Chapter-1

1 Introduction

The monsoonal climate over the Indian subcontinent and other south Asian countries is a consequence of the unique geographical settings of ocean and landmasses that causes a peculiar air-sea interaction process over the north Indian Ocean (NIO) (*Webster, 1994; WCRP Report, 2006*). There are two monsoonal periods (NE winter monsoon and SW summer monsoon) which are observed over the subcontinent and surrounding oceans. During the NE winter monsoon (December – February), wind mainly blow over NIO from the landmasses to the ocean and during the SW summer monsoon, wind blow in the reverse direction. Normally SW monsoonal winds are stronger and enriched with moisture that causes heavy precipitation over the landmasses. On the contrary, NE monsoon winds are relatively weaker and dry in nature. Except very small part of south India, India does not receive any significant rain during NE monsoon period (*Webstar,1994; Gadgil et al,1984).*

When winds blow over the north Indian Ocean during the both the monsoons, it accelerates the ocean water in the form of ocean current and cools the ocean surface by bringing cooler water from the sub-surface layer to the surface layer though Ekman pumping and vertical turbulent mixing in the mixed layer. On the other hand, ocean supplies moisture to the overlaying atmosphere through evaporation process, and energy mainly through latent heat flux and long-wave radiation (*McCreary, 1993; Shetye et al., 1996; Nayak, 2006*). The sea surface temperature is a key parameter behind these above mentioned processes, which mainly controls or being controlled by these mechanisms (Fairall et al, 1996).

The chlorophyll concentration in the water of Open Ocean plays an important role in the control of SST by trapping the solar radiation in the surface layer (*Jerlove, 1976; Paulson and Simpson, 1977; Morel and Maritorena, 2001; Satyendtanath et al 1991; Nayak, 2006*). When the chlorophyll concentration is high, SST of the open ocean can be increased. In the coastal ocean, the situation is much more complicated due to prevailing of strong upwelling along the coast driven by wind stress curl and Ekman transport of coastal water from the coast towards the off shore (*Price et al., 1987; Larissa E. Back, 2002*). On the other hand, high upwelling regions are rich in nutrients and chlorophyll and are assumed as highly productive areas (Banse and McClain, 1986; Brock, 1991; Smith, 1991; Dwivedi and Choubey, 1998)

The monsoonal climate over the Indian subcontinent and surrounding oceans exhibits large variability in seasonal (intra-annual) to inter-annual (year-to-year) scales (Goswami and Ajayamohan, 2001; Gadgil 2003). The monsoonal climate is largely dependent on the air-sea interaction process over the north Indian Ocean (*Ramesh Kumar et al, 1999; Gadgil et al., 1984)*. As SST is the key parameter of this air-sea interaction process, it is naturally very important to examine its seasonal and inter annual variability over the north Indian Ocean for a better understanding monsoonal climate and its variability over the India and surrounding oceans.

In view of the above, in this thesis, attempts have been made to analyse the recent data sets: Sea Surface Temperature, Chlorophyll concentration, wind field, and other associated parameters of air-sea interaction over the north Indian Ocean to examine their intra and inter-annual variability and possible connection among them (Timothy , 2002).

Following is a brief discussion of segmentation of the present thesis in several sections. In chapter-2, the study area is discussed. The details of used data and methodology for analysis are discussed in chapter-3. In chapter 4, the results of the analysis of above parameters are reported. The main results are contained in two sections, Intra and Inter annual, in which the monthly, and annual cycles of the SST, Chlorophyll, Wind speed, Ekman pumping and rain fall during 2000 to 2006 are analyzed. In chapter-5 the main results are summarized and conclusions are presented.

1.1 Role of Remote Sensing in Oceanography

Remote sensing is an impotent tool in retrieval of oceanic, physical and biological properties in global scale. The ocean is a complex system of interaction between natural and human components that continues to be stressed by a rapidly growing world population. To sustain the Ocean's ecosystem, it is essential to improve our understanding of the system components, their interrelationships, the changes undergone and subsequently the reason behind it. Satellite remote sensing system can provide some of the data necessary to provide with the relevant answers to these questions through repeated observations of the Earth's natural systems over spatial scales ranging from regional to global and temporal scales ranging from minutes to decades.

Satellite remote sensing of the ocean and atmosphere is a rapidly evolving field. A wide range of operational sensors are already in orbit, and new platforms with enhanced sensor capabilities continue to be planned, constructed and launched. One of the major important factors in this context is the ability to combine different remote sensing, in situ, and historical data sets using computer overlay and visualization techniques in a geographic information system (GIS) environment.

Satellite sensor data have proven useful to the atmospheric and ocean sciences communities. It will be useful to mention that scientific study of the biological, physical, and chemical processes are associated with the causes of the perturbations to atmospheric and ocean systems and in the resultant health and socioeconomic effects on humans. *Clark (1993)* reviews the applications of satellite sensor data to a wide range of marine pollution problems in "Satellite Remote Sensing of Marine Pollution." The ocean observing systems are extremely important in understanding the complex interactions between the earth's oceans and atmosphere, and in improving our assessment and prediction capabilities.

Oceanic upper mixed-layer structure, ocean heat storage, and sea surface temperature (SST) play important roles in the evolution of atmospheric events. In turn, these parameters are driven by processes responsible for surface energy fluxes. We seek to improve remote sensing methods in studies of mixed-layer dynamics, air-sea interactions, meso to large-scale circulation, and internal sea waves. We are also working on improving our understanding of the ocean's role in the global climate changes. So, what exactly is remote sensing? For the purposes addressing this, we will use the following definition:

"Remote sensing is the science (and to some extent, art) of acquiring information about the Earth's surface without actually being in contact with it. This is done by sensing and recording reflected or emitted energy and processing, analyzing, and applying that information."

1.2 Importance of various parameters in Oceanic process

1.2.1 Sea surface Temperature

The sea surface temperature (SST) variations play a very important role in the genesis and maintenance of meteorological and oceanographic processes such as monsoon depressions and subsequent floods, large-scale sea level fluctuations and genesis of tropical cyclones. Many low lying coastal regions of South Asia are adjacent to river deltas and have large population. The dense population, poor economy and several other socio-economic factors make these areas most vulnerable to the impact of climate change.

Variability of Sea surface temperature (SST) is important as the duration and intensity of SST provide the basis for studies related to climatic change scenario and convection from cooling sub-surface layer. This situation is encountered in the Polar Regions, where cold water sinks to the bottom of the ocean. This process replenishes the deeper waters and is responsible for the currents below the upper kilometer of the ocean. Areas of deep winter convection are the Weddell Sea and the Ross Sea in the Southern Ocean and the Greenland Sea and the Labrador Sea in the Arctic region.

In this study an attempt has been made to estimate the recent SST on the Arabian Sea and Bay of Bengal. The annual and inter-annual variabilities have also been studied.

1.2.2 Chlorophyll

Ocean color is a key parameter for understanding oceanic, biological and physical processes. The satellite acquires ocean color data to constitute a powerful tool for determining the abundance of ocean biota on a global scale. It is well known that the biological processes in the ocean are largely controlled by the presence of phytoplankton, which form the base of food chain, and are responsible for CO2 fixation acting as sink (*E. D. McAlister*). Apart from that it affects the ocean surface heating and light penetration. Significant large-scale oceanic and atmospheric differences sufficiently alter the circulation patterns and thermal structure of the region to produce variability in phytoplankton biomass. This is very well observed on satellite images. The penetrative power of solar radiation is a function of the water clarity and may vary at different locations. There is sufficient light and heat throughout the year, so that there are continual small rises and falls of population as zooplankton and phytoplankton populations. There are also changes from year to year in plankton population. This can be linked to changes in the climate, through winter mixing variability, temperature and light availability. The variation in the wavelength characteristics of reflected light from the oceans due to changes in biological productivity also has a climatic influence. Regions of greater productivity reflect more incident radiation and allow less of it to warm the lower reaches of the upper ocean. A contrasting effect of phytoplankton is the warming of the upper ocean by the increased absorption of radiation with the increase of biomass, which is well reported by *Neera Chaturvedi (2002)*. At present, the understanding of the time and space variability of most biological properties is quite inadequate. In order to develop any model for biophysical coupling, the study of relationship of parameters, at temporal and spatial basis is a prerequisite. The present study makes use of

SeaWiFS data for the period 2000-2006, to understand the variability in chlorophyll pattern in the Arabian Sea and the Bay of Bengal.

1.2.3 Wind

The summer strong southwest winds produced by the Asian monsoon blow across the NW Arabian Sea creates a broad region of upwelling, characterized by cool sea surface temperatures and enriched phytoplankton biomass. Understanding the relationship between wind stress and upwelling in the coastal region is an important factor. Upwelling is directly related to the Ekman transport offshore, and is thus linearly proportional to the alongshore wind stress. Farther offshore, open-ocean upwelling is driven by the positive curl in the wind stress. In the offshore region the strongest wind is accompanied by weaker wind stress curl and diminished upwelling (indicated by warmer sea surface temperatures and decreased phytoplankton pigment content) (*David and warren, 1992*)In atmospheric general circulation and summer insulation forcing, the large changes in the wind stress curl occur over water surface; however, the offshore locations lies outside of the region, where the changes in the SW monsoon drive large changes in open-ocean upwelling. In contrast to the coastal sites, where upwelling is directly related to the wind stress, the offshore sites appear to be located in a region, where the wind stress curl does not change much over a large range of summer insulation. The upwelling takes place, due to ocean are directly affected by the wind, i.e. transfer of momentum from the atmosphere to the ocean. The balance of forces therefore involves frictional forces, which cause a departure from geostrophic flow; water moves across isobars from areas of high pressure to areas of low pressure. The layer in which the flow is non-geostrophic is known as the Ekman layer.

The direction of water movement in the Ekman layer varies with depth (Matthias, 2002). The details are complicated, but when only the steady state is considered, an important result is that the net (i.e vertically averaged) transport in the Ekman layer is directed perpendicular to the wind direction, to the left in the southern hemisphere and to the right in the northern hemisphere.

1.3 Literature review

The climate of North Indian Ocean is influenced mainly by two types of monsoon wind system. The monsoon system in which the wind blows from the southwest of India and adjacent areas is characterized by severe rainfall. Recently, such phenomena is being investigated to find the role of North Indian Ocean in regional monsoons and the Indian Ocean in El Niño-Southern Oscillation (ENSO) forcing respectively [*Hastenrath and Greischar,* 1993; *Murtugudde and Busalacchi,* 1999; *Schiller et al.,* 2000; *Loschnigg and Webster,* 2000; *Rao and Sivakumar,* 2000; *Xie et al.,* 2002; *Meehl et al.,* 2003]. In regional climate variability, earlier studies of the North Indian Ocean are typically motivated by the unique aspect of the region, namely, the seasonally reversing monsoonal forcing and its subsequent effect [*Lighthil,* 1969; *Schott and McCreary,* 2001 for a review]. Numerous studies reported so far address the impact of monsoonal forcing on the physical, biological, and biogeochemical variability of the North Indian Ocean basin

The Arabian Sea and the Bay of Bengal also exercise a profound influence on climate. Though both are located in the same latitude and receive the similar amount of solar radiation from the Sun, the Bay of Bengal is much warmer than the Arabian Sea and subjected to many more storms. The ocean plays a major role in keeping the Arabian Sea relatively dry. Recent research shows that there are two causes behind the phenomena.

(1) The strong winds of the Arabian Sea force a vigorous oceanic circulation and the heat received at the surface is transported southward and into the deeper ocean. The winds over the Bay of Bengal, in contrast, are more sluggish and the bay is unable to remove the heat received at the surface.

(2) The Bay of Bengal receives more rainfall as well as freshwater from the large rivers especially the Ganga and the Brahmaputra. This fresh water stabilizes the water column, making it more difficult for the winds to mix the warm, stable surface layer with the cooler water below. In the Arabian Sea, there is no such stabilizing effect. As a consequence, the mixing with the cooler water below is more vigorous compared to that in Bay of Bengal. Since a sea surface

temperature of about 28°C is necessary for convection to take place in the atmosphere, this condition is satisfied in the Bay of Bengal but not in Arabian Sea *(Vinayachandran et al, 1997*). Thus, in spite of their geographical similarities, the two arms of the north Indian Ocean are strikingly different in terms of climate. The Arabian Sea mainly responds to the reversing monsoonal forcing and its effect is seen in the Somali upwelling region in the western boundary of the Arabian Sea with the Somali Current directed equator ward during the Northeast (winter) monsoon and pole ward during the Southwest (summer) monsoon.

It is known that most of the SST variability in the Arabian Sea can be attributed to changes in surface heat fluxes [*Murtugudde and Busalacchi,* 1999; *Rao and Sivakumar,* 2000]. *Holt and Raman* [1986] using the data from the Monsoon Experiment (MONEX-79) have shown that the evaporation over the Arabian Sea is about two to three times higher during the active monsoon period as compared to break monsoon period. Latent heat flux shows the heat lost through evaporation at the sea surface. Shenoi et al. (1999) reports high latent heat flux over the northwestern Arabian Sea and the Bay of Bengal and low latent heat flux over the south-eastern Arabian Sea (because of weak winds) during the northeast monsoon; and high latent flux in the southeastern Arabian Sea (including the Lakshadweep Sea) in April. So it is evident from the above discussion that the variability of ocean parameters both in Arabian Sea and The Bay Of Bengal influences the climatological pattern over Indian sub continent and its surroundings to a considerable extent. In the present study, this cause and effect process is discussed in an elaborate manner.

Chapter-2

2 Study Area

The north Indian Ocean lies between 30°N to 10°S latitude and 45°E to 105°E longitude. In view of the climatological variability prevailing over the study area, it is divided into three sub-regimes namely Arabian Sea, Bay of Bengal and Equatorial Indian Ocean (Figure2.1) for simpler and better interpretation. The segmentation is based on different climatic conditions, ocean circulation patterns, topographical features etc.

Figure 2.1 Location of study Area

2.1 Geographical position

2.1.1 North Indian Ocean

It is extended between the latitude 30°N to 10°S and longitude 40°E to 105°E. The North Indian Ocean (NIO) is bound on the north by Southern Asia (including the Indian subcontinent); on the west by the Arabian Peninsula and Africa; on the east by the Malay Peninsula, and on the south by the Southern Ocean. The North Indian oceanic variability is fundamentally affected by the northern land boundary that consists of the Asian continent and the Indian subcontinent, which bisects the Northern Indian Ocean into the Arabian Sea and the Bay of Bengal

2.1.2. Arabian Sea

The Arabian Sea is a part of NIO, extended between 30^{o}N to 5^{o}N latitude and 40^{o}E to 80^{o}E longitude. It is bound on the east by India, on the north by Pakistan and part of the southern Persian littoral, on the west by Arabian Peninsula, on the south, approximately by a line between Cape Guardafui, the north-east point of Somalia, Socotra and Kanyakumari (Cape Comorin). It has two important branches — the Gulf of Aden in the southwest, connecting with the Red Sea through the strait of Bab-el-Mandeb; and the Gulf of Oman to the northwest, connecting with the Persian Gulf. Besides these larger ramifications, there are the gulfs of Cambay and Kutch on the Indian coast.The maximum width of the Arabian Sea is approximately 2,400 km, and its maximum depth is 4,652 metres. This region is very important for the monsoonal activity over the Indian and other south Asian land masses.

2.1.3.Bay of Bengal

The Bay of Bengal is north-eastern doamin of NIO, extended between the latitude 5^{o}N to 30^{o}N and longitude 80^{o}E to 105^{o}E. This is a semi enclosed basin alike the Arabian Sea, bounded by India on the west, by Bangladesh, Myanmar, and part of India on the north, and Burma and Malaysia on the east. Indonesians island situated in side the Bay. The Bay of Bengal is the region of intense cyclone prone area, all most all the cyclone which hits the east coast of Indian and Bangladesh are generated over the Bay.

2.1.4. Equatorial region

This domain is the equatorial part of the NIO extended between the latitude 5^{o}N to 10oS and longitude 45^{o}E to 105^{o}E. African continent situated on the western side, and Java, Sumatra and Singapore are situated on the stern side of this domain.

Chapter-3

Data & Methodology

3.1 Data

3.1.1 Sea surface Temperature

NCDC/NOAA daily High-Resolution SST dataset product is developed at National Climatic Data Center (NCDC) by using the optimum interpolation technique (Reynolds et al., 2007). In this technique, the available *in situ* SST data over the globe (based on ship-and buoy observations) are blended with those from the Advanced Very High Resolution Radiometer (AVHRR) infrared satellite observations. The analyses have a spatial grid resolution of 0.25° and temporal resolution of 1 day. The product for the domain of north Indian Ocean (present study regions) during 2000-2006, was down loaded (ftp://eclipse.ncdc.noaa.gov/pub/OI-daily/NetCDF) and used for the present study.

3.1.2 Chlorophyll

The daily chlorophyll ASCII data during 2000-2006 with spatial resolution of 0.1X0.1 over study domain are downloaded from http://oceanwatch.pfel.noaa.gov/. The data are based on chlorophyll-a concentration images, retrieved from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS).

3.1.3 Wind Field

The daily wind field netCDF data (U and V components) during 2000-20006 for our study area in spatial resolution of 25X25 km are downloaded from the site http://las.pfeg.noaa.gov/oceanWatch/oceanwatch.php#. These products are derived from the Sea winds instrument aboard NASA's QuikSCAT satellite.

3.1.4 Precipitation

*The NCEP/*NCAR daily reanalysis product of precipitation over the India and surrounding oceans during 2000-2006 are collected from http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.surfaceflux.html. The data are available in netCDF format and with spacial resolution of 1.875X1.9047 degree.

3.1.5 Latent Heat Flux:

*The NCEP/*NCAR daily reanalysis product of Latent heat flux, over the study area during 7 year from 2000-2006 data is collected from http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.surfaceflux.html. The data are available in netCDF format with 1.875X1.9047 degree spacial resolution.

3.2 Methodology

As it has been described above, all the data are avialable in daily scale during 7 year of study period (from 01-Jan-2000 to 31-Dec-2006). To study intra and inter annual variability, the daily data are converted into monthly data and then thse monthly data are used to prepair climatology over the north Indian ocean. In addition to that, statistics of the data are made for further analysis. For doing this, FERRET 5.5.1, a open source analysis package is extensively used. In the following, we are describing the statistics used in this study.

3.2.1 Calculation of monthly anomaly

Monthly anomaly of parameters is estimated by subtracting the monthly climatology from the monthly observation of any study year.

For example, SST anomaly = Monthly mean SST - Climatic monthly mean SST

3.2.1.2 Calculation of annual anomaly

The annual anomaly of parameters can be estimated by subtracting the mean of the parameters whole the study period of 7 year (2000-2006) from the annual average of individual year.

For example SST annual anomaly = Mean SST of Individual year - Mean of SST over 7 year study period.

3.2.2 Statistical Analysis

3.2.2.1 Calculation of Mean

It is defined as the sum of value of group of items divided by the number of items.

