CHAPTER-1

Introduction

1.1 Purpose and Scope

Human civilization depends on the Earth's natural system. Hence complete understanding of the dynamics of Earth's climate is essential for the sustainable development of humanity on Earth. In the tropics we have a large population where the climate is mainly driven by monsoon rainfall. It is therefore indispensable to understand the causes of past climatic changes which plays a vital role in decoding past, present and future monsoon variability. India's economy is largely dependent on rainfall from the southwest monsoon (SWM); hence, slight changes in SWM rainfall can have immense societal impacts in this region. Numerous endeavours have been made to understand the factors responsible for SWM rainfall variations, and several global phenomena like the ENSO (El Niño–Southern Oscillation) (Goswami et al., 1999; Annamalai and Liu, 2005), the Atlantic sea surface temperature (Goswami et al., 2006; Yadav, 2017), Eurasian snow cover (Hahn and Shukla, 1976; Pant and Rupa Kumar, 1997; Bamzai and Shukla, 1999), the pre-monsoon 500 hPa ridge (Mooley et al., 1986), the Indo- Pacific warm pool (Parthasarathy et al., 1988, 1991), the Pacific decadal oscillation (Krishnan and Sugi, 2003), and the Atlantic multi-decadal oscillation (Krishnamurthy and Krishnamurthy, 2016) have been correlated with variations in SWM rainfall. The Indian Ocean warm pool (IOWP) has also been identified as the prominent source of moisture for SWM rainfall (Ninomiya and Kobayashi, 1999; Gimeno et al., 2010).

Variations in the palaeoproductivity of the coastal regions off Somalia and Oman have been considered to understand past changes in SWM related upwelling (Sirocko et al., 1993; Naidu and Malmgren, 1996; Gupta et al., 2003; Tiwari et al., 2010). Most of these studies are based on Foraminifera production during monsoon seasons. However, the siliceous productivity which is restricted to the SWM season, can essentially serve as a better proxy than foraminifera for upwelling studies. The present study is therefore aimed to understand past variations in siliceous productivity in the Somali upwelling region, as well as palaeo-upwelling strength and its relationship with SWM rainfall. The ocean is under saturated with respect to silica; thus, biogenic silica flux in sediments is a function of its export flux, which is controlled by its production at the surface and its dissolution in the water column as well at the sediment–water interface (Hurd, 1973; Broecker and Peng, 1982). The use of biogenic silica as a proxy for the study of palaeo-upwelling requires an understanding of its production and burial efficiency. Sediment trap studies from the western Arabian Sea have indicated that the biogenic silica flux mimics the SWM upwelling (Haake et al., 1993).

Greenhouse gases especially the atmospheric concentration of CO_2 has been identified as the major internal factor which influence the global climate (Frakes et al., 1992). The CO_2 concentration of the atmosphere in turn is modulated by several natural processes (Taylor and Lloyd, 1992). Carbon export flux (CEF), downward transport of particulate organic carbon in ocean, intimately related with the global climate through the modulation of CO_2 in the atmosphere and its influence on the heat budget. CEF is a major sink for atmospheric carbon dioxide thus it influences global climate (Falkowski et al, 1998). The CEF is much larger than carbon burial since a minor portion of it is ultimately buried in the sediment (Paytan and Griffith, 2007). Increase in CEF has been suggested as a reason for the reduction in atmospheric CO_2 during Last Glacial Maximum (LGM). Aeolian flux was assumed as the nutrient supplier for the increased CEF during LGM (Martin, 1990). Though the relation between CEF and aeolian flux were much studied in high nutrient and low chlorophyll (HNLC) regions, their relation in other oceanic regions need attention.

Nitrogen fixation by micro-organisms is the major source of nitrate in the surface ocean with minor inputs from river and atmospheric systems (Altabet, 2007). However, the removal of oceanic nitrate is significantly influenced by denitrification and autotrophic assimilation (Altabet, 2006; Sigman et al., 2009; Galbraith et al., 2013). Denitrification occurs in the water column as well as at sediment water interface in continental margins and significantly affects the earth's climate by altering the radiative properties of the atmosphere, through the production of N_2O (Ravishankara et al., 2009) from nitrate. Hence understanding oceanic nitrogen cycle is very important in the context of biological sequestration of CO_2 as well as production of N_2O; both have been recognized as important drivers of climate variability. Every process in the nitrogen cycle produces distinct isotopic composition of the product and the substrate (Sigman et al., 2009). Isotopic composition of organic nitrogen present in the marine sediments has been widely used in the recent decades to understand the influence of individual processes on the nitrogen cycle during the past (Altabet et al., 1995; Gruber and Sarmiento, 1997; Altabet et al., 1999; Sigman et al., 2000; Bange et al., 2005; Brunner et al., 2013). The Arabian Sea forms a natural laboratory to study the marine biogeochemistry. Number of studies have been carried out from various regions of the Arabian Sea, especially from the coastal regions of northern part for understanding the palaeoclimate, productivity and denitrification processes (Altabet et al., 1995; Reichart et al., 1998; Suthhof et al., 2001; Altabet et al., 2002; Pichevin et al., 2007; Mobius et al., 2011; Kao et al., 2015). However the impact of other physical processes like lateral advection of nutrients on productivity and nitrogen cycling in open ocean region needs to be understood.

