CHAPTER I

Introduction

The oceans and the atmosphere are closely linked to form one of the most dynamic component of the climate system. The surface layer is the region of the ocean that is in constant contact with the atmosphere, and through which all air-sea interaction takes place. Energy is transferred from the atmosphere to the ocean surface layer that influences the upper ocean characteristics and in turn, energy from the ocean is fed back to the atmosphere affecting the atmospheric circulation, the weather and the climate. The passage of a tropical cyclone over any warm tropical ocean is one of the best examples of air-sea interaction, which stimulates several modes of oceanic variability. The behaviour of the ocean during normal atmospheric conditions and that during extreme weather conditions exemplifies the role of atmospheric forcing in determining the resultant characteristics of the ocean. The energy and momentum transfer from wind to water, and its transfer to remote locations and further to deep oceans, vary in time and space and this plays an important role in determining the dynamics of the upper ocean.

The Indian Ocean is the smallest of the major oceans and is considered by many investigators to be the most complex and the least understood oceanographically. Interestingly, this area is most dynamic because of the changing wind patterns associated with the Indian monsoons. The periodic reversals in the winds and associated changes in the current pattern of the upper ocean in this semi enclosed basin makes it unique compared to the Atlantic or Pacific Oceans. The limited northward extent, presence of warmest Sea Surface Temperature (SST) in the
southeastern Arabian Sea warm pool, the Indian Ocean Dipole, tele-connections with ElNiño/LaNiña, etc. further adds to the unique nature of the North Indian Ocean. Many of the physical phenomena which are well understood in other oceans remain to be explored in detail for North Indian Ocean and thus it makes a perfect basin to study the various aspects of upper ocean response to the passage of cyclone, in particular and its spatio-temporal variability. The present study addresses the details of oceanic response and its variability associated with passage of cyclones.

1.1 Cyclones

A warm-core, non-frontal, synoptic-scale low-pressure system, originating over tropical and sometimes subtropical waters, with an organized deep convection, and a closed surface wind circulation about a well-defined center is referred as cyclone. Once formed, a tropical cyclone is maintained by the extraction of heat energy from the ocean at relatively higher temperature and promotes heat export to the low temperatures of the upper troposphere. Depending on sustained surface winds, the system is classified as tropical disturbance, tropical depression, tropical storm, or tropical cyclone within category 1-5. The cyclone is accompanied by thunderstorms, and circulation of winds near the Earth's surface, which is clockwise in the southern hemisphere and counter-clockwise in the northern hemisphere.

Research at Colorado State University has proved the importance of the surrounding environment with horizontal and vertical wind shear playing significant roles in thermodynamic processes which determine the formation of a tropical cyclone (Gray, 1979). There are six environmental factors that influence the formation of a tropical cyclone - a critical value of earth's vorticity, low-level relative vorticity, vertical wind shear, minimum SST of 26-27°C, potentially unstable troposphere and mid-troposphere humidity. Almost all these factors are satisfied in tropical oceans at any time especially during the summer. Among these, the changes in low level vorticity and vertical wind shear leads to favourable cyclonic conditions.

Cyclones mainly draw their energy from the warm water of the tropics and latent heat of condensation thereof. Sufficient depth in mixed layer, apart from a minimum SST,
is also required, since as the tropical cyclone gains energy from the ocean and favours upwelling. If the upwelled water is too cool, the ocean may no longer be capable of sustaining the development process in atmosphere. Thus, a stationary cyclonic disturbance will not often develop if the depth of the warm surface layer is too shallow.

The passage of a tropical cyclone over the warm tropical ocean stimulates several modes of oceanic variability. Price et al. (1994) reported that the ocean’s response occurs in two stages—forced stage and relaxation stage. The forced stage response is the local response excited by the strong wind stress during the passage of cyclone, includes the mixed layer currents (Sanford et al., 1987) and substantial cooling of the mixed layer and sea surface (Black, 1983; Stramma et al., 1986; Ginis and Dikinov, 1989) and this consists of a geostrophic current and an associated trough in sea surface height. The relaxation response is the non local baroclinic response to the wind stress curl following the passage of cyclone. The time scale of the forced stage response is the cyclone’s residence time (half day). The relaxation stage response is comparatively longer (5-10 days), which is the e-folding of mixed layer currents (Price, 1983 and Gill, 1984).

