MONITORING SPATIAL AND TEMPORAL VARIATION OF OCEAN PRODUCTIVITY IN THE BAY OF BENGAL USING REMOTE SENSING

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DEDICATION

Specially dedicated to

my beloved parents, family, siblings

and all my fellows friends

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ABSTRACT

Ocean productivity plays an important role in the global carbon cycle, climate change and food supply. An alarming issue about the ocean productivity is that it is decreasing gradually in most world biomes where the decreasing rate in certain oceans, such as in the Bay of Bengal is higher as compared to other oceans. Although historically the Bay of Bengal is less productive as compared to the other oceans, there are large number of population living along the coastal areas depend on food supply from this bay. Therefore, productivity of the Bay of Bengal is very crucial and this study investigates the trend of ocean productivity by monitoring the long term variation of Chlorophyll-a concentration, and its relationships with sea surface temperature, precipitation and ocean current. Several steps of processing were adopted, which includes i) estimate the spatial and temporal variation of all parameters, ii) examine the variation of all parameters along the five selected transects from coastal to offshore area, iii) perform change detection of all parameters, and iv) investigate relationships between Chlorophyll-a and all other parameters. Results indicated several aspects, such as i) ocean productivity in the Bay of Bengal varies spatially and seasonally, ii) during northeast monsoon, Chlorophyll-a concentration in the western part of the bay is remarkably high but low in other parts particularly in the middle part of the bay, iii) during southwest monsoon, the observed Chlorophyll-a concentration is high in the south-western and north-western part of the bay, whereas the middle part of the bay maintains low productive, iv) anomaly of Chlorophyll-a concentration is high (1 to 2.5 mg/m^3) in coastal area and very low (less than 0.5 mg/m^3) in the offshore area, v) low Chlorophyll-a area (0-0.10 mg/m^3) fluctuates highly from year to year, while very less fluctuation observed in high Chlorophyll-a concentrated area (1-6.5 mg/m^3), vi) sea surface temperature and precipitation are normally higher during southwest monsoon as compared to northeast monsoon, and vii) strong ocean current was observed in western part of bay during both seasons. As conclusion, this study highlights the potential of remote sensing technique in monitoring ocean productivity, and identified that the productivity of the Bay of Bengal is changing with no constant rate of change from year to year. The rate of change depends on several factors including temperature, precipitation, ocean current, and location.

ABSTRAK

Produktiviti lautan memainkan peranan penting dalam kitaran karbon global, perubahan iklim dan bekalan sumber makanan. Isu-isu yang membimbangkan berkenaan dengan produktiviti lautan ialah penurunan secara beransur-ansur dalam kebanyakan biom di dunia, di mana kadar penurunannya di sesetengah lautan seperti di Teluk Bengal adalah lebih tinggi berbanding dengan lautan lain. Walaupun mengikut sejarah Teluk Bengal adalah kurang produktif berbanding dengan lautan lain, tetapi sebilangan besar penduduk sepanjang pinggir laut bergantung kepada bekalan sumber makanan daripada teluk ini. Oleh itu, produktiviti Teluk Bengal adalah sangat penting dan kajian ini menyiasat aliran produktiviti lautan dengan memantau perubahan jangka masa panjang kepekatan klorofil-a, dan hubungannya dengan suhu permukaan laut, hujan dan arus lautan. Beberapa langkah pemprosesan telah digunakan termasuk i) menganggarkan perubahan ruang dan masa bagi semua parameter, ii) memeriksa perubahan semua parameter sepanjang lima garisan terpilih dari kawasan pantai ke luar pesisir, iii) melaksana pengesanan perubahan bagi semua parameter, dan iv) menyiasat hubungan antara klorofil-a dengan semua parameter. Hasil kajian menunjukkan beberapa aspek seperti i) produktiviti lautan di Teluk Bengal adalah berbeza mengikut ruang dan monsun, ii) semasa monsun timur laut, kepekatan klorofil-a di bahagian barat teluk adalah amat tinggi tetapi rendah di kawasan-kawasan lain terutamanya di bahagian tengah teluk, iii) semasa monsun barat daya, kepekatan klorofil-a yang diperhatikan adalah tinggi di bahagian barat daya dan barat laut teluk manakala bahagian tengah teluk mengekalkan produktiviti yang rendah, iv) anomali kepekatan klorofil-a adalah tinggi (1 hingga 2.5 mg/m^3) di kawasan pantai tetapi sangat rendah (kurang daripada 0.5 mg/m^3) di kawasan luar pesisir, v) kawasan klorofil-a yang rendah (0-0.10 mg/m^3) mengalami perubahan yang besar dari tahun ke tahun, manakala kurang perubahan dilihat pada kawasan berkepekatan klorofil-a yang tinggi (1-6.5 mg/m^3), vi) suhu permukaan laut dan hujan biasanya lebih tinggi semasa monsun barat daya berbanding dengan monsun timur laut, dan vii) arus lautan yang kuat dilihat di bahagian barat teluk semasa kedua-dua monsun. Kesimpulannya, hasil kajian telah menekankan potensi teknik penderiaan jauh dalam memantau produktiviti lautan dan mengenal pasti Teluk Bengal sedang berubah dengan tiada kadar perubahan tetap dari tahun ke tahun. Kadar perubahan ini bergantung kepada beberapa faktor termasuk suhu, hujan, arus lautan, dan lokasi.

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LIST OF ABBREVIATIONS

AS	-	Arabian Sea
AVHRR	-	Advanced Very High Resolution Radiometer
CDOM	-	Colored Dissolve Organic Matter
CO_2	-	Carbon dioxide
COCTS	-	Chinese Ocean Color and Temperature Sensor
CRS	-	Coordinate Reference System
CZCS	-	Coastal Zone Color Scanner
DCT	-	Discrete Cosine Transform
DN	-	Digital Number
EC	-	Equatorial Current
EICC	-	East India Coastal Current
EICC	-	East India Coastal Current
ENSO	-	El-Nino-Southern Oscillation
GAC	-	Global Area Coverage
GLI	-	Global Imager
GPP	-	Gross Primary Production
IDCT	-	Inverse Discrete Cosine Transform
IOD	-	Indian Ocean Dipole
L2	-	Level 2
LAC	-	Local Area Coverage
MERIS	-	Medium Resolution Imaging Spectrometer
MODIS	-	Moderate Resolution Imaging Spectroradiometer
MOS	-	Modular Optical Scanner
N	-	Nitrogen
NASA	-	National Aeronautics and Space Administration

NASA GES DISC	-	Goddard Earth Sciences Data and Information Services Center
NH_4	-	Ammonium
NIR	-	Near Infrared
NO	-	Nitric Oxide
NO_2	-	Nitrogen Dioxide
NOAA	-	National Ocean and Atmosphere Administration
NO_X	-	Refers to Nitric Oxide and Nitrogen Dioxide
NPP	-	Net Primary Production
OCI	-	Ocean Color Imager
OCM	-	Ocean Color Monitor
OCTS	-	Ocean Colour and Temperature Sensor
OSCAR	-	Ocean Surface Current Analyses-Real Time
PAR	-	Photosynthetically Active Radiation
RMSE	-	Root Mean Square Error
SeaDAS	-	SeaWiFS Data Analysis System
SeaWiFS	-	Sea-Viewing Wide Field-of-View Sensor
SECC	-	South Equatorial Counter Current
SMC	-	Summer Monsoon Current
SSH	-	Sea Surface Heights
SST	-	Sea Surface Temperature
TOC	-	Stores Organic Carbon
TRMM	-	Tropical Rainfall Measuring Mission
TSM	-	Total Suspended Matter
U	-	Zonal velocity
V	-	Meridional velocity
VSCS	-	Very High Intense Cyclone
WGS 84	-	World Geodetic System-84
WICC	-	West India Coastal Current
WMC	-	Winter Monsoon Current

LIST OF SYMBOLS

L_w	-	Water leaving radiance
b_b^λ	-	Backscatter coefficient
a^λ	-	Absorption coefficient
R_{rs}	-	Remote sensing reflectance
ρ_w	-	Extraterrestrial reflectance
r	-	Correlation coefficent

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Ocean covers over 71 percent of the Earth's surface and plays an important role in the Earth's systems including climate and weather (NOAA, 2014). Ocean is known as the largest active reservoir of carbon and primary sink of anthropogenic Carbon dioxide (CO_2). Oceanic plants like phytoplankton absorb CO_2 during photosynthesis and releases through respiration process (Sarangi *et al*., 2005). Phytoplankton is an essential part of the organic carbon transportation from the upper to deep ocean (Marinov *et al*., 2010). More than a hundred million tons of carbon in the form of CO_2 is fixed into organic material and similar amount of organic carbon is transferred into marine ecosystems by sinking and grazing for each day (Field *et al*., 1998; Behrenfeld *et al*., 2006). The role of phytoplankton is very significant in the climate change and total global carbon cycle as it may changes the sea surface temperature through absorption of solar radiation for photosynthesis, and cause the climate change (Chisholm, 2000; Marzeion *et al*., 2005). The amount of carbon (organic matter) produced by phytoplankton defines the ocean productivity. Ocean productivity can also be defined more precisely as a measure of the rate of growth of organic matter through photosynthesis and chemosynthesis in producer organisms based on the oxygen released and carbon taken in (Martin, 2004).

