CHAPTER - 4

MARINE ATMOSPHERIC BOUNDARY LAYER CHARACTERISTICS OVER ARABIAN SEA AND BAY OF BENGAL
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4.1 INTRODUCTION

The prime focus of this study is to examine the dynamics of marine atmospheric boundary layer (MABL) over Arabian Sea and Bay of Bengal during the different seasons using data from satellite derived QuikSCAT sea wind sensor. MABL is the layer just above the sea surface, influenced by the presence of the ocean surface and plays an important role in the exchange of momentum, mass and energy across the surface and influences to a large extent the atmospheric and oceanic circulations. The planetary boundary layer (PBL) process over land and ocean constitute important physical inputs in the numerical simulation of the monsoon (Rao, 1988, Krishnamurti et al. 1973, Manabe et al. 1974, Shukla et al. 1981) and PBL physics are usually incorporated in models by adopting suitable parameterisation schemes (Kusuma, et al, 1991).

4.1.1 Arabian Sea

Arabian sea is one of the important play grounds of the South Asian monsoon especially in wind and SST regimes. Seasonal variation of wind is well documented in literature, northeasterly during winter and during summer it is southwesterly. Many field studies were carried out to bring out the characteristics of Arabian Sea. The IIOE (International Indian Ocean Expedition, 1963-1965) paved the way to study thermal and kinetic features of the monsoon flow over the Arabian Sea and adjoining West Indian Ocean. In this expedition, the experimental arrangement consists of a six leveled logarithmically scaled vertical sensors mounted on a floating mast, measurements were made between 1.6 m and 8 m above mean sea level under a variety of stability and wind speed conditions (Badgley, et al 1972). The radiosonde and dropsonde data were first used in this experiment and they provide valuable information about the marine atmosphere over Indian Ocean region and the results were discussed in Bunker (1965). After the IIOE Indo-Soviet Monsoon Experiment
(ISMEX) in 1973 and monsoon Experiment in 1979 were carried out. Using ISMEX data set Jambunathan and Ramamurty (1975) studied the air sea temperature distribution over West Indian Ocean and Pant (1978) studied the MABL structure over West Indian Ocean. INDOEX (Indian Ocean Experiment) were carried out in 1998 to bring out characteristics of aerosol, radiation and solar absorption at the surface and in the troposphere including the ITCZ cloud systems (Ramanathan et al, 1995).

4.1.2 Bay of Bengal

Most of the rainfall occurs in association with synoptic systems such as lows and depressions, which are generated over the warm oceans and subsequently propagate to Indian land mass. Many of them are formed and intensified over Bay of Bengal and then moved to land mass. The Bay of Bengal is exceptionally fertile to these systems and play an important role in the monsoon variability (Gadgil and Mohanty, 2000). Many observational studies based on satellite data suggest that tropical SST and deep convection are strongly related (Graham and Barnett, 1987). It is due to the sensible and latent heat fed deep convection formed in the atmosphere at the ocean surface. The sensible and latent heat transfer in the ABL over the region plays vital role in the generation of deep convection. Hence the process in the ocean and atmosphere are strongly interrelated each other and their coupling mechanism is important in identifying features of deep convection. It has been known that the more pronounced variabilities in SST and other meteorological parameters are in the Bay of Bengal than the Arabian Sea (Krishnamurty, et al 1988). Studies carried out over Pacific Ocean showed that MABL plays a vital role in the growth and maintenance of the tropical disturbances (Neelin et al 1987; Yano and Emanuel, 1991). They reported further that the boundary layer itself gets modified by the disturbance and their interaction can lead in the variability of deep convection on subseasonal and seasonal time scales.

Several studies were carried out in the Bay of Bengal to explore the ABL features since the last two decades. The first two major field experiments were MONSOON-77 and MONEX-79 and they involved several Indian and Soviet ships. The third experiment conducted were MONTBLEX-90 (Monsoon trough boundary layer experiment) during the period 18-31 August, 1990 and 9-19 September 1990 in
the head Bay. From the above field experiments, dynamic and thermodynamic
c characteristics of the MABL over Bay of Bengal were found (Mohanty and Das,
1986; Mohanty and Mohankumar, 1990). Another field cruise named BOBMEX
(Bay of Bengal monsoon experiment) was carried out in the Bay of Bengal during
the months of July and August, 1999, a BOBMEX-Pilot experiment was also conducted
during the period October to November, 1998 to study the features of MABL
associated with convection and to study the coupling between atmosphere and ocean
(Sikka and Sanjeevarao, 2000).