Mean, $\overline{X} = \sum_{i=1}^{n} X_i / N$

3.2.2.2 Calculation of Standard Deviation

Standard deviation is the square root of the arithmetic mean of the square deviation

Standard Deviation, $\sigma = \sqrt{\sum_{i=1}^{n} (X_i - \overline{X})^2 / N}$

$\overline{X}$ = Mean value

3.2.3 Computation of Ekman pumping from wind stress

Monthly averaged wind stress over the north Indian Ocean are estimated using the monthly wind field data during 2000-2006 and then Ekman pumping is estimated as follows (Gill, 1982):

Calculation of wind stress:

Zonal component of wind stress , τ_x =C_D* ρ_A *I UI *U_x

Meridional component of wind stress τ_y = C_D* ρ_A *IUI *U_y

Where

U_x =Zonal Wind component

U_y =Meridional wind component
IUI= $(U_x{}^2 + U_y{}^2)^{0.5}$

$C_D = 1.1\text{x}10^{-3}$ for $|U| < 6ms^{-1}$

= (0.61+0.063*|U|)*0.001 for $6ms^{-1} < |U| < 22\ ms^{-1}$

ρ_A =1.3kg/m^3 (Density of air)

Calculation of Ekman pumping

Fluid parcel in the Ekman layer (layer extending from surface to the depth up to which wind impact is significant) is mainly subjected by two dominant forces: Coriolis force and force due to turbulent shear stress. Mathematically it can be expressed as

$$vf = -\frac{1}{\rho}\frac{\partial \tau_x}{\partial z} \qquad \text{(1)}$$

$$uf = \frac{1}{\rho}\frac{\partial \tau_y}{\partial z} \qquad \text{(2)}$$

Where, u = velocity of wind in Zonal-direction
v = velocity of wind in meridional-direction
τ_x = Zonal -component of turbulent stress
τ_y = meridional -component of turbulent stress
ρ = density of water ≈ 1025
f = Coriolis parameter
= 2Ω sin φ
Where, Ω is the angular velocity of Earth
= 2πr
= 2*3.42*6378.1
=7.272*10-5 red/s
And φ = latitude
r = Radius of Earth

Differentiating equation 1 with respect to Y and equation 2 with respect to X and rearranging the terms, we can have

$$\frac{\partial u}{\partial x} = \frac{1}{\rho f}\frac{\partial}{\partial x}\frac{\partial \tau_y}{\partial z} \qquad \text{(3)}$$

$$\frac{\partial v}{\partial y} = -\frac{\partial}{\partial y}\left(\frac{1}{\rho f}\frac{\partial \tau_x}{\partial z}\right) \qquad \text{(4)}$$

Now using above two equations in equation of continuity which can be expressed as :

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (5)$$

We can have,

$$\frac{\partial w}{\partial z}=\frac{1}{\rho f}\left[\frac{\partial}{\partial y}\frac{\partial \tau_x}{\partial z}-\frac{\partial}{\partial x}\frac{\partial \tau_y}{\partial z}\right]-\frac{1}{\rho f^2}\frac{\partial \tau_x}{\partial z}\frac{\partial f}{\partial y}$$

Integrating above equation with respect to z from surface to bottom of the Ekman layer, and using the boundary condition

(i) at the surface (Z=0) w=0, when $\tau_x = \tau_{x_{\max}}$ and $\tau_y = \tau_{y_{\max}}$;

(ii) at the bottom of the Ekman Layer(z=D), w=w_e, when τ_x =0 and τ_y =0

$$We = -\frac{\left(\frac{\partial \tau_{x_{\max}}}{\partial y}-\frac{\partial \tau_{y_{\max}}}{\partial x}\right)}{\rho f}+\frac{1}{\rho f}\frac{\partial f}{\partial y}*\tau_{x_{\max}}$$

Where, w_e = vertical velocity at depth D (bottom of the Ekman Layer).

Chapter-4

Results

4.1 Study of Intra and Inter annual variability of Sea Surface Temperature

As it has been described in chapter 1, that the monsoonal climate over the Indian subcontinent and other south Asian countries is a consequence of the unique geographical settings of ocean and land masses. SST is the key parameters of air-sea interaction process. Thus the study of its variability in intra and inter annual scale may provide vital information about air-sea interaction process (heat and water fluxes) and climate of Ocean environment. In the section 4.1.1, we are going to examine the intra annual variability of SST over the north Indian Ocean based on climatology prepared using 7 year SST data (during 2000-2006) of 0.25 X0.25 latitude-longitude grid derived from NCDC data (see chapter 3 for more information about the data) and in section 4.1.2, its inter annual variability during 2000-2006 will be explored.

4.1.1 Intra-annual variability

4.1.1.1 Spatio-temporal variability of SST

The annual evolution of SST climatology of the north Indian Ocean (NIO) is shown in Figure 4.1.1.1. The figures suggest that during January, warm water front with mean temperature of 28.5 ^{0}C situated in south of the equator, which is elongated in south east direction. During this period, Arabian Sea and Bay of Bengal are relatively cooler with mean temperature of 26.92^{o}C and 27.6^{o}C respectively. Western Arabian Sea is relatively cooler (22 ^{0}C) than the eastern Arabian Sea. The Arabian Sea SST increases at normal to the Arabian coast and exhibit maximum (28.5 ^{0}C) in the south west coast of India. A similar temperature gradient exists in the Bay of Bengal, lower SST in western part than the eastern part. South of India and south west of Sri Lanka, relatively cooler water patches are seen in the ocean than its surrounding.

During February, the SST pattern is almost similar to the January SST pattern. However, the equatorial warm front is relatively warmer along its eastern side (Somali coast). The front is divided into western and eastern fronts separated by relatively cold water joining Arabian Sea and south equatorial Indian Ocean. The cold water patch along the south of India and Sri Lanka is reduced significantly and confined in a smaller area.

During March, with the movement of sun from southern hemisphere to the northern hemisphere, the equatorial ocean warmed up significantly (up to 30 ^{0}C) and it became wider towards the Arabian Sea and Bay of Bengal. Earlier cold fronts which were elongated parallel to the Arabian coast in Arabian Sea and parallel to the east coast of India in BOB are almost disappeared. Thermal equator (TE) is in well developed during this period and a small patch of cold water is seen along the Somali coast.

During April almost all part of NIO (including AS and BOB) is covered by very warm water, and thermal equator is intensified (33 ^{0}C) and shifted to the north. Western Arabian Sea is up to 4.5 ^{0}C warmer than its annual average SST. The ocean is warmest (32 ^{0}C) during this month. This warm pool is seen clearly in SST anomaly figure. During May, the thermal equator is slightly disturbed and cold water from southern Indian Ocean propagates towards the equatorial ocean. During this period, AS and BoB experienced highest SST (29.87 ^{0}C and 30.18 ^{0}C respectively) during the year. With the onset of monsoon winds and western boundary current developed along the Somali coast, and resultant Ekman pumping (see section 4.3.1.3), cold SST is seen along the Somali coast.

During June, when sun is in the extreme position in the northern hemisphere and monsoonal wind is strong over the tropical Indian ocean, SST of AS is decreases significantly, where as BOB is still remain relatively warmer. Dumbbell shape thermal equator is formed with relatively cooler SST than earlier months. This can be attributed as collapse of Indian ocean warm pool. During this period, cold water from Arabian Sea to the BoB advected along the south coast of India and Sri Lanka (Shankar et al., 2000).

During July and September, the SST pattern in NIO is almost similar to the June pattern; however, SST is relatively cooler in the equatorial Indian Ocean as compared to the previous month. Cooling of western Arabian Sea in July and August is almost of similar extent and more than the month of June. Western Arabian Sea is relatively warmer during September than the earlier months. SST of BOB decreases continuously during this period. Cooler water of Arabian Sea, continuously advected to BOB along the south coast of India and Sri Lanka.

During October and November, when monsoon is collapsed, SST of the north Indian Ocean is almost uniform over most part of the basin.

During December, when winter North East monsoon winds blows from Asian subcontinent to tropical Indian Ocean, cold fronts (SST decreases) reappears along the Arabian coast and along east coast of India. Equatorial Indian Ocean warms up and thermal equator reappears. This pattern is intensified in next month, January.

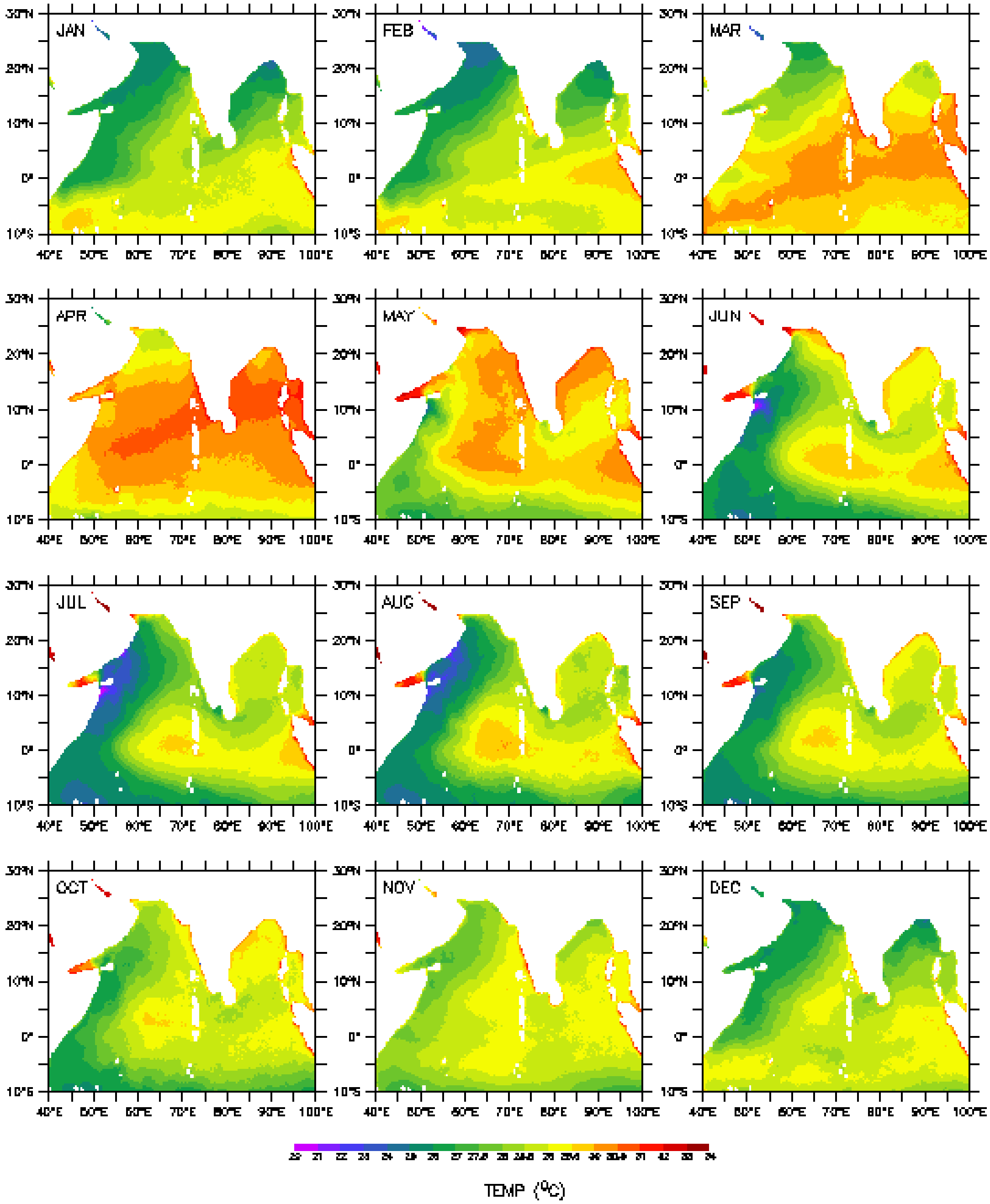


Figure- 4.1.1.1: Annual evolution of SST climatology of the north Indian Ocean based on monthly data during 2000-2006.

In an annual scale (see Fig 4.1.1.2a for annual average SST, and Fig. 4.1.1.2b for standard deviation), the warm water front seen in the equator (known as thermal equator) with an average temperature of 32 ^{0}C. Very cold water situated in the western Arabian Sea, with isotherms parallel to the coast of Arabia and Somali (22 ^{0}C). Relatively cooler water situated in the northern BOB than its central part. Both east and west coast of India, ocean water is much warmer. Standard deviation of SST in Figure 4.1.1.2b suggest that the SST of central equatorial Indian Ocean remain almost uniform over the year with very small variation (up to 0.5 ^{0}C), whereas western equatorial Indian Ocean, and western Arabian Sea, and northern BOB exhibit highest fluctuation over the year.

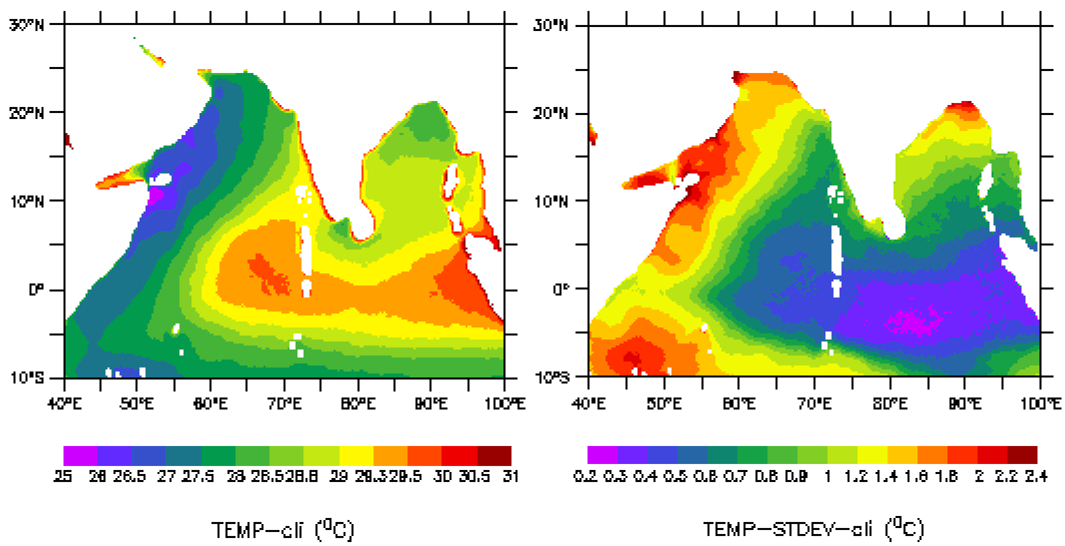


Fig 4.1.1.2:Climatologycal Mean of SST and Standard Deviation of monthly climatology during study period.

4.1.1.2 Comparison of mean SST in different basins

The evolution of mean SST of Arabian Sea, Bay of Bengal, and Equatorial Indian Ocean are presented in figure 4.1.1.3 As shown in the figure, every domain exhibits bimodal cycle of SST. In January to April the SST of BoB gradually increases from 27.60^{o}C to 30.18^{o}C with increase rate of +0.86^{o}C /month. During April to May, SST remains almost equal, since then it decreases gradually until August from 30.26°C to 28.85°C with cooling rate of -0.47°C /month. From August, the SST of BOB again increases up to 29.28°C in month of October with increasing rate of +0.22°C. Since then, it again decreases up to 28.14°C in December with the cooling rate of -0.57°C /m.

Although the SST pattern of Arabian Sea exhibits the similar bi-annual cycle as in BOB, but the warming and cooling rates are significantly different. Further, the Arabian Sea SST (ASST) remains cooler than BOB though out the year. In beginning of a year (January), ASST is relatively cooler (26.9 ^{0}C) than BOB (almost 0.7 ^{0}C). The ASST remain almost the same value in February, since then it increases up to 29.87°C in the month of May, with warming rate of +0.97°C /m which is less than that of BOB. From May to August the ASST decrease from 29.87°C to 26.92°C with cooling rate of -.98°C which is more than that of BOB. Then ASST increases until October when it exhibits a secondary peak of 28.32°C. During this period, the warming rate is (0.80 °C/m). From October to November, ASST remains constant and then it decreases up to 27.64°C at the end of year with cooling rate of -0.89°C /m.

In EQ domain, the SST shows almost similar pattern as of BOB, however there is significant difference in winter monsoon in the northern hemisphere. During January to March, the SST of EQ remains higher than the AS and BOB, and again higher in December. During April to November, the SST of equatorial basin parallel to the SST of BOB. The warming rate of Equatorial basin during winter (January – April) is much less than that of BOB. In the scale of whole the domain of NIO, SST exhibits a bi-annual cycle which is an average picture of three different basins described earlier.

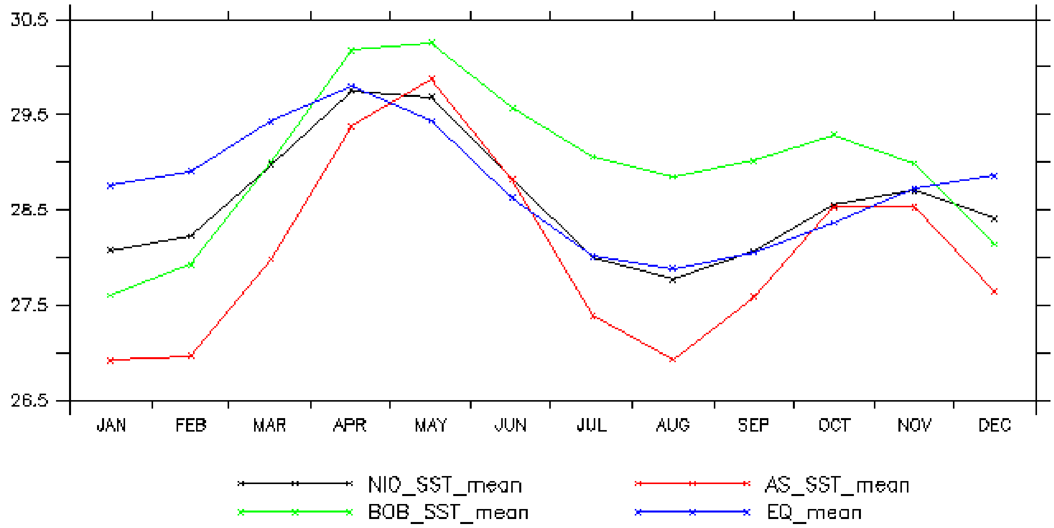


Figure-4.1.1.3: Comparison of basin average pictures of SST in Arabian Sea (red), Bay of Bengal (green), Equatorial Indian Ocean (blue) and whole the domain (black).