1.2 Oceanic response to the cyclone passage

The oceanic response to the passage of a cyclone depends on a number of air-sea parameters with maximum response to intense, slow moving cyclones. Price (1981), Shay et al. (1992), Price et al. (1994), Dickey et al. (1998), Jacob et al. (2000) and Morey et al. (2006b) studied in detail the upper ocean temperature response to the passage of cyclones. Marked asymmetry in SST response is reported about the cyclone track, with maximum response on the right side. However the rightward bias is less for slow moving cyclones compared to that for rapidly moving cyclones (Price, 1981). Price et al. (1994) reported the details of various factors that determine the structure and amplitude of the upper ocean currents generated by cyclone passage, also in two stages. The strong wind stress in forced stage generates mixed layer currents with a time scale equal to the residence period of the cyclone. During
relaxation stage, the energy of the mixed layer currents are dispersed as near inertial frequency currents that penetrate into the thermocline, in response to the wind stress curl of the cyclone (Geisler, 1970 and Gill, 1984). Similar to that of SST, significant rightward bias is observed in mixed layer currents caused by the asymmetry in wind field. The wind stress vector rotates clockwise on the right side of the track and remains nearly parallel with the mixed layer currents and generates inertial currents which propagate to a greater distance and depth (Jacob et al., 2000).

1.2.1 SST and mixed layer cooling

The SST response depends on the mixed layer thickness with larger response in thinner mixed layer and in steep upper thermocline temperature gradient (Price, 1981 and Morey et al., 2006b). There is marked asymmetry in the general wind field on both sides of the track with clockwise rotation of the wind vector on right side and anticlockwise rotation on left side of the track in northern hemisphere (Cardone et al., 1977 and Price, 1981). The wind stress and stress curl are in near-resonant coupling with mixed layer currents on the right side of the track and forces high mixed layer velocities. This results in significant drop of SST, caused by the strong entrainment and near inertial mixed layer currents on right side of the cyclone track (Federov et al., 1979; Pudov et al., 1979 and Price, 1981).

Morey et al. (2006a) studied the upper ocean response to surface heat and momentum fluxes associated with a major hurricane Dennis (July 2005) in the Gulf of Mexico. He reported with the help of a numerical model that surface heat fluxes are primarily responsible for widespread reduction (0.5° to 1.5°C) of SST and momentum fluxes are responsible for stronger surface cooling (2°C) near the center of the storm. Mahapatra et al. (2007) reported a shift in the region of maximum surface cooling to the left of the cyclone track in the coastal region of the landfall owing to the importance of coastal dynamics and bottom topography.

There is strong cooling in the mixed layer directly beneath the cyclone track due to intense upwelling. The upwelling considerably enhances the entrainment under slowly moving hurricanes and reduces the rightward bias of the SST response. The pressure
Chapter I – Introduction

Gradients set up by the upwelling and the horizontal advection play an important role in dispersing energy from the mixed layer after the passage of cyclone (Chang and Anthes, 1978 and Price, 1981). The cooling directly beneath the cyclone track is in two stages- direct cooling and post storm cooling. The direct cooling is much lesser than post storm cooling and the magnitude decreases with depth. The cooling depends on many factors including ocean structure beneath the storm (i.e. location), storm speed, time of year and storm intensity (Cione and Uhlhorn, 2003).

1.2.2 Inertial Oscillations

On a non-rotating earth, in the absence of any force the water in motion will move in the same direction at the same speed unless otherwise it is opposed by an external force. But in a rotating earth, the moving water will experience Coriolis force. In the northern hemisphere (southern hemisphere) the Coriolis force deflects the water parcel to the right (left) at right angles to the direction of motion which will result in the water parcel to move in a circle. These oscillations continue even after the forcing stops as a consequence of inertia and is referred as inertial oscillation.

The inertial oscillation is considered as the manifestation of unforced ocean dynamics. It is the balance between the rate of change of velocity and Coriolis force (Gill, 1982). Webster (1968) reported that inertial currents occur at all depths in the ocean with velocities ranging from 10 to 80 cm/s. The amplitude varies depending on the strength of generating mechanisms and they decay due to friction when the forcing stops (Pond and Pickard, 1986). Generally inertial oscillations are observed after the passage of cyclones. The direction of rotation is clockwise (anticyclonic) in northern hemisphere and is anticlockwise (cyclonic) in southern hemisphere.