Holt and Raman (1987) studied the structure of boundary layer over the
Arabian Sea and Bay of Bengal during active and break phases of monsoon using
ISMEX-77 & MONEX-79 data set. They found that the height of the boundary layer
decreases during active phase and increases during weak phases of monsoon. Sam et
al, 2003 examined the temporal evolution of turbulent kinetic energy, sensible and
latent heat fluxes and drag coefficient using radiosonde data taken at the BOBMEX-
99 during the different epochs of Indian summer monsoon. They reported that
simulation results using 1-D model agree with the observational analysis. TOGA
COARE (Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response
Experiment), which was aimed to describe the coupling of the west Pacific warm pool
to the atmosphere (Webster and Lukas, 1992), gave an insight to the atmosphere
ocean coupling on time scales of intra seasonal (Godfrey and Lindstorm, 1989;
Shinoda et al. 1998). The energy supplied by the atmosphere is mostly trapped in the
MBL, except in the region of deep convection. Mahrt and Ek (1993) studied the
spatial variability of the turbulent fluxes and roughness lengths over a heterogeneous
surface using the flight data during clear sky days and found that the effective
roughness length is about 1 m. So, it is very important to understand the various
c characteristics such as drag coefficient, roughness length and other parameters of the
MABL.

4.2 Objective of the study

The study is focused on the dynamical characteristics of the marine
atmosphere over Arabia Sea and Bay of Bengal with QuikSCAT wind products and
TMI SST derived from satellites. This high-resolution data set can be used to derive a
better understanding of the MABL and provides valuable information over the
Arabian Sea and the Bay of Bengal since it is very difficult to get the data in the region. Many studies were made to calibrate the reliability of the data set and it can be found in Bentamy et al (2002) and also available in the website http://www.ifremer.fr/cersat/english. Goswami and Rajagopal, (2004) also made comparison of the QuikSCAT wind in situ observations taken from satellite data and buoys located over Arabian Sea and Bay of Bengal and found that this dataset agrees well with observations. So, the surface information on wind vector and its products are reliable to study the characteristics of wind stress, frictional velocity, roughness length and wind stress curl on seasonal basis.

4.3 Data and Methods

4.3.1 Data description

The data sets used for the present study are the zonal and meridional components of the surface wind, wind stress and wind stress curl from 20th June 1999 to 30th December, 2003 taken from the two dimensional surface wind fields measured by the SeaWinds scatterometer on board of QuikSCAT satellite of National Aeronautics and Space Agency, the description can be found in the QuikSCat Mean Wind Field User Manual. In addition to ERS-2 scatterometer launched by European Space Agency (ESA) in April 1995, a new scatterometer, Sea Winds was launched onboard QuikSCAT satellite by NASA/JPL in June 1999 (http://podaac.jpl.nasa.gov/quickscat/).

4.3.1.1 SeaWinds sensor overview

The SeaWinds instrument uses a rotating dish antenna with two spot beams that sweep in a circular pattern. The antenna radiates microwave pulses at a frequency of 13.4 GHz across broad regions on Earth's surface. The instrument collects data over ocean, land, and ice in a continuous, 1,800-wide-wide band centred on the spacecraft's nadir sub track, making approximately 1.1 million ocean surface wind measurements and covering 90% of Earth's surface each day. The SeaWinds instrument on QuikSCAT is an active microwave radar designed to measure electromagnetic backscatter from wind roughened ocean surface. QuikSCAT/SeaWinds is a conically scanning pencil-beam scatterometer. A pencil-
beam scatterometer has several key advantages over a fan-beam scatterometer; it has a higher signal-to-noise ratio, is smaller in size and it provides superior coverage.

4.3.1.2 Introduction to QuikSCAT

QuikSCAT has two major systems, the space borne observatory system and the ground data processing system. The SeaWinds observatory instrument is specialised microwave radar designed to measure winds over the oceans. The ground system computers produces wind measurements within 3 days of receiving raw QuikSCAT data from the spacecraft, with no backlog, throughout the mission. QuikSCAT data products currently include global backscatter data and 25 km resolution ocean wind vectors in the measurement swaths. There are also plans to provide spatially and temporally averaged, gridded, wind field maps and other special products.

4.3.2 Product description

This section describes the main characteristics of the QuikSCAT mean wind fields produced at CERSAT, and provides detailed specifications of the format of the data files.

4.3.2.1 Spatial coverage

The QuikSCAT mean wind fields cover global oceans from 80° North to 80° South in latitude and 180° West to 180° East in longitude.