Indus sediment flux is the major source of sedimentation in the Arabian Sea which forms Indus submarine fan. The Indus submarine fan extends over 106 km^2 in the Arabian Sea with up to 9 km thick pile of sediments (Coumes and Kolla, 1984; Clift et al., 2001). An area of approximately 106 km^2 in the Himalayan region is currently drained by Indus river with an annual sediment discharge of about 450 x 106 $T.yr^{-1}$ before damming (Milliman et al., 1984), represents the fifth largest sediment flux in the world (Bourget et al., 2013). The Indus River runoff peaks during the southwest monsoon season due to high precipitation and snow melting (Karim and Veizer, 2002). The drainage basin of the Indus River composed of high relief and poorly consolidated sediments, which is the major cause for the high sediment flux (Giosan et al., 2006) along with large runoff. Numerous studies in the recent times have been aimed at to understand the evolution of Indus submarine fan sedimentation (Bourget et al., 2013 and references therein). Clift and Giosan (2014) indicated that a significant portion of the eroded sediment in the Indus drainage system is stored in the floodplains except the suspended loads. Another study by Clift et al. (2014) has shown that the sediment transfer from river mouth to submarine fan is mainly controlled by sediment mixing and reworking associated with sea-level changes. Therefore the correlation of sedimentation in the Indus submarine fan and climate over the Indus drainage basin is very complex. However, Bourget et al. (2013) has compared the late Quaternary sedimentation in Indus submarine fan with the sea level changes during the past, and observed that the high sedimentation events represents low sea levels. Thus, comparison of sediment flux reconstructions with climate, tectonic changes in source area and sea level changes may help in understanding submarine sedimentation.

The present seasonal changes that have bearing on the very objectives of the present study are summarised in the following lines.

1.2 Atmospheric Circulation

Atmospheric wind pattern over the Arabian Sea varies in direction and speed from season to season. Seasonal average of wind speed and precipitation maps for 1979 to 2015 are presented in Figures 1.1 to 1.8. Seasonal maps are prepared using ERA-Interim data (Berrisford et al., 2011) in an online tool called Climate Reanalyzer (http://cci-reanalyzer.org). Wind direction over the study area is controlled by the differential heating of land and ocean and subsequent shift in ITCZ. During boreal summer (June-August) the Asian landmass warms quicker than the Indian Ocean, supporting the northward shift of the ITCZ (Trenberth et al., 2000), this pulls the cross equatorial low level jet (Findlater, 1978), the southwest monsoon. The associated southwesterly winds dominate the atmospheric circulation throughout the boreal summer. The southwesterly winds are very strong at the western boundary than other parts of the basin (Figure 1.1). It can be observed from the seasonal wind speed map that the meridional winds (Southwest to Northeast) are strong in the western part while the eastern part is dominated by the zonal winds. Southwest winds carry the moisture from the western Indian Ocean towards Indian sub-continent and give rise to the well-known seasonal rainfall (southwest monsoon rainfall) over western part of the country (Figure 1.2). Southwest monsoon rainfall is the lifeline for the Indian agriculture and economy (Gadgil and Gadgil, 2006). The maps show the seasonal average pattern; however, the northern limit of southwesterly winds and rain belt shifts northward throughout the season. The surface wind direction remain unchanged during the autumn season (Sep-Nov; Figure 1.3) in the western part of the basin. In the eastern part the wind direction shifts towards equator resembling a clockwise wind flow over the basin. This change in the wind direction in the eastern part of the basin might have been caused by the opposing effect of northeast wind flow from Indian sub-continent. However the average wind speed is reduced during this season. The latitudinal position of maximum rainfall region shifts towards equator during autumn (Figure 1.4). This shift is modulated by the location of maximum solar insolation and ITCZ. During winter (December to February) the northeast winds dominates the atmospheric pattern, the Northeast monsoon. This show a reverse pattern as compared to summer season. However the region of maximum wind speed remains in the western part of the basin (Figure 1.5). The wind flows from the surrounding landmass to the ocean basin, due to the fact that land mass is cooler than Indian Ocean. The position of ITCZ locates at around 10^{o} S during boreal winter. There is no sign of precipitation in the western part of Indian sub-continent (Figure 1.6). However, the Northeast monsoon is the major rainy season for southeastern part of Indian sub-continent (Rajeevan et al., 2012).

The northeasterly winds bring moisture from Bay of Bengal basin towards the southeast coastal region of India and give raise to the rainfall. Spring season (March to May) is characterized by the cyclonic wind flow in the study area (Figure 1.7). The rain belt starts to shift towards north during this season along with the maximum solar insolation (Figure 1.8).