The inertial period \( T \) is a function of Coriolis force \( f \), which in turn varies with latitude and hence it increases towards the equator.
Chapter I – Introduction

\[ T = \frac{2\pi}{f} \]  

where \( f = 2\Omega \sin(\Phi) \), ‘\( \Omega \)’ (7.292 x 10^{-5} \text{ rad/s}) is the angular velocity of the earth and ‘\( \phi \)’ is the latitude of observation. The radius of the circle is: \( r = \frac{V}{f} \)  

where ‘\( V \)’ is the inertial current speed.

The forcing perturbations and the availability of energy in the ocean system is expected to generate inertial oscillations. Wind forcing is a major initiator of the inertial oscillation (Pollard, 1970; Pollard and Millard, 1970; Weller, 1982 and Poulian et al., 1992). The horizontal temperature gradients in the ocean interacting with the vertical mixing may also generate sustained inertial oscillations (Pedlosky and Stommel, 1993). Lien et al. (1996), Brink (1989), Shay and Chang (1997), Firing et al. (1997), Saji et al. (2000) and Jacobs et al. (2001) have reported inertial oscillations after the passage of various cyclones. The inertial oscillations are initially excited primarily in the surface mixed layer and then propagate down into the thermocline and away from the forcing region (Lien et al., 1996). Garret (2001) and Chiswell (2003) proved that deep inertial oscillation could penetrate only towards equator. The duration of the wind as compared with the inertial period is the most important factor, which governs the amplitude of the inertial oscillation (Gonella, 1971). The largest inertial amplitude reported so far is 1.7 m/s associated with an unusually large and strong hurricane Gloria (Price et al., 1994). This maximum amplitude was found in the mixed layer to the right rear quadrant of the storm. Shenoi and Antony (1991), Rao et al. (1996), Saji et al. (2000), Hareeshkumar et al. (2001) and Joseph et al. (2007) have reported inertial oscillations in the North Indian Ocean under various meteorological conditions.

There is marked asymmetry in circulation pattern on both the sides of the cyclone track. The near inertial oscillations are stronger where the wind direction rotates clockwise, resonating with the inertial oscillations. It happens on the right side of the track in northern hemisphere and left side of the track in southern hemisphere. These inertial currents exist for a period of a few weeks, which depends on the intensity of the cyclone and the local dynamics. The inertial band account for more than 50% of the total kinetic energy in the mixed layer (Pollard, 1980 and Thomson et al., 1998).
The frequency of inertial oscillation depends mainly on the local latitude, but generally the observed frequency varies from the theoretical value. Factors affecting the frequency of the inertial oscillations are latitudinal variation of Coriolis factor, which is capable of generating mean eastward or westward drift (Ripa, 1997), divergence in the quasi geostrophic flow field (Weller, 1982), vorticity in the quasi geostrophic flow field (Mooers, 1975 and Perkins, 1976), dissipation of energy through friction or other means (Pollard, 1970) and stratification and eddy viscosity of the water (Gonella, 1971). Many studies have reported a shift between the theoretical and the observed frequencies (White, 1972; Kundu, 1976; Millot and Crepon, 1981 and Saji et al., 2000, Elipot, et al., 2010). The observed inertial frequency less (higher) than the theoretical frequency is termed as red (blue) shift. Gonella (1971) has reported that the difference is smallest when the transfer of momentum is at a maximum due to the homogeneity of the surface layer. Thomson et al. (1998) have reported a blue shift of 1.3 % in the northeast Pacific. White (1972) suggested that frequency shift observed in the equatorial currents were due to a positive doppler shifting of the frequency of the inertial wave by the zonal mean flow past the moored system. The lowering of the inertial frequency is possible through the large-scale flow altering background vorticity (Mooers, 1975; Perkins, 1976 and Weller, 1982). The dissipation of inertial oscillation energy by the bottom friction or turbulent mixing downward from the surface layer is another reason for lowering of inertial frequency (Pollard, 1980). Poulian (1990) and Jacobs et al. (2001) reported a red shift in the observed inertial frequency in North Pacific and Korea Strait respectively. Salat et al. (1992) reported a red shift of 10% in the shelf-slope front off northeast Spain.

1.2.3 Surface wave

The passage of a tropical cyclone generates violent waves which are a major threat to the navigation in the open ocean and turns disastrous as it approaches the coast. The cyclonic wind induced wave height increases significantly with intensity of the cyclone. Kumar et al. (2001 and 2003) studied in detail the estimation of wind speed and wave height during cyclones and found that the empirical relation holds good when the wave height is more than 3 m. In another study, Kumar et al. (2004) analysed the wave characteristics off Visakapatnam, during the passage of a cyclone
in November 1998 and reported significant variability in wave spectra during cyclone passage. The swells generated by the cyclone travel long distance, thereby affecting the distant locations. Cyclone generated waves play a significant role in design of coastal and offshore structures (Young, 2003).