4.3.2.2 Spatial resolution

The QuikSCAT mean wind fields are provided on a rectangular 0.5°x0.5° resolution grid. The data are projected on a 0.5° rectangular grid of 720 columns and 320 lines. A grid cell spans 0.5° in longitude and 0.5° in latitude. Latitude and longitude of each grid cell refers to its centre. The origin of each data grid is the grid cell defined by 179.75° West in longitude and 79.75° North in latitude. The last grid cell is centered at 79.75° South and 179.75° East.
4.3.2.3 Temporal resolution

Mean winds fields are available from 20 July 1999 to present. Three different temporal resolutions are provided and they are daily mean, which covers the time period from 0h to 24h in the current day, weekly mean, which covers the time period from Monday 0h to Sunday 24h in the current week and monthly mean, which covers the time period from the first day at 0h to the last day at 24h in the current month.

4.3.2.4 Main parameters

The main parameters derived from the QuikSCAT wind field are (1) Wind speed modulus (0 - 60 ms$^{-1}$), (2) Zonal wind component (-60 - 60 ms$^{-1}$), (3) Meridional wind component (-30 - 30 ms$^{-1}$), (4) Wind stress modulus (0 - 2.5 Pa), (5) Zonal wind stress component (- 2.5 - 2.5 Pa), (6) Meridional wind stress component (- 2.5 - 2.5 Pa), (7) Wind vector divergence (- 10$^{-3}$ - 10$^{-3}$ s$^{-1}$), (8) Wind stress curl (- 2.5 - 2.10$^{-5}$) and (9) Estimated error of each of the above parameters is provided with the same unit.

4.3.3 Methodology description

4.3.3.1 Retrieving wind vectors from scatterometer measurements

Scatterometer instruments on board satellites can routinely provide an estimation of the surface wind vector with high spatial and temporal resolution over all ocean basins. Although the exact mechanisms responsible for the measured backscatter power under realistic oceanic conditions are not fully understood, theoretical analysis, controlled laboratory and field experiment, and measurements from space borne radars all confirm that backscatter over the oceans power at moderate incidence angles is substantially dependent on near-surface wind characteristics (speed and direction with respect to the radar viewing geometry). At the present time, the microwave scatterometer is the only satellite sensor that observes wind in terms of wind speed and wind direction. To date, the most successful inversions of scatterometer measurements rely on empirically derived algorithms. An empirical relationship is typically given by the following harmonic formula:
\[ \sigma^0 = \sum_{j=0}^{k} A_j(\lambda, P, \theta, U) \cos(j\chi) \]  \hspace{1cm} (4.1)

Where \( k \) is the degree of \( \sigma^0 \) representation that uses cosines as orthogonal basis (number of harmonics), \( \lambda \), the scatterometer wavelength, \( P \), the polarization, \( \theta \), the radar incidence angle, \( U \) the wind speed for neutral stability and \( \chi \) is the angle between wind direction and radar azimuth. \( A \) are the model coefficients to be determined through regression analysis. Surface wind speed and direction at a given height are retrieved through the minimization, in \( U \) and \( \chi \) space, of the Maximum Likelihood Estimator (MLE) function defined by

\[ F = -\sum_{i=1}^{N} \left( \sigma_{i}^0 - \sigma_{m}^0 \right) \frac{1}{\text{Var}[\sigma_{m}^0]} \]  \hspace{1cm} (4.2)

Where \( \sigma^0_m \) and \( \sigma^0 \) are the measured and estimated, from (1), backscatter coefficients, respectively. Variance (\( \sigma^0_m \)) stands for \( \sigma^0 \) variance estimation. \( N \) is the number of measured \( \sigma^0 \) used in the wind vector estimation. This approach yields up to four solutions and an ambiguity removal procedure is needed in order to estimate the most probable wind vector (Quilfen et al, 2001). A main task for a scatterometer investigator is the calibration of the sensor data. The calibration involves both the determination of the empirical model (1) and the development of the surface wind retrieval algorithm. A second task consists in validating the accuracy of backscatter coefficients and wind estimates and their comparison with other sources of data. Since July 1999, two scatterometers are available and provide surface wind estimates with different instrumental configurations. The first one is on board the European Remote Sensing satellite 2 (ERS-2) and the second is the NASA scatterometer SeaWinds on board QuikSCAT. The use of both wind estimates should potentially lead to a more refined wind field analysis calculated from satellite data.

4.3.3.2 Wind stress estimation

To estimate surface wind stress, \( \tau \) for each scatterometer wind vector, the bulk formulation is used:

\[ \tau = \left( \tau_x, \tau_y \right) = \rho C_w W(u, v) \]  \hspace{1cm} (4.3)

Where \( W \), \( u \) and \( v \) are the scatterometer wind speed, zonal component (eastward) and meridional component (northward), respectively. The surface wind is assumed to be
parallel to the stress vector. \( \rho \) is the density of surface air equal to 1.225 \( \text{kg/m}^3 \). \( C_D \) is the drag coefficient. The magnitude of the stress is:

\[
|r| = C_D W^2 \rho \quad (4.4)
\]

There have been many estimates of \( C_D \). We have selected the one published and recommended by Smith (1988), which was chosen by the WOCE community.