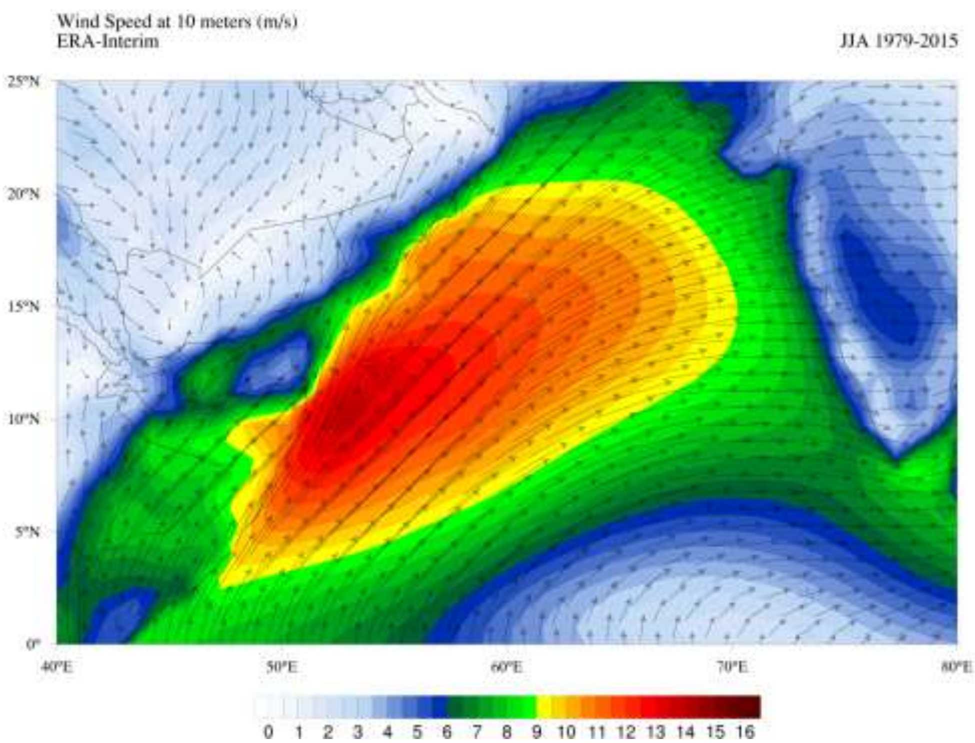

Figure 1.1: Long term average wind speed (m/s) map for summer season (June-August) at 10m above surface. Map prepared using ERA-Interim data (Berrisford et al., 2011) in an online tool called Climate Reanalyzer (http://cci-reanalyzer.org).

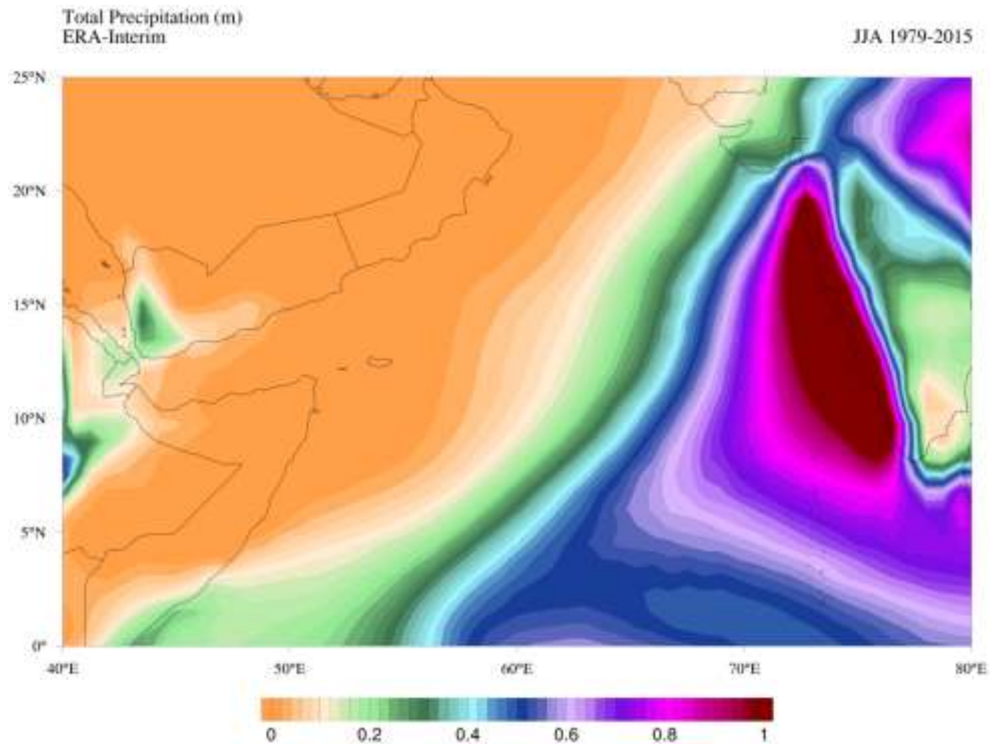

Figure 1.2: Long term average precipitation map (m) for summer season (June-August). Map prepared using ERA-Interim data (Berrisford et al., 2011) in an online tool called Climate Reanalyzer (http://cci-reanalyzer.org).