Apart from the above, the upper ocean responds in many folds to the passage of a tropical cyclone which has significant impacts on the physical, chemical and biological properties. The wind induced mixing produces significant change in chlorophyll-a concentration and salinity of the upper ocean. The increase in primary productivity associated with the cyclone passage and the subsequent increase in phytoplankton biomass has been an active field of research (Shiah et al., 2000, Madhu et al., 2002, Vinayachandran and Mathew, 2003 and Vinayachandran et al., 2005). However, the present study has been aimed at identifying in detail the properties of reduction in SST, cooling of the mixed layer, the inertial oscillations and the modification on waves associated with the passage of tropical cyclones.

1.3 Cyclones in North Indian Ocean

The north Indian Ocean is subdivided into two tropical cyclone areas, the Arabian Sea (AS) and the Bay of Bengal (BoB). The frequency and intensity of tropical cyclone experienced in this area are less compared to other oceans, on an average six occurrences per year, which is about 6.5% of cyclone occurrences (wind speeds greater than or equal to 17m/s) in the world waters (Neumann, 1993 and McBride, 1995). The BoB is the area of higher incidence of cyclones compared to AS because of the favorable conditions and is about 5 to 6 times the frequency in the Arabian Sea (Dube et al., 1997 and Chinthalu et al., 2001). These disturbances move towards north, northeast or northwest based on various cyclone parameters such as seasonality, initial position, intensity, speed and size of the cyclone (Deo et al., 2001).

The tropical cyclones in the North Indian Ocean exhibit significant temporal variation in which the seasonal variation is more remarked than the annual variation. The variability in cyclone genesis is associated with the location of the thermal equator as it moves north and south with seasons (Lal, 1991; Menon, 1997 and Asnani, 2005).
India Meteorological Department (IMD) has prepared a detailed atlas on the tracks and frequency of storms for the period 1877-1990. The first part describes the cyclones during the period 1877 to 1970 and the second part during the period 1971 to 1990 (IMD, 1979 and IMD, 1992). The cyclone tracks available in the Unisys website for the period 1945 to 2006 also exhibits significant inter-annual and seasonal variability in terms of the originating area, intensity, track, and landfall.

The cyclones in BoB are most destructive, when they strike the low lying coastline. The piling up of water due to the funnel shape of the coastline and the narrow continental shelf combined with the high population density along the coastal areas amplifies the damage and loss of property. Interestingly, vulnerability to storm surges is not uniform along Indian coasts in terms of height of the storm surge and frequency of occurrence. And, of course, east coast of India faces higher vulnerability than that along west coast. Among the cyclones that crossed the coasts of India, the most disastrous as indicated by were as given below:

- The cyclone that hit Calcutta in October 1737 coinciding with a violent earthquake, accounts for a toll of 3,00,000 lives accompanied by a 12m high storm surge (Lander and Guard, 1998).
- Midnapore Cyclone of October 1942 was accompanied by gale wind speed of 225 km/hr.
- Rameswaram Cyclone of December 1964 wiped out Dhanuskodi in Rameswaran Island from the map with storm surge of 3-5m.
- Bangladesh Cyclone of November 1970 took toll of about 3,00,000 people with storm surge of 4-5m (Lander and Guard, 1998).
- Andhra Cyclone of November 1977 took a toll of about 10,000 lives with maximum wind speed of 200 km/hr and storm surge of 5m (Lander and Guard, 1998).
- Orissa super cyclone of October 1999 has been estimated for maximum wind speed of 260-270 km/hr in the core area which produced a huge storm surge that
led to pile up of more than 6m of water and took a toll of nearly 10,000 people (Kalsi and Srivastava, 2006).

Many studies have been conducted recently on the various aspects of the Orissa super cyclone (October 1999), one of the most destructive cyclones in Indian history. Most of these studies address the cyclone genesis, intensification, forecasting the track, landfall and other atmospheric parameters (Rajesh et al., 2005; Kalsi and Srivastava, 2006; Bhaskar Rao and Hariprasad, 2006; Loe et al., 2006 and Kalsi, 2006). The upper ocean response to the passage of cyclones are addressed by Nayak et al. (2001), Madhu et al. (2002), Vinayachandran and Mathew (2003); they focused on the biological response and the impact on primary productivity. Mahapatra et al. (2007) studied the transformation of the upper ocean's response in the near-coastal waters to the 1999 Orissa super cyclone using a 3-dimensional model. He reported region of maximum surface cooling on the left of the cyclone track which indicates the importance of coastal dynamics and bottom topography in upper ocean response.