Frictional velocity, \( u_* \) is obtained from the formula

\[
u_* = \sqrt{\frac{\tau}{\rho}} \quad (4.5)
\]

where \( \tau \) is the wind stress and \( \rho \) is the density of air. The roughness length, \( z_0 \) is calculated using

\[
\overline{U} = \frac{u}{k} \ln \frac{z}{z_0} \quad (4.6)
\]

where \( \overline{U} \) is the mean wind, \( k \) is Von Kármán constant and the value is taken as 0.4 and \( z \) is the reference height and is taken as 10 m.

### 4.4 Spatial variation of surface layer parameters

#### 4.4.1 Surface wind

The climatology of the surface wind pattern derived from QuikSCAT SeaWinds scatterometer for different seasons are presented in Fig.4.1. Here, the figures are presented over the region 50\(^\circ\)E-100\(^\circ\)E to 25\(^\circ\)S-25\(^\circ\)N to bring out the features over the entire monsoon domain. In the figure, the left top panel shows wind pattern for winter (January), which represents northeasterly over the Arabian Sea and Bay of Bengal since January belongs to northeast monsoon season. In the south of 10\(^\circ\)S, the prominent wind direction is southeasterly. The winds from equatorial region and 20\(^\circ\)S converge around 11\(^\circ\)S and blow towards east. The top right panel of the figure shows similar features during pre-monsoon season (April). During April, the surface winds are in transition stage from northeasterly to southwesterly and hence winds are feeble both in the Arabian Sea and Bay of Bengal. The wind over the west peninsular coastal belt is relatively stronger and the direction is northwesterly. In Indian Ocean (south of the equator) the speed and direction of the wind are same but the convergent zone is shifted to the north and now occupies over the equator, but the wind is feeble in comparison with that in winter. The wind pattern during southwest
monsoon (July) is presented in the left bottom panel of the Fig.4.1. In this, the surface wind is stronger compared to all other seasons and is due to the intensification of the surface wind by the Low Level Jetstream (LLJ). The LLJ core occurs at 850 hPa over the Indian subcontinent during the southwest monsoon period only (Joseph and Raman, 1966; Findlater, 1966). This strengthening of the surface wind results in the abundant transfer of moisture from the sea surface to the atmosphere over this region for the maintenance of the southwest monsoon. The bottom right panel of the figure shows the wind pattern during the post monsoon season (November). During this period, the prominent surface wind direction is northeasterly due to the influence of post monsoon and the strength is relatively low.

![Wind patterns for different seasons](image)

Fig.4.1 Averaged surface wind in ms\(^{-1}\) for the years from 1999 to 2003 during January, April, July and November representing different seasons.

### 4.4.2 Frictional velocity

Frictional velocity is the scaling parameter of wind speed (Stull, 1997). As described in the previous section, it can be evaluated from the wind stress available from QuikSCAT data set. Fig.4.2 gives frictional velocity \( (u_\tau) \) over the Arabian Sea.
and Bay of Bengal during the four seasons. During winter, spatial variation of $u_*$ is small both in the Arabian Sea and Bay of Bengal. The isolines of $u_*$ are oriented with values increasing towards north with slightly high values in the Bay of Bengal. During pre-monsoon period, the value of $u_*$ over Arabian Sea is around $0.15 \text{ ms}^{-1}$ and that over Bay of Bengal is between 0.1 and 0.25 centered near the central Bay of Bengal region surrounded by contours of increasing values. The frictional velocity values are high during southwest monsoon season compared to all other seasons. The highest values (more than $0.55 \text{ ms}^{-1}$) are found near Somali coast in the Arabian Sea. In the Bay of Bengal, the highest value is more than $0.375 \text{ ms}^{-1}$ in the central Bay. During the southwest monsoon season surface winds as well as the vertical wind shear are strong resulting high $u_*$. The horizontal variation of frictional velocity over both the Arabian Sea and Bay of Bengal is small during the post-monsoon season and the value is around $0.2 \text{ ms}^{-1}$. Maximum spatial variation of frictional velocity among the four seasons is during the southwest season in the south Arabian Sea, varying from $0.3 \text{ ms}^{-1}$ to $0.5 \text{ ms}^{-1}$ followed by the variation during the pre-monsoon season over the Bay of Bengal, varying from $0.1 \text{ ms}^{-1}$ to $0.25 \text{ ms}^{-1}$.

Fig.4.2 Averaged frictional velocity in $\text{ms}^{-1}$ for the years from 1999 to 2003 during January, April, July and November representing different seasons.
4.4.3 Roughness parameter

Fig. 4.3 Averaged roughness parameter in mm for the years from 1999 to 2003 during January, April, July and November representing different seasons.

