelvin waves contribute substantially to the variability of the monsoon circulation. This study indicated that the equatorial Kelvin waves are one of the major features determining the circulation in the eastern equatorial Indian Ocean.

Mc Creary et al., (1996) used a linear continuously stratified model to investigate the forcing mechanisms of East India Coastal Current (EICC). The model solutions suggested that local alongshore winds are very important driving agents throughout the year. The collapse of these winds at the end of the SW monsoon season accounts for the generation of a southward EICC in fall along the south coast of India as suggested by Mc Creary et al., (1993). The interior Ekman pumping was found to be equally important which contribute to the northeastward EICC in spring along the northern coast as suggested by Shetye et al., (1993).

Shankar et al., (1996) used a linear continuously stratified model to investigate the dynamics of EICC forced by interior Ekman pumping and local alongshore winds. They found that in response to interior Ekman pumping , baroclinic Rossby waves are excited in the interior of the bay and propagate to the western boundary where they generate a northward coastal current, if the interior circulation is cyclonic and vice versa. The model EICC flowed northward along the Indian coast from March to September and equatorward along India and Sri Lanka coast from October to January. In contrast to the observations, the onset of southward flow was delayed by several months in spring and flow along Sri Lanka coast does not reverse to flow southward in summer.



### **1.2.2.3 Equatorial and southern subtropical Indian Ocean**

A number of modeling studies have been carried out to identify the forcing mechanism of Equatorial Jets. Wyrki (1973) suggested that the EJ's were directly forced by the equatorial winds between the two monsoons.

O'Brien and Hulburt (1974) used a 2 1/2 layer model to demonstrate that a strong eastward equatorial jet does not develop as a direct response to the westerlies. They have also noted that the rossby wave reflected from the eastern boundary of their model basin were an important part of the equatorial response and were responsible for the disappearance of the wind forced equatorial jets two months after the onset of the westerly winds in the equatorial regions.

Based on current record obtained near Gan Island (0°41'S, 73° 10'E), Knox (1976) and Mc Phaden (1982) confirmed the importance of direct wind forcing. Knox (1976) determined that the pressure gradient term was a significant part of the zonal momentum balance at Gan, indicating the importance of remote forcing by propagating equatorially trapped waves.

Cane (1980) studied the dynamics of the equatorial currents using a 1 1/2 layer model with a constant thickness mixed layer embedded in the active layer. The numerical solutions suggested that the equatorial surface and undercurrent are mainly wind-driven.

Cane and Moore (1981) demonstrated theoretically the existence of a standing equatorial mode composed of long Kelvin and Rossby waves. They pointed the possibility of resonance when the ocean is forced by windstress with a period equal to 4 times the time it takes an equatorial Kelvin wave to cross the basin.

With 2 1/2 years of wind, current and temperature data from the Gan Island, Mc Phaden (1982) suggested that there is a net downward

propagation of energy in the form of equatorial Kelvin and non-dispersive Rossby waves.

Gent et al., (1983) presented an analytical linear model, which when forced by the large semiannual zonal component of the Hellerman and Roseinstein wind stress produced semi-annual reversals of the equatorial currents. It was demonstrated that reflections at lateral walls were essential for a realistic result.

Kindle and Thompson (1989) examined the circulation of the Indian Ocean using a reduced gravity model with one active layer and realistic basin geometry for the entire Indian Ocean north of 30°S. The Hellerman and Roseinstein monthly mean wind stress climatology is used to force the model. The numerical simulations reproduced the observed 26 day oscillations along the equator and the 50 day oscillations between the equator and Madagascar.

Jensen (1993) used a 3 1/2 layer isopycnal model to study the variability of currents in the equatorial Indian Ocean. The solutions are compared with observations and solutions of a 1 1/2 layer model. The model was forced for 21 years with the Hellerman Roseinstein monthly averaged windstress. Both solutions reproduced the main features of the observed wind driven seasonal circulation in the Indian Ocean above the main thermocline.

Anderson and Carrington (1993) used a 16-level GCM of the Indian Ocean driven by United Kingdom Meteorological Office (UKMO) wind stress and Hellerman Roseinstein wind stress data to study the circulation in the Indian Ocean and compared the results with the observations between 55°E and 73°E on equator. They obtained weaker fall jet when the Hellerman Roseinstein wind stress data were used, but a stronger fall jet was obtained when UKMO wind stress data were applied.

Han et al., (1999) obtained solutions to a hierarchy of ocean models ( 2 1/2 layer to 4 1/2 layer, linear and non-linear systems) to isolate the processes that drives the WJ's and to estimate their relative contribution to the total response. They concluded that direct forcing by the semi-annual component of the wind is the dominant forcing mechanism of the WJ's, accounting for 81% of their maximum amplitude. Almost half of this amount (35%) was due to the model's having a mixed layer, which concentrates the WJ into a thinner layer.

Woodburry et al., (1989) used a non-linear reduced gravity model of Indian Ocean developed by Luther and O'Brien (1985) to simulate the major features of the large scale upper ocean circulation in the southern hemisphere and equatorial regions. The model forced by climatological winds, could simulate the major currents such as South Equatorial Current, South Equatorial Counter Current and Somali current in their observed locations.