Ocean primary productivity is an important element of the Earth's carbon cycles, and in anticipating the reaction of marine biota to conceivable changes in radiative or other physical forcing because of the increasing of global temperature (Antoine *et al*., 1996; Behrenfeld *et al*., 2001; Wang *et al*., 2009). Scientists found that global ocean productivity/Chl-a concentration is experiencing a declination (Gregg *et al*., 2005), most likely because of the effect from global warming and anthropogenic (human activities) distortions (Raju *et al*., 2011).

Monitoring ocean productivity/Chl-a concentration is important but it is almost an impossible task by using conventional ship survey technique due to time constraint, high cost, and accessibility consideration (MacFadyen, 1998). Hence, remote sensing technique has been applied to overcome the limitations of conventional technique in terms of cost, time, and data availability (Sarangi *et al*., 2005) as ocean color satellites make the synoptic sampling at high frequency over large oceanic regions possible (Joint and Groom, 2000). The launches of ocean color sensors such as Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) in 1997 followed by Moderate Resolution Imaging Spectroradiometer (MODIS) in 1999 on Terra spacecraft and in 2002 on Aqua have provided an unique opportunity for the monitoring of long term time series data for oceanography study.

Many studies have been conducted to monitor ocean productivity/Chl-a concentration and its variation using remote sensing technique (Macfadyen, 1998; Sarangi *et al*., 2005; Chathurvedi, 2005; Madhu *et al*., 2006; Abbas *et al*., 2012). However, there are several factors such as sea surface temperature, precipitation, and ocean current that affect the Chl-a concentration directly or indirectly and the influence of these factors on the ocean productivity/Chl-a concentration is varied based on location at the ocean, time/season, human interference, as well as environmental condition.

Several studies examined the relationship between Chl-a concentration and Sea Surface Temperature (SST) and found that the increasing of SST have a high impact on oceanographic parameters as well as the Chl-a concentration (Kamykowski, 1987; Madhupratap *et al*., 2003; Behrenfeld *et al*., 2006; Sarangi *et al*., 2008). Basically, low SST contributes to high Chl-a concentration. Nevertheless, the relationship between SST and Chl-a concentration varies according to regional location and SST variation (Chaturvedi, 2005). Thus, it is vital to examine the concrete long-term relationship between Chl-a concentration and SST as global temperature continues to rise (Jutla *et al*., 2011).

Ocean current is another important oceanic parameter in determining the variation of Chl-a concentration. The inter-relationship between ocean current, SST, and Chl-a concentration is strong as high intensity of ocean current is able to cool the ocean surface temperature. The probability for phytoplankton to bloom is high in cold water (Sarangi *et al*., 2008). Moreover, the movement of water due to the ocean current may cause ocean circulation like gyre and cyclonic storm to occur (Nerverkar and Kumar, 2006). These activities basically bring the nutrient from deep ocean into the surface (euphotic layer) and thus, increase the Chl-a concentration (Prasanna Kumar *et al*., 2002).

The variation of ocean productivity/Chl-a concentration can also be observed due to the precipitation. The importance of precipitation in relation to ocean productivity has been highlighted by the previous studies as precipitation is enriched in biological forms of Nitrogen (NO_x, NH_4, and organic N) and subsequently acts as a source of plant nutrients in estuaries and coastal ocean waters (Paerl *et al*., 1990). High amount of precipitation produce large freshwater on the land that brings nutrients into the coastal ocean through river discharge (Acker *et al*., 2005; Sachoemar *et al*., 2010) from adjacent landmass such as agriculture field (Arhonditsis *et al*., 2002; Balachandran *et al*., 2008). Studies also found that the amount of precipitation also influences the other oceanic parameters variation such as salinity and temperature of the ocean (Gomes *et al*., 2000; Perumal *et al*., 2009).

It is reviled from the above background information that the monitoring of ocean productivity is important and this can be done using remote sensing technique very effectively as long-term data with very high temporal resolution are available from dedicated ocean color sensors without any sort of costs. Several oceanic and non-oceanic factors directly affect the ocean productivity or Chl-a concentration. However, the impacts of these factors are not constant and varied based on several locational and environmental conditions. Therefore, it is hardly possible to draw any substantial conclusion from the findings of other studies about the ocean productivity, its change and its relationships with oceanic, climatic and environmental factors without conducting a proper investigation for a particular area of an ocean. Nevertheless, proper consideration should be given for the selection of parameters that can affect ocean productivity although few parameters such as SST, ocean current, and precipitation, are commonly investigated individually or jointly with another two or three by the researcher very frequently.

1.2 Problem Statement

It is obvious that the productivity of the ocean is important but researchers found that primary production of ocean is decreasing and the rate of decline of ocean primary productivity is about 1% per year in most global biomes (Gregg and Conkright, 2002; Boyce *et al*., 2010; Henson *et al*., 2013). The declination of ocean primary productivity is believed to be the result of changes in sea surface temperature due to the impact of global warming (Boyce *et al*., 2010; Henson *et al*., 2013) and natural variability (Gregg and Conkright, 2002).

However, studies found that similar to the other part of the ocean, Chl-a concentration in the Bay of Bengal has declined and the primary productivity in the Bay of Bengal is low as compared to the adjacent Arabian Sea due to the several reasons (Rao *et al*., 1994; Madhupratap *et al*., 2003). Gregg *et al*., (2005) found that

Chl-a concentration had declined by about 17% from 1998 to 2003 (approximately 2.8% per year) in the Bay of Bengal and the declination rate is higher than the global ocean primary productivity declination rate. However, the ocean productivity trend in the Bay of Bengal varies with respect to locations and other factors (Kamykowski, 1987; Kumari and Babu, 2009).

Although many studies have been conducted in Bay of Bengal, very few studies considers all of the important factors. For example, some studies focused on the effects of SST on ocean productivity (Chathurvedi, 2005; Sarangi *et al*., 2008; Jutla *et al*., 2011), while other studies are focused on the other parameters like precipitation, ocean current, natural disaster and so on (Gauns *et al*., 2005; Smitha *et al*., 2006; Yan and Tang, 2009; Borrione *et al*., 2013; Everett *et al*., 2014; Jyothibabu *et al*., 2015). Moreover, monitoring of ocean productivity in the Bay of Bengal is sometimes only restricted to a certain part of the bay. For examples, some studies were conducted to analyze the Chl-a production in the western part of the Bay of Bengal (Madhu *et al*., 2006), whereas, other studies are focused on the variability of Chl-a concentration in the southern part only (Sarangi *et al*., 2008; Girishkumar *et al*., 2012).

As a result, there are still substantial uncertainties in productivity of the ocean in the Bay of Bengal where ocean productivity variation due to the internal and external factors is still remains in doubt. As a matter of fact, SST, precipitation, and ocean current are related to one and another and combined effect from all those parameters on the variation of ocean productivity is really important to understand a complete scenario of the ocean productivity of the Bay of Bengal.

