Chapter 1

Introduction

INTRODUCTION

1.1 IMPORTANCE OF OCEANS

Earth's climate is a complex system comprising of the atmosphere, hydrosphere, lithosphere and biosphere, which interacts with each other and maintains the conditions feasible for life to sustain on the earth. With oceans occupying approximately 70% of the earths' surface, and containing about 97% of its surface water, their role in climate regulation cannot be undermined. They are the main source of water feeding the hydrological cycle. The oceans have been the cradle to the genesis of life on earth. Their importance in the economic development can be known from the fact that most of the world's megacities are located in the coastal zones. Though the coastal areas account for just 10% of the land surface, yet they are densely populated and exhibit higher rates of population growth and urbanization *(Brown et al., 2013; Neumann et al., 2015).* They are also the reservoirs of minerals and petroleum.

The oceans are the source of food and livelihood, with about a billion people relying on fish as their main source of protein. Approximately 50% of the global primary production comes from the oceans (*Field et al., 1998)*. They support the greatest biodiversity on the planet and are one of the largest carbon reservoirs in the earth system. Besides, they also store vast amount of energy radiated by the sun and maintain the heat balance of the earth.

1.1.1 Oceans as Heat Sinks

The oceans play a very crucial role in maintaining the earths' temperature. They not only act as heat sinks but also help in the distribution of heat across the globe. The incoming solar radiations are absorbed by the oceans in a similar way as land surfaces. However, as compared to the land surfaces, the oceans due to higher heat capacity of water require much more energy from the sun to warm up. Besides, the oceans also take longer time to change their temperature significantly. As a result, they store large amount of heat for a longer duration and they act as a heat sink.

Additionally, the oceans also help in distributing the earth's heat through wind and currents. In the summer season, the differential heating of land and ocean results in pressure gradient, which generate winds. While blowing from one direction to the other, the winds help in transport of the atmospheric heat across the globe. The surface winds, when blowing above the sea surface, push against the top oceanic layers, and lead to the formation of oceanic currents. These currents, although slower in movement, than the surface wind, have higher heat content and they transfer the heat absorbed by the oceans.

The vast expanse of the oceans and their higher heat capacity makes them ideal heat sinks and the physical processes of wind and current help in distribution of the heat across the globe.

1.1.2 Oceans as Sinks of Carbon dioxide

Oceans play a predominant role in the carbon cycle. They are the main storehouse of carbon, and have been reported to contain 50 times more carbon than the atmosphere. It has been estimated that since the era of the industrial revolution, the oceans have taken up approximately 30-50% of anthropogenic-sourced Carbon dioxide (CO_2) from the atmosphere and have contributed enormously in slowing the rate of global warming. Recent study has indicated that in the last decade from 2004 to 2013, the global ocean has absorbed 2.6 billion tonnes of carbon per year, representing nearly 30% of anthropogenic emissions over this period (*Laurent Bopp & Chris Bowler, 2015).*

The sequestering process of carbon in oceans happens through the 'Physical and Biological Carbon pumps' that are operational in the oceans as shown in Fig. 1 while Fig. 2 shows diagrammatically the flow of CO_2 in oceans by the Physical pump and the Biological Pump.