4.1.2 Inter-annual variability of SST

4.1.2.1 Spatio-temporal variability of SST

To analyze the inter-annual variability of SST in the north Indian Ocean, monthly SST pictures during 7 year from 2000-2006 are used to estimate monthly standard deviations of SST and are presented in Figure 4.1.2.1. The figures suggest that there are significant changes in SST at different regions of north Indian Ocean in monthly scale. In January and February, there is hardly any fluctuation of SST in most part of the north Indian ocean in year to year (standard deviation is less than 0.5 ^{0}C). During March, there are significant fluctuation of SST in year to year mostly in western Arabian Sea (coast of Arabia), in western Equatorial Indian Ocean (Somali coast) and in northern Bay of Bengal, where estimated standard deviations are up to 3 ^{0}C. During April, most of fluctuations are seen in north-western Arabian Sea. The inter-annual variability of SST during May is very much significant in south-western Arabian Sea and western equatorial Indian Ocean (south from the Somali coast) which is of 3 ^{0}C standard deviation. There is significant fluctuation of SST also found in water of south-western Bay of Bengal (up to 1.5 ^{0}C). The variability is maximum (up to 5 ^{0}C) in most part of north-western Indian Ocean (that includes Arabian Sea) in June which is the period of on set of SW monsoon over the ocean. During July, large variability (up to 4 ^{0}C) is only seen in north-western Arabian Sea. The variability of SST in August is much weaker, and very much confined along the coast of Arabia and Somalia. Similar weaker SST variability is also exists in the western Arabian Sea during the month of September. The variability is the least during October and November in north Indian Ocean. During December (the month of NE winter monsoon), significant variability up to 1.5 ^{0}C standard deviation exists in the water of northern Arabian Sea and north-western equatorial Indian Ocean, along the Somali coast. Inter-annual variability of mean SST in different active domains of north Indian Oceans characterized by large standard deviations (demarcated with rectangular boxes in red color), are plotted in Figure 4.1.2.2 for different months. All the figures suggest that, 2003 is the warmest year and 2000 is the coldest year.

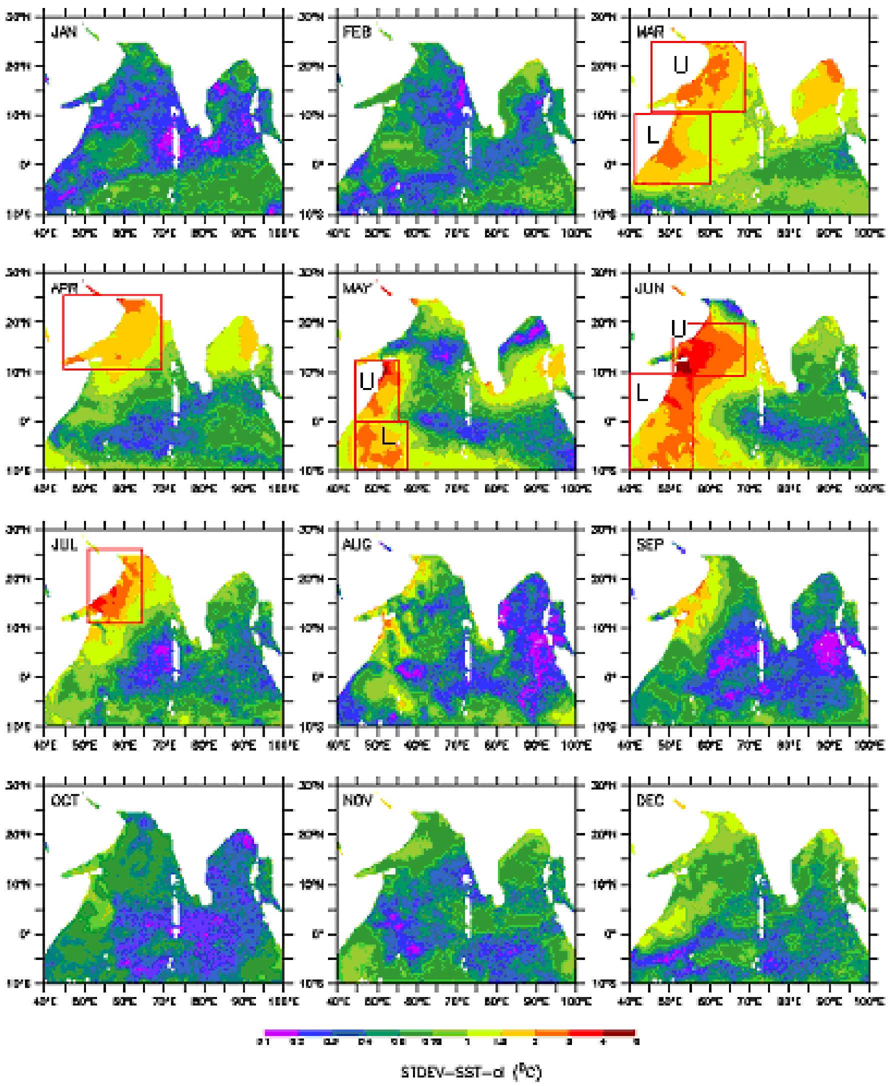
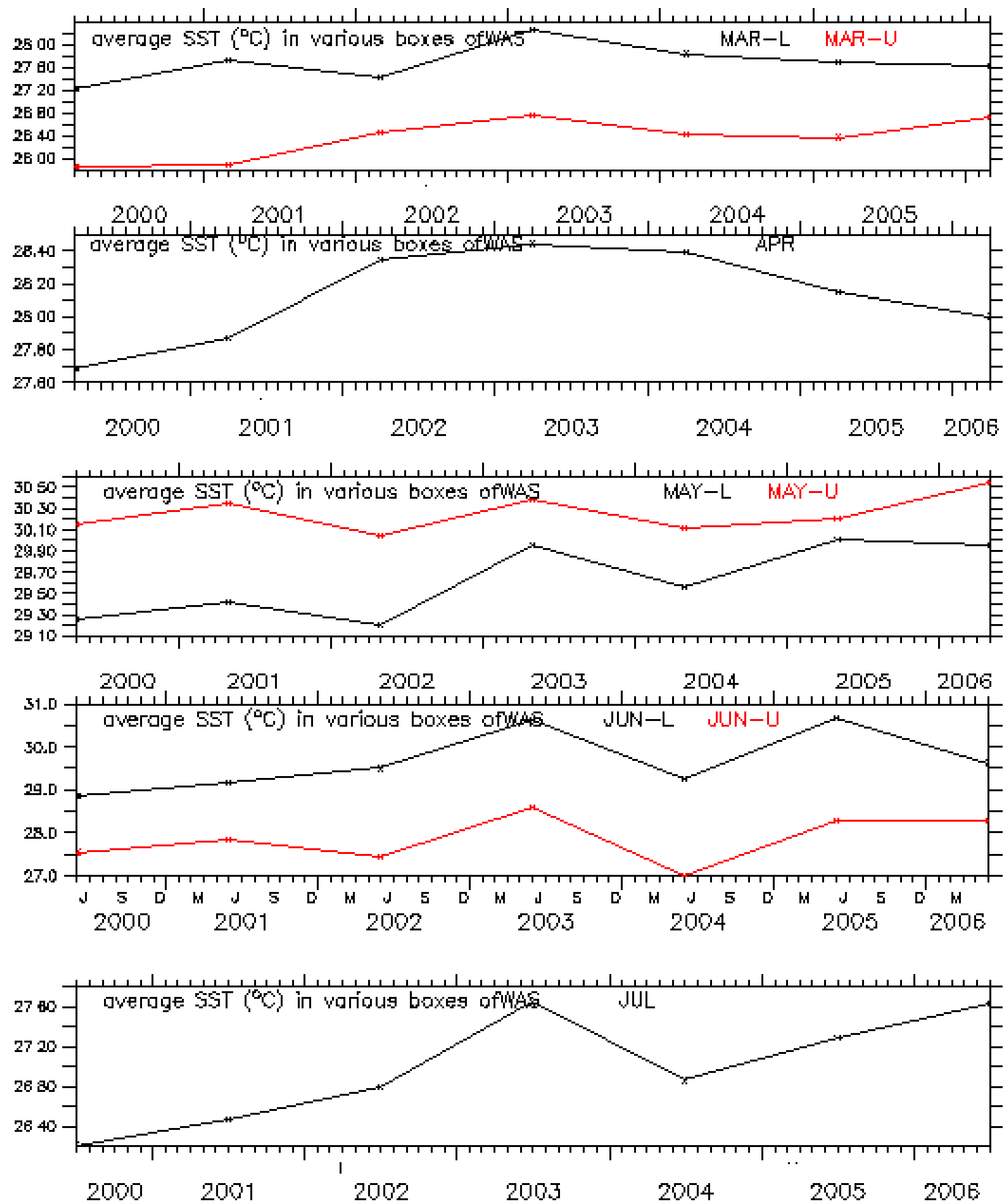


Figure 4.1.2.1: Monthly picture of standard deviations of SST during 2000-2006, in order to identify various active regions in the north Indian Ocean of large inter-annual variability. The boxes drawn in red color are the region of large standard deviation, attributed as the regions of active air-sea interaction processes. The mean SST data of these boxes are plotted in Fig. 4.1.2.2 to analyze its inter-annual variability.



4.1.2.2 Variability of monthly SST mean over different active domains (based on standard deviation) during 7 years of study period. Panel from up to down: panel 1 is for month of March, 2nd is for April, 3r is for May, 4th is for June, 5th is for July.

To analyze the inter-annual variability of SST in north Indian Ocean in an annual scale, annual average SST and their anomaly of Individual years from the 7 year mean, are shown in Figure 4.1.2.3 and 4.1.2.4. The standard deviations of annual mean SST of 7 years also estimated and shown in Figure 4.1.2.5.

The broad scale patterns of annual mean SST during all the 7 years are almost similar to each other (similar to their annual climatology): warm water in the central and eastern equatorial Indian Ocean (known as thermal equator, TE), cold water in the western equatorial Indian Ocean and western Arabian Sea, and warm coastal water around India. The figures also suggest that, there is strong inter-annual variability exist among the annual SST pictures. The north Indian Ocean exhibits warmest SST in 2003 and coldest SST in 2000 during 7 years of study period. The intensity and horizontal spreading of TE is the weakest and the intensity of the cold water of western north Indian Ocean (along western Arabian Sea and Somali coast) is the strongest during 2000. During 2000 to 2003, the intensity of TE and warming of coastal water around India increases and cold intensity of western north Indian Ocean water decreases. After 2003 up to 2005, the situation is reversed: TE decreases its intensity and western north Indian Ocean increases its cold intensity. In the basin scale of north Indian Ocean, the SST all over the ocean increases during 2000 to 2003 and then it decreases until 2005. As suggested by estimated standard deviation of annual SST during the 7 years (see Figure 4.3.5), there are large inter-annual variability are seen in south-western and south-eastern equatorial north Indian Ocean, in the water mass adjacent to Somali coast, in north-eastern Arabian sea and Bay of Bengal. Central equatorial Indian Ocean and Bay of Bengal exhibit vary weaker inter-annual variability than the Arabian Sea counter part.

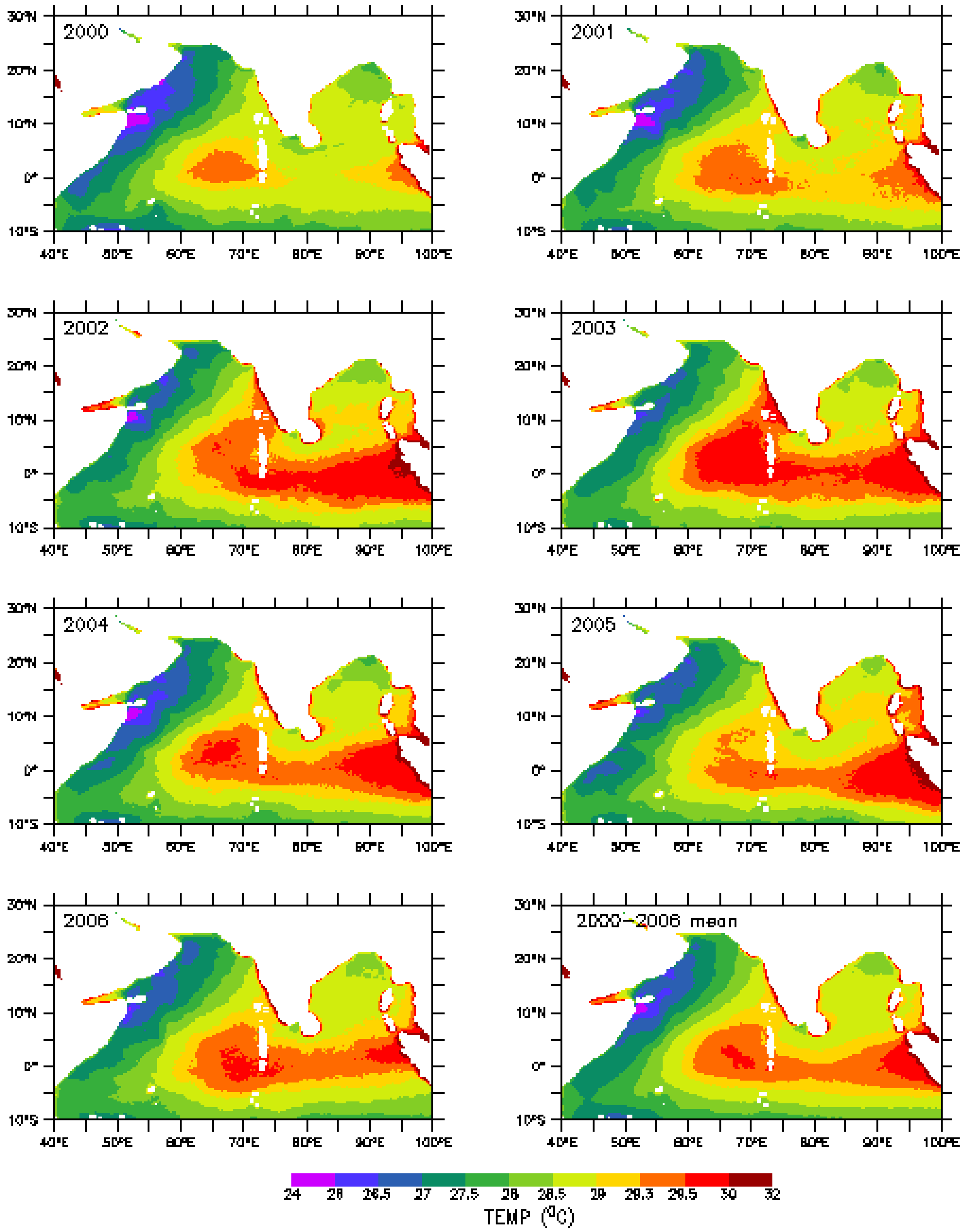


Figure-4.1.2.3: Annual mean picture of SST in the north Indian Ocean during 2000-2006.

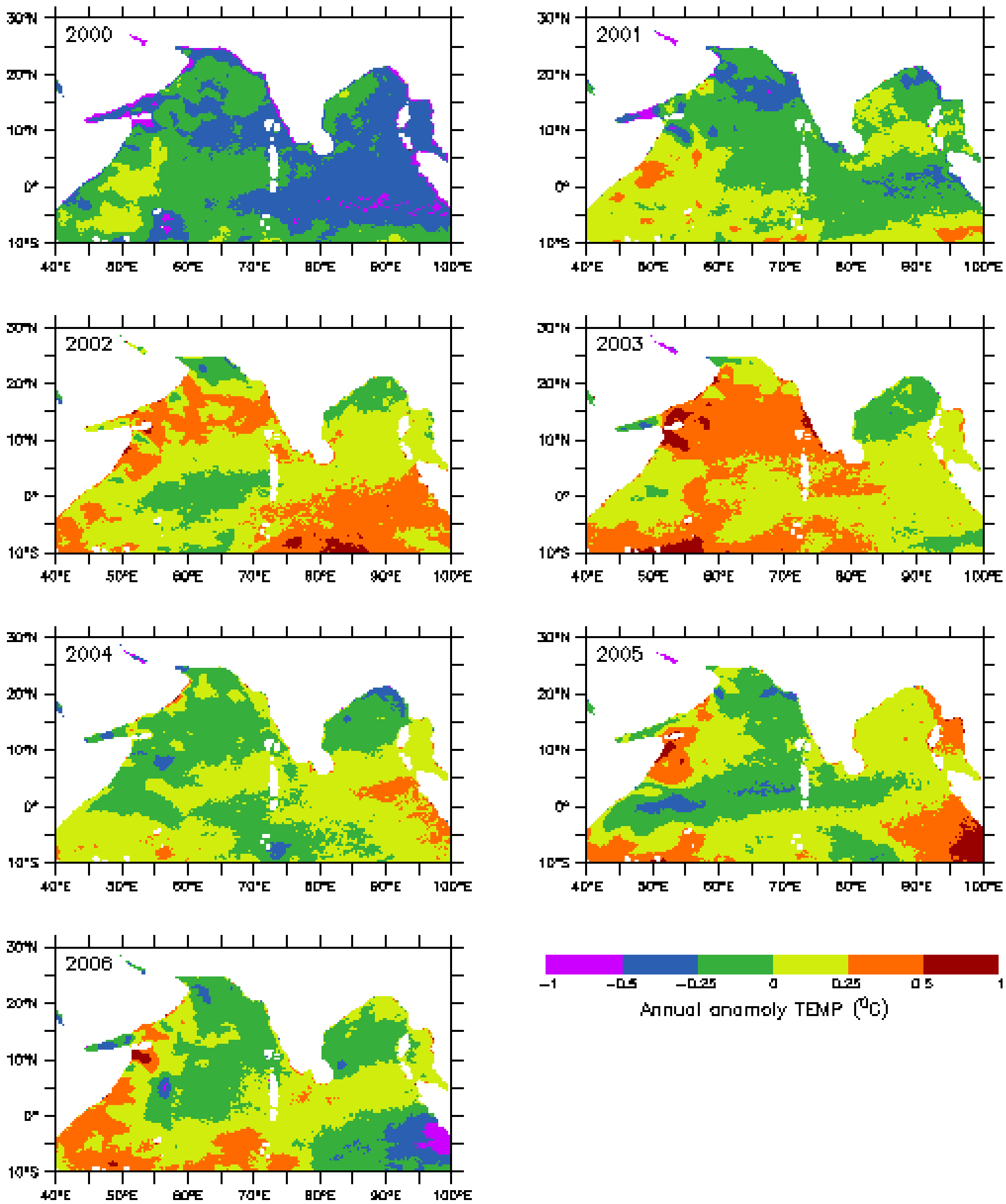


Figure-4.1.2.4: Annual anomaly picture of SST during 7 year study period.

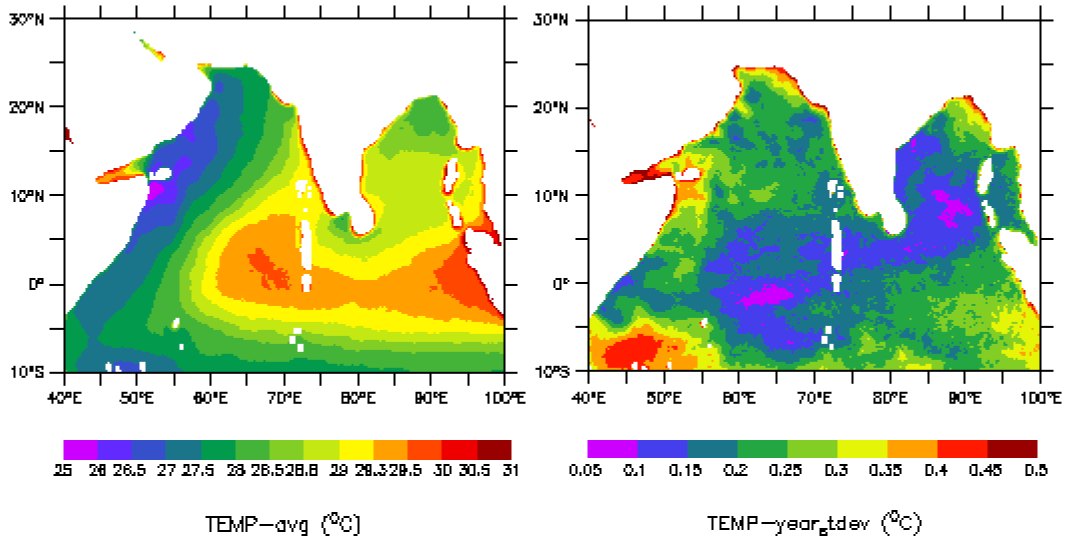


Figure 4.1.2.5: Mean and standard deviations of SST during 7 year (2000 to 2006) of study period prepared using the yearly mean picture of SST.