1.3 Research Objectives

The main objective of this study is to monitor long term ocean productivity in the Bay of Bengal with respect to sea surface temperature, precipitation and ocean current. There are several specific objectives that need to be addressed in order to achieve the main objective:

1. to determine spatial and temporal variation of the ocean productivity,

2. to investigate spatial and temporal variation of different affecting parameters; sea surface temperature, precipitation, and ocean current, and

3. to examine the relationships between affecting parameters and the ocean productivity.

1.4 Scope of Study

1. This study uses MODIS Aqua for Chl-a concentration, and SST determination. MODIS was selected to use in this study because of the long term availability of data (since 2002 until recently), better spatial resolution (i.e. 250 m, 500 m, and 1 km) as compared to other sensors like SeaWiFS (i.e. 1.1 km for LAC and 4.5 km for GAC) and high temporal resolution (1 to 2 days).

2. The other satellite data that were used in this study are Tropical Rainfall Measuring Mission (TRMM) and Ocean Surface Current Analyses-Real Time (OSCAR). Data from TRMM were used for precipitation measurement and OSCAR data were used to determine the ocean current. These data were selected due to the availability of data to cover the period of study. Moreover, product derived from TRMM and OSCAR satellites are easy to process as these data are available in readable format.

3. Collection of in-situ data for validation of Chl-a concentration and other parameters cannot be carried out in this study due to the cost and time-constrains. However, in-situ data was collected from other sources (i.e. NASA Ocean Motion program and NOAA National Data Buoy Center) that provided in-situ measurement data collected through buoy and ship drift technique.

4. There are many different internal and external oceanic parameters that influence the ocean productivity/Chl-a concentration directly or indirectly. However, based on the previous studies conducted by other researchers in monitoring the variation of ocean productivity; SST, precipitation, and ocean current were selected as these parameters affect the variation of the productivity.

5. In this study, all the oceanic parameters (i.e. SST, precipitation, and ocean current) include Chl-a concentration were analysed in three methods: i) spatial and temporal variation, ii) quantitative variation, and iii) change detection. The spatial and temporal variation was carried out by observing the variation of each parameter in monthly basis according to the monsoonal changes in the bay which are northeast monsoon (November to February) and southwest monsoon (June to September). The quantitative and change detection method involves the analysis of rate of changes of classified data between one base year (i.e. 2003) and other years (from 2004 to 2014).

6. The relationships between all oceanic and environmental parameters with the ocean productivity/Chl-a concentration were determined using the correlation analysis. Correlation coefficient (r) value was used to determine the strength between examined parameters and further investigation were made from the obtained r value in order to determine that the investigated parameter are positively, negatively, or not correlated.

7. This study was carried out in Bay of Bengal, which is located in north-eastern part of Indian Ocean and boarded by four countries; India, Bangladesh, Sri Lanka, and Myanmar. This study area has been selected because of its importance in supporting food production for the population in surrounding areas especially in India, Bangladesh and Myanmar. Besides that, Bay of Bengal is known as one of the World's 64 largest marine ecosystems which has unique characteristics in terms of seasonal reversing monsoon, receive large amount of water discharge from five main rivers (i.e. Cauvery, Krishna, Godavari, Ganges, and Irrawaddy), and the frequent occurrence of natural disaster like cyclones that contribute to the high variation of ocean productivity at this area (Sabarudin and Sarker, 2014).

1.5 Significance of Study

In general, ocean productivity/Chl-a concentration is changing rapidly in spatial and temporal ways and is affected by many internal and external factors such as SST, precipitation, and ocean current. Therefore, concrete relationship between these factors and Chl-a concentration is vital to examine the exact behaviour of affecting parameters to the Chl-a concentration variation. The monitoring of ocean productivity/Chl-a concentration variation due to the affecting parameters and how it changes in seasonal and annual term provides the information about short-term and long-term trend of Chl-a concentration variation. The trend of Chl-a concentration variation is important for future prediction of ocean productivity at certain areas.

This study also intends to improve the limitations of previous studies in terms of study area, limited parameter used, and specific time period. Thus, the outcome of this study will provide the information about ocean productivity variation in the whole Bay of Bengal area by considering the oceanic and environmental factors; SST, precipitation, and ocean current for short term and long term based analysis. This long term observation (more than a decade) will benefit future research in providing complete data and information about the trend of variation of ocean productivity due to the examined factors.

Moreover, the information about ocean productivity is useful for meteorological and climatologically purposes. Phytoplankton converts carbon dioxide to oxygen through photosynthesis process, and the declination of phytoplankton may reduce the amount of carbon dioxide from the atmosphere which is a major greenhouse gas (388,500 ppb) that causes global warming. The changes of ocean productivity can be used to determine climate change at certain areas (Wang *et al*., 2009). Furthermore, study about Chl-a concentration distribution may benefit the food production industry. The spatial distribution of Chl-a concentration provides the information about the habitat of the oceanic organisms and their exact spatial location. This valuable information helps food industry to increase the productivity effectively by identifying the potential fishing zones (Nayak *et al*., 2003; Marzeion *et al*., 2005). Due to the increasing population of the people nearby the Bay of Bengal, the marine productivity is really important as it is the main source of food for them.

1.6 Study Area and Dataset used

1.6.1 Study Area

The area of study, Bay of Bengal (Figure 1.1) (Lat. 13° 31' 54.2634" N and Lon. 87° 32' 22.4982"E), is located at the northeastern part of the Indian Ocean, bordered by India and Sri Lanka to the west, Bangladesh to the north, and Myanmar to the east. The bay occupies an area of about 2.2 million sq km with the average depth of 2600 m. It is known as the largest bay in the world with a unique semi-enclosed tropical basin and is characterized as a region with tropical climate, high rainfall, and monsoon variation. The seasonal reversing monsoon with large amount of water discharged from Brahmaputra and Irrawaddy rivers contribute to the unstable trend of ocean productivity/Chl-a concentration and makes Bay of Bengal an unique place to study.

The climate at Bay of Bengal is dominated by the monsoon current (Shetye *et al*., 1993). There is a well-developed anti-cyclonic gyre in the Bay of Bengal and a pole-ward east India coastal current (EICC) during the pre-monsoon months (February to May). The EICC flows pole-ward along the southern part of the Indian coast and equator-ward farther north during southwest monsoon (June – Sept) (Sarangi *et al*., 2008). However, during northeast monsoon (from Nov to Feb), the EICC is equator-ward all along the coast. The weather is very active particularly in November as the monsoon season often brings in severe cyclones, which affects Eastern India as well as other parts of countries (Vinayachandran and Mathew, 2003).

Freshwater from the rivers such as the Irrawady, Brahmaputra, Ganges, Godavari, Krishna, and Cauvery have influenced the coastal part of the bay (Subramanian, 1993). For example, the Ganges-Brahmaputra delta is the fourth largest in the world, comprising approximately 105,640 km^2 contribute ~15,000 m^3 s^-

[1] mean annual volume river discharge associated with an immense suspended sediment load of ~ 1000 million tonnes into the Bay of Bengal (Tilstone *et al*., 2011). The freshwater from river discharge influences the temperature, salinity, and water density at the coastal region of the bay where a noteworthy impact of river water is available, the temperature and salinity of the water are not the same as the offshore part of the Bay of Bengal.

The Bay of Bengal is full of biological diversity, diverging amongst coral reefs, estuaries, fish spawning and nursery areas, and mangroves. However, Bay of Bengal has a conflict in issue of habitat such as degradation of mangrove habitats, coral reefs, and loss of seagrasses. It is believed that this issue occurred due to several factors that are; 1) lack of coastal development plans, 2) increasing trade in products from coastal habitats, 3) coastal development and industrialization, 4) ineffective marine protected areas, 5) upstream development that affects water-flow, 6) intensive upstream agricultural practices, and 7) increase in tourism (Banglapedia, 2015).

A quarter of the world's population lives in the countries bordering the Bay of Bengal (Aziz Ahmad *et al*., 1998), since the World Bank (2015) reported that the population of India has reached 1 billion in year 2014, followed by Bangladesh with 156 million, Myanmar with 53 million, and Sri Lanka with 20 million of people. The increasing number of population might increases a very high demand for marine resources in future. Moreover, of the four hundred million people living in the Bay of Bengal catchment area, many subsist at or below the poverty level (McGinley, 2008). Therefore, long term planning of the preservation and managing of marine productivity at the Bay of Bengal is considered urgent. Nevertheless, high population density in this area may contribute to the sewage production, runoff, and disturbance to the coastal environment.

