Chapter 2

Study Area: The Arabian Sea

2 STUDY AREA: THE ARABIAN SEA

2.1 INTRODUCTION

The present study was limited to **Arabian Sea** (as shown in Fig 2.1), located in the northwestern part of the Indian Ocean. It has been reported to be one the most productive regions of the world oceans *(Madhupratap et al., 1996)* 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*). Historically, the Arabian Sea has been the principal sea route between Europe and India *(Morgan, 2017).* As a result, it has been extensively explored by the Arab and European travelers, and has been known by different names like the *'Indian Sea', 'Persian Sea', 'Sindhu Sagar', 'Sindh Sea', and 'Erythraean Sea' (Jenott, 2004; Kamat, 2017).* Geographically, it extends in an area of about 1,491,000 square miles (3,862,000 square km). The depth of the sea varies as it joins the Indian Ocean to the south, but it is generally approximated at 8,970 feet *(New World Encyclopedia, 2016).* There are a large number of rivers that drain into the Arabian Sea. These include the Sindhu River that flows through Pakistan and others like Netravathi, Sharavathi, Narmada, Tapti and Mahi, that flows through western coastal states of India.

The uniqueness of Arabian Sea lies in the fact that it is land-locked from three sides, with countries like Iran and Pakistan in the north, Oman, Yemen, and Somalia in the west, and India in the east. Besides, the sea is connected with adjoining water bodies through gulfs; the most prominent among them is the Gulf of Aden in the southwest, which connects it with the Red Sea;

and the Gulf of Oman to the northwest, which connects it with the Persian Gulf. There are also the Gulf of Khambat and Gulf of Kutch on the Indian coast.

Fig. 2.1: Study Area – The Arabian Sea *(Source: Norman Einstein)*

The various aspects and / or themes and / or factors which have been attempted on Arabian Sea are highlighted in Fig 2.2 and are subsequently discussed in the entire subsequent chapter.