4.1.2.2Comparison of mean SST in different basins

The annual mean SST during 7 year (2000-2006) study period over different domain Based on the homogeneous characteristics of rate of changes of warming and cooling (Kothawale, D. R. et al, 2007) of north Indian Ocean, the entire basin divided into three domain i.e Arabian Sea, Bay of Bengal, and equatorial domain which are compared in figure 4.1.2.6. The mean SST of Arabian Sea remain almost same (27.8 ^{0}C) during 2000 and 2001, and then it increases up to 28.4 ^{0}C in 2003 with annual increase rate of 0.3 ^{0}C. Since 2003, it cools slowly up to 27.85 ^{0}C (in 2006) with the rate 0.1 0C/year. The annual average SST of Bay of Bengal started increasing from 28.6 ^{0}C in 2006 up to 20.3 ^{0}C in 2003 with the increase rate of 0.55 ^{0}C/year and then it almost uniform until 2006. The equatorial north Indian Ocean exhibits almost similar pattern of Bay of Bengal. Based on the observations, SST of BoB shows relatively higher where as Arabian Sea shows lower value during study period.

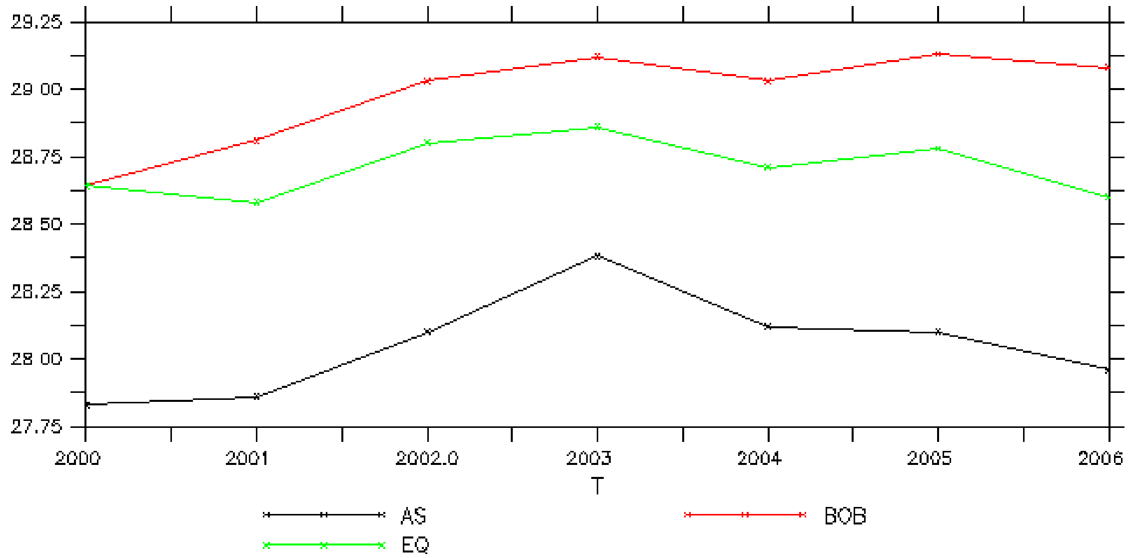


Figure-4.1.2.6: Comparison of inter-annual variability basin average SST of Arabian Sea (AS), Bay of Bengal (BoB) and Equatorial Indian Ocean (EQ).

4.2 Study of Intra and Inter annual variability of Chlorophyll in north Indian Ocean

The chlorophyll concentration in the water of open oceans may play an important role in the control of SST by trapping the solar radiation in the surface layer. When the chlorophyll concentration is high, SST of the open ocean can be increased. But in the coastal ocean, the situation is much more complicated due to prevailing of strong upwelling along the coats driven by wind stress curl and Ekman transport of coastal water towards the off shore. On the other hand, high upwelling regions are rich in nutrients and hence rich in chlorophyll and highly productive area.

In this chapter, we are going to explore the intra and inter annual variability of chlorophyll concentration in the water of the north Indian Ocean. The monthly climatology of Chlorophyll concentration data prepared from monthly composites of 7 year (during 2000-2006) data in a grid of 0.1 X0.1, obtained from

SeaWiFS (Sea-viewing Wide Field-of-View Sensor) radiometer observations, are used here together with monthly chlorophyll data of individual years.

4.2.1 Intra-annual variability

4.2.1.1 Spatio-temporal variability of chlorophyll

The annual evolution of Chlorophyll concentration of the climatological year in the north Indian ocean is shown in figure 4.2.1.1. In January the chlorophyll in the NIO is found in the range between 0.42mg/m3 to 0.34mg/m3 with the mean value 0.38mg/m^3. In this month very high chlorophyll (0.65mg/m3) is seen in the western, northern and south eastern Arabian Sea (surrounding Lakhadweep) and in coastal regions of BOB (0.49mg/m^3). The similar observation also reported by Levy et al., 2007. Small value of Chlorophyll is observed in Equatorial Indian Ocean (0.19mg/m^3). In February, chlorophyll concentration in NIO is almost similar pattern as observed in January. In the Arabian Sea, the chlorophyll concentration is relatively larger than the values observed in previous month and the values are ranges between 0.45mg/m^3 and 0.36mg/m^3 with an average value 0.4mg/m^3. There is large chlorophyll patch is seen in just north of the equatorial Indian ocean which is elongated from Somali coast in west to Lakhadweep in the east, indicating transport of phytoplankton (though advection and diffusion) in the ocean water. In this month, the values are relatively smaller in the water of BOB compared to the chlorophyll observed in the month of January.

During March, large chlorophyll values are mostly confined in northern Arabian Sea and in coastal water of northern BOB (as similar magnitude observed in previous month), The elongated equatorial chlorophyll patch is very much reduced and confined in the Somali coast. During April the chlorophyll concentration in Arabian Sea started decreasing and minimal values are reported in the month of May. In the month of May, large chlorophyll concentration is observed along the coast of Somali and Arabia (0.21mg/m^3 to 0.27mg/m^3 with mean 0.24mg/m^3). With the onset of SW monsoon in the month of Jun, large chlorophyll bloom are observed along the coast of Somali, north-western, south-eastern coastal Arabian Sea, and in northern coastal water of BOB (2 mg/m^3).

In July, however in large part of northern Arabian Sea, data are missing (probably due to cloud cover), large chlorophyll (bloom 2 mg/m^3) are observed most part of the Arabian Sea, south coast of India and Sri Lanka, and in north western BOB (along the coast of India). Large chlorophyll is also observed in southern BOB, proximity of Sri Lanka. Similar feature also observed in subsequent monsoon periods (Aug and Sep). With the removal of SW monsoon, during October and November, chlorophyll concentration gradually decreases their strength in the Arabian Sea and BOB and confined in costal water (western Arabian Sea and BOB). With the onset of NE monsoon in December, the chlorophyll in Arabian Sea and BOB gradually increases during subsequent month (Jan-March, spring bloom in March).

In an annual scale, western Arabian Sea (Arabian Sea as a whole) is very rich in chlorophyll where as Bay of Bengal and equatorial Indian Ocean are poor in chlorophyll (as seen in figure-4.2.1.2 for mean and standard deviation). Chlorophyll data also undergo very large fluctuation (intra annual variability) in the Arabian sea and BOB data. In summary, chlorophyll data show large monsoonal variability in the Arabian Sea and BOB.

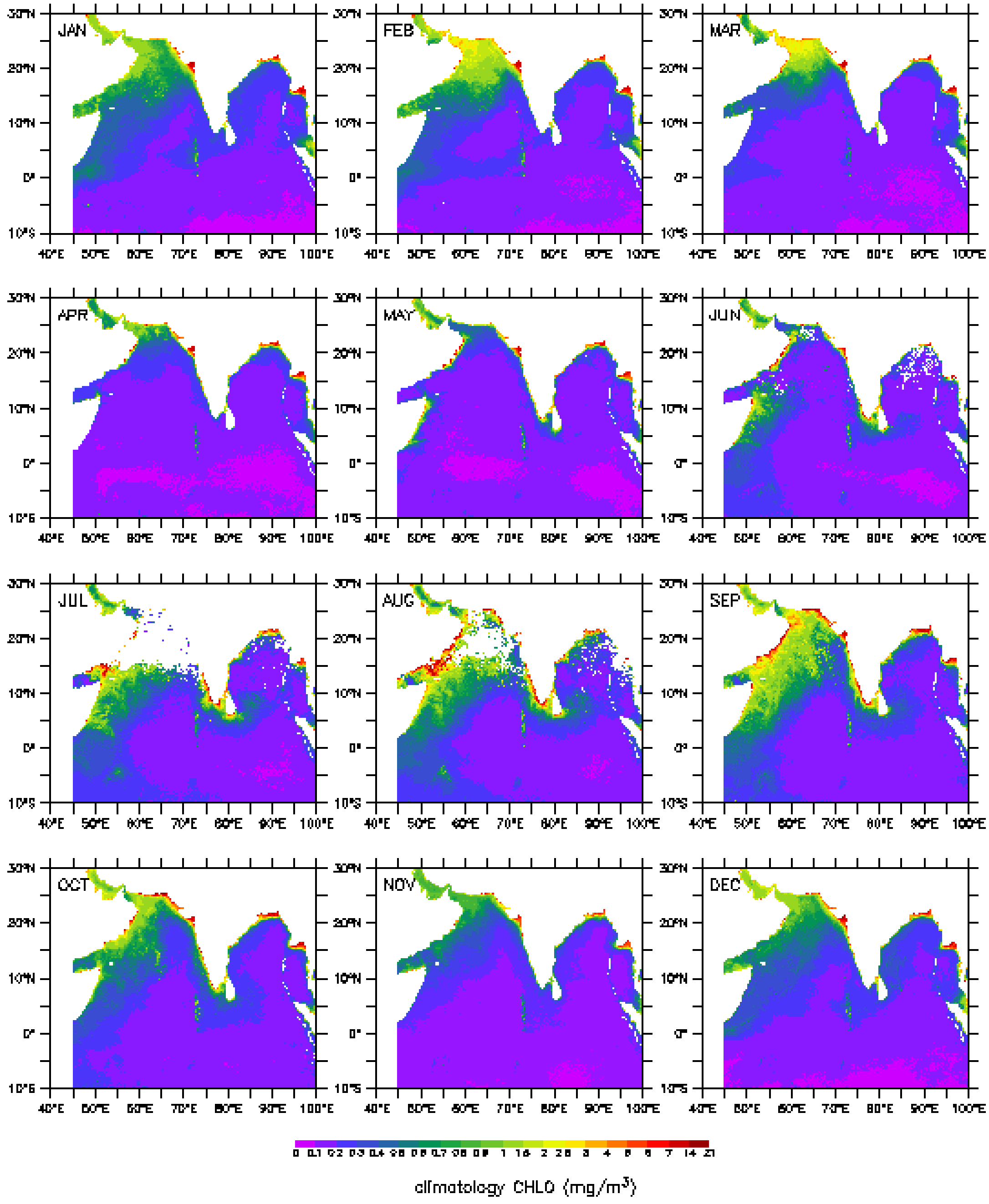


Figure-4.2.1.1: Annual evolution of chlorophyll climatology of the north Indian Ocean based on monthly data during 2000-2006.

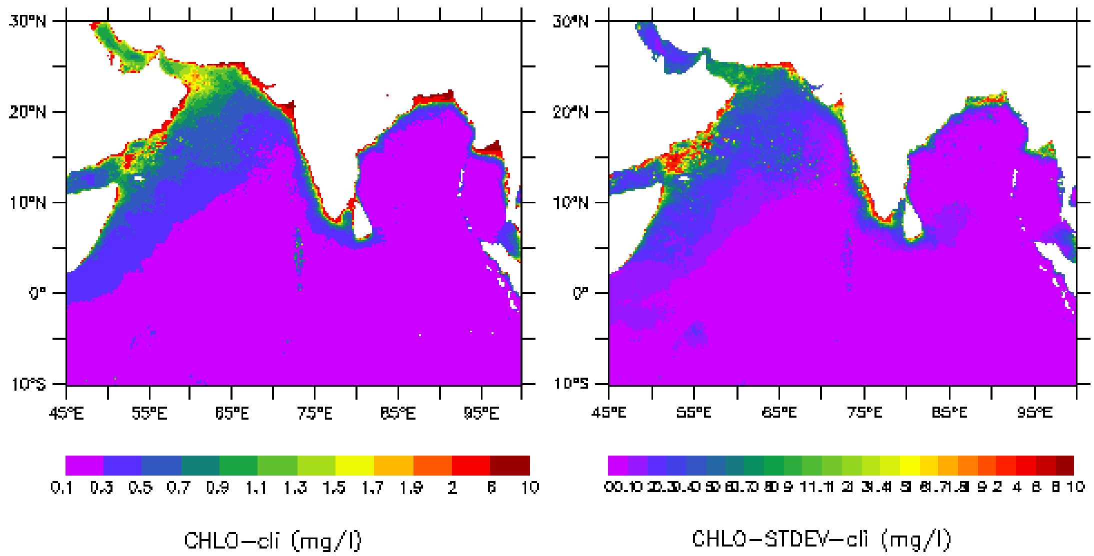


Figure 4.2.1.2 Climatologycal Mean of chlorophyll and Standard Deviation of monthly climatology during study period.

4.2.1.2 Comparison of mean chlorophyll in different basins

Annual evolution of mean chlorophyll data over different domains of north Indian Ocean are compared in figure 4.2.1.3. Over whole the domain of north Indian Ocean, the chlorophyll data exhibits bimodal variation (together with its sub domains, AS, BOB, and Equatorial Indian Ocean). In January the average chlorophyll in NIO is 0.38 mg/m^3 and it increase to 0.40mg/m^3 in February with increasing rate +0.02mg/m^3/m. Since then it decrease to 0.23mg/m^3 in April with decreasing rate 0.08mg/m^3/m. With the on set of summer monsoon over the NIO in May, chlorophyll concentration increases up to 0.52mg/m^3 in Sep with increasing rate of 0.06mg/m^3/m. After the collapse of summer monsoon, the chlorophyll of NIO again decreases to 0.36mg/m^3 in November with decrease rate of 0.08mg/m^3 mg/m^3/m and then it remain constant up to December.

Chlorophyll in Arabian Sea undergoes a bi-annual cycle with two pick in Feb (0.8 mg/m^3) and then in Sep (1.15 mg/m^3). The minimum values are observed in April (0.35 mg/m^3) and then in Nov (0.6 mg/m^3). The chlorophyll in BOB water also exhibits similar bi-annual cycle as similar to that of Arabian Sea, but the amplitudes (0.5 mg/m^3 and 0.6 mg/m^3) are much smaller than the cycle of Arabian Sea. The winter maximum of BOB is seen in January instead of February as for the case of BOB. However, chlorophyll in the Equatorial ocean shows the similar bi-annual cycle, the absolute values remain smaller (within 0.15 to 0.25 mg/m^3) throughout the year. Again the difference between maxima and minima are relatively smaller than that of AS and BOB. From all the domains reflect that, the concentration of chlorophyll relatively higher value over the Arabian Sea where as equatorial region shows lesser and Bay of Bengal show moderate value then other domains during study period.

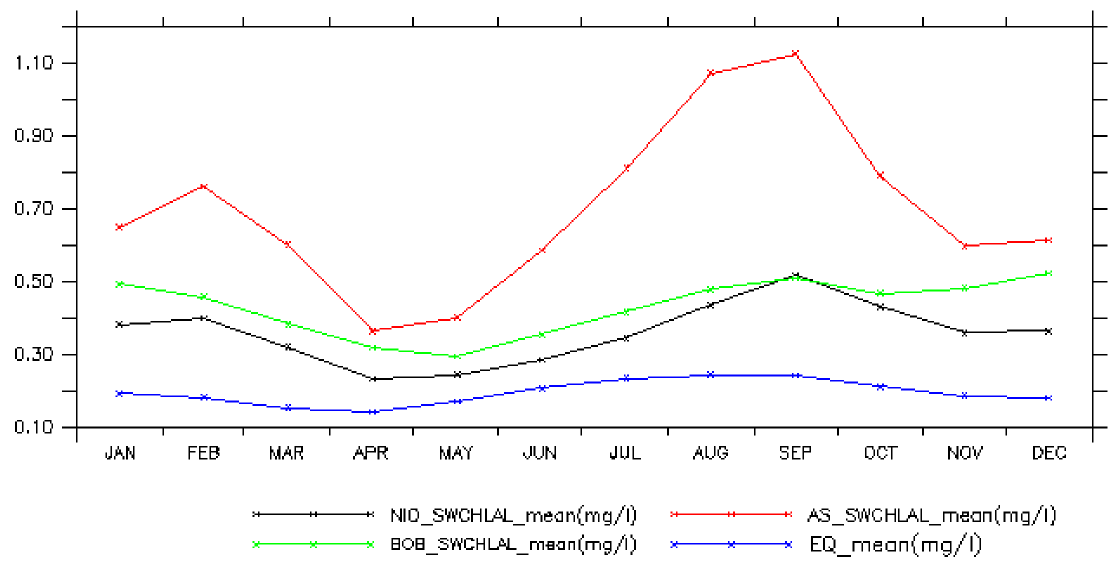


Figure-4.2.1.3: : Comparison of basin average pictures of chlorophyll in Arabian Sea (red), Bay of Bengal (green), Equatorial Indian Ocean (blue) and whole the domain (black).

4.2.2 Inter-annual variability

4.2.2.1 Spatio-temporal variability of chlorophyll

To analyze the inter-annual variability of chlorophyll in the north Indian Ocean, monthly chlorophyll concentration pictures during 7 year from 2000-2006 are used to estimate monthly standard deviations of chlorophyll during the same period and that is shown in Figure 4.2.2.1.