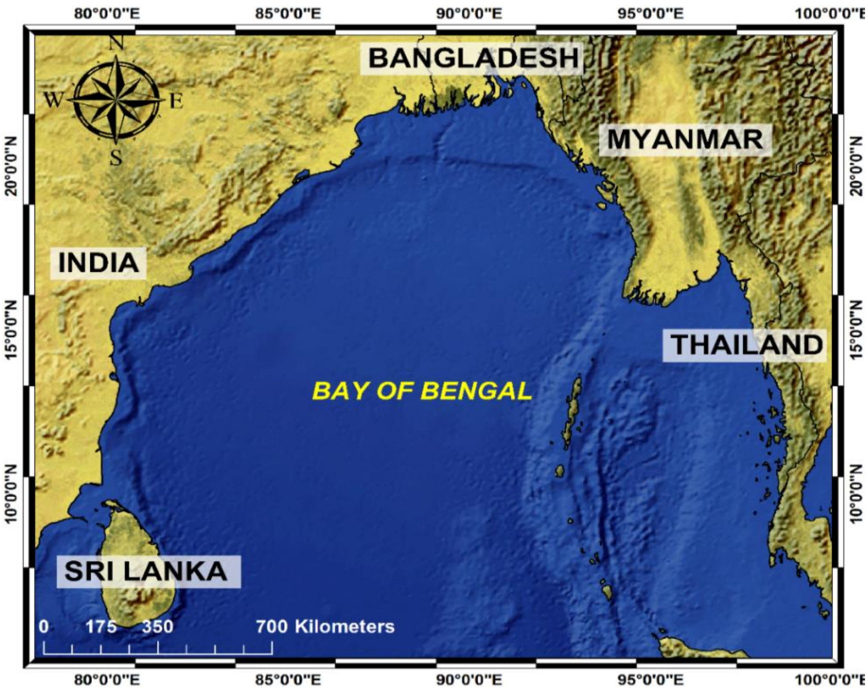

Figure 1.1 Location of Bay of Bengal

1.6.2 Dataset Used

Each parameter was computed using different type of data from different sources. Satellite imagery used for this study are Moderate Resolution Imaging Spectroradiometer (MODIS), Tropical Rainfall Measuring Mission **(**TRMM), and Ocean Surface Current Analyses-Real Time **(**OSCAR), while in-situ data were obtained from NASA Ocean Motion Program and National Data Buoy Center, respectively.

1.6.2.1 Moderate Resolution Imaging Spectroradiometer (MODIS)

This study used MODIS data from 2003 to 2014 for Chl-a concentration and sea surface temperature determination. MODIS data product for Chl-a concentration and SST were downloaded from National Aeronautics and Space Administration (NASA) Ocean Colour Group (http://oceancolor.gsfc.nasa.gov).

MODIS has 36 spectral bands with range from 0.4 µm to 14.4 µm. It has three types of spatial resolutions i.e. 250 m at nadir (channel 1 and 2), 500 m (channel 3 to 7), and 1 km (channel 8 and above). MODIS takes one to two days to cover the entire surface of the Earth.

In this study, level 2 (L2) of MODIS Aqua data were used to determine Chl-a concentration and SST, respectively. L2 data consists of derived geophysical variable that has undergone geometric and atmospheric correction. Band 9, 11, and 12 were used for Chl-a concentration while band 31 and 32 of L2 product were used for SST computation (see Table 1.1).

Table 1.1: Selected MODIS L2 data and the characteristics

Level	**Band**	**Bandwidth**	**Spatial resolution (m)**	**Parameter**
L2	9	438-448 (nm)	1000	Chl-a
	11	526-536 (nm)	1000	Chl-a
	12	546-556 (nm)	1000	Chl-a
	31	10.78-11.28 (µm)	1000	SST
	32	11.77-12.27 (µm)	1000	SST

1.6.2.2 Tropical Rainfall Measuring Mission (TRMM)

Precipitation data were acquired from NASA GES DISC (Goddard Earth Sciences Data and Information Services Center) (http://disc.sci.gsfc.nasa.gov). TRMM (Tropical Rainfall Measuring Mission) is a joint satellite mission of United States and Japan to monitor tropical and subtropical precipitation and to estimate its associated latent heating (NASA, 2014). The details information about TRMM data used in this study are presented in Table 1.2.

Table 1.2: Detail specifications for selected TRMM data product

Data Set	TRMM_3B43 (Monthly Rainfall Product)
Data Version	Version 7
Platform	Tropical Rainfall Measuring Mission
Sensor	TRMM Precipitation Radar, TRMM Microwave Imager, TRMM Visible Infrared Scanner
Spatial resolution	0.25 degree x 0.25 degree
Temporal resolution	Monthly
Parameters	Precipitation rate

1.6.2.3 Ocean Surface Current Analyses-Real Time (OSCAR)

Ocean current data were obtained from OSCAR (Ocean Current Surface Analyses-Real Time) at www.oscar.noaa.gov. OSCAR project developed a processing system and data center to provide operational ocean surface velocity fields from satellite altimeter and vector wind data. The OSCAR product is known as a product constructed from TOPEX/Poseidon sea surface heights (SSH), scatterometer winds (W), and both AVHRR and in-situ sea surface temperatures (SST) (Bonjean and Lagerloef, 2002). Details about the ocean current data used for this study are presented in Table 1.3.

Table 1.3: Detail specifications for OSCAR data

Data	Ocean surface currents
Data Type	Monthly mean
Variable type	U (Zonal velocity) and V (Meridional velocity) mean
Spatial resolution	0.33 degree x 0.33 degree
Unit	m/s

1.6.2.4 In-situ Data

In-situ data is essential to validate every parameter used in this study. In-situ measurements for all parameters were collected from NASA Ocean Motion program (www.oceanmotion.org) and National Data Buoy Center (www.ndbc.noaa.gov). NASA's Ocean Motion and Surface Current program provides a comprehensive review of the ocean surface circulation and provides in-situ data for a certain oceanic parameter from ship drift data which covers the entire world's ocean. In this study, Chl-a concentration and SST in-situ data were obtained from this program.

The other oceanic parameters such as ocean current and precipitation were validated by using buoy data. National Data Buoy Center - OceanSITES, known as an international system of long-term, open ocean reference stations measuring dozens of variables and monitoring full depth of the ocean down to the seafloor.

REFERENCES

Abbas, A. A., Mansor, S. B., Pradhan, B., and Tan, C. K. (2012). Spatial and Seasonal Variability of Chlorophyll-a and Associated Oceanographic Events in Sabah Water. *In Earth Observation and Remote Sensing Applications (EORSA), 2012 Second International Workshop*. IEEE, 215-219.

Acker, J. G., Harding, L. W., Leptoukh, G., Zhu, T., and Shen, S. (2005). Remotely-sensed Chl a at the Chesapeake Bay Mouth is correlated with Annual Freshwater Flow to Chesapeake Bay. *Geophysical Research Letters*, 32(5), 1-4.

Aiken, J., Moore, G. F., and Hotligan, P. M. (1992). Remote Sensing of Oceanic Biology in Relation to Global Climate Change. *Journal of phycology*, 28(5), 579-590.

Alexander, M. A., Scott, J. D, and Deser, C. (2002). Processes that Influence Sea Surface Temperature and Ocean Mixed Layer Depth Variability in a Coupled Model. *Journal of Geophysical Research – Oceans*, 105(16), 823-842.

Antoine, D., André, J. M. and Morel, A., (1996). Oceanic Primary Production: 2. Estimation at Global Scale from Satellite (Coastal Zone Color Scanner) Chlorophyll. *Global Biogeochemical Cycles*, 10, 57-69.

Arhonditsis, G., Tsirtsis, G., and Karydis, M. (2002). The Effects of Episodic Rainfall Events to the Dynamics of Coastal Marine Ecosystems: Applications to a Semi-Enclosed Gulf in the Meditteranean Sea. *Journal of marine systems*, 35(3), 183-205.