Roughness length, $z_0$, is the length from the surface up to which the wind velocity becomes zero. Generally, information on $z_0$ is derived using data observed in connection with field experiments over land or ocean. Since it is difficult to take such observations during all seasons over entire region, the characteristic features of $z_0$ are not properly studied. By the advent of high resolution satellite derived wind data, this parameter can be evaluated with reliability. Here, spatial distribution of $z_0$ is presented for winter, pre-monsoon, southwest monsoon and post monsoon seasons in the Fig.4.3. During winter, $z_0$ values vary from 0.2 mm to 1 mm and are more than 0.5 mm over the entire coastal belt except over the Sri Lankan region. The values are high (more than 1 mm) over the north AS and Somali coast. During the pre-monsoon season, the roughness length is more than 9 mm over the entire south Bay of Bengal and coastal regions of Somali due to feeble wind over these regions in
the transition period. During the southwest monsoon season, the values are extremely low (in range of $10^{-4}$ mm) both over Arabian Sea and Bay of Bengal due to the high wind speed associated with the monsoon. In the post-monsoon season, there are regions of small values of the parameter ($< 1 \times 10^{-4}$) over southwest Arabian Sea and central Bay of Bengal. High values are found over the west peninsular region (more than 1 mm), over the head Bay of Bengal (more than 9 mm) and south Bay of Bengal (more than 10 mm). The range of roughness length is maximum in both Arabian Sea and Bay of Bengal during the post monsoon season due to large spatial variation of wind.

4.4.4 Wind stress curl

The wind stress curl depends mainly on the surface wind. The wind stress curl is a measure of rotation of the force applied by the wind. The zonal wind stress in the equatorial region is westerly during pre-monsoon season and largest during spring and fall that drive the equatorial spring and fall jets in the Indian Ocean (Wyrtki, 1973). The atlas by Hastenrath and Lamb (1979) gave a complete reference to the atmospheric fields over the equatorial region. The climatological wind stress and curl of the wind stress showed maximum amplitude off the coast of Somalia (Hellerman and Rosenstein, 1983). However, the curl changes its sign during northeast and southwest monsoon seasons. Here, we made an attempt to study the wind stress curl over different parts of the AS and BOB during the four seasons and influence of monsoon activity on wind stress curl. The mean distribution of wind stress curl is presented in Fig.4.4. Winter season is characterized by cyclonic stress (positive values) over the equatorial region ($10^\circ$N to $10^\circ$S) with a maximum value of $1.5 \times 10^{-7}$ Nm$^{-3}$ but on either side of the equatorial belt anticyclonic stress is seen. Maximum value is found around $-1.5 \times 10^{-7}$ Nm$^{-3}$, but on the northern side, the value of negative stress is less ($-0.5 \times 10^{-7}$ Nm$^{-3}$). During pre-monsoon period the area and intensity of the cyclonic stress is decreased. Over the southern part, the anticyclonic stress increases and shifts towards north. During the southwest monsoon season, the cyclonic stress is extended to both AS and BOB, the value (more than $-3.5 \times 10^{-7}$ Nm$^{-3}$) of stress curl is more over the east central AS (near Somali coast). But near Sri Lanka, anticyclonic wind stress curl is noticed. During the post-monsoon season positive values are found over the equatorial region and negative values are seen on either side of the equatorial belt.
Fig. 4.4 Averaged wind stress curl (Nm$^{-3}$) parameter for the years from 1999 to 2003 during January, April, July and November representing different seasons.

4.5 Dependence of wind with surface parameters

4.5.1 Momentum flux (wind stress)

The surface flux of momentum or wind stress influences all aspects of air-sea interactions. For example, it drives the growth of capillary and surface gravity waves, the development of the mixed layer and even the large-scale circulation of the oceans. An improved understanding of the wind stress vector is of interest to meteorologists, oceanographers, and climatologists alike (Dobson and Toulany, 1991). Wind stress is the pressure exerted on the surface of the ocean by wind and here it is expressed in the unit Pascal (Pa). The relation of surface wind speed at surface with wind stress, roughness length are studied over Arabian Sea and Bay of Bengal for January, April, July and November representing winter, pre-monsoon, southwest monsoon and post monsoon seasons respectively. The surface wind stress estimated by using bulk aerodynamic formulae stated in equation (4). The relation of the wind stress with surface wind over Arabian Sea (15°N-20°N & 60°E-70°E) and Bay of Bengal (15°N-
20°N & 85°E-90°E) shows a good relation in an exponential way. The Fig.4.5 and Fig.4.6 show the wind speed against wind stress over Arabian Sea and Bay of Bengal for different seasons. In all seasons the wind stress related to wind field in the same way. Since wind stress depends on the square of wind speed, it is a non-linear relationship. viz, the stress versus wind speed curves upward. The wind stress increases with the wind in an exponential way resulting the power law fit. On the basis of the interrelationship, one can obtain an equation to evaluate wind stress from the wind speed at any location in Arabian Sea and Bay of Bengal during any season.