The figures suggest that there are significant inter-annual variability is seen in different parts of north Indian Ocean. During January, large variability exists in the north-western Arabian Sea (up to 0.4 mg/m^3) and along the coast of Somalia (0.2 mg/m^3) and south India extending northern Sri Lanka (0.2 mg/m^3). During February, the variability has large values in north-western Arabian Sea (up to 2 mg/m^3) and in the water of north-western equatorial Indian Ocean, region between Somali coast and Lakhadweep. There is less variability in the Bay of Bengal water. Similar kind of variability also observed in the month of March. During April, large variability is only confined in northern coastal Arabian Sea, and Bay of Bengal. In May, the period of pre onset of SW Monsoon, large variability are observed only in the region of coastal water of western Arabian Sea and in Somali coast. During April-May the fluctuation is not much pronounced then in Jun it fluctuate along the Somali, south coast of India and around the Sri Lanka coast. July and August, due to cloud the deviation can’t identified. However east and west of India and Somali coast were found to have more deviation then previous months. In September the deviation is 0.6 to 5mg/m3 along the west and northern part of Arabian sea and along the coast of India. In October its fluctuation decrease then previous month then it gradually decreases in November and December.

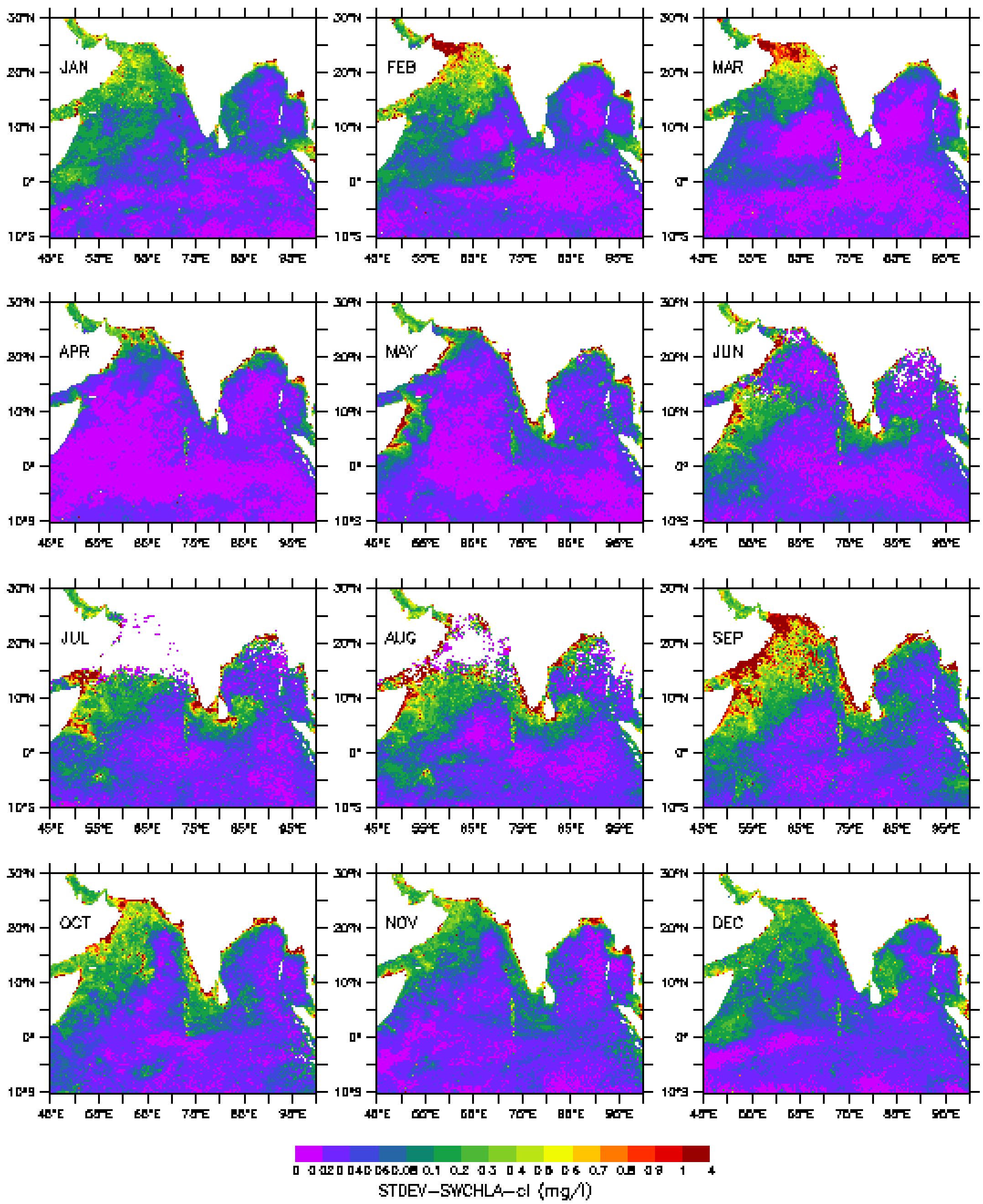


Fig 4.2.2.1: Monthly picture of standard deviations of chlorophyll during 2000-2006, in order to identify various active regions in the north Indian Ocean of large inter-annual variability.

Inter annual variability of chlorophyll show in figure 4.2.2.2. During study period the variation of chlorophyll found along western part of Arabian sea and Somali coast and costal part of continent. During 2000 the chlorophyll varies from 0.24 to 0.42mg/m^3 with basin average 0.35mg/m^3. During 2001 the chlorophyll varies from 0.21 to 0.51mg/m3 with basin average 0.35mg/m^3. in this year the average concentration is same as previous month. During 2002 the chlorophyll varies from 0.23 to 0.55mg/m3 with the basin average value of 0.36mg/m^3. In this year it increases slightly compared to the year 2001. Then it decrease during 2003 and chlorophyll varies from 0.22 to 0.52mg/m^3 with the basin average of 0.35mg/m3. During 2004 it varies from 0.21 to 0.46mg/m3 with the basin average value of 0.35mg/m^3. In the year 2005, the chlorophyll varies from 0.23 to 0.57mg/m3 with basin average value of 0.37mg/m^3 and during 2006 the chlorophyll varies from 0.23 to 0.6mg/m^3 with basin average value of 0.37mg/m3.

The variable of chlorophyll anomaly is show in the figure 4.2.2.3. This figure shows year to year variation from it seven year climatic mean. During 2000 the chlorophyll increase from 0.2 to 1.5mg/m3 along the west and north coast of Arabian sea and 0 to 0.1mg/m3 increase over central part of Bay of Bengal. However it is found to be decreasing from 0 to 0.1mg/m3 over the either side of 10^o latitude of equator from its climatic mean. From 2001 the chlorophyll decreases in between 0.2 to 2mg/m^3 along the west coast of Arabian Sea. Where as it increases from 0 to 0.1mg/m^3 south east part of Arabian Sea. During 2002 the chlorophyll decreases along the Somali coast and it increases in north of Arabian sea. During 2003 the chlorophyll increases from 0 to 0.1 mg/m^3 along the south part and it decreases from 0.1 to 2mg/m^3 along the west coast and central part of Arabian sea. In this period chlorophyll is found to increase from 0.1 to 1.5mg/m^3 at northern coast of BoB. During 2004 the chlorophyll is found to increase from 0.1 to 1.5mg/m^3 over the northern central Arabian sea where as it is found to decrease from 0 to 0.1mg/m^3 in east part of NIO. During 2005 the chlorophyll is found to increase from 0.1 to 1.5mg/m3 over all side of coastal area and from 0 to 0.1mg/m^3 over the central part of Indian Ocean. This year chlorophyll is found to be more then other years. During 2006 the chlorophyll increase from 0.1 to 1.5mg/m^3 along the North part of Arabian Sea. Where as in south west part it decreases from 0 to 0.1mg/m3.

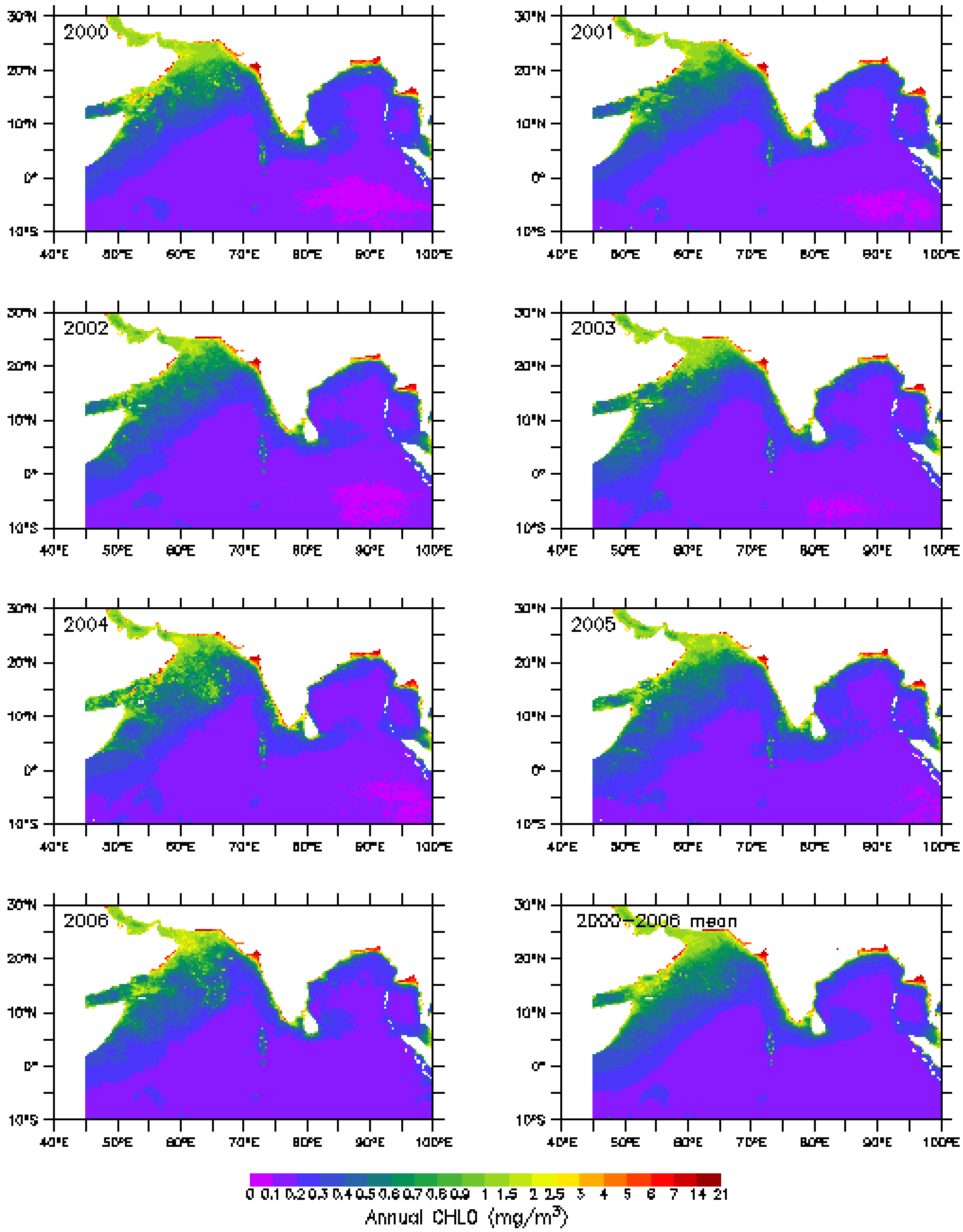


Figure-4.2.2.2: : Annual mean picture of chlorophyll in the north Indian Ocean during 2000-2006.

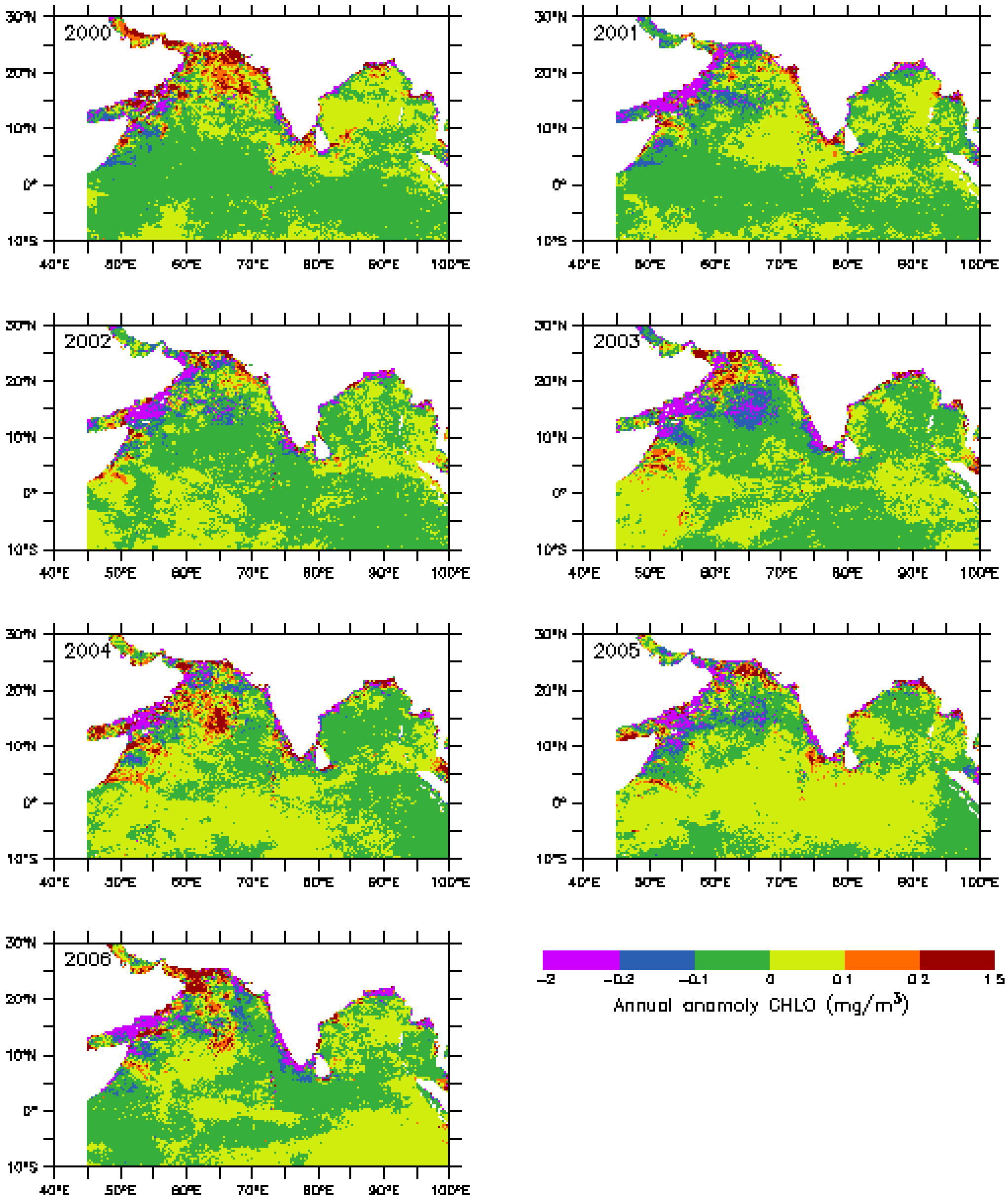


Figure-4.2.2.3 : Annual anomaly picture of chlorophyll during 7 year study period.

4.2.2.2 Comparison of mean chlorophyll in different basins

The variation of mean chlorophyll in different domain is shown in figure 4.2.2.4. In Arabian sea domain, the mean Chlorophyll is found to be 0.71 mg/m^3 in the year 2000 and it increase to 0.78 mg/m^3 in the year 2001 then it decreases up to 0.68 mg/m^3 in 2002 and the average values are maintained at 0.67 mg/m^3 in 2003, 0.7mg/m^3 in 2004, 0.72mg/m^3 in 2005 and 0.71mg/m^3 in 2006. In Bay of Bengal the chlorophyll shows 0.42mg/m3 in 2000, 0.43mg/m^3 in 2001and 2002, 0.44mg/m^3 in 2003, 0.43mg/m^3 in 2004 and it remain constant up to 2006.In this domain it shows lesser chlorophyll then AS during climatic period. In equatorial domain the chlorophyll varies in between 0.18 to 0.2mg/m^3 during all the year of climatic period. The wind field of Arabian Sea shows relatively higher intensity where as equator lesser intensity during the study period.

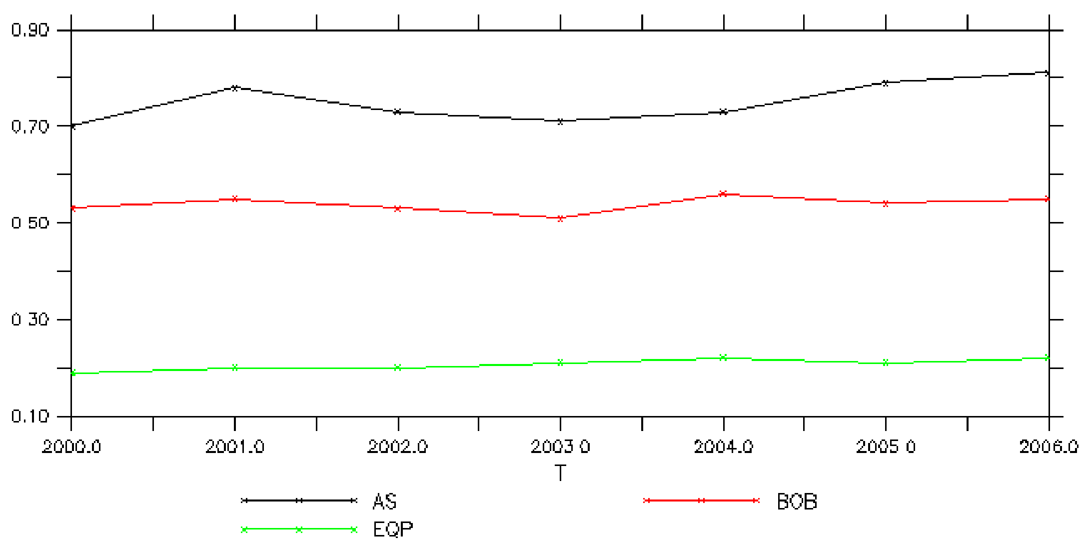


Figure-4.2.2.4: Comparison of inter-annual variability basin average chlorophyll of Arabian Sea (AS), Bay of Bengal (BoB) and Equatorial Indian Ocean(EQ).

4.3 Variability of Wind field and Ekman pumping in the north Indian Ocean

The Indian subcontinent and surrounding of north Indian Ocean are highly dominated by monsoonal climate. During the NE winter monsoon (December – February) wind mainly blows over NIO from land masses of Indian subcontinent (south Asia) to the ocean and during the SW summer monsoon, it blows in the reverse direction (from NIO to the Indian Land masses). Normally SW monsoonal winds are stronger and enriched in moisture, which causes heavy precipitation over the land masses. In the contrary, NE monsoon winds are relatively weaker and dry, except very small part of South India, India does not receive any significant rain fall. When winds blow over the Ocean during both the monsoons, it accelerates the ocean water (in the form of ocean current) and drives Ekman pumping though wind stress curl. On the other hand, ocean supply moisture to the atmosphere though evaporation process.

In this chapter, the intra and inter annual variability of wind speed over the north Indian Ocean are studied. Monthly climatology of wind data, prepared from monthly composites of 7 year (during 2000-2006) QuickScatt wind field data are used in this analysis.