Aziz Ahmad, H., Ahmed, L., Atapattu, A., Chullasorn, S., Lui, Y. P., Maniku, M. H., Nickerson, D. J., Pimoljinda, J., Purwaka, T. H., Saeed, S., Soetopo, E., Suseno, and Yadava, Y. S. (1998). Regional Stewardship for Sustainable Marine Resources Management in the Bay of Bengal. In: K. Sherman, E.

Okemwa and M. Ntiba (Ed.) *Large Marine Ecosystems of the Indian Ocan: Assessment, Sustainability, and Management*. Blackwell Science. ISBN: 0632043180.

Balachandran, K. K., Jayalakshmy, K. V., Laluraj, C. M., Nair, M., Joseph, T., and Sheeba, P. (2008). Step-up Multiple Regression Model to Compute Chlorophyll a in the Coastal Waters off Cochin, Southwest Coast of India. *Environmental monitoring and assessment*, 139(1-3), 217-226.

Banglapedia. (2015). Retrieved from www.banglapedia.org

Behrenfeld, M. J., and Falkowski, P. G. (1997). Photosynthetic Rates Derived from Satellite-Based Chlorophyll Concentration. *Limnology and oceanography*, 42(1), 1-20.

Behrenfeld, M. J., Boss, E., Siegel, D. A., and Shea, D. M. (2005). Carbon-based Ocean Productivity and Phytoplankton Physiology from Space. *Global biogeochemical cycles*, 19(1).

Behrenfeld, M. J., O'malley, R. T., Siegel, D. A., Mcclain, C. R., Sarmiento, J. L., Feldman, G. C., Milligan, A. J., Falkowski, P. G., Letelier, R. M. and Boss, E. S. (2006). Climate-Driven Trends in Contemporary Ocean Productivity. *Nature*, 444, 752-755.

Behrenfeld, M. J., Randerson, J. T., Mcclain, C. R., Feldman, G. C., Los, S. O., Tucker, C. J., Falkowski, P. G., Field, C. B., Frouin, R. and Esaias, W. E. (2001). Biospheric Primary Production during an ENSO Transition. *Science*, 291, 2594-2597.

Bhattacharya, M. and Mishra, A. K. (2005). Estimation of Primary Productivity in the Case 2 waters of North-Eastern Bay of Bengal. *Indian Institute of Remote Sensing, India*.

Bonjean, F. and Lagerloef, G. S. E. (2002). Diagnostic Model and Analysis of the Surface Currents in the Tropical Pacific Ocean. *Journal of Physical Oceanography*, 32(10), 2938-2954.

Borrione, I., Aumont, O., and Schlitzer, R. (2013). Primary Productivity and Circulation Patterns Downstream of South Georgia: A Southern Ocean Example of the ''Island Mass Effect''. *Earth System Science: Bridging the*

Gaps between Disciplines. Perspectives from a Multi-disciplinary Helmholtz Graduate Research School, 38-41.

Boyce, D. G., Lewis, M. R., and Worm, B. (2010). Global Phytoplankton Decline over the Past Century. *Nature*, 466(7306), 591-596.

Briney, A. (2015). Ocean Currents Drive the World's Climate. http://geography.about.com/od/physicalgeography/a/oceancurrents.htm.

Callaway, E. (2010). A new kind of chlorophyll – and it only took 67 years to find. Nature. Retrieved from http://blogs.nature.com/news/2010/08/a_new_kind_of_chlorophyll_and.html.

Caputi, N., Chubb, C., and Pearce, A. (2001). Environmental Effects on Recruitment of the Western Rock Lobster, Panulirus Cygnus. *Marine and Freshwater Research*, 52(8), 1167-1174.

Carder, K. L., Chen, F. R., Cannizzaro, J. P., Campbell, J. W., and Mitchell, B. G. (2004). Performance of the MODIS Semi-analytical Ocean Color Algorithm for Chlorophyll-a. *Advances in Space Research*, 33(7), 1152-1159.

Carder, K. L., Chen, F. R., Lee, Z. P., Hawes, S. K., and Kamykowski, D. (1999). Semianalytic Moderate-Resolution Imaging Spectrometer Algorithms for Chlorophyll a and Absorption with Bio-optical Domains based on Nitrate-depletion Temperatures. *Journal of Geophysical Research: Oceans (1978–2012)*, 104(C3), 5403-5421.

Catto, J. L., and Pfahl, S. (2013). The Importance of Fronts for Extreme Precipitation. *Journal of Geophysical Research: Atmospheres*, 118(19), 10-791.

Chaturvedi, N. (2005). Variability of Chlorophyll Concentration in the Arabian Sea and Bay of Bengal as Observed from SeaWiFS Data from 1997-2000 and its Interrelationship with Sea Surface Temperature (SST) Derived from NOAA AVHRR. *International Journal of Remote Sensing*, 26(17), 3695-3706.

Chauhan, P., Nagur, C. R. C., Mohan, M., Nayak, S. R. and Navalgund, R. R. (2001). Surface chlorophyll-a Distribution in Arabian Sea and Bay of Bengal using IRSP4 Ocean Colour Monitor Satellite Data. *Current science*, 80(2), 127-129.

Chen, X., Pan, D., Bai, Y., He, X., Chen, C. T. A., and Hao, Z. (2013). Episodic Phytoplankton Bloom Events in the Bay of Bengal Triggered by Multiple Forcings. *Deep Sea Research Part I: Oceanographic Research Papers*, 73, 17-30.

Chisholm, S.W. (2000). Oceanography: Stirring times in the Southern Ocean. *Nature*, 407, 685-687.

Ciotti, Á. M., Cullen, J. J., and Lewis, M. R. (1999). A Semi-Analytical Model of the Influence of Phytoplankton Community Structure on the Relationship between Light Attenuation and Ocean Color. *Journal of Geophysical Research: Oceans (1978–2012)*, 104(C1), 1559-1578.

Darecki, M., and Stramski, D. (2004). An evaluation of MODIS and SeaWiFS Bio-optical Algorithms in the Baltic Sea. *Remote Sensing of Environment*, 89(3), 326-350.

Emery, W. J., Castro, S., Wick, G. A. Schluessel, P., and Donlon, C. (2001). Estimating Sea Surface Temperature from Infrared Satellite and In Situ Temperature Data. *Bulletin of the American Meteorological Society*, 82(12), 2773-2785.

Epply, R. W., Stewart, E., Abbot, M. R., and Heyman, V. (1985). Estimating Primary Production from Satellite Chlorophyll: Introduction to Regional Differences and Statistics for the Southern California Bight. *J. Plankt. Res*, 7, 57-70.

Everett, J. D., Baird, M. E., Roughan, M., Suthers, I. M., and Doblin, M. A. (2014). Relative Impact of Seasonal and Oceanographic Drivers on Surface Chlorophyll a Along a Western Boundary Current. *Progress in Oceanography*, 120(2014), 340-351.

Feldman, G., Kuring, N., Ng, C., Esaias, W., McClain, C., Elrod, J., Maynard N., Endres R. E. Brwon J., Walsh S., Carle M., and Podesta, G. (1989). Ocean Color: Availability of the Global Data Set. *Eos, Transactions American Geophysical Union*, 70(23), 634-641.

Field, C. B., Behrenfeld, M. J., Randerson, J. T. and Falkowski, P. (1998). Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components. *Science*, 281, 237-240.

Fitch, K. and Kemker, C. (2014). Algae, Phytoplankton and Chlorophyll. Fundamentals of Environmental Measurements. Fondriest Environmental, Inc. 22 Oct. 2014. Web. (http://www.fondriest.com/environmental-measurements/parameters/water-quality/algae-phytoplankton-and-chlorophyll).

Flynn, K. J. (1988). The Concept of "Primary Production" in Aquatic Ecology. *American Society of Limnology and Oceanography*, 33(5), 1215-1216.

Franz, B. (2006). Implementation of SST Processing within the OBPG. *Ocean Color Documents (< http://oceancolor.gsfc.nasa.gov/DOCS/modis_sst/>).*

Garcia, C. A. E., Garcia, V. M. T., and McClain, C. R. (2005). Evaluation of SeaWiFS Chlorophyll Algorithms in the Southwestern Atlantic and Southern Oceans. *Remote Sensing of Environment*, 95(1), 125-137.

Garcia, D. (2010). Robust Smoothing of Gridded Data in One and Higher Dimensions with Missing Values. *Computational statistics & data analysis*, 54(4), 1167-1178.