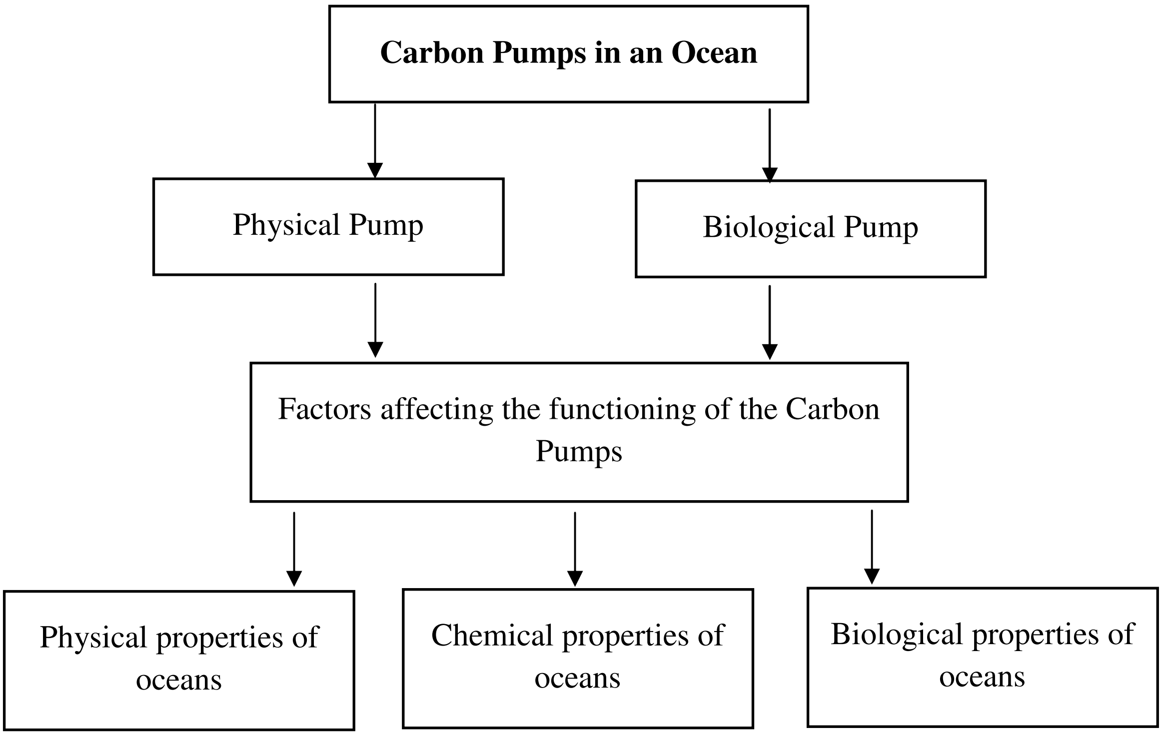

Fig. 1.1: Carbon pumps in an ocean

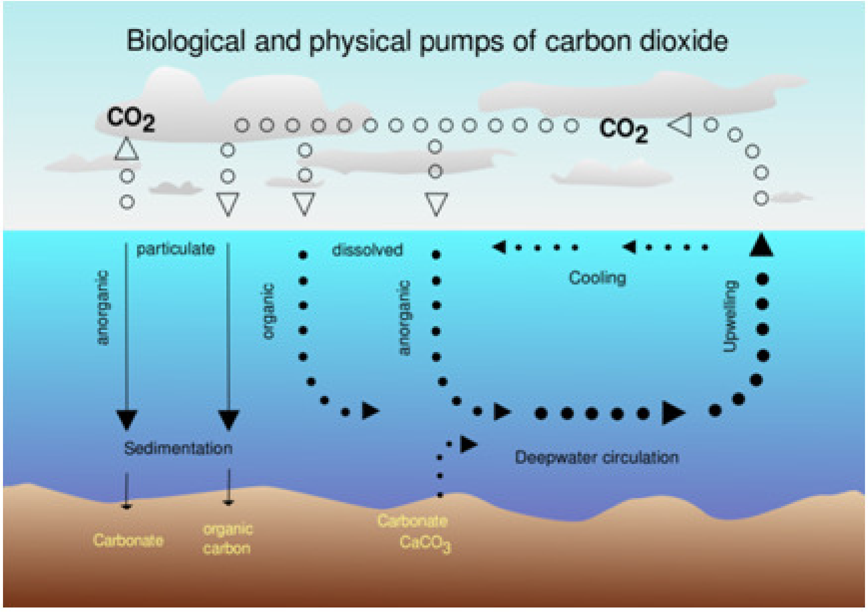

Fig. 1.2: Physical and Biological Carbon Pump in Oceans (*source: NASA*)

These carbon pumps are regulated by the physical, chemical and biological properties of the oceans (*Heinze et al., 2015*).