4.3.1 Intra-annual variability

4.3.1.1 Spatio-temporal variability of Wind Speed

The annual evolution of winds over the north Indian Ocean is shown in figure 4.3.1.1. As shown in figure, winds during December, January, and February (the period of winter in the northern hemisphere) blow over the Arabian Sea (north Indian Ocean) and Bay of Bengal from NE. During May-Sep (the period of summer in the northern hemisphere) winds blow over the Arabian Sea and Bay of Bengal from SW direction. March-April, October-November are the transition period, when weak wind prevail over the ocean. SW monsoon winds are stronger than the NE monsoon winds. Wind over the Arabian Sea is stronger than the Bay of Bengal during both the monsoons. During winter (Dec-Feb), Westerly winds are prevailing over southern equatorial Indian Ocean. During summer, westerly winds are prevailing over the central equatorial Indian Ocean above the equator. During the same period, south-easterly winds prevail in south of equator.

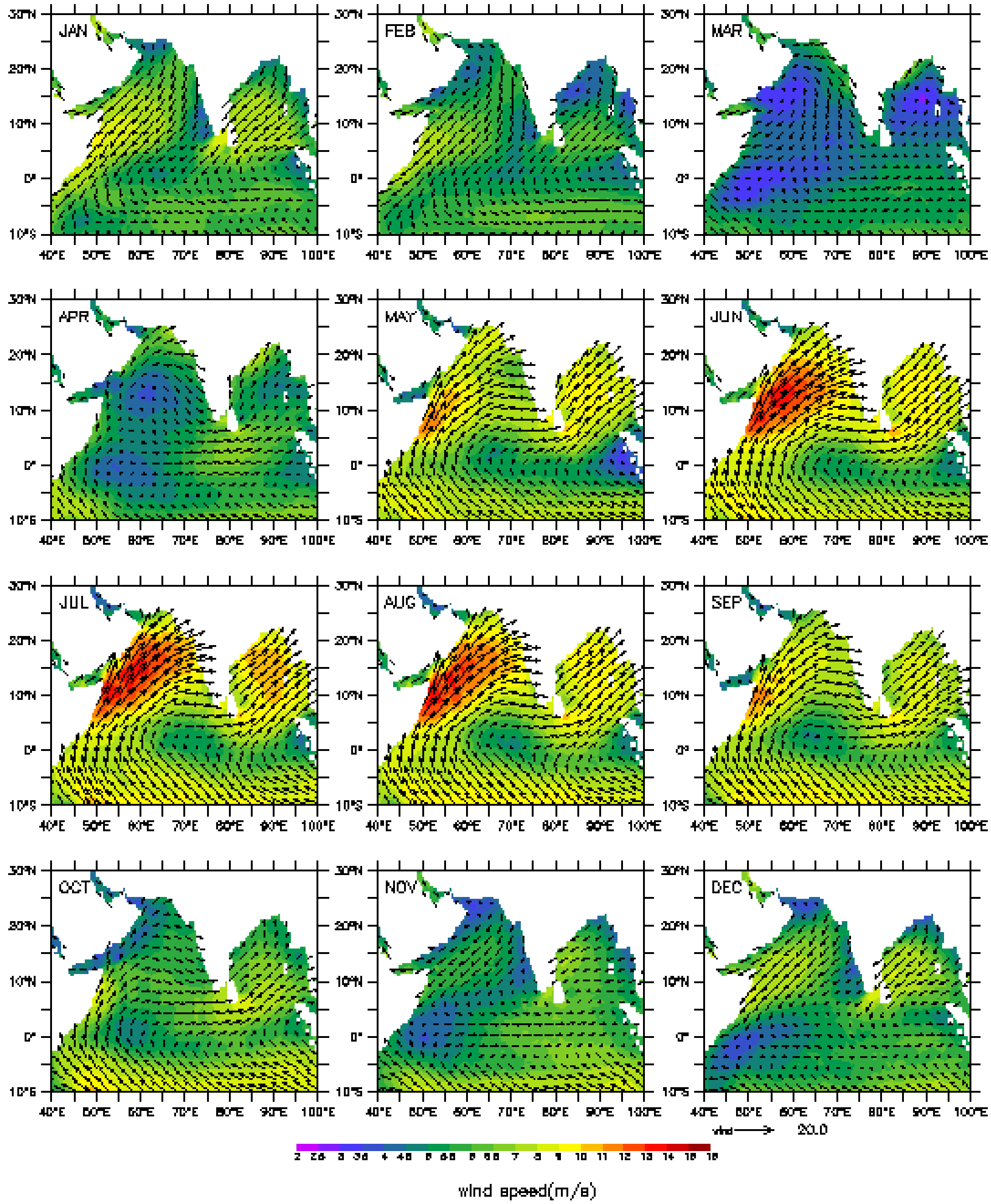


Figure-4.3.1.1 : Annual evolution of wind field climatology of the north Indian Ocean based on monthly data during 2000-2006.

As seen in Fig 4.3.1.2, the standard deviation of wind field in year, suggest that large change is seen in western Arabian Sea, Central Bay of Bengal, and south-western north Indian Ocean.

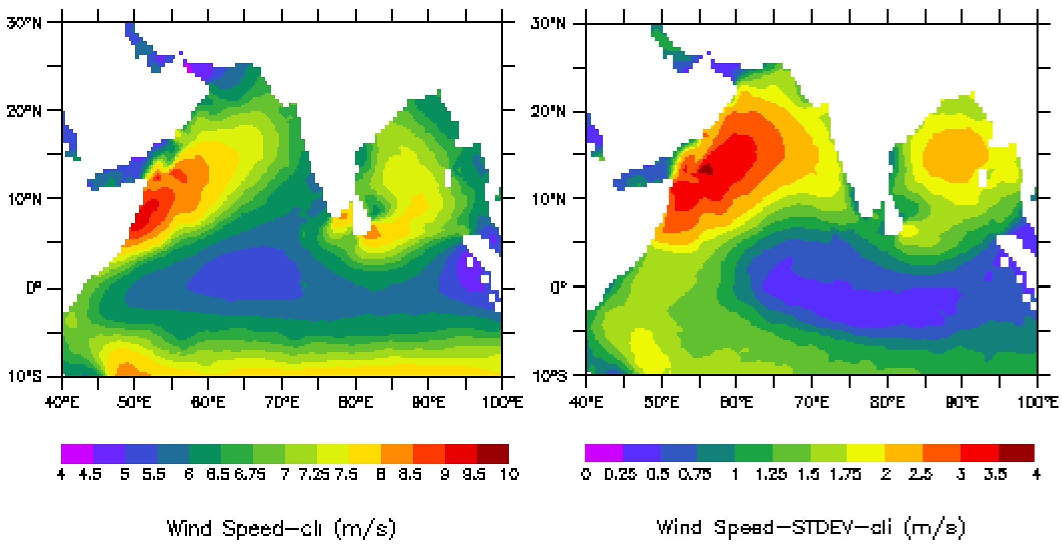


Fig 4.3.1.2: Climatologycal Mean of wind field and Standard Deviation of monthly climatology during study period.

4.3.1.2 Comparison of mean Wind Speed in different basins

The evolution of mean wind field of Arabian Sea, Bay of Bengal, and Equatorial Indian Ocean are compared in figure 4.3.1.3. As shown in the figure, every domain exhibits bimodal cycle of wind. From January to March the intensity of wind decreases then it remains all most similar up to April. When SW monsoon start over Indian Ocean, the magnitude of wind increases sharply up to July (peak monsoon period) then after the wind gradually decreases till October after that the wind speed again increases to secondary peak over all the domain.

During SW monsoon period, relatively highest peak magnitude of wind occurring over all selected the domains and secondary peak is exhibited in NE monsoon period. Where as during two transition period (March-April and October-November) lowest wind magnitude are observed.

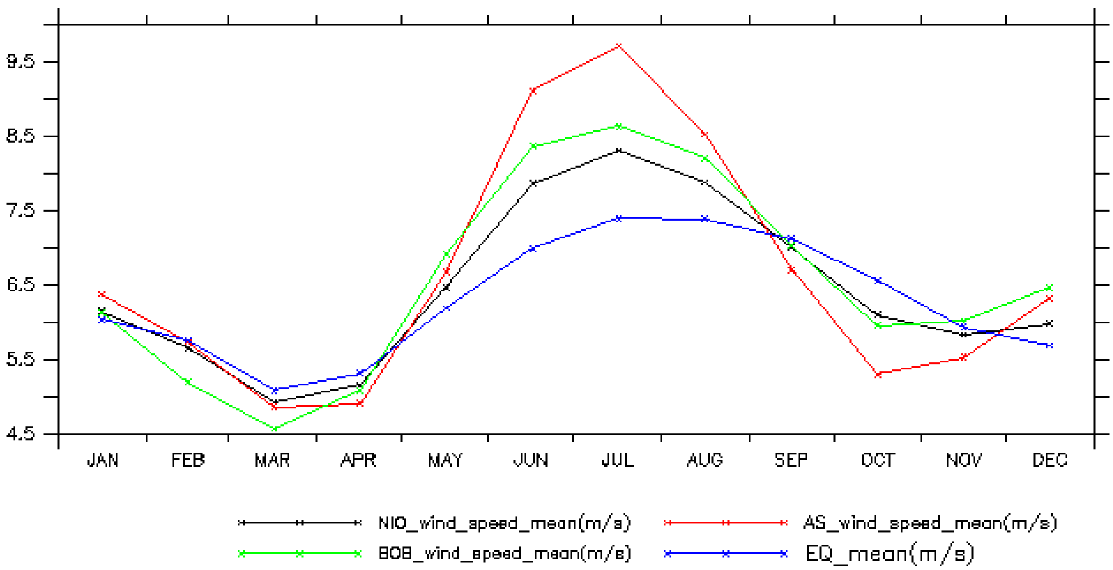


Figure 4.3.1.3: Comparison of basin average pictures of wind field in Arabian Sea (red), Bay of Bengal (green), Equatorial Indian Ocean (blue) and whole the domain (black).

4.3.1.3 Ekman Pumping

Ekman pumping is estimated over the north Indian Ocean using the monthly climatological wind fields and that is shown in Figure 4.3.1.4 (see the section 3.2.3 for the methodology to estimate Ekman pumping). The figure suggest that, there is strong upwelling (0.6 to 5m/s) and down welling (0.5 to 5m/s) are prevailing in equatorial Indian ocean though out the year. During the Dec-Feb, the period of NE winter monsoon, upwelling areas are mostly in north to the equator and down welling areas are in south to the equator. The situation is reversed in SW monsoon period (May-Sep). During the SW monsoon, high upwelling is observed along the coast of Somali, and Arabia (western Arabian sea), South-east coast of India, and east coast of Sri Lanka. There are significant upwelling is observed along west coast of Sri Lanka during the NE monsoon.

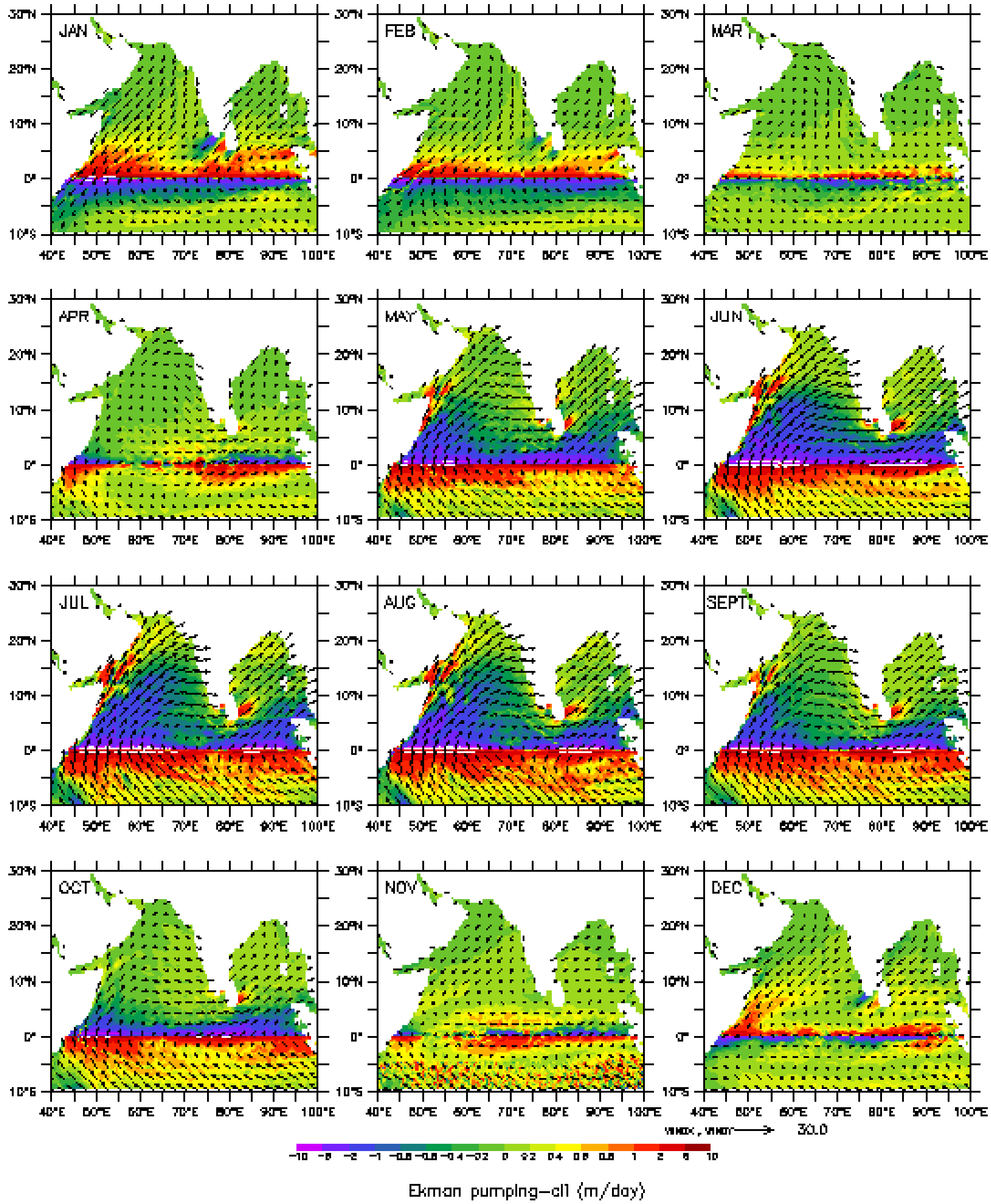


Figure-4.3.1.4: Annual evolution of Ekman pumping climatology of the north Indian Ocean based on monthly data during 2000-2006.

4.3.2 Inter-annual variability

4.3.2.1 Spatio-temporal variability of Wind field

To evaluate the inter-annual variability of wind field in the north Indian Ocean, monthly wind pictures during 7 year from 2000-2006 are plotted in Figures 4.3.2.1 and monthly standard deviations of wind field during the same period has been plotted in Figure 4.3.2.2. The figures suggest that there are significant changes in wind magnitude at different regions of north Indian Ocean in monthly scale.

In January, wind speed of north east coast of India and south east of north Indian ocean shows relatively more (standard deviation 1 to 1.5) fluctuation, where as other part of north Indian Ocean fluctuations are found to be less. During February, the fluctuation of wind intensity over west coast of Arabian Sea, west coast of Sri Lanka and south eastern part of Indian Ocean are relatively more (Standard deviation 1 to 1.5) then other part of the basin. In this month the fluctuation of wind is more then January. During March, the standard deviation wind intensity is up to 1.5 along the Somali coast while along the west coast of India shows relatively lesser standard deviation (0.4m/s). During April the standard deviation of wind intensity is less then 0.4m/s along the south west coast of India and mid of south equator but it relatively fluctuates more (1.2 to 1.5m/s) over the Bay of Bengal, Sri Lanka coast and south west coast of north Indian ocean. During May, the standard deviation off wind intensity is, significantly increasing in between 1.4 to 2m/s along the Somali coast and central Bay of Bengal where as other part of basin it fluctuates up to 0.5m/s. During July, the highest fluctuation of wind is found along the central Arabian sea (Standard Deviation up to 2m/s) where as other parts are very less fluctuation (up to 0.5m/s). During July, the southern part of Arabian sea relatively higher wind intensity is found compared to other part of north Indian ocean. During

August and September, the standard deviation of wind magnitude is more over Arabian sea and Bay of Bengal then south part of Indian Ocean. In October the fluctuation of wind is nearly uniform in between 0.6 to 1.5m/s through out the basin. In November, the fluctuation of wind intensity over the west coast of India and south west coast NIO is found to be relatively lesser then other part of the north Indian Ocean. During December, the wind fluctuation is less (0.2 to 0.5m/s) through North Indian Ocean. In this month fluctuation is found to be less then previous months.

From annual average (Figure-4.3.2.2) it is reflected that, along Somali and south east coast of Sri Lanka, the magnitude of wind is in-between 7.5 to 9.5m/s where as along the equator the magnitude of wind is in-between 0.45 to 6m/s in all the year

The anomaly of wind Speed from 2000 to 2006 is shown in figure 4.3.2.3. During 2000 the wind speed increases around Sri Lanka and central part of NIO (maximum up to 0.25 to 0.75m/s) where as Somali coast and Bay of Bengal the wind speed decreases (up to 0.1 to 0.3m/s) from the climatic mean. During 2001, the wind speed decrease from 0.3 to 0.75 m/s over the north east part of Bay Bengal. In this year wind speed increases from 0.1 to 0.75m/s along north of equator. During 2002 the east part of Arabian sea and Bay of Bengal shows decrease of wind speed from 0.1 to 0.2m/s where as west coast of NIO show increase from its climatic mean value. During 2003, the wind speed decreases from 0.1 to 1m/s over the north part of Arabian Sea and Bay of Bengal. Where as wind speed increase from 0.1 to 0.75m/s over the south part of North Indian ocean. During 2004 the wind speed increase in between 0 to 0.75m/s along the west coast of India and it spread towards western part of Indian ocean where as it decreases from 0.1 to 0.3m/s over Bay of Bengal from its climatic mean. During 2005, the wind speed decreases from 0.1 to 0.75m/s in west coast of NIO and east coast of Bay of Bengal where as it increases from 0.1 to 0.75m/s along the equator and south coast of India from climatic mean.

During 2006 the anomaly shows decrease from 0.1 to 1m/s other then south of NIO. However it increases from 0.1 to 0.75m/s along the south east part of NIO from its climatic mean.