Gauns, M., Madhupratap, M., Ramaiah, N., Jyothibabu, R., Fernandes, V., Paul, J. T. and Prasanna Kumar, S. (2005). Comparative Accounts of Biological Productivity Characteristics and Estimates of Carbon Fluxes in the Arabian Sea and the Bay of Bengal. *Deep Sea Research Part II: Topical Studies in Oceanography*, 52(14), 2003-2017.

Girishkumar, M. S., Ravichandran, M., and Pant, V. (2012). Observed Chlorophyll-a Bloom in the Southern Bay of Bengal During Winter 2006–2007. *International Journal of Remote Sensing*, 33(4), 1264-1275.

Glossary of Meteorology. American Meteorological Society. (2015).

Gomes, H. R., Goes, J. I., and Saino, T. (2000). Influence of Physical Processes and Freshwater Discharge on the Seasonality of Phytoplankton Regime in the Bay of Bengal. *Continental Shelf Research*, 20, 313-330.

Gordon, H. R., and Wang, M. (1994). Retrieval of Water-leaving radiance and Aerosol Optical Thickness over the Oceans with SeaWiFS: A Preliminary Algorithm. *Appl. Opt,* 33, 443-452.

Gregg, W. W., and M. E. Conkright. (2002). Decadal Changes in Global Ocean Chlorophyll. *Geophys. Res. Letter,* 29(11), 1730.doi:10.1029/2002GL014689.

Gregg, W. W., Casey, N. W., and McClain, C. R. (2005). Recent Trends in Global Ocean Chlorophyll. *Geophysical Research Letters*, 32(3).

Gregg, W. W., Ginoux, P., Schopf, P. S., and Casey, N. W. (2003). Phytoplankton and Iron: Validation of a Global Three-Dimensional Ocean Biogeochemical Model. *Deep Sea Research Part II: Topical Studies in Oceanography*, 50(22), 3143-3169.

Hastenrath, S., and Lamb, P. J. (1979). Surface Climate and Atmospheric Circulation. Climatic Atlas of the Indian Ocean, Part-I.

Henson, S., Cole, H., Beaulieu, C., and Yool, A. (2013). The Impact of Global Warming on Seasonality of Ocean Primary Production. *Biogeosciences Discussions*, 10(1), 1421-1450.

Hosoda K. (2010). A Review of Satellite-Based Microwave Observations of Sea Surface Temperatures. *Journal of Oceanography*, 66(4), 439 - 473.

Hu, C., Lee, Z., and Franz, B. (2012). Chlorophyll-a Algorithms for Oligotrophic Oceans: a Novel Approach Based on Three-Band Reflectance Difference. *Journal of Geophysical Research: Oceans (1978–2012)*, 117(C1).

Islam, M. M., and Tat, C. W. (2001). A Comparison of Empirical Algorithms for Chlorophyll Concentration in Singapore Regional Waters. In *Paper presented at the 22nd Asian Conference on Remote Sensing* (Vol. 5, p. 9).

Jagadeesan, L., Jyothibabu, R., Anjusha, A., Mohan, A. P., Madhu, N. V., Muraleedharan, K. R., and Sudheesh, K. (2013). Ocean Currents Structuring the Mesozooplankton in the Gulf of Mannar and the Palk Bay, Southeast Coast of India. *Progress in Oceanography*, 110(2013), 27-48.

Johnson, R., Strutton, P. G., Wright, S. W., McMinn, A., and Meiners, K. M. (2013). Three Improved Satellite Chlorophyll Algorithms for the Southern Ocean. *Journal of Geophysical Research: Oceans*, 118(7), 3694-3703.

Joint, I. and Groom, S. B. (2000). Estimation of Phytoplankton Production from Space: Current Status and Future Potential of Satellite Remote Sensing. *Journal of experimental marine Biology and Ecology*, 250, 233-255.

Joseph, A. (2013). *Measuring ocean currents: tools, technologies, and data*. Newnes.

Jutla, A. S., Akanda, A. S., Griffiths, J. K., Colwell, R. and Islam, S. (2011). Warming Oceans, Phytoplankton, and River Discharge: Implications for Cholera Outbreaks. *The American journal of tropical medicine and hygiene*, 85(303).

Jyothibabu, R., Vinayachandran, P. N., Madhu, N. V., Robin, R. S., Karnan, C., Jagadeesan, L., and Anjusha, A. (2015). Phytoplankton Size Structure in the Southern Bay of Bengal Modified by the Summer Monsoon Current and Associated Eddies: Implications on the Vertical Biogenic Flux. *Journal of Marine Systems*, 143(2015), 98-119.

Kahru, M., Kudela, R., Manzano-Sarabia, M., and Mitchell, B. G. (2009). Trends in Primary Production in the California Current Detected with Satellite Data. *Journal of Geophysical Research: Oceans (1978–2012)*, 114(C2).

Kamykowskiw, D. (1987). A Preliminary Biophysical Model of the Relationship between Temperature and Plant Nutrients in the Upper Ocean. *Deep Sea Research*, 34, 1067-1079.

Katara, I., Illian, J., Pierce, G. J., Scott, B., and Wang, J. (2008). Atmospheric Forcing on Chlorophyll Concentration in the Mediterranean. In *Essential Fish Habitat Mapping in the Mediterranean* (pp. 33-48). Springer Netherlands.

Khalil, I.B. (2007). Seasonal and Spatial Variability of Sea Surface Temperature (SST) and Chlorophyll-a Concentration using MODIS Data in East Kalimantan waters, Indonesia. Master Philosophy. International Institute for Geo-Information Science and Earth Observation, Enschede, The Netherlands.

Koslow, J. A., Pesant, S., Feng, M., Pearce, A., Fearns, P., Moore, T., Matear, R., and Waite, A. (2008). The Effect of the Leeuwin Current on

Phytoplankton Biomass and Production off Southwestern Australia. *Journal of Geophysical Research: Oceans (1978–2012)*, 113(C7), 1-19.

Kumari, B. and Babu, K.N. (2009). Provincial Nature of Chlorophyll and Sea Surface Temperature Observed by Satellite. *International Journal of Remote Sensing*, 30(4), 1091-1097.

Lapucci, C., Rella, M. A., Brandini, C., Ganzin, N., Gozzini, B., Maselli, F., Massi L., Nuccio C., Ortolani A., and Trees, C. (2012). Evaluation of Empirical and Semi-Analytical Chlorophyll Algorithms in the Ligurian and North Tyrrhenian Seas. *Journal of Applied Remote Sensing*, 6(1), 063565-1.

Lenanton, R. C., Joll, L., and Jones, K. (1991). The Influence of the Leeuwin Current on Coastal Fisheries of Western Australia. *Journal of the Royal Society of Western Australia*, 74, 101-114.

Lindsey, R., and Scott, M. (2010). What are Phytoplankton?. In NASA Earth Observatory. Retrieved from http://earthobservatory.nasa.gov/Features/Phytoplankton/

Macfadyen, A. (1998). Modeling Primary Productivity from Satellite-Derived Chlorophyll in the Monterey Bay Region. *International Papers of the Monterey Bay Aquarium Research Institute*, 19.

Madhu, N. V., Jyothibabu, R., Maheswaran, P. A., John Gerson, V., Gopalakrishnan, T. C., and Nair, K. K. C. (2006). Lack of Seasonality in Phytoplankton Standing Stock (Chlorophyll-a) and Production in the Western Bay of Bengal. *Continental shelf research*, 26(16), 1868-1883.

Madhupratap, M., Gauns, M., Ramaiah, N., Prasanna Kumar, S., Muraleedharan, P., De Sousa, S., Sardessai, S. and Muraleedharan, U. (2003). Biogeochemistry of the Bay of Bengal: Physical, Chemical and Primary Productivity Characteristics of the Central and Western Bay of Bengal during Summer Monsoon 2001. *Deep Sea Research Part II: Topical Studies in Oceanography*, 50(5), 881-896.

Marinov, I., Doney, S. C. and Lima, I. D., (2010). Response of Ocean Phytoplankton Community Structure to Climate Change over the 21st

Century: Partitioning the Effects of Nutrients, Temperature and Light. *Biogeosciences*, 7, 3941-3959.