Rao (1986, 1987), Rao and Sivakumar(1998), Premkumar et al. (2000), Rao and Premkumar (1998), Shenoi et al. (2002), and Sengupta et al. (2002) reported the significant reduction in SST and mixed layer cooling associated with the passage of various cyclones in the North Indian Ocean. Sengupta et al. (2007) reported that pre-monsoon and post monsoon cyclones differ significantly in the reduction of SST in North Bay of Bengal. He reported that a shallow upper layer of freshwater due to river runoff and monsoon rains reduces the cooling during post monsoon cyclones.

The response of upper ocean physical and biological properties to the passage of May 2003 cyclone in the southern Bay of Bengal reports a decrease in SST up to 5°C, associated with the deepening of mixed layer by about 12m (Smitha et al., 2006). Changes in the current pattern associated with cyclone passage are reported in many studies. Saji et al. (2000) and Joseph et al. (2007) reported the inertial oscillation generated by the passage of cyclones from buoy observations in the BoB.
1.4 Objectives

The time series observations along the track of a tropical cyclone are very crucial for understanding the oceanic response and its variability. However the observations in the cyclone track are limited, especially the in-situ time series observations. There are many studies, which report the atmospheric characteristics and upper ocean responses during the passage of cyclones in world oceans. The majority of the reports on cyclone passage in North Indian Ocean concentrate on the atmospheric parameters of tropical cyclone, its genesis, intensification and forecasting whereas the report on oceanic response are limited due to the inadequate in-situ observations. In this context, the North Indian Ocean requires detailed studies of this aspect, especially the spatio-temporal variability. The establishment of moored buoy network in 1997 in the Indian Seas provided a wealth of information regarding the upper ocean characteristics and this could thereon disclose the oceanic response to cyclone passage and its spatio-temporal variability. The present study is a first of its kind to understand the characteristics of inertial oscillation and its variability in North Indian Ocean utilizing moored buoy observations, as most apt choice.

The objectives of this study are:

- To understand the upper ocean response to extreme atmospheric forcing due to cyclones in the North Indian Ocean highlighting the reduction in SST, cooling of the mixed layer, inertial oscillation and the response in the wave characteristics.

- To analyse the spatio-temporal variability of cyclone frequency in North Indian Ocean with an emphasis on the inter-comparison between AS and BoB.

- To identify the relative importance of various factors that controls the upper ocean response to cyclones highlighting the cooling in SST.
1.5 Scheme of the thesis

The doctoral thesis has been arranged into six chapters. The first chapter gives a general introduction to the ocean surface layer responses on the passage of cyclones with reviews related to the significant reduction in SST, the mixed layer response, the inertial oscillations and change in wave characteristics. A detailed literature review on the above aspects depicting the studies carried out elsewhere and specifically, in the North Indian Ocean is presented in this chapter.

The details of data sets used and the various mathematical and analytical methods applied in this study are given under chapter II.

Chapter III deals with the spatio-temporal variability in cyclone frequency in North Indian Ocean. The inter-annual, intra-annual and spatial variability of tropical cyclones in the North Indian Ocean are addressed in detail. The long term observations of monthly average SST and sea level pressure are also utilized to identify the role of local dynamics in the spatio-temporal variability of cyclones.

The upper ocean response to cyclone passage in North Indian Ocean are addressed in two chapters. Chapter IV deals with the characteristics of oceanic response in AS and Chapter V describes the same in BoB. The drop in SST, the sudden increase in wave height, change in current pattern, fluctuations in wind direction, rotation in surface current direction etc. are studied in detail, utilizing the in-situ buoy observations during the passage of cyclones. The spatial response of the upper ocean has been studied utilizing the TMI-SST data. Detailed analysis of the variability in oceanic response and important conclusions are provided at the end of each chapter.

Chapter VI presents the conclusion of the study listing all major findings and its implications. The asymmetric response in wave characteristics is also presented. The oceanic response to cyclones in terms of intensity, relative location, proximity to track and drop in SST are analysed in detail with an emphasis on variable response between AS and BoB.

Reference list is appended.