4.5.2 Roughness parameter

Roughness length \((z_0)\) of wind can be physically interpreted as the virtual origin of the wind profile. The roughness length can be calculated by plotting \(\ln(z)\) against the measured wind at that height and extrapolated the best fit straight line down to the level where the winds are zero. Generally roughness length is estimated by the graphical procedure with different levels but in ocean, the measurement for different levels quite difficult. Therefore, the roughness parameter is calculated by using equation (4). Fig.4.7 defines the wind speed dependence of roughness length over Arabian Sea for different seasons. In all the season the dependence of \(z_0\) is as defined by Chamock, (1955). The values of the roughness parameter in the figure have a multiplying factor of \(10^3\). The \(z_0\) increases as the wind speed decreases and after a critical value of \(z_0\) the \(z_0\) increase with wind speed. The critical value for Arabian Sea under the study region is 4.68 ms\(^{-1}\) and the value of \(z_0\) is 0.06 × 10\(^{-3}\) m. The average values of \(z_0\) for winter, pre-monsoon, southwest monsoon and post monsoon seasons are 0.15 × 10\(^{-3}\), 0.33 × 10\(^{-3}\), 0.24 × 10\(^{-3}\) and 0.15 × 10\(^{-3}\) respectively for the corresponding wind speed are 6.39 ms\(^{-1}\), 4.76 ms\(^{-1}\), 11.04 ms\(^{-1}\) and 5.89 ms\(^{-1}\).

In the case of Bay of Bengal also the Chamock’s relation holds good, but it has many uncertainties and is clear from Fig.4.8. The wind speed is relatively low in the Bay of Bengal while comparing with the Arabian Sea. Generally the increase of \(z_0\) with decrease of wind speed and increase of \(z_0\) with increase of wind speed after the critical value of wind speed are noticed with many irregularities. The average values of \(z_0\) for winter, pre-monsoon, southwest monsoon and post monsoon seasons
Fig. 4.5 Relation of wind stress with wind speed for different seasons for Arabian Sea.
Fig. 4.6 Relation of wind stress with wind speed for different seasons for Bay of Bengal.
Fig. 4.7 Relation of roughness parameter to wind speed during different seasons over Arabian
Fig. 4.8 Relation of roughness parameter to wind speed during different season over Bay of Bengal

are $0.51 \times 10^{-3}$ m, $1.19 \times 10^{-3}$ m, $0.80 \times 10^{-3}$ m and $0.50 \times 10^{-3}$ m respectively for the corresponding wind speed are 5.32 ms$^{-1}$, 4.6 ms$^{-1}$, 9.52 ms$^{-1}$ and 5.90 ms$^{-1}$.
4.5.3 Frictional velocity

The frictional velocity $u_*$ is one of the important scaling variables in the surface boundary layer or MABL (Monin and Obukhov, 1954) and is computed from wind stress and density of the air. The equation to evaluate $u_*$ is given in (5). $u_*$ is drawn against the surface wind for different seasons for Arabian Sea and Bay of Bengal (Fig.4.9 and fig.4.10). From the observation, we can delineate that $u_*$ varies with wind in linear way. For both Arabian Sea and Bay of Bengal, $u_*$ increases as the wind increases. For winter (January) and southwest monsoon (July) the variation can be represented properly by a linear fit, but for pre-monsoon and post monsoon $u_*$ values very little randomly distributed to either side of the least square fit line. This uneven distribution of the $u_*$ from the fit line may be due to the influence of wind direction because the April and November are months of transition in which reversal of wind direction from northeast to southwest and southwest to northeast take place respectively. So, during these periods the wind direction varies widely. This may influence the frictional velocity.