Maritorena, S., Siegel, D. A., and Peterson, A. R. (2002). Optimization of a Semianalytical Ocean Color Model for Global-scale Applications. *Applied Optics*, 41(15), 2705-2714.

Martin S. (2004). An Introduction to Ocean Remote Sensing. Cambridge University Press.

Marzeion, B. A., Timmermann, A., Murtugudde, R. and Jin, F. F. (2005). Biophysical Feedbacks in the Tropical Pacific. *Journal of Climate*, 18, 58-70.

May, P. (2015). Chlorophyll. In School of Chemistry. Retrieved from http://www.chm.bris.ac.uk/motm/chlorophyll/chlorophyll_h.htm.

McGinley, M. (2008). Bay of Bengal Large Marine Ecosystem. Retrieved from http://www.eoearth.org/view/article/150447.

Merino, M., Monreal, A., and Duarte, C. M. (2004). Ocean Currents and Their Impact on Marine Life. *Marine Ecology, CM Duarte, ed., in Encyclopedia of Life Support Systems (EOLSS), developed under the auspices of UNESCO, Eolss Publishers, Oxford, UK*, 1À22.

Mitchell, B. G. (1994). Ocean Color from Space: A Coastal Zone Color Scanner Retrospective. Special section, *J. Geophys. Res.* 99, 7291-7570.

Moore, S. D., McCabe, G. P., and Craig, B. A. (2009). Introduction to the Prantice of Statistic. W. H. Freeman and Company. New York.

Murty, V. S. N., Subrahmanyam, B., Gangadhara Rao, L. V., Reddy, G. V. (1998). Seasonal Variation of Sea Surface Temperature in the Bay of Bengal during 1992 as derived from NOAA-AVHRR SST Data. *International Journal of Remote Sensing*, 19, 2361-2371.

Nagamani, P. V., Chauhan, P., and Dwivedi, R. M. (2008). Development of Chlorophyll-a Algorithm for Ocean Colour Monitor Onboard OCEANSAT-2 Satellite. *Geoscience and Remote Sensing Letters, IEEE*, 5(3), 527-531.

Nagamani, P. V., Hussain, M. I., Choudhury, S. B., Panda, C. R., Sanghamitra, P., Kar, R. N., Das, A., Ramana, I. V. and Rao, K. H. (2013). Validation of

Chlorophyll-a Algorithms in the Coastal Waters of Bay of Bengal Initial Validation Results from OCM-2. *Journal of the Indian Society of Remote Sensing*, 41(1), 117-125.

Nagamani, P., Shikhakolli, R., and Chauhan, P. (2011). Phytoplankton Variability in the Bay of Bengal during Winter Monsoon Using Oceansat-1 Ocean Colour Monitor Data. *Journal of the Indian Society of Remote Sensing*, 39(1), 117-126.

Nayak, S., Solanki, H. U., and Dwivedi, R. M. (2003). Utilization of IRS P4 Ocean Colour Data for Potential Fishing Zone-A Cost Benefit Analysis. *Indian journal of marine sciences*. 32(3): 244-248.

Nerverkar, J. and Kumar, P. S. (2006). Seasonal Variability of the Mixed Layer in the Central of Bay of Bengal and Associated Changes in Nutrients and Chlorophyll. *Deep Sea Research Part 1*, 53, 820-835.

NOAA. 2014. OCEAN. (http://www.noaa.gov/ocean.html).

O'Reilly, J. E., Maritorena, S., Mitchell, B. G., Siegel, D. A., Carder, K. L., Garver, S. A., Kahru, M., and McClain, C. (1998). Ocean Color Chlorophyll Algorithms for SeaWiFS. *Journal of Geophysical Research: Oceans (1978–2012)*, 103(C11), 24937-24953.

Paerl, H. W., Rudek, J., and Mallin, M. A. (1990). Stimulation of Phytoplankton Production in Coastal Waters by Natural Rainfall Inputs: Nutritional and Trophic Implications. *Marine Biology*, 107(2), 247-254.

Pattabiraman, V., Munavar, M., and Suresh, K. (2012). Comparative Study on Chlorophyll Distributions in the Coastal Regions of Northeastern Arabian Sea and Southern Bay of Bengal Based on Indian Seasons and Rainfall Distributions. In *Asia Pacific Conference on Environmental Science and Technology Advances in Biomedical Engineering* (Vol. 6).

Perumal, N. V., Rajkumar, M., Perumal, P., and Rajasekar, K. T. (2009). Seasonal Variations of Plankton Diversity in the Kaduviyar Estuary, Nagapattinam, Southeast Coast of India. *Journal of Environmental Biology*, 30(6), 1035-1046.

Prasanna Kumar, S., Muraleedharan, P. M., Prasad, T. G., Gauns, M., Ramaiah, N., De Souza, S. N., Sardesai, S., and Madhupratap, M. (2002). Why is the Bay of Bengal Less Productive During Summer Monsoon Compared to the Arabian Sea?, *Geophysical Research Letters*, 29(24), 88-1.

Prieur, L., and Sathyendranath, S. (1981). An optical Classification of Coastal and Oceanic Waters Based on the Specific Spectral Absorption Curves of Phytoplankton Pigments, Dissolved Organic Matter, and Other Particulate Materials. *Limnology and Oceanography*, 26(4), 671-689.

Raju, K., Vijayaraghavan, K., Seshachalam, S., and Muthumanickam, J. (2011). Impact of Anthropogenic Input on Physicochemical Parameters and Trace Metals in Marine Surface Sediments of Bay of Bengal off Chennai, India. *Environmental monitoring and assessment*, 177(1-4), 95-114.

Ramage, C. S. (1984). Climate of the Indian Ocean north of 35 S. In *Climate of the Oceans* (pp. 603-671). Elsevier New York.

Rao, C. K., Naqvi, S. W. A., Kumar, M. D., Varaprasad, S. J. D., Jayakumar, A., George, M. D., Singbal, S. Y. S. (1994). Hydrochemistry of the Bay of Bengal: Possible Reasons for a Different Water-Column Cycling of Carbon and Nitrogen from the Arabian Sea. *Marine Chemistry*, 47, 279–290.

Rao, D. P., and Sastry, J. S. (1981). Circulation and Distribution of Some Hydrographical Properties during the Late Winter in the Bay of Bengal. *Mahasagar*, 14(1), 1-15.

Rao, K. H., Smitha, A., and Ali, M. M. (2006). A study on Cyclone Induced Productivity in South-Western Bay of Bengal during November-December 2000 using MODIS (SST and chlorophyll-a) and Altimeter Sea Surface Height Observations. *Indian Journal of Marine Sciences*, 35(2), 153-160.

Rao, S. A., Saha, S. K., Pokhrel, S., Sundar, D., Dhakate, A. R., Mahapatra, S., Ali, S., Chaudhari, H. S., Shreeram, P., Vasimalla, S. and Srikanth, A. S. (2011). Modulation of SST, SSS over Northern Bay of Bengal on ISO Time Scale. *Journal of Geophysical Research: Oceans*, 116(C9).

Rayner, N. A., Brohan, P., Parker, D. E., Folland, C. K., Kennedy, J. J., Vanicek, M., Ansell T. J. and Tett, S. F. B. (2006). Improved Analyses of

Changes and Uncertainties in Sea Surface Temperature Measured in Situ since the Mid-Nineteenth Century: The Had SST2 dataset. *Journal of Climate*, 19(3), 446-469.

Reddy, P., Salvekar, P. and Nayak, S. (2008). Super Cyclone Induces a Mesoscale Phytoplankton Bloom in the Bay of Bengal. *Geoscience and Remote Sensing Letters, IEEE*. 5: 588-592.

Rybicki, G. and Lightman, A. P. (1979). The Planck Spectrum. Radiative Processes in Astrophysics. New York: Wiley-Interscienc, 3-4 and 20-23.

Sabarudin, N. S., and Sarker, M. L. R. (2014). Ocean Primary Productivity Variation due to the Cyclone: A Case Study at Bay of Bengal. *Jurnal Teknologi*, 71(5).