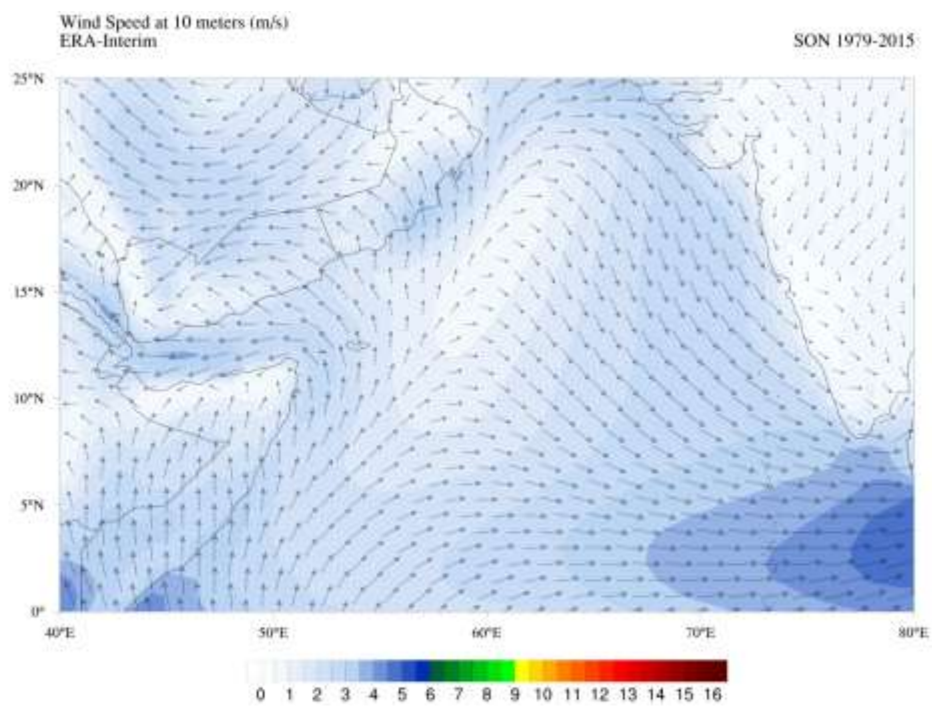

Figure 1.3: Long term average wind speed (m/s) map for autumn season (September-November) at 10m above surface. Map prepared using ERA-Interim data (Berrisford et al., 2011) in an online tool called Climate Reanalyzer (http://cci-reanalyzer.org).

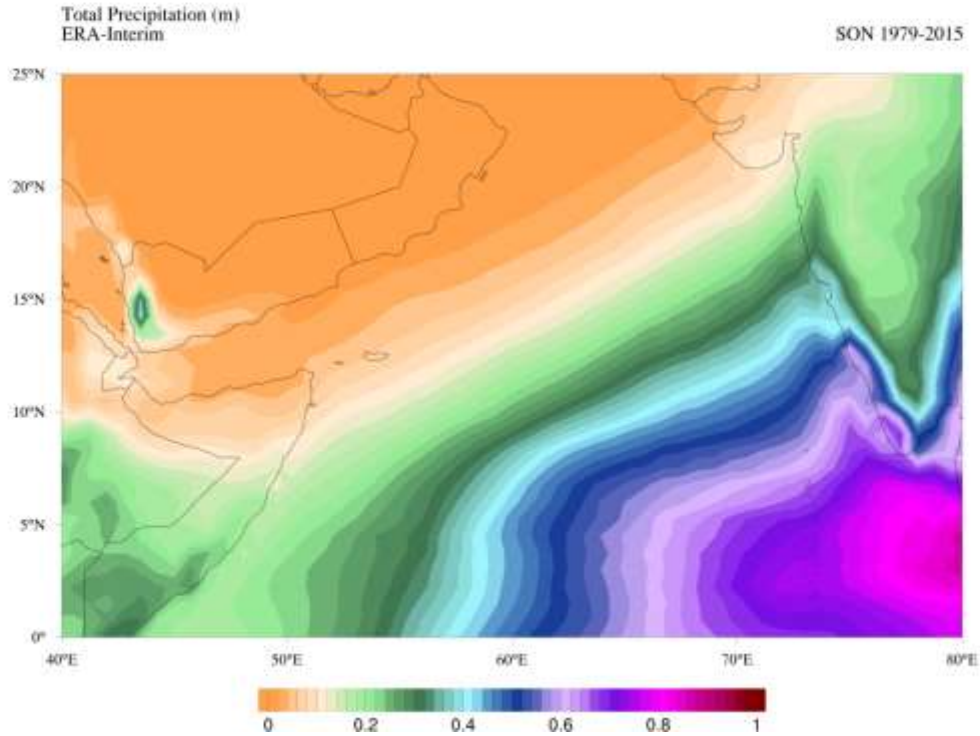

Figure 1.4: Long term average precipitation map (m) for autumn season (September-November). Map prepared using ERA-Interim data (Berrisford et al., 2011) in an online tool called Climate Reanalyzer (http://cci-reanalyzer.org).