The **Physical Carbon Pump** is a solubility pump that transports carbon from the surface of the ocean to its deeper layer. CO_2 like other gases is soluble in water and forms carbonic acid (H_2CO_3). Depending upon the gradient of CO_2 between the atmosphere and the ocean surface, molecules of CO_2 diffuse into the sea water and dissolve in it to form carbonic acid (H_2CO_3), through the processes of hydration. The carbonic acid in turn dissociates in the saline water to form dissolved inorganic carbons (DIC) which are prominently in the form of bicarbonates (HCO_3^{1-}) and carbonates (CO_3^{2-}) and a small amount of undissolved CO_2, as given in Equation 1 *(Weiss, 1974; Liss and Merlivat, 1986; Wanninnkhof, 1992; Nightingale et al., 2000;; Dickson et al., 2007):*

$$CO_2 + H_2O \longleftrightarrow H^+ + HCO_3^- \longleftrightarrow 2H^+ + CO_3^{-2} \quad \ldots\ldots\ldots\ldots\ldots \text{ Equation 1}$$

The amount of CO_2 that diffuses and dissolves in the sea surface water is dependent on physical properties of water such as temperature, wind and sea surface mixing. The solubility of CO_2 gas in seawater is inversely proportional to the Sea Surface Temperature (SST). Increasing SST decreases CO_2 solubility, while decreasing SST increases its solubility. Besides, as the deeper water layers are cooler, the freshly dissolved CO_2 gets transported downward. This works in the form of a pump and is called as the **'Solubility Pump'** of CO_2 *(Volk and Hoffert, 1985).*

The **Biological Carbon Pump** is driven by the microscopic, free floating phytoplankton, found in the oceans. The phytoplankton being the primary producers in the food chain of the marine ecosystem, absorb sunlight for fixation of CO_2 through the process of photosynthesis. They take CO_2 and water (H_2O) from their surrounding and use the energy from the sun to produce glucose ($C_6H_{12}O_6$) and oxygen (O_2). The Biological Carbon Pumps assimilate CO_2 into organic carbon which subsequently gets can be converted into other organic compounds and result in the increase in the biomass of the phytoplankton. These phytoplankton, also require light and nutrients to assimilate the carbon. As the phytoplankton are the source of food for the secondary and many of the tertiary producers, the increase in the overall biomass of the phytoplankton result in the increase in the productivity of the marine ecosystem. Eventually, with the death of the phytoplankton and other organisms in the oceans, their detritus sink to the bottom of the ocean layers, where they decompose and release carbon and other nutrients back into the oceanic waters. It has been reported that approximately 25% of the organic carbon, which is fixed in the ocean surface layer, eventually sinks through the water column *(Schlitzer, 2000)*. Hence, we can see the importance of phytoplankton as not only the main drivers of the marine food chain but also as the cushions that absorb the excess CO_2 from the atmosphere.

1.1.3 Biological Productivity in Oceans

The oceans covering approximately 70% of the Earth's surface, constitutes over 90% of the habitable space on the planet *(UNESCO/Rio+20).* They support diverse forms of lives from microscopic unicellular prokaryotes to diverse species of fishes and mammals. The biological significance of oceans can be acknowledged from the fact that the ocean primary production (PP) makes up approximately half of the global primary production *(Field et al., 1998).* This 50% share of global primary production is contributed by marine phytoplankton *(Falkowski et al., 2004).*

Phytoplankton are microscopic, aquatic plants, that move or drift according to the movement of the water masses. Among the most commonly found phytoplankton in the oceans are the cyanobacteria, diatoms, dinoflagellates, green algae, and coccolithophores. These phytoplankton in the ocean absorb solar radiation to fix CO_2 to organic carbon through the process of photosynthesis as shown in Equation 2.

$$CO_2 + 2H_2O + \text{Light energy} \longrightarrow CH_2O + O_2 \quad \text{......................................Equation 2}$$

The rate at which photosynthesis occurs is known as **Primary Production (PP)** and it is dependent on the distribution of phytoplankton, their biomass and availability of nutrients. Physical processes like ocean circulation, wind, upwelling, dust events, etc. regulates the distribution of nutrients in the surface layer and in turn affects the growth and productivity of phytoplankton (*Siegel et al., 1999; Santoleri et al., 2003*). Productivity also varies with the temperature of the water (*Thomas et al., 2003*) and availability of light (*Gohin et al., 2003*; *Kogeler & Rey, 1999*) and takes place within the euphotic zone, which extends from the surface to a depth where there is 1% of the light intensity from the surface.