Sachoemar, S. I., Yanagi, T., Hendiarti, N., Sadly, M., and Meliani, F. (2010). Seasonal Variability of Sea Surface Chlorophyll-a and Abundance of Pelagic Fish in Lampung Bay, Southern Coastal Area of Sumatra, Indonesia. *Coastal Marine Science*, 34(1), 82-90.

Sadhuram, Y., Sarma, V. V., Ramana Murthy, T. V., and Prabhakara Rao, B. (2005). Seasonal Variability of Physico-Chemical Characteristics of the Haldia channel of Hooghly estuary. India. J. Earth Syst. Sci., 114 (1), 37-49.

Saha, D., Deo, M. C., and Bhargava, K. (2013). Variability and Statistical Distribution of Ocean Current Observations. In *Proceedings of the International Symposium on Engineering under Uncertainty: Safety Assessment and Management (ISEUSAM-2012)* (pp. 805-821). Springer India.

Sampathkumar, P. and Ananthan, G. (2010). Phytoplankton. Centre of Advanced Study in Marine Biology Annamalai University.

Sarangi, R. K., Chauhan, P. and Nayak, S. R. (2005). Inter-annual Variability of Phytoplankton Blooms in Northern Arabian Sea during Winter Monsoon (February-March) using IRS-P4 OCM Data. *Indian Journal of Marine Sciences*, 34(2), 163-173.

Sarangi, R., Nayak, S. and Panigrahy, R. (2008). Monthly Variability of Chlorophyll and Associated Physical Parameters in the Southwest Bay of

Bengal Water using Remote Sensing Data. *Indian Journal of Marine Sciences*, 37, 256-266.

Sathyendranath, S., Stuart, V., Irwin, B. D., Maass, H., Savidge, G., Gilpin, L., and Platt, T. (1999). Seasonal Variations in Bio-Optical Properties of Phytoplankton in the Arabian Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*, 46(3), 633-653.

Schafer, P., Ittekkot, V., Bartsch, M., Nair, R. R. (1996). Fresh Water Influx and Particle Flux Variability in the Bay of Bengal. *In: Particle Flux in the Ocean. Wiley, New York*, pp. 271-292.

Sene, K. (2013). Flash Floods: Forecasting and Warning. *Springer Science + Business Media Dordrecht*.

Shankar, D., Vinayachandran, P. N., and Unnikrishnan, A. S. (2002). The Monsoon Currents in the North Indian Ocean. *Progress in Oceanography*, 52(1), 63-120.

Shetye, S. R., Gouveia, A. D., Shankar, D., Shenoi, S. S. C., Vinayachandran, P. N., Sundar, D., Michael, G. S., Nampoothiri, G. (1996). Hydrography and circulation in the Western Bay of Bengal during the Northeast Monsoon. *Journal of Geophysical Research*, 101(C6) 14, 011-14, 025.

Shetye, S. R., Gouveia, A. D., Shenoi, S. S. C., Sundar, D., Michael, G. S., and Nampoothiri, G. (1993). The Western Boundary Current of the Seasonal Subtropical Gyre in the Bay of Bengal. *J. Geophys. Res*, 98(C1), 945-954.

Smith, K. L., Ruhl, H. A., Bett, B. J., Billett, D. S. M., Lampitt, R. S., and Kaufmann, R. S. (2009). Climate, Carbon Cycling, and Deep-Ocean Ecosystems. *Proceedings of the National Academy of Sciences*, 106(46), 19211-19218.

Smitha, A., Rao, K.H. and Sengupta, D., (2006). Effect of May 2003 Tropical Cyclone on Physical and Biological Processes in the Bay of Bengal. *International Journal of Remote Sensing*. 27(23): 5301-5314.

Speer, B. R. (1997). Photosynthetic Pigments. In Glossary. Retrieved from http://www.ucmp.berkeley.edu/glossary/gloss3/pigments.html.

Subramanian, V. (1993). Sediment load of Indian rivers. *Current Science*, 64(11-12), 928-930.

Suryanarayana, A., Murty, C. S., and Rao, D. P. (1992). Characteristics of Coastal Waters of the Western Bay of Bengal during Different Monsoon Seasons. *Marine and Freshwater Research*, 43(6), 1517-1533.

Tang, S., Chen, C., Zhan, H., and Zhang, T. (2008). Determination of Ocean Primary Productivity using Support Vector Machines. *International Journal of Remote Sensing*, 29(21), 6227-6236.

The World Bank Group. (2015). Retrieved from data.worldbank.org

Tilstone, G. H., Angel-Benavides, I. M., Pradhan, Y., Shutler, J. D., Groom, S., and Sathyendranath, S. (2011). An Assessment of Chlorophyll-a Algorithms Available for Seawifs in Coastal and Open Areas of the Bay of Bengal and Arabian Sea. *Remote sensing of environment*, 115(9), 2277-2291.

Tilstone, G. H., Lotliker, A. A., Miller, P. I., Ashraf, P. M., Kumar, T. S., Suresh, T., Ragavan, B. R., and Menon, H. B. (2013). Assessment of MODIS-Aqua Chlorophyll-a Algorithms in Coastal and Shelf Waters of the Eastern Arabian Sea. *Continental Shelf Research*, 65, 14-26.

Tripathy, M., Raman, M., Dwivedi, R. and Ajai, A. (2012). Frequency of Cyclonic Disturbances and Changing Productivity Patterns in the North Indian Ocean Region: A Study Using Sea Surface Temperature and Ocean Colour Data. *International Journal of Geosciences*. 3: 490-506.

Twardowski, M. J., Lewis, M. R., Barnard, A., and Zaneveld, J. R. V. (2005). In-water Instrumentation and Platforms for Ocean Color Remote Sensing Applications. *Remote sensing of Coastal Aquatic Environments*, 347.

University of Michigan. (2008). The Flow of Energy: Primary Production of Higher Trophic Levels. www.globalchange.umich.edu.

Vinayachandran, P. N. and Mathew, S. (2003). Phytoplankton Bloom in the Bay of Bengal during the Northeast Monsoon and its Intensification by Cyclones. *Geophysical Research Letter*, 30, 11-26.

Vinayachandran, P. N., Chauhan, P., Mohan, M., and Nayak, S. (2004). Biological Response of the Sea around Sri Lanka to Summer Monsoon. *Geophysical Research Letters*, 31(1).

Vinayachandran, P. N., McCreary, J. P., Hood, R. R. and Kohler, K. E. (2005). A Numerical Investigation of the Phytoplankton Bloom in the Bay of Bengal during Northeast Monsoon. *Journal of Geophysical Research*, 110, C12001.

Wang, G., Garcia, D., Liu, Y., De Jeu, R., and Johannes Dolman, A. (2012). A three-Dimensional Gap Filling Method for Large Geophysical Datasets: Application to Global Satellite Soil Moisture Observations. *Environmental Modelling & Software*, 30, 139-142.

Wang, H., Li, X., Long, H., Gai, Y., and Wei, D. (2009). Monitoring the Effects of Land Use and Cover Changes on Net Primary Production: A Case Study in China's Yongding River Basin. *Forest ecology and management*, 258(12), 2654-2665.

Ware, D. M. and Thomson, R. E. (2005). Bottom-up Ecosystem Trophic Dynamics Determine Fish Production in the Northeast Pacific. *Science,* 308(5726), 1280-1284.

Wentz, F. J., Gentemann, C., Smith, D., and Chelton, D. (2000). Satellite Measurements of Sea Surface Temperature through Clouds. *Science*, 288(5467): 847-850.

Wetzel, R. G. (2001). Limnology: Lake and River Ecosystems (3rd ed.). San Diego, CA: Academic Press.

Wyrtki, K. (1973). Physical Oceanography of the Indian Ocean. Vol. 3 of Ecological studies: analysis and synthesis. In B. Zeitschel, and S. A. Gerlach (Eds.), *Biology of the Indian Ocean* (pp. 18–36). London: Chapman and Hall Ltd.

Yan, Z., and Tang, D. (2009). Changes in Suspended Sediments Associated with 2004 Indian Ocean tsunami. *Advances in Space Research*, 43(1), 89-95.

Zoran, M. and Weber, C. (2007). Use of Multi-temporal and Multispectral Satellite Data for Urban Change Detection Analysis. *Journal of Optoelectronics and Advanced Materials*, 9, 1926-1932.