4.5.4 Wind against SST and Rainfall

An attempt is made to relate QuikSCAT wind and TMI SST over Arabian Sea and Bay of Bengal for southwest monsoon season is given in Fig.4.11. In both cases the SST shows a decreasing trend with wind speed. In Arabian Sea the slope of decrease is comparatively less than that of the Bay of Bengal. The linear equation of the decreasing trend is $U = -0.233xSST + 17.527$ where $U$ is the wind speed and SST is the Sea Surface temperature. The relation in the Bay of Bengal is same but the decreasing trend is higher with respect to wind speed and the equation obtained is $U = -1.334xSST + 48.026$. The range of SST in Arabian Sea is from 26.81°C to 29.41°C with wind ranges from 7.89 ms$^{-1}$ to 14.24 ms$^{-1}$ during July representing southwest monsoon season and the range of SST in Bay of Bengal is from 27.72°C to 29.86°C with a wind range from 4.41 ms$^{-1}$ to 14.77 ms$^{-1}$, but the average value is high for Arabian Sea. Fig.4.11c and fig.4.11d show the dependence of precipitation (downloaded from the web site ftp.ncep.noaa.gov) with wind at surface and SST over
Fig. 4.9 Relation of frictional velocity with wind speed during different seasons over Arabian Sea
Fig. 4.10 Relation of frictional velocity with wind speed during different seasons over Bay of Bengal.

Arabian Sea and Bay of Bengal. The relation of rainfall over Arabian Sea with temperature and wind is not encouraging. In the Bay of Bengal for July (aggregate of July from 2000 to 2003) the rainfall against wind and temperature shows linear fit and the corresponding equations are given in respective figures. The rainfall increases in
Fig. 4.11 Depending relations of sea surface parameters over Arabian Sea and Bay of Bengal.

trend with wind i.e., as the wind increases rainfall increases indicating organized convection. Due to the convergence of wind organized cloud band formed (Joseph and Sijikumar, 2004) and this cloud band feeds moisture by the LLJ to enhance the rainfall activity. As in the case of SST (Fig. 4.11d) the rainfall shows a decrease in
trend with increase of SST. The sea surface cools with the rainfall. The SST shows a decreasing linear trend with rainfall.

4.5.5 Drag coefficient

Fig.4.12 Relation of drag coefficient with wind for different season over Arabian Sea.

Fig.4.13 Relation of drag coefficient with wind for different season over Bay of Bengal.

The variation of drag coefficient is also drawn for different years for both Arabian Sea and Bay of Bengal. Fig.4.12 and Fig.4.13 shows the variation of drag coefficient in Arabian Sea over the considered region. The Bay of Bengal shows the
same trend as that of the Arabian Sea. From the figure it is clear that the drag coefficient varies with wind speed not in a linear way, it tends to increase from a critical value wind speed 4 ms$^{-1}$.

4.6 Temporal variation of frictional velocity and drag coefficient

4.6.1 Frictional velocity over Arabian Sea and Bay of Bengal

Frictional velocity ($u_*$) is very important parameter as the scaling parameter of the velocity, information of values of $u_*$ is important in various atmospheric boundary layer studies. To examine the general variation of $u_*$ in different season, time series graph of frictional velocity is plotted for the entire year from 1$^{\text{st}}$ January to 31$^{\text{st}}$ December (averaged for 1$^{\text{st}}$ Jan, 2$^{\text{nd}}$ Jan and so on up to 31$^{\text{st}}$ Dec for 2000 to 2003) for both Arabian Sea and Bay of Bengal. The 5 day moving average values of the frictional velocity is represented in Fig.4.14 in which solid line indicates the values for Arabian Sea and dotted line indicates that for the Bay of Bengal. It is observed that the values of $u_*$ in both Arabian Sea and Bay of Bengal are found to be around 0.18 ms$^{-1}$ (for Arabian Sea the value is 0.19 ms$^{-1}$ and for Bay of Bengal, 0.17 ms$^{-1}$) from January to end of May. During monsoon period the value of $u_*$ is increased and it remains almost constant with a little fluctuation around 0.35 ms$^{-1}$ in Arabian Sea and around 0.33 ms$^{-1}$ in Bay of Bengal. After the monsoon season the $u_*$ comes back to its pre-monsoon value. During monsoon season the value of $u_*$ in both Arabian Sea and Bay of Bengal are different. The increased $u_*$ during southwest monsoon season is due to the monsoon surge associated with low level Jetstream and associated modulation in the surface wind. During monsoon period the $u_*$ exhibits variability similar to intra seasonal oscillation (ISO) found over Indian monsoon region (Sikka and Gadgil, 1980). This pattern of $u_*$ is maintained till the end of the monsoon period. The variability of $u_*$ is attributed to the active and weak cycles in the Indian monsoon. The activity of these epochs, especially in the wind pattern is greater in the Bay of Bengal than that in the Arabian Sea so that the variability in $u_*$ is also high in the Bay of Bengal. As monsoon is recedes, the values return to the earlier status. The situation is same over the Arabian Sea and Bay of Bengal.
Fig. 4.14 Day to day variation of frictional for Arabian Sea (solid line) and for Bay of Bengal (dotted line) averaged of four years from 2000 to 2003.