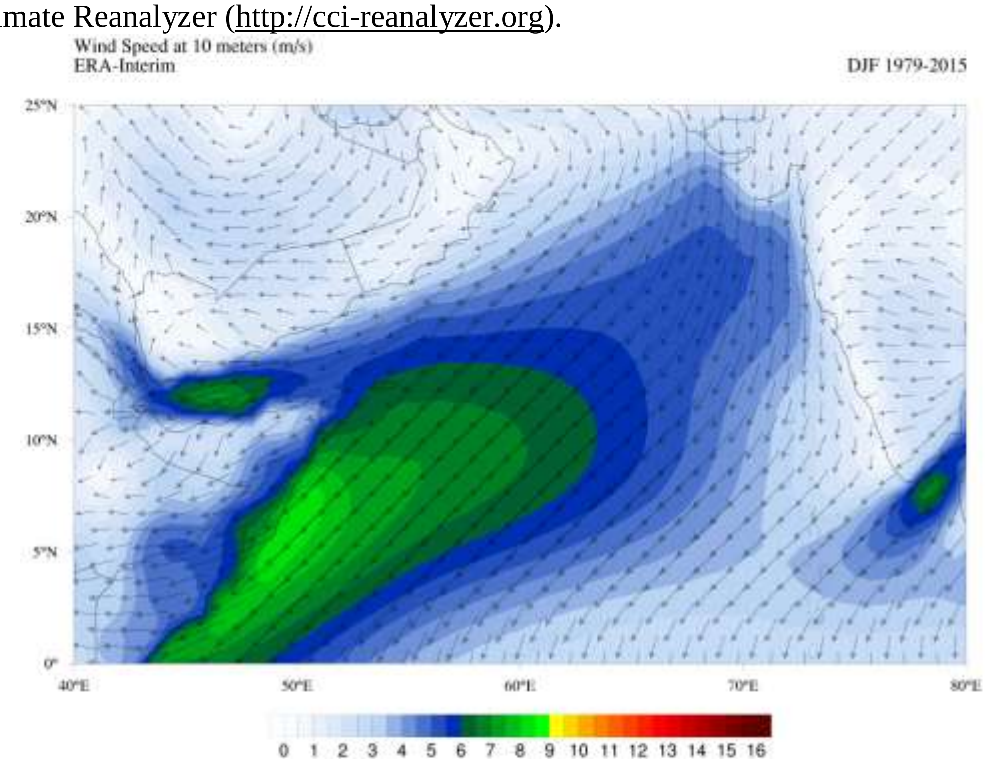

Figure 1.5: Long term average wind speed (m/s) map for winter season (December-February) at 10m above surface. Map prepared using ERA-Interim data (Berrisford et al., 2011) in an online tool called Climate Reanalyzer (http://cci-reanalyzer.org).

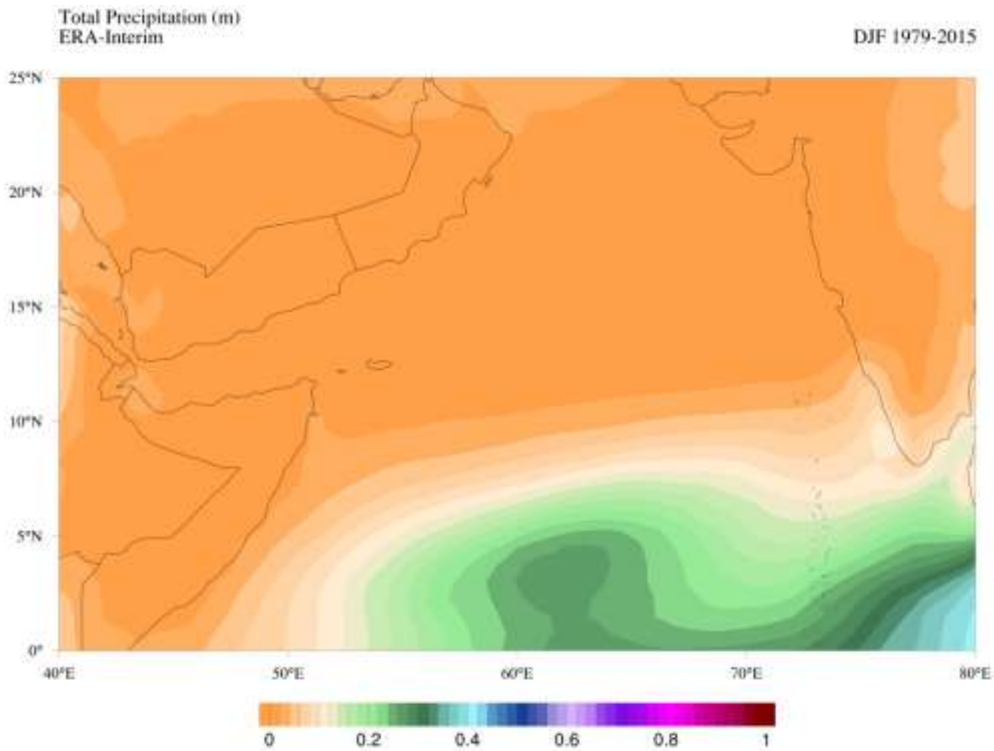

Figure 1.6: Long term average precipitation map (m) for winter season (December-February). Map prepared using ERA-Interim data (Berrisford et al., 2011) in an online tool called Climate Reanalyzer (http://cci-reanalyzer.org).

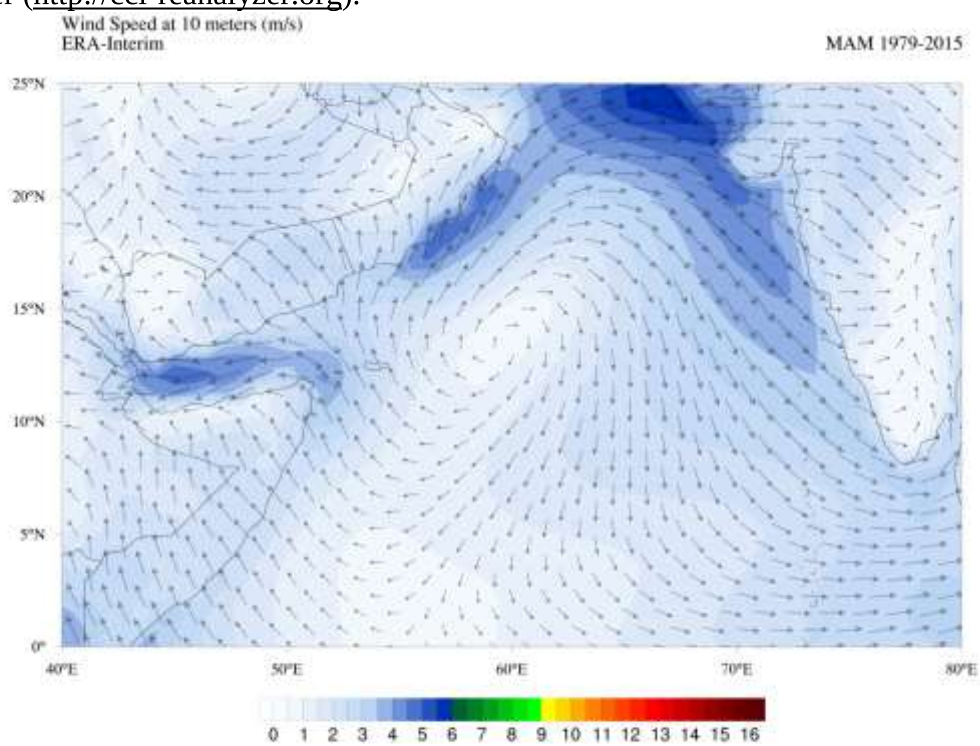

Figure 1.7: Long term average wind speed (m/s) map for spring season (March-May) at 10m above surface. Map prepared using ERA-Interim data (Berrisford et al., 2011) in an online tool called Climate Reanalyzer (http://cci-reanalyzer.org).