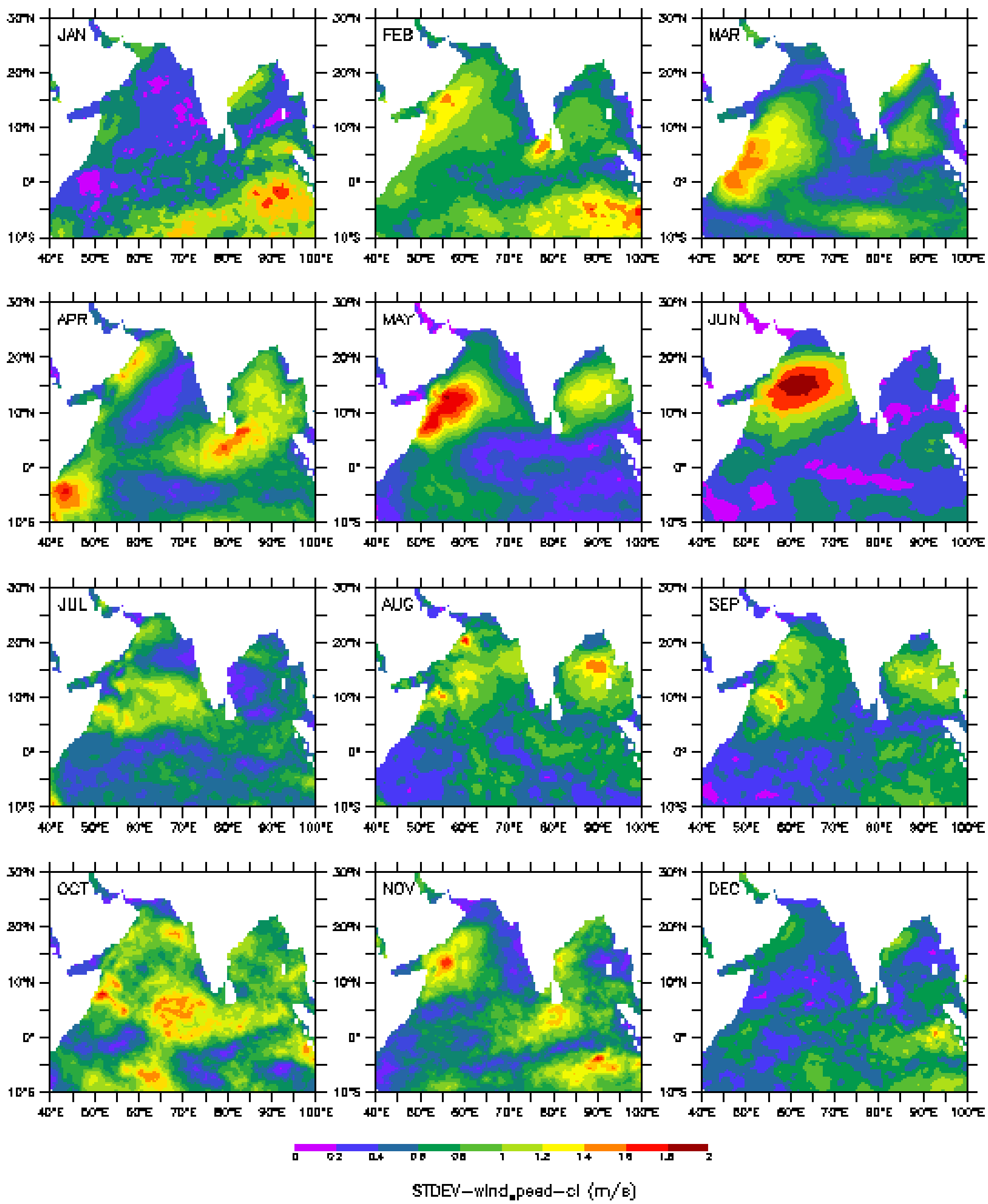


Figure-4.3.2.1: Monthly picture of standard deviations of wind field during 2000-2006, in order to identify various active regions in the north Indian Ocean of large inter-annual variability.

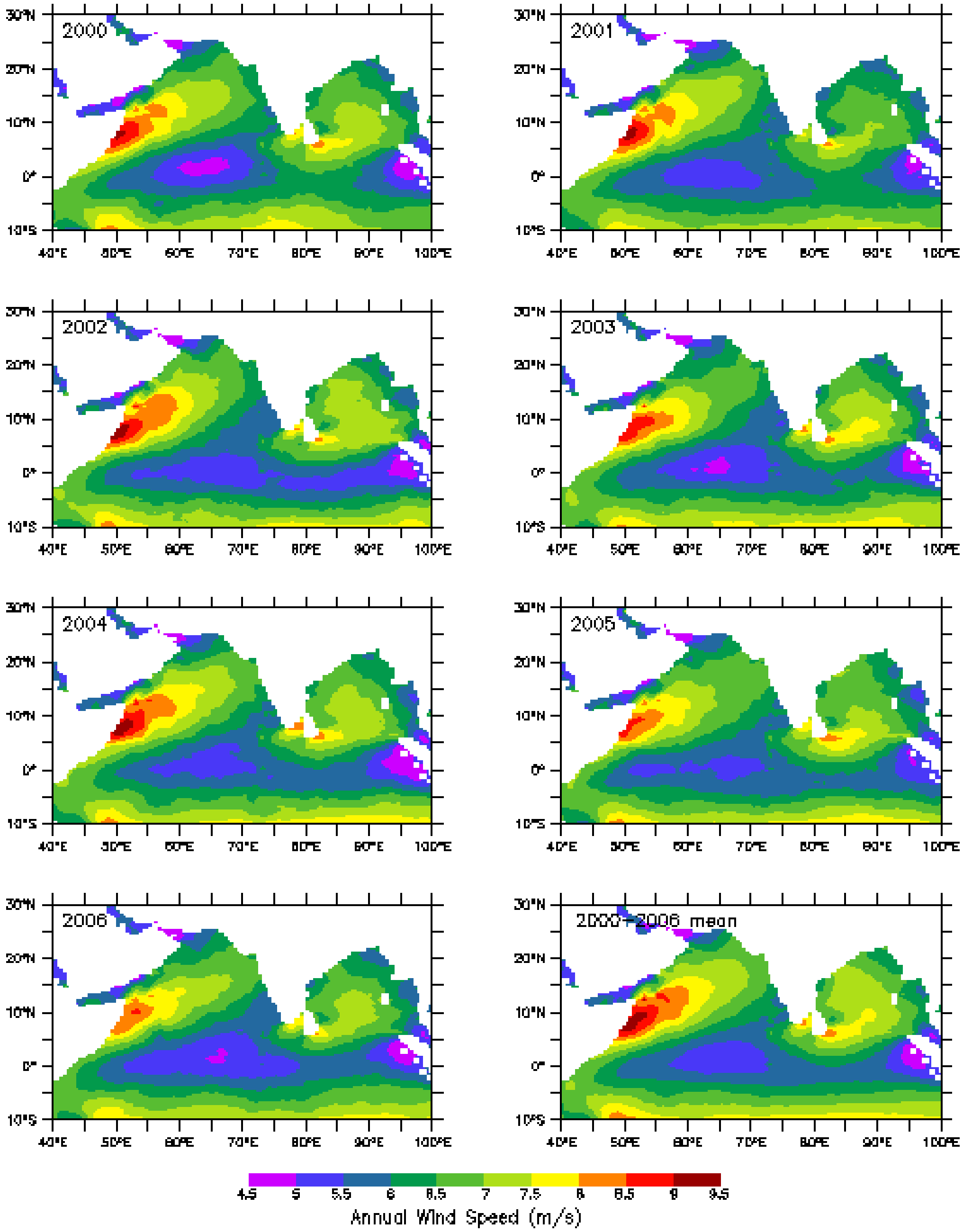


Figure-4.3.2.2: Annual mean picture of wind field in the north Indian Ocean during 2000-2006.

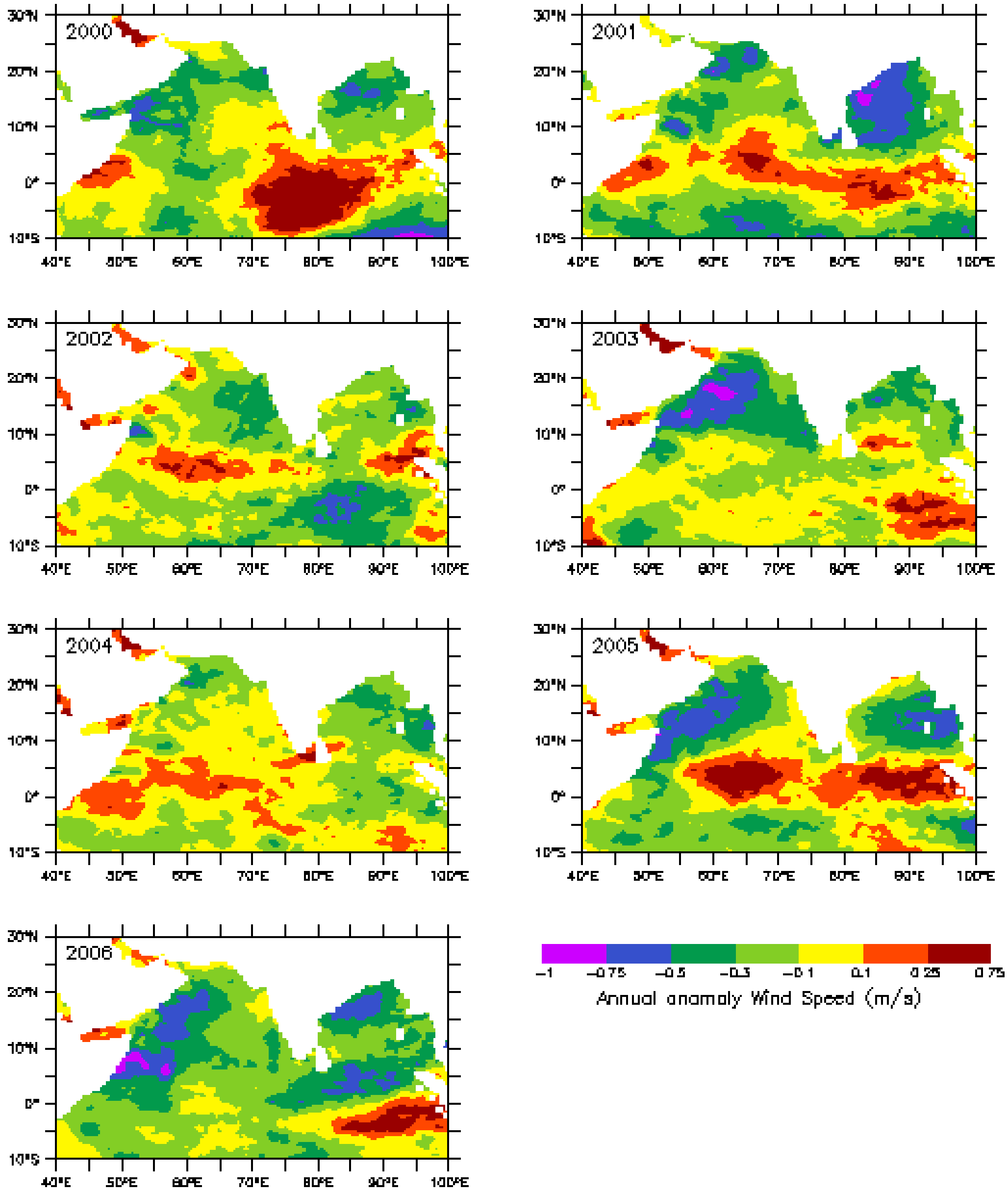


Figure-4.3.2.3 : Annual anomaly picture of wind field during 7 year study period.

4.3.2.2 Comparison of mean Wind Speed in different basins

The annual variation of average of wind speed in different basin is show in figure 4.3.2.4. From Arabian Sea domain it is found that, the wind speed is 6.65m/s in 2000 and it gradually increases to 6.7m/s in 2002 then it decreases to

6.54m/s in 2003 then it increases 6.77m/s in 2004. Then it again decreases 6.63m/s in 2005 and then increases to 6.54m/s in 2006.In BoB domain the wind speed is found to be less compared to Arabian sea, however during 2003 it is found to be more (+0.08m/s) then Arabian domain. In this domain the wind speed show 6.55m/s in 2000 and it gradually increases up to 6.62m/s in 2004 then it decreases to 6.43m/s in 2005 and again it increases to 6.55m/s in 2006. The equatorial domain, show less wind speed compared to other two domains.

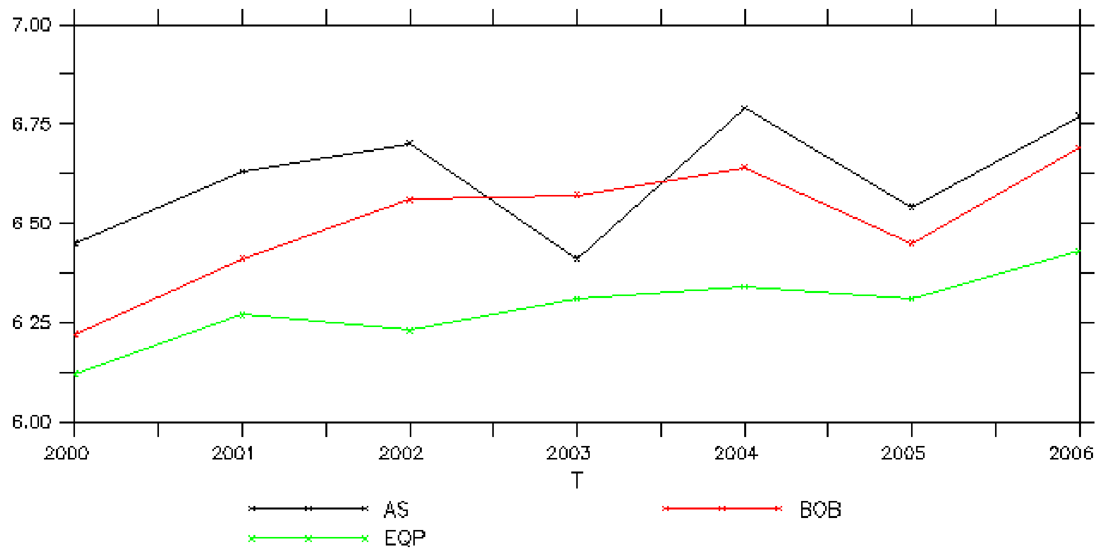


Figure-4.3.2.4: Comparison of basin average pictures of wind field in Arabian Sea (black), Bay of Bengal (red) and Equatorial Indian Ocean (green).

Chapter-5
Discussion & Conclusion

5.1 Intra-annual variability

It has been described in previous chapter that SST of different part of north Indian Ocean undergo large intra annual and inter annual variability. In intra annual scale, western north Indian Ocean, along the coast of Arabia, and Somali, and northern Bay of Bengal show large changes of SST during the monsoons. During the SW summer monsoon (June-Sept), temperature largely cools down along the western north Indian Ocean (see Fig. 4.1.1.1). The qualitative explanation of this large cooling are mainly due to (1) mixing of cooler subsurface water with the surface layer owing to Ekman pumping along the coast of Arabia, and Somali, driven by SW strong monsoon winds (Fig 4.3.1.5), and due to (2) horizontal transport of colder water by Monsoon Somali Currents (see Fig. 5.1, Shenoi et al.,1999). The chlorophyll in the western coastal north Indian Ocean increases during the same period mainly due to supply of nutrients by coastal upwelling. In this period, water of gulf of Aden remains warmer than adjacent cold water of Arabian Sea, suggesting that the water remain isolated from the mixing and transport process with the oceanic water of south-western Arabian Sea. Large inter seasonal change of northern Bay of Bengal water is mainly due to the fact that, this part of Bay remain much cooler in winter and warmer in spring and summer than the southern Bay. This can be attributed mainly to the contrast of solar heating during both the seasons (Winter and summer) where horizontal advection takes cooler water from Arabian sea to Bay of Bengal along the south of Sri Lanka during summer season as sees in the figure 5.1. River run off into this region from the rivers (Brahmaputra and Ganga etc) also exhibit the winter cooling in the coastal regions.

SST and Chlorophyll analysis suggest that there is transport of cooler water from south-east Arabian Sea to the Bay along the coast of Sri Lanka during summer monsoon. This is also further supported by prevailing SMC (SW

Monsoon Current) and WICC (West India Coastal Current) (see the Fig 5.1, adopted from Shenoi et al.,1999).