Photosynthesis by phytoplankton not only fixes CO_2, but also drives the biological carbon pump and plays a significant role in the cycling of the carbon. The uniqueness of productivity of oceans is that unlike the other component of the global carbon cycle, the amount of carbon fixed through primary production is much more than the amount of carbon reserved in the marine biota *(Siegenthaler and Sarmiento, 1993*). It is estimated that the phytoplankton transfer about 10 gigatonnes of carbon from the atmosphere to the deep ocean each year (*NASA*). *Broecker (1982*) reported that the phytoplankton in the oceans store more carbon away from the atmosphere than the terrestrial biosphere. Apart from playing a significant role in the carbon cycle, the importance of the phytoplankton can also be evaluated from the fact that **they provide 50% of the oxygen on earth** *(UNESCO/Rio+20)*. Besides, as the phytoplankton form the basis of the marine food chain, their productivity affects the overall productivity of the oceans and can be indicator of the status and ecological significance of the marine ecosystem.

In recent years, a lot of studies have been done to estimate the trend of productivity in the marine ecosystems (*Worm et al. 2005; Behrenfeld et al. 2006; Doney, 2006; Piontkovski & Castellani, 2009; Boyce et al., 2010)*. Satellite measurements of ocean color provide a means of quantifying ocean productivity on a global scale and linking its variability to environmental factors. The ocean color sensors in the satellite are able to capture synoptic views of the vast oceans over long period of time, which is required for climate change related studies.

1.2 CLIMATE CHANGE AND OCEANS

In today's era, one of the biggest challenges being faced by human being is Climate Change which is threatening the survival of not just humans but a variety of flora and fauna. The marine ecosystem is no exception and it too is bearing the consequences of climate change. Fig 1.3 shows the conceptual cause – effect relationship between Climate Change and its impact on Oceans

Fig. 1.3: Climate change and Oceans

1.2.1 Impacts of Climate Change on Physical Properties of Oceans

The most direct impact of changing climate is the **rising sea surface temperature** *(Bindoff et al., 2007).* The increase in the SST leads to a cascade of events like rising sea level *(Church, 2001; Meehl et al., 2005)*, decreased sea-ice extent, altered pattern of ocean currents, wind circulation and precipitation *(Goswami et al., 2006; Zhang et al., 2007).* The rise in temperature and altered wind patterns can adversely affect the mixing and stratification of the surface ocean *(Sarmiento et al., 2004)*, limiting the supply of nutrients. Warmer SSTs may affect the frequency and strength of tropical storms *(Emanuel, 2005; Webster et al., 2005),* increasing the vulnerability of coastal habitats.

Apart from the increasing SST, the other direct impact of climate change on oceans is their **acidification**. The increase in atmospheric CO_2 has led to a greater uptake of CO_2 by the oceans. This has resulted in a decrease in the pH of the oceanic waters and they are turning acidic *(Bates et al., 2014).* Rapid ocean acidification has a detrimental impact not only on the marine calcifying organisms *(Feely et al., 2004),* but also the phytoplankton, fishes and other invertebrates (*Heinze et al., 2015*).

1.2.2 Impacts of Climate Change on Marine Ecosystem and Productivity

The impact of climate change is posing a serious challenge to the marine organisms. The growth and metabolism of marine phytoplankton is influenced by the temperature of the sea water. Each of the phytoplankton species requires a threshold temperature for its survival and maximum growth rate. Their productivity increases with increasing temperature until a species-specific maximum is reached, after which the rates decline rapidly *(Eppley, 1972).* Hence in the current scenario of rising SST, the survival of marine phytoplankton and their productivity is threatened, which in turn threatens the survival of other marine organisms.

The warmer sea would also compel the marine organisms to shift its habitat leading to change in its spatial distribution *(Walther et al., 2002; Parmesan and Yohe, 2003).* However, as the phytoplankton form the base of the marine food web, the change in their spatial distribution and overall abundance may alter the fishery ranges and yields (*Iverson, 1990; Chavez et al., 2003; Ware and Thomson, 2005; Cheung et al., 2009a, 2009b).*