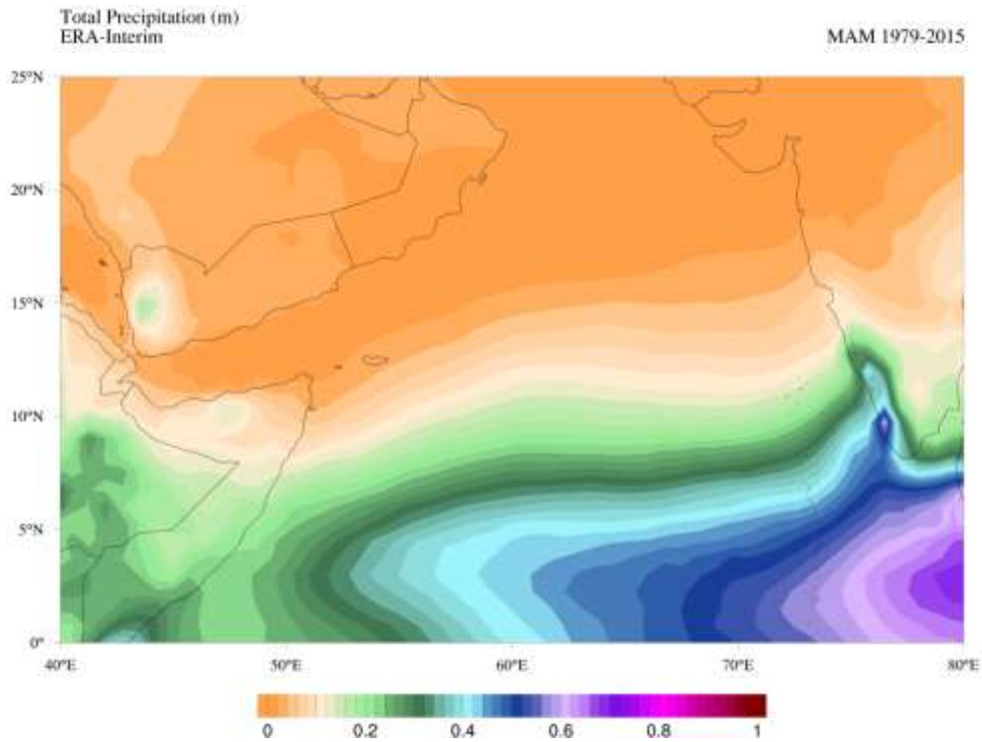

Figure 1.8: Long term average precipitation map (m) for spring season (March-May). Map prepared using ERA-Interim data (Berrisford et al., 2011) in an online tool called Climate Reanalyzer (http://cci-reanalyzer.org).

1.2 Physical Oceanography

The surface water circulation is controlled by changes in atmospheric wind pattern related with annual migration of ITCZ (Wyrtki, 1973). Schott and McCreary, (2001) and Schott et al. (2009) have discussed various processes associated with the seasonal surface circulation of Indian Ocean. During summer, intense southwest winds along the east African coast help to form the Somali current (SC) towards north. The Somali current is generally associated with near shore upwelling and eddies such as southern gyre, great whirl and Soccotra eddy (Schott et al., 1990; Beal and Chereskin, 2003; Schott et al., 2009). These eddies induce intense upwelling which pumps out the low temperature and nutrient rich subsurface water to the surface along the coast of northeast Africa and Arabia (Young and Kindle, 1994). Substantial reduction in SST occurs at the western part of the Basin along Somalia and Oman coast (Figure 1.9) due to upwelling of cold waters. This Somali current pushes surface circulation in clockwise movement. There are minor eddies along the Omani coast that creates Ras al Hadd Jet (RHJ). West Indian coastal current (WICC) is part of the clockwise flows which parallels the west coast of India and flows towards equator. During winter season the SC and WICC were reversed due to the northeast winds. The WICC flows from south to north while SC flows from north to south, producing a counter clock surface circulation over the basin. The northeast winds during winter cools the surface waters on the northeastern part of the basin (Figure 1.10).

1.4 Productivity

Productivity in the Arabian Sea differs between eastern and western part of the basin. Overall the productivity in the Arabian Sea reflects the seasonal changes in surface ocean characteristics (Qasim, 1977; Brock et al., 1991). More than half of the annual productivity in the western Arabian Sea occurs during summer because of intense upwelling (Haake et al., 1993; (Figure 1.9). Observational/model results suggest that the surface productivity in the Central and Northern Arabian Sea during southwest monsoon are caused by horizontal advection of upwelled nutrients from the coastal areas, with a smaller contribution from vertical mixing (Young and Kindle, 1994; Kumar et al., 2001; Kawamiya, 2001; Kone et al., 2009). Low productivity was observed during autumn and spring seasons throughout the basin (Haake et al., 1993). During winter, cold northeast monsoonal winds lower the sea surface temperature in northern Arabian Sea and causes convective mixing (Figure 1.10).