### **1.3 Objectives of the thesis**

The 3-D circulation of the Indian Ocean is very complex and is controlled by both local and remote forcings because of the peculiar geographical and climatic settings of Indian Ocean. The most important local forcing that control the circulation are the surface wind, internal density field and the processes of advection and diffusion. Strong and variable winds force the ocean locally, and they excite large scale waves such as Rossby and Kelvin waves which travel long distances to affect the ocean remotely. At any instant of time, the 3-D circulation at any geographical area is the resultant of both the local and remote forcings. Circulation is also affected by forcing that occurred elsewhere during the previous season or months. Identification of these forcing functions that control the variability of circulation at different time and space scales and simulation of circulation should be the main objective of any modeling study. We do not have sufficient information on the nature of circulation at different depths,

especially at intermediate and deeper levels in the Indian Ocean. Purely observational studies cannot obtain information on the variability of circulation on such larger space and time scales. To determine the physical and dynamical mechanism underlying the variability of circulation in the Indian Ocean, a variety of ocean circulation models such as diagnostic, semi-diagnostic and prognostic should be developed for the Indian Ocean area. 3D circulation models that could be run in diagnostic, semi-diagnostic and prognostic modes are the best for the study of circulation in the Indian Ocean.

There have been many studies, both observational and modeling, on the circulation and water mass characteristics in the tropical Indian Ocean. The detailed literature survey carried out in sections 1.2.1 to 1.2.2.3 of this chapter reveals that practically all the studies were focused on the theoretical or modeling aspects of a particular current or on a particular basin of the Indian Ocean such as Arabian Sea or Bay of Bengal. All these modeling studies were concentrated on the application of reduced gravity models of varying complexity or prognostic models based on idealized forcing functions. These existing models mainly deal with the upper layer circulation, and there is not much information on the circulation in the intermediate, deep and bottom layers. The existing numerical models of Indian Ocean also do not incorporate all site-specific forcing functions such as fresh water fluxes and river discharge into the coastal areas. Remote forcing from Rossby and Kelvin waves affect the Indian Ocean circulation considerably. Regional models of circulation developed for specific regions of Indian Ocean such as Arabian Sea, Bay of Bengal and equatorial Indian Ocean would obstruct the passage of these waves to different areas of the Indian Ocean, affecting the circulation pattern considerably. It is, therefore, necessary to develop 3-dimensional models of circulation that span entire area of Indian Ocean. The system of currents in the Indian Ocean are interdependent, and the analysis and interpretation of currents in the Indian Ocean area should be carried out in

an integrated manner to identify correctly the forcing functions that control large scale circulation in the Indian Ocean.

One of the main objectives of this thesis is to study the three dimensional circulation of the Indian Ocean using a fully non-linear, primitive equation type, sigma co-ordinate 3-dimensional circulation model, which can be run on diagnostic, semi-diagnostic and prognostic modes. Such a model could identify both local and remote forcing of Indian Ocean circulation. The other objectives of the thesis are the following:

- (i) To study the steady state 3-dimensional circulation of Indian Ocean based on semi-diagnostic calculation
- (ii) To simulate the climatic 3-dimensional circulation of Indian Ocean using the state of art sigma co-ordinate model.
- (iii) To study the sensitivity of Indian Ocean circulation to different wind fields
- (iv) To compare the model results with available information on currents and hydrography of Indian Ocean and to bring out the relative roles of local and remote forcing on the general circulation of Indian Ocean.

A brief outline of the thesis is as follows: Besides this introductory chapter, the thesis contains five other chapters. In chapter-2, a detailed description of the state of art 3-dimentional, sigma co-ordinate model that has been used to the tropical Indian Ocean is given. The model description includes details such as boundary and initial conditions, numerical solution procedure and the forcing parameters of the model.

In chapter-3, monthly mean circulation at various levels of Indian Ocean was calculated by running the model in the semi-diagnostic mode. A detailed analysis of the model results on the spatial variability of currents in the Bay of Bengal, Arabian Sea and southern subtropical

Indian Ocean and its comparison with available information on the currents are presented.

Chapter-4 deals with the simulation of climatic circulation in the Indian Ocean. A detailed analysis of simulation results during various seasons and its comparison with available information on currents are presented.

Results of the circulation model vary depending on the dynamics, spatial resolution, numerical scheme, parameterization of physical processes and the forcing parameters. Wind stress is the main mechanical forcing term that influences significantly on the upper layer circulation. Winds derived from the numerical models of atmospheric circulation are not very realistic for the equatorial and near equatorial regions because of the breakdown of the assumption of geostrophy in these large scale models. Actual observed winds give more reliable information on the wind stress fields at equatorial and near equatorial regions. One sensitivity experiment was carried out by forcing the simulation model with winds derived from Quikscat scatterometer. Results of the response of the tropical Indian Ocean to the Quikscat wind fields are presents in chapter-5.

In chapter-6, the summary and conclusions of the present work and future research prospects are presented.