Additionally, the warming of sea may also alter their physiology, behavior and productivity of organisms *(Somero, 2012*). Several studies have shown that the physiological changes alter the phenology of the organisms. Hence, when the life cycles of the organisms are altered, it may lead to a mismatch of trophic components of the food chain *(Brander, 2010)*, which will have a catastrophic effect on the dynamics of the marine ecosystem. In the changed environment, the organisms have the choice to acclimatize and adapt or migrate or die off, which eventually will lead to local extinction *(Parmesan, 2006).*

The stress of climate change on marine organisms is further escalated in warmer waters as it reduces the subsurface oxygen concentration *(Keeling et al., 2010).* This becomes challenging for many organisms to adapt and often lead to mass mortality. In this context the study done by *Diaz & Rosenberg (2008)* is alarming, as they reported on the expansion of hypoxic regions especially in the productive oceans of the world.

The pressure of climate change and its impacts are more predominant in the coastal ecosystems and the gulfs. Due to large scale developmental work *(UNEP, 2002)* and rapid population growth there has been an extensive loss and degradation of ecologically productive coastal habitats (*Sheppard et al., 1992, 2010).* Moreover, the climate change has increased the frequency of harmful algal bloom outbreaks *(Bauman et al., 2010; Richlen et al., 2010)* as well. On a global scale there has been an intense deterioration of marine coastal ecosystems *(Jackson, 2010)* with 50% of salt marshes, 35% of mangroves, 30% of coral reefs, and 29% of seagrasses already either lost or degraded.

1.3 STUDIES DONE TO ASSESS THE IMPACTS OF CLIMATE CHANGE IN ARABIAN SEA

Arabian Sea has been reported to be one the most productive regions of the world oceans (*Codispoti, 1991)* and has been classified as a **'Class I High Productive Ecosystem'**, with annual productivity greater than 300g C m^{-2} yr^{-1} *(UNEP Large Marine Ecosystem Report).* However, it is unique from the other marine ecosystems of the world because of its unique geographical location that makes it interlocked between lands on three sides. Moreover, it is strongly influenced by monsoonal winds which affect its physical and biological properties.

However, Arabians Sea could not gather the attention of researchers for a long time and no significant study was carried out the prior to 1960s. Few of the noteworthy studies done in late 1950s were localized and were limited to the coastal areas of the Arabian Sea *(Jayaraman and Gogate, 1957; Jayaraman et al., 1959; Ramamirtham and Jayaraman, 1960).* In the early 1960s, the focus of the international oceanographic researchers shifted towards the basin and many important expeditions, namely the International Indian Ocean Expedition (IIOE, 1959–65) and the Indian Ocean Experiment (INDOEX, 1979) were carried out. These expeditions have been instrumental in the understanding of the physical and biological properties and processes of Arabian Sea.

Further in the 1990s, several international studies under different programmes like Netherlands Indian Ocean Program, (1992–1993), the Arabesque, (1994), German JGOFS, (1995–1997), NASEER, (1992–1995), JGOFS-India, (1994–1997) and the US-JGOFS, (1994–1996) expanded the knowledge of the region *(Smith and Madhupratap, 2005).*

Since then several studies in the past have been done to assess different physical and biological processes in the Arabian Sea, using both *in situ* as well as satellite data (*Kabanova, 1968; Qasim, 1977; Swallow, 1984; Rao and Goswami, 1987; Banse, 1987; Gunderson et al., 1998; Gardner et al., 1999; Stelfox et al., 1999; Caron and Dennett, 1999; Nair et al., 1999., Wiggert et a1., 2000; Roman et al., 2000; Dickson et al., 2001; Solanki et al. 2001; Weller et al., 2002; Kumar et a1., 2001, 2004, 2009; Tang et al., 2002; Chaturvedi et al., 2003; Chauhan et al., 2004; Madhu, 2004; Wiggert et al., 2005; Goes et al., 2005; Parab et al., 2006; Prakash and Ramesh, 2007; Dwivedi et al., 2008; Habeebrehman, 2009; Naqvi et al., 2010; Piontkovski and Claereboudt, 2012; Tripathy et al., 2012; Nandkeolyar et al., 2013).*

As the most evident impact of climate change is the warming of the oceans, hence, a majority of the studies done in the Arabian Sea focus primarily on SST, its characteristics *(Babu et al., 2007)*, trend *(Singh, 2000, Kumar et al., 2002)* and its impact on phytoplankton *(Arnone, 1987, Solanki et al., 2001). Singh & Sarkar (2003)* evaluated the SST along the coastal regions of Arabian Sea for the period 1985 to 1998. *Shukla and Mishra (1977)* assessed the correlation between SST and wind speed over Central Arabian Sea using 60 years data from 1901 to 1960. *Kumar et al. (2009)* assessed the response of the Arabian Sea to global warming and reported that post 1995 there has been a disruption in the natural decadal cycle in the SST, followed by a secular warming.