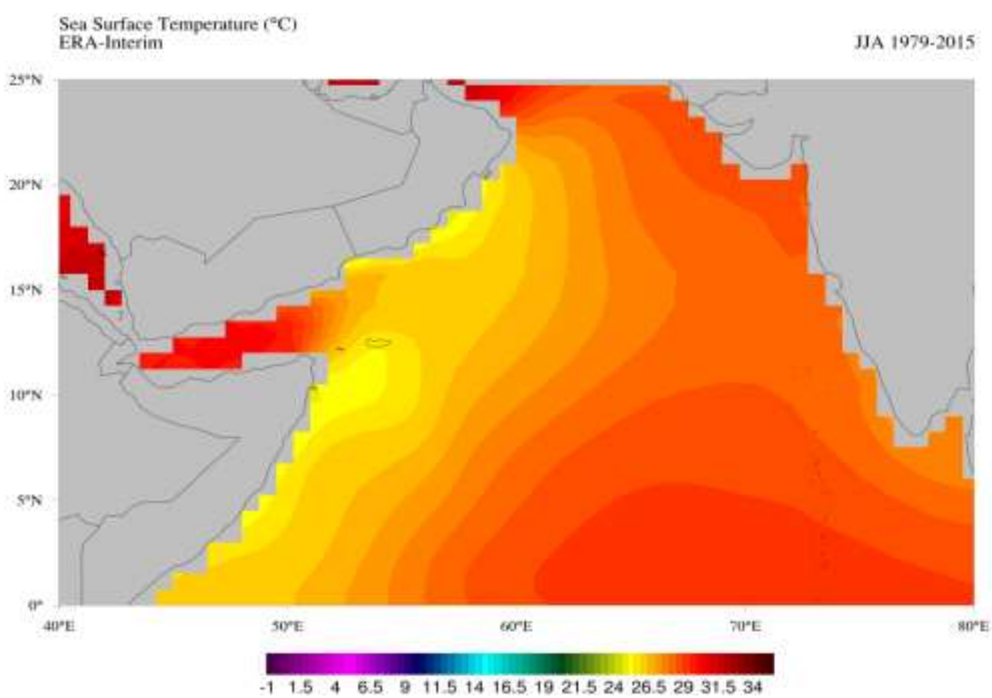

Figure 1.9: Climatological mean SST during the summer season. Note the low SST in the western part of the basin. Map prepared using ERA-Interim data (Berrisford et al., 2011) in an online tool called Climate Reanalyzer (http://cci-reanalyzer.org).

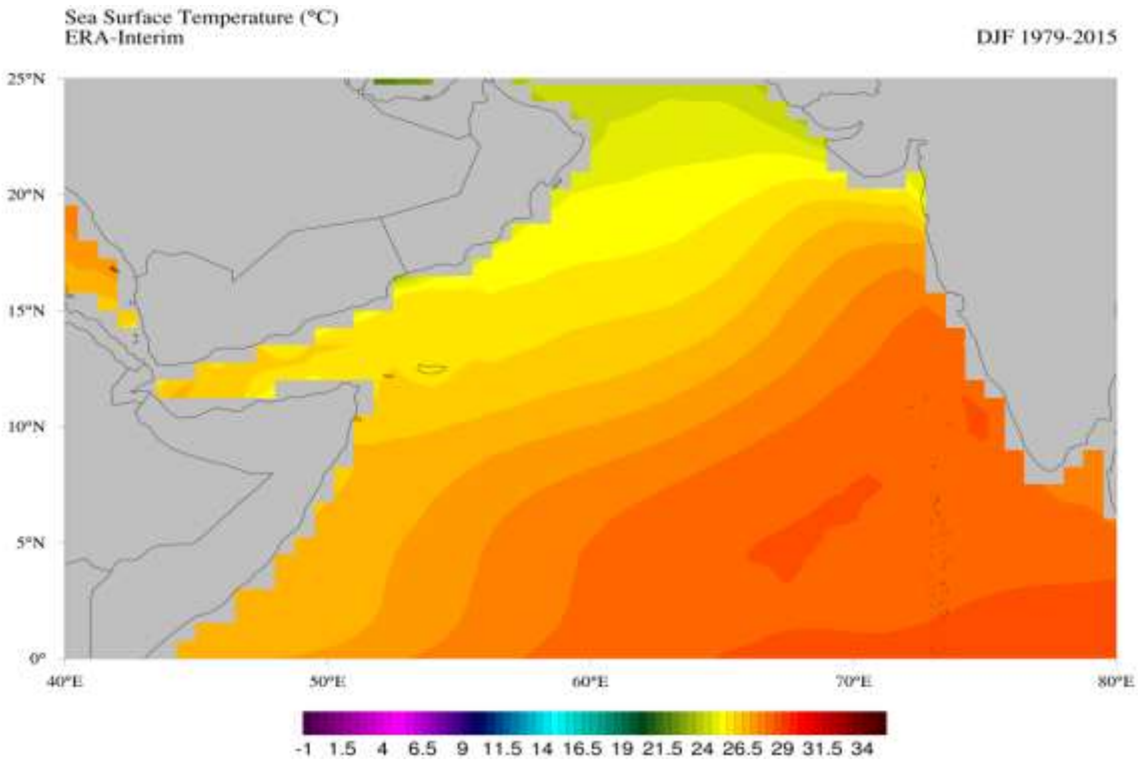

Figure 1.10: Climatological mean SST during the winter season. Note the low SST in Northern arabian sea caused by the wind induced cooling. Map prepared using ERA-Interim data (Berrisford et al., 2011) in an online tool called Climate Reanalyzer (http://cci-reanalyzer.org).