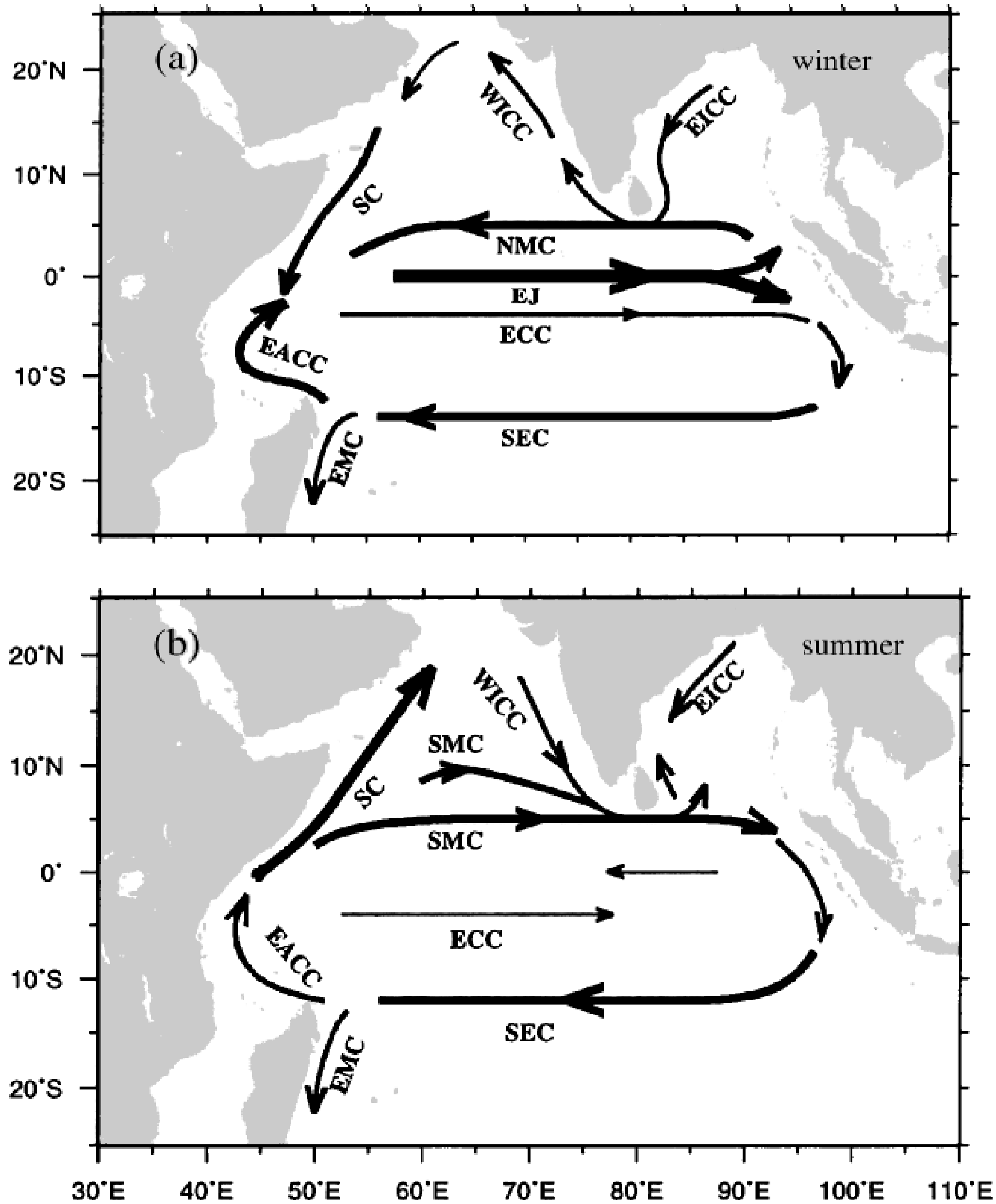
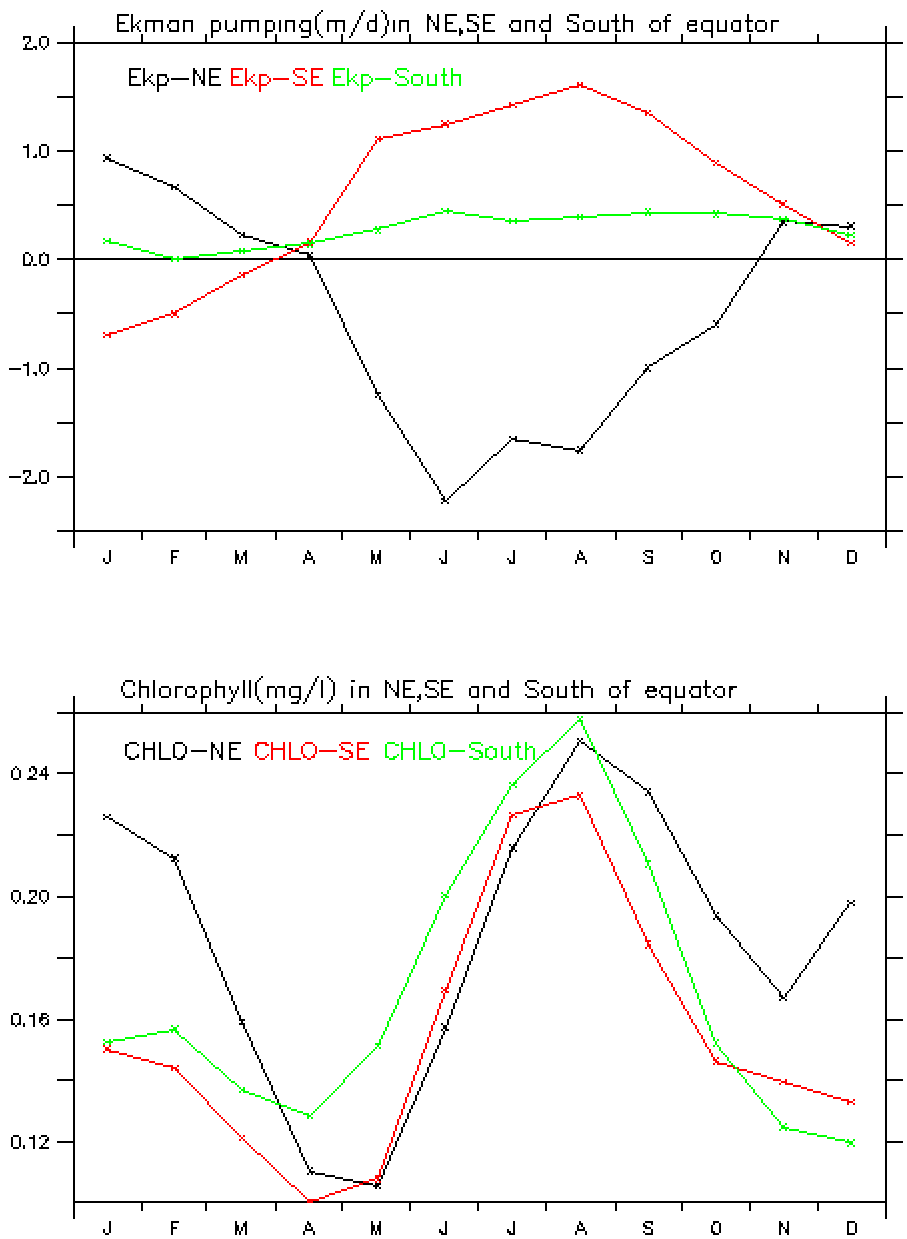


Figure 5.1: Schematic of major surface currents in the Indian Ocean during (a) the northeast monsoon and (b) the southwest monsoon. The major currents depicted are: South Equatorial Current (SEC), Northeast Monsoon Current (NMC), Equatorial Counter Current (ECC), Equatorial Jet (EJ), East African Coastal Current (EACC), Somali Current (SC), Southwest Monsoon Current (SMC), West India Coastal Current (WICC), East India Coastal Current (EICC) and East Madagascar Current (EMC). The thickness of the curve represents the relative magnitude of the current (adopted from Shenoi et al. 1999).

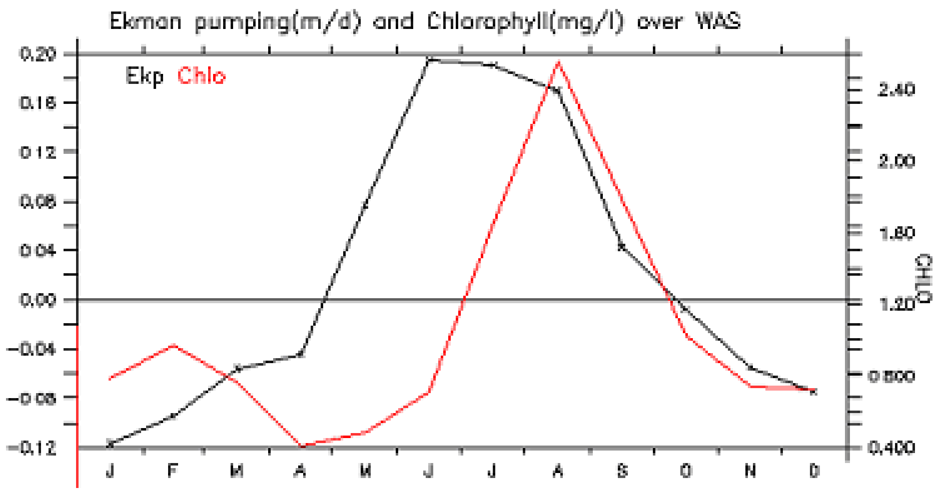
The computed Ekman pumping velocity in Fig 4.3.1.5, suggests that there is high upwelling and down welling are prevailing in the central equatorial Indian ocean. Mean Ekman pumping velocity over 0-5 ^{0}N latitude and 55-85E longitude (black) and 0-5^{o}S latitude and 55-85 ^{o}E longitude (red), are plotted in Fig 5.2a and the mean chlorophyll over the same regions are plotted in Fig.5.2b. As regarding the north-central equatorial Indian Ocean, upwelling prevails during the winter and chlorophyll increases in this region. During this time, westward NE Monsoon Current (NMC) is prevailing in this region, which brings mostly surface water (having less nutrients) from eastern side to western side. This suggests that, chlorophyll growth in this region is due to upwelling of subsurface nutrient rich water to the near-surface layer though Ekman pumping. In summer, down welling is prevailing in this part of the ocean, but high growth of chlorophyll is observed. This is mainly due to horizontal transport of nutrient rich water from Somali coast to this region by SMC (Southwest Monsoon current). In an another study *Levy, et al., 2007* have suggested that input of nutrients can be mediated by upwelling, by convection, or by horizontal advection.

Regarding the southern central Equatorial Indian Ocean, during winter mostly down welling prevails in this region, but chlorophyll increases in this period. This mainly due to the supply of nutrient rich water from western side (Africa Coast) to this region by Equatorial Counter Current (ECC) as seen in Fig. 5.1. During summer, mostly upwelling prevails in this region and increase of (high) chlorophyll in this period mainly due to the upwelling of sub-surface water to the surface layer.



Figute 5.2: In the upper panel, average Ekman pumping velocity (m/day) estimated in 0-5 N (black), 0-5 S (red) and green (5-10S). In the lower panel, average chlorophyll observed in the same regions as for the Ekamn pumping.

As it has been described that, western Arabian Sea is the region of active air-sea interaction process. Winds are very strong over this region during the monsoon that drives Ekman pumping. Its impact on SST and chlorophyll concentration is highly significant. In the Figure 5.3, we have shown the variability of Ekman pumping versus chlorophyll. The figure suggest that when Ekman pumping increases from 0 m/day in April, growth of Chlorophyll concentration increases up to the withdrawal of SW monsoon in August . Since August, chlorophyll decreases together with decrease of upwelling.



Figute 5.3: variability of Ekman pumping versus chlorophyll in western Arabian Sea.

5.2 Inter-annual variability

SST also exhibits strong inter-annual variability during 2000-2006. 2003 year is the warmest period in north Indian Ocean and 2000 being the coldest year. Chlorophyll and wind field (Ekman pumping) are also exhibiting the similar inter-annual variability. High chlorophyll growth is seen in the northern Arabian Sea during the colder year (2000) and decrease of chlorophyll is seen in warmer water in 2003 (Fig. 4.2.2.3). Comparison between wind field and SST over the same domain suggest that inverse relationship may exist between inter annual variability of SST and wind filed during the study period of 7 year from 2000-2006 (see Fig. 5.4).

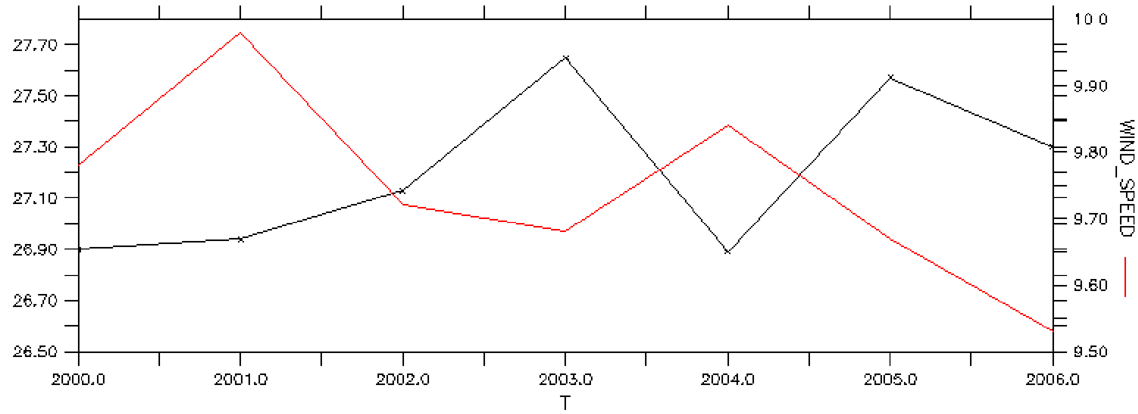


Fig. 5.4: Comparison between annual mean SST and wind speed over the Arabian Sea.

One can associate rainfall inter-annual variability with the variability of winds and SST over the active air-sea interaction areas of north Indian ocean as seen in standard deviation (figure 4.1.2.1). SST and wind field largely controls the evaporation process over the north Indian Ocean. Thus region of large inter-annual variability of Evaporation over the Arabian Sea and north Indian Ocean may depict some signature of inter-annual variability of rainfall over the India. To do that, monthly standard deviation of Evaporation (/latent heat flux) over the study region during 2000-2006 are analysed in Figure 5.5. The figure suggests that the place of large change of evaporation over the ocean is different in different months. Therefore, to explore relation between the Indian rain fall and evaporation over the selected active regions (region of large standard deviation) are analysed (Figure 5.6). The figures suggest that there is significant positive co-relation exists between these two parameters for different months.

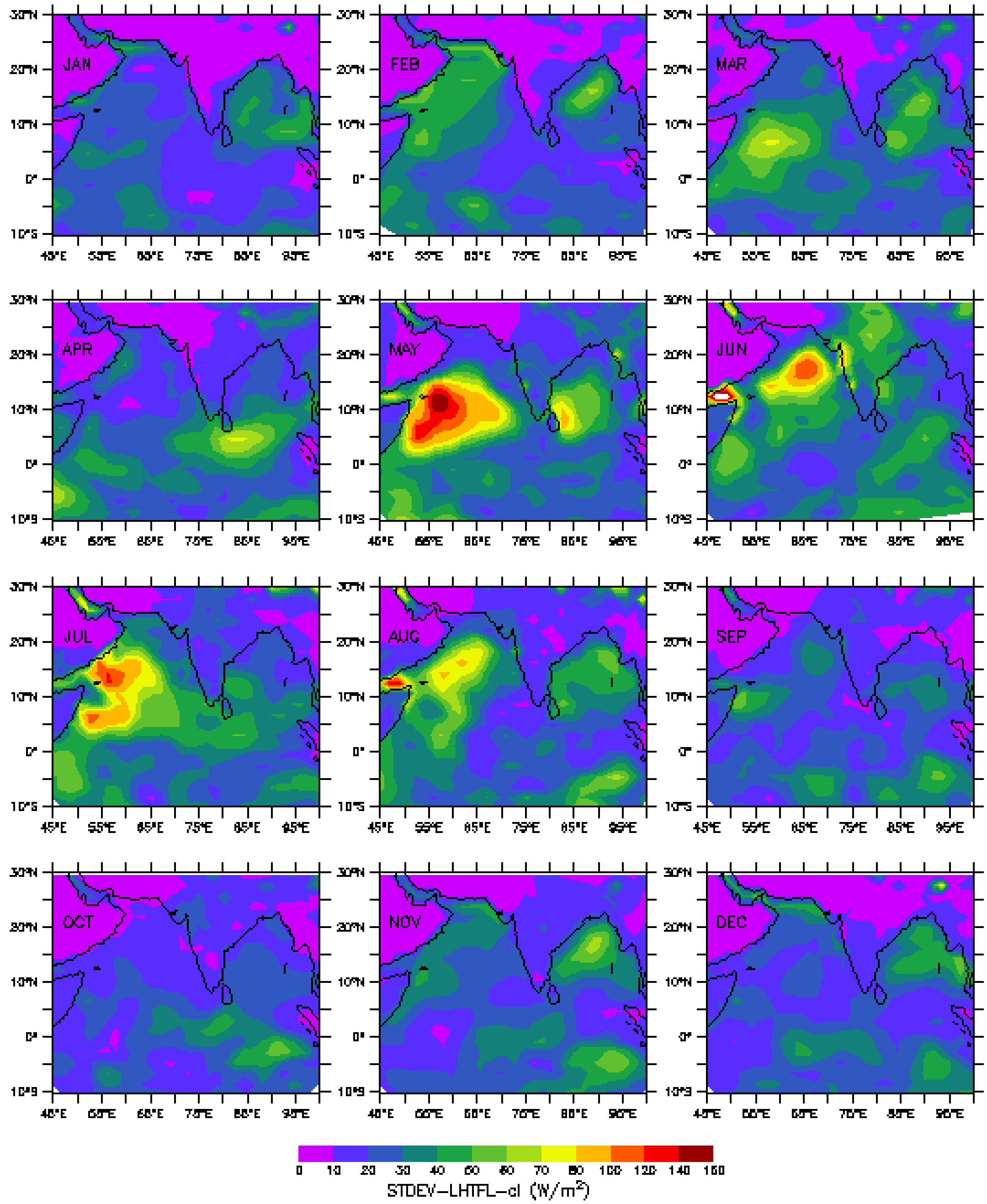


Figure-5.5: : Monthly picture of standard deviations of Latent heat flux during 2000-2006, in order to identify various active regions in the north Indian Ocean of large inter-annual variability.

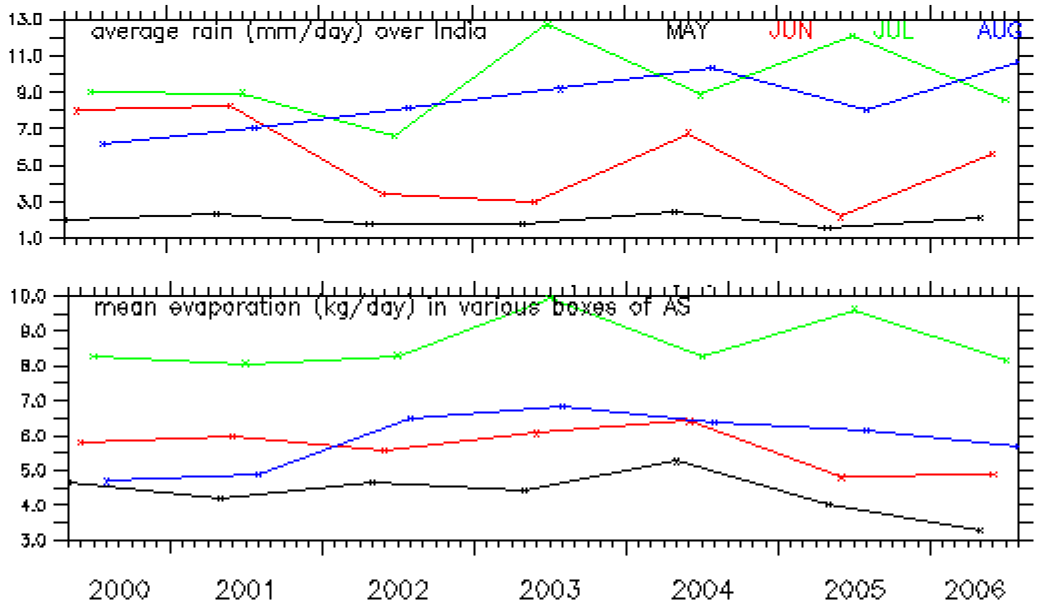


Figure-4.6: The relation between inter-annual variability of evaporation and precipitation during 2000-2006. Upper panel is for rainfall and lower panel is for evaporation. Various colors used in the figure are: black is for May, red is for Jun, green is for July, and blue is for August.

5.3. Concluding remarks:

In this study, efforts have been made to analyse 7 year data sets of SST, chlorophyll, Winds and other associated parameters of air-sea interaction processes in north Indian Ocean to examine their intra and inter annual variability and explore possible relation among them. These parameters are exhibiting very strong monsoonal variability in intra and inter annual scales. There exists strong relationship among these parameters. In intra annual scale, western Arabian Sea and north western equatorial Indian Ocean are the most active regions of air-sea interaction processes. Central equatorial Indian Ocean, where SST remains almost uniform over the year, exhibits large Ekman pumping due to strong wind curl. However the chlorophyll concentration data, supports the prevailing of Ekamn pumping (upwelling and down welling) in this region.

In inter-annual scale, northern Arabian Sea and southern-north Indian Ocean are very active regions of air-sea interaction process. There exist inverse relation between wind field and SST in the Arabian Sea. During the 7 year study period from 2000-2006, 2003 is the warmest year and 2000 is the coldest year. There exist good relation between the Indian rainfall and the evaporation process over the western and central Arabian Sea during the summer monsoon months.

The results of this study can be considered with caution due to limited 7 year data set used in this study. Another limitation of this study is that, the possible causes of intra and inter annual variability exhibited in SST and Chlorophyll data are explored though qualitative arguments and no attempt is made to find the quantitative explanation. In future investigation, attempts to be made to improve our quantitative interpretation with more satellite data sets along with in situ observations.

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