Besides, one of the most dreadful impacts of climate change is the increase in the frequency and intensity of cyclonic events. Although relatively fewer cyclones are formed in the Arabian Sea in a year, yet occasionally highly intense cyclone like Gonu, could lead to large scale destructions in the coastal areas of Arabian Sea. Hence, the cyclonic events in Arabian Sea have also been analyzed comprehensively. *Kumar et al. (2009)* in their study concluded that the Arabian Sea is experiencing a regional climate-shift after 1995, which is accompanied by a fivefold increase in the occurrence of ‘most intense cyclones’. *Evan et al. (2010*) studied the Climatology of Arabian Sea Cyclonic Storms and concluded that since early 1990s, there has been an increase in the numbers, duration, and intensity of Arabian Sea cyclones. *Tripathy et al. (2012)*, analyzed the impact of cyclones on SST and biological productivity, and concluded that the occurrence of cyclonic events results in short term-nutrient enrichment of upper-stratified ocean, which increase the biological productivity of the oceans.

An assessment of phytoplankton biomass and its seasonal variations in Arabian Sea has also been extensively studied. *Bhattathiri et al. (1996)* studied the phytoplankton distribution in the Eastern and Central Arabian Sea during different seasons. Variability of Chlorophyll-a in Eastern and Western Arabian Sea has been studied by *Tang et al., (2002; 2005)* and *Mudgal et al., (2009)*. *Nair et al. (1999)* and *Kumar et al. (2000)* reported that the biological productivity of the Arabian Sea is tightly coupled with the physical forcing mediated through nutrient availability. *Pillai et al. (2000)* studied the seasonal variations in physico-chemical and biological characteristics of the Eastern Arabian Sea. *Ravichandran et al. (2012)* evaluated the chlorophyll a variability in the southeastern Arabian Sea using Argo profiling.

The impact of convective mixing in increasing the phytoplankton biomass and productivity of Arabian Sea has also been a focal study by many researchers *(Banse et al., 1996; Madhupratap et al., 1996; Kumar et al., 2001; Dwivedi et al., 2008)*. Recently, many studies have been done in the gulfs of the Arabian Sea. *Piontkovski et al. (2011, 2013)* studied the seasonal and interannual variability of chlorophyll-a in the Gulf of Oman and compared with open Arabian Sea.

The International Indian Ocean Expedition (IIOE, 1959–65), the Indian Ocean Experiment (INDOEX, 1979), and the studies done under the JGOFS have been instrumental in the understanding of the productivity of Arabian Sea. These studies highlighted that during summer season, the open waters of the Arabian Sea remain oligotrophic (nutrient-depleted), with surface chlorophyll-a in the range of 0.1 to 0.5 mg m^{-3}, and primary productivity in the range from 100 to 500 mg C m^{-2} d^{-1}. Subsequently, *Banse (1987),* and *Pant (1992)* also arrived at similar conclusions. However, *Kumar et al. (2001)* reported a fairly high biological production (up to 1700 mg C m^{-2} d^{-1}) in the central Arabian Sea, along 64^{o}E, during the summer monsoons of 1995 and 1996 owing to physical and chemical changes resulting from upwelling, advection, cyclonic wind stress, etc.

Goes et al. (2005) reported an increase in the productivity of the Western Arabian Sea, between the years 1997-2004. They correlated satellite-derived SST against chlorophyll-a (indexed as phytoplankton biomass) during the south west monsoon season and concluded that the increasing in productivity was mainly because of the increase in the strength of sea surface winds. However, the limitation of this study was its geographical extent. They analyzed the region of Arabian Sea between 52°-57° E, 5°-10° N which covered only about 1% of its total area.