The convective mixing during northeast monsoon period intensifies the vertical entrainment of nutrients to euphotic zone and influences the surface productivity. The northeast monsoon period is the second most productive period in Arabian Sea (Haake et al., 1993).The instrumental observational data of all India rainfall, oceanography and climate are available only for the last century. Therefore past SWM variability are estimated from indirect proxies. Several proxies from marine sediment records have been studied to understand the changes in SWM and its forcing mechanisms (Clemens et al., 1991; Prell et al., 1992; Sirocko et al., 1993; Naidu and Malmgren, 1996; Sirocko et al.1996; Overpeck et al., 1996; Schulz et al., l998; Gupta et al., 2003; Jung et al., 2004; Tiwari et al., 2010). Proxy indicators are prone to be influenced by processes that are not related to changes in the monsoon and/or climate (Clemens and Prell, 2003). Most of the Palaeo-SWM reconstructions since LGM were based on marine sediment cores from the Arabian Sea (Overpeck et al., 1996; Sirocko et al. 1996; Zonneveld et al., 1997; Gupta et al., 2003; Jung et al., 2004; Tiwari et al., 2010; Balaji et al., 2018). However, database spanning the late Quaternary period from Somali upwelling region and open Arabian Sea, which can provide insight into several monsoon-related oceanographic processes, is sparse.

1.5 Research Gaps

Marine records from Arabian Sea have suggested a strengthened southwest monsoon during the Holocene (Sirocko et al., 1993; Sarkar et al., 2000). However the palaeoclimatic records from Indian subcontinent and west coast indicate a weakened southwest monsoon precipitation during the Holocene (Fleitmann et al, 2007; Anand et al., 2008; Govil and Naidu, 2010). A detailed understanding of the palaeoclimatic records is therefore essential.

The Arabian Sea experiences high aeolian dust deposition from surrounding desert regions (Arabian and African deserts). The dust plays a dominant role on climate directly due to influence on nutrient flux and thereby carbon sequestration in the oceans. The effect of dust flux on carbon export flux in the study area has not been explored properly and understood.

The surface productivity in Arabian Sea is modulated by upwelling, lateral advection and convective mixing. Most of the palaeo-productivity records are from the coastal regions of India and Arabia. The knowledge about the palaeo-productivity in open Arabian Sea is very limited and the influence of lateral advection of upwelled waters on the productivity at different time periods needs to be established. Erosion of mountain belts is enforced by the interplay between high frequency climate change and low frequency tectonic activity. Tectonic activity dominant over million year time scale is considered to be the prime cause for Himalayan erosion with climate playing a secondary role. However, recent studies highlight the importance of climate in controlling erosion over shorter time scales. The relation between Himalayan erosion and terrigenous sediment flux to Northern Indian Ocean is yet to be thoroughly understood.

1.6 Objectives

Keeping in view the above research gaps the precise objectives of the study are as follows:

1. To reconstruct the temporal variation of southwest monsoon using upwelling proxy.
2. To understand the past variations in aeolian flux in the Arabian sea and its impact on carbon export flux.
3. To reconstruct the palaeo-productivity variations in the open Arabian sea and to establish the influence of lateral advection on palaeo-productivity.
4. To assess the role of Himalayan climate, Himalayan erosion and sea level on Indus sub marine fan sedimentation.

1.7 Study Area

Northern Indian Ocean is a unique oceanic basin with Indian sub-continent in the middle that divides the Arabian Sea and Bay of Bengal. Uniqueness of this region is that it is mainly influenced by seasonal atmospheric forcing (Tindale and Pease, 1999). Present study is focused on the northwestern Indian Ocean i.e. Arabian Sea. It is surrounded by land from three sides, east, west and north. The present climate of the surrounding land mass is mostly arid except the eastern part.

1.8 Outline of Thesis

- **Chapter 1** Introduction to Indian summer monsoon/Southwest monsoon. A review of previous research work, research gaps and objective of the thesis and the study area is highlighted in this chapter.
- **Chapter 2** Materials and methods used in this study to achieve the objectives and a detailed description of experimental/analytical techniques have been discussed in this chapter.
- **Chapter 3** A discussion on Somali upwelling during the last 18.5 ka B.P. and highlights its relationship with the southwest monsoon precipitation over the Indian sub-continent. This chapter also provides reasoning for the contrasting results between marine and terrestrial records of ISM
- **Chapter 4** A discussion on aeolian flux and carbon export flux in western Arabian Sea and the possible relation between aeolian flux and carbon export flux are presented. Also the role of western Arabian Sea in carbon sequestration during last 18.5 ka B.P. is discussed in this chapter.
- **Chapter 5** Presents a reconstruction of palaeo-productivity from open ocean region of Northern Arabian Sea. The variations in nitrogen isotopic records from coastal and open ocean regions are discussed and possible reasons are presented in this chapter.
- **Chapter 6** Provides a detailed discussion on lithogenic sedimentation in the Indus submarine fan during last 34.6 ka B.P. First order relation between reconstructed sedimentation pattern and sea level changes, Himalayan climate and tectonic changes are discussed in this chapter.
- **Chapter 7** A summary of the results and inferences from this study.