Fig. 4.15 Day to day variation of drag coefficient for Arabian Sea (solid line) and for Bay of Bengal (dotted line) averaged of four years from 2000 to 2003.
4.6.2 Drag Coefficient over Arabian Sea and Bay of Bengal

The features of drag coefficient over the area in Arabian Sea and Bay of Bengal are studied using the 5-day moving average values are presented in Fig.4.15. It is found that the values of $C_d$ in both the Seas are found to be different and the higher values found over the Bay of Bengal during the entire period. The general pattern varies with season. Over the Arabian Sea, the value is almost constant ($1.14 \times 10^{-3}$) during the period from November to May. During southwest monsoon period values of $C_d$ are more compared to other seasons. From first week of May, the value increases and reaches a maximum by June first week ($1.42 \times 10^{-3}$) and decreases thereafter. The slope of increase is much more than that of the decrease in the Arabian Sea. Generally the values $C_d$ in the Bay of Bengal are higher than that of the Arabian Sea in all the periods. The $C_d$ over Bay of Bengal starts to increase form 1st week of March and reaches maximum during the monsoon season ($1.35 \times 10^{-3}$). The variability in $C_d$ over the Bay of Bengal is more than that over the Arabian Sea especially in the monsoon season. The variability in $C_d$ is found throughout the year in the Bay of Bengal, but it is very small in the Arabian Sea except in the post monsoon season. The values of $C_d$ are found to decrease after withdrawal of monsoon, in middle of November.

4.7 Intraseasonal variations in frictional velocity and drag coefficient

Intraseasonal oscillation (ISO) is one of the major oscillations in the equatorial region as a northward/northeastward propagating surge during the southwest monsoon (Yasunari, 1979, 1981; Sikka and Gadgil, 1980; Krishnamurthy and Subramanyam, 1982). This ISO has two major components and they are 30-60 day and 10-20 day mode can be seen in spectral analysis of precipitation, convection and in many circulation parameters (Chen and Chen, 1993; Numaguti, 1995; Kiladis and Wheeler, 1995).

Using wavelet technique suggested by Torrence and Compo (1998), we unraveled the different time frequency domains, which embedded in the marine boundary layer parameters such as frictional velocity and drag coefficient. Fig.4.16
represents the wavelet analysis of the frictional velocity in Arabian Sea and Bay of Bengal. The daily frictional velocity values from 1 January 2000 to 31st December 2003 were used for the analysis. From the figure it is evident that the variability of frictional velocity is different in both the Arabian Sea and Bay of Bengal. In the Arabian Sea the variability around 60 day is prominent with 95% confidence level. This oscillation is found to vary with a periodicity of 35-64 day but in the Bay of Bengal the periodicity is from 25 day to 65 day.

Fig. 4.16 Wavelet analysis of frictional velocity over Arabian Sea and Bay of Bengal

The confidence level varies from year to year. The variability under 10-20 day mode is also exists, but this variation is found in all the seasons with 99% confidence. Fig. 4.17 shows wavelet analysis for drag coefficient. The variability of drag coefficient is different for Arabian Sea and Bay of Bengal as that of the frictional velocity. The variability with 40-55 day mode in the Bay of Bengal is seen in all the years during monsoon months with 95% confidence level. But in the Arabian Sea it is evident only during the monsoon months of the years 2000 and 2002. During 2001 and 2003, it is difficult to understand the prominent mode of oscillations. The 10-20 day mode (QBM) is also significant in the Bay of Bengal in all the period irrespective of the monsoon months.
Dynamic characteristics of the marine atmospheric boundary layer (MABL) using high resolution satellite derived QuikSCAT data set with a spatial resolution of 0.25 X 0.25 latitude longitude grid for the parameters surface wind, frictional velocity ($u_*$), roughness parameter ($z_0$) and drag coefficient ($C_D$) for different seasons are studied. Surface wind pattern shows more strength during the southwest monsoon season due to modulation by the Low Level Jetstream. $C_D$ is more during southwest monsoon season due to the strong wind and less during winter. The spatial variation of $u_*$ over the seas is small during the post-monsoon season (0.2 ms$^{-1}$) and maximum is during southwest season followed by the pre-monsoon season over the Bay of Bengal. The mean characteristic features of the wind stress curl during winter season is positive over the equatorial region with a maximum value of $1.5 \times 10^{-7}$ Nm$^{-2}$ but on either side of the equatorial belt anticyclonic wind stress is dominated. The interrelationship between $u_*$ and surface wind speed in both Arabian Sea and Bay of Bengal are found to be exponential. From a critical value of wind (around 4 ms$^{-1}$), $C_D$ increases to either side. The variabilities of the frictional velocity and drag coefficient are also examined over Arabian Sea and Bay of Bengal using the wavelet technique and found that the variabilities in 30 to 60 day mode are prominent over the entire period over the Bay of Bengal.