Similarly, for the Eastern Arabian Sea, *Prakash & Ramesh (2007)*, investigated the productivity trend during an 8-year period from 1997 to 2005, using satellite derived Chlorophyll-a concentrations. They concluded that there was no significant change of phytoplankton biomass over the 8 years.

Piontkovski & Claereboudt (2012) went for a more comprehensive assessment of productivity of Arabian Sea. They studied the inter-annual changes in SST and chlorophyll-a across the Arabian Sea, by subdividing the entire basin into 61 units, each of 2° × 2° area, for the period 1997 to 2009. They observed that there was no overall increase in chlorophyll-a, during the period 1997-2009. However, there was higher variability of chlorophyll-a in western regions of the sea in comparison to eastern regions. Besides, there was no enlargement of the productive area in the Arabian Sea, over time. On the contrary, they concluded that several regions in its eastern basin showed a decline in chlorophyll-a concentration.

1.4 RESEARCH GAPS

The above-mentioned studies carried out in the Arabian Basin, are either limited to a particular region or zone within the Arabian Sea. In many of these studies, the entire basin has been divides into 2°×2° or 1°×1° subsets, which are large areas averaged out to give the approximation. Secondly, most of the studies do not differentiate the open ocean regions from the Gulfs. As the Gulfs have proximity to land and are closed bodies, their hydrographic features are different from the open oceans and hence cannot be generalized. Moreover, the SST and wind pattern over the gulfs show significant variation from the pattern of the open ocean. Clubbing the marginalized gulf and Arabian Sea together would give a misrepresentation of the results. Thirdly, a comprehensive monthly, seasonal and annual assessment of the impact of climate change on SST, Wind Speed and Biological Productivity has not been done. Fourthly, the studies do not pertain to the assessment of the impact of climate change in the recent years.

To address these research gaps, the present study has been undertaken. Focusing on the impact of climate change on the productivity of the Arabian Sea, a comprehensive climatological assessment of the spatial and temporal variability of SST, wind and phytoplankton biomass has been carried out. The specific research objectives are mentioned in section 1.5

1.5 OBJECTIVES OF THE PRESENT STUDY

The objectives of the present study are as follows:

1. Assessment of the impact of climate change in Arabian Sea on its sea surface temperature and wind speed
2. Analysis of long term spatio-temporal variability of phytoplankton productivity in the Arabian Sea
3. Correlate the impact of climate change on primary productivity of Arabian Sea.

1.6 THESIS STRUCTURE

The objectives of the present study have been covered in **7 chapters** of the thesis which are described as follows:

Chapter 1: Introduction

This chapter gives an introduction to the field of research, highlighting importance of oceans and the need to assess the impact of climate change in the oceans. It also gives an account of the importance of Arabian Sea and the studies done so far in the basin. The chapter discusses about the existing gaps in the studies that have been done and the objectives with which the present study was taken up.

Chapter 2: Study Area

This chapter discusses the geographical location and the unique features of the Arabian Sea. It highlights the reasons for its high productivity and also gives a brief account of the gulfs and marginalized sea in the Arabian Sea, with their distinct oceanographic features. It sets the basis for dividing the entire basin into different sub-regions for assessment of spatio-temporal variability of the physical and biological variables.

Chapter 3: Evidence of climate change in Arabian Sea from multi decadal study of spatio-temporal variability of SST

This chapter gives an account of the rising SST in different domains of the Arabian Sea. The chapter highlights the seasonal as well as annual trends of SST in different domains, including the gulfs and marginal sea of the Arabian Sea.

Chapter 4: Assessment of the changing pattern of wind speed in Arabian Sea

This chapter focuses on the seasonal and interannual variability of wind speed over Arabian Sea.

Chapter 5: Spatio-temporal variability of phytoplankton productivity in the Arabian Sea

This chapter describes the spatial and temporal variability of productive areas of the Arabian Sea and also the interannual variability of phytoplankton biomass using satellite data.

Chapter 6: Correlation of the changing climate on the biological productivity of the Arabian Sea

This chapter correlates the changing trend in the physical variables like SST and wind speed. over the biological productivity of the Arabian Sea.

Chapter 7: Summary and Conclusion

This chapter summarizes the results of the present research work and highlights the impact of climate change on productivity of Arabian Sea. It also gives a brief account of the future scope of work.