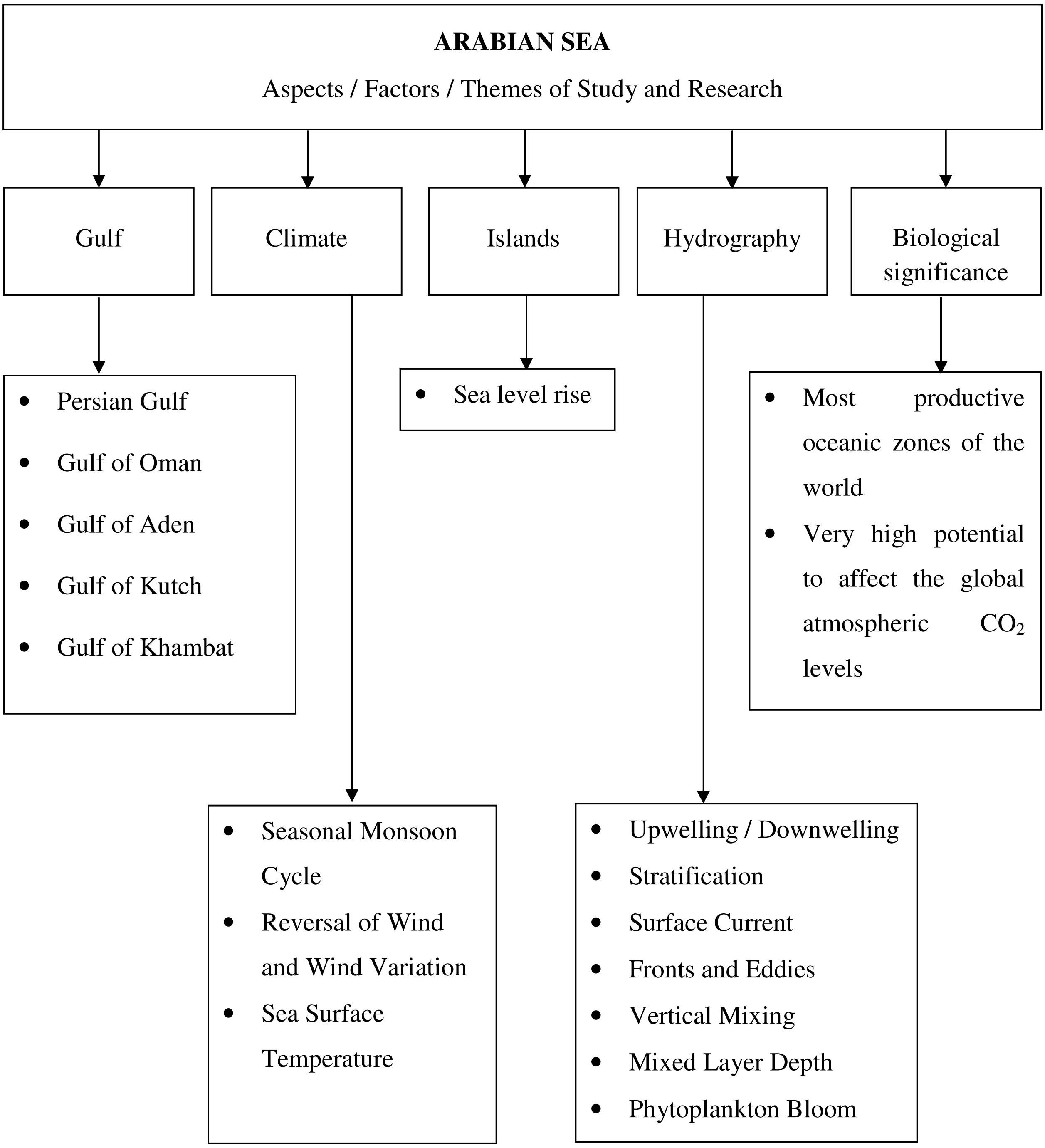

Fig 2.2: Aspects / Factors / Themes of Study and Research over Arabian Sea

2.2 THE GULFS OF THE ARABIAN SEA

The Persian Gulf (24-3° N; 48-56.5° E), is a semi-enclosed shallow, marginal sea with an average water depth of 25 m and a maximum depth of only 90 m. It is spread over an area of 239,000 km^2, and is 990 km in length. It is connected to the Gulf of Oman through the 56 km wide Strait of Hormuz. The effect of the seasonal differences of insolation, along with cold winds from the nearby highlands, results in extreme temperature (ranging from 16 to 35°C) *(Chao et al., 1992),* and salinity (ranging from 36 to 43 ppt) *(Reynolds, 1993)*, in the Persian Gulf. However**,** despite the extreme conditions, the offshore waters of the Persian Gulf are high in nutrient and support a variety of marine photoautotroph like the macro algae, phytoplankton, mangroves, sea grass beds, and intertidal vegetation *(Muzaini & Jacob, 1996).*

The Gulf of Oman (22°3-26°5' N; 56.5-61°43'E) connects the Arabian Sea with the Persian Gulf. It is a strait, connecting the Arabian Sea with the Persian Gulf. The gulf is 320 km wide 560 km long. The most powerful eddy currents of the Arabian Sea are located close to the Omani coast. The coastal areas of the Gulf of Oman support a mixture of habitats including mangrove swamps, lagoons and mudflats.

The Gulf of Aden (10°-15°N; 43°-52° E), which is in the west, connects the Red Sea with the Arabian Sea, via the Bab el-Mandeb (Bāb al-Mandab) Strait. It is about 900 km long, with average depth of 1800 m, and covers an area of about 220×10^3 km^2. Its importance lies in the fact that provides an outlet to the saline water masses of the Red Sea into the Arabian Sea *(Saafani & Shenoi, 2007).*

The Red Sea (12°29′N-27°57′N; 34°36′E-43°30′E) is approximately 2,100 km long and 280 km wide. The Red Sea is a very deep basin with maximum depths around 2740 m and a mean depth near 490 m; its sill depth is about 110 m *(Matthias & Godfrey, 2003).* The Red Sea is linked to the Mediterranean Sea by the Suez Canal in the north whereas in the south, it is connected to the Arabian Sea at through the Gulf of Aden. The waters of the Red Sea are warm and saline. Seasonal surface water temperatures range from 21-28°C in the north to 26-32°C in the south. Salinities in the Red Sea range from 37% in the south to 42% in the north. A consequence of these extreme conditions is that some species within the Red Sea (e.g. mangroves, shallow sea grasses) probably exist at the limits of their physiological tolerance *(PERSGA/GEF, 2002).*

The Gulf of Kutch (22°15'-23°4' N; 68°20'-70°40' E) encloses an area of 7350 km^2. Towards the western end, the Gulf is about 75 km. wide and 60 m deep, while in the eastern end it is 18 km. wide and less than 20 m deep. It is under the influence of strong tidal currents. High rate of evaporation, along with the release of salty water from the adjoining saltpans of Rann of Kutch, makes the eastern part of the Gulf, more saline (40%) than the western part (35%). The temperature of the Gulf waters varies between 24-30°C. The Gulf of Kutch is one of India's only coastal areas endowed with coral reefs. It provides a platform for different habitats like coral reefs, mangroves, creeks, mud flats, islands, rocky shore, sandy shore etc. and hence is enriched in biodiversity *(Dixit et al., 2010)*

Gulf of Khambat (between 72°2' E to 72°6' E and 21-22°2' N), is one of the major fishing areas along western Indian coast. It is about 80 km wide at mouth and tapers to 25 km along the coast. It is about reach of 140 km in length and is characterized by several inlets and creeks formed by the confluence of rivers. The Gulf is shallow with about 30 m average depth and abounds in shoals and sandbanks. It is known for its extreme tides. The tidal range at Gulf of Khambat is the largest along the Indian coastline *(Kumar & Kumar, 2010).*

2.3 THE ISLANDS IN THE ARABIAN SEA

Despite being surrounded by land from three sides, the depth of a major part of Arabian Sea has been reported to be 8,970 feet *(Kumar & Prasad, 1999).* As a result, there is no island in the central Arabian Sea. However, one of the most notable features of Arabian Sea in the Maldive Ridge, along its sea floor, that also runs further south into the Indian Ocean and gives rise to the Maldive Island. The Lakshadweep Islands are a part of the Maldive Ridge. Additionally, several small islands like Socotra and Masirah in the west and the Astola Island is located in the north are known for their unique flora and fauna and are rich productive areas. (*Chisholm, 1911*)

2.4 CLIMATE OF THE ARABIAN SEA

Owing to its unique geographical location, Arabian Sea, a tropical oceanic basin comes under the influence of strong monsoonal winds**.** It is characterized by a regular, seasonal monsoon cycle consisting of the Northeast Monsoon (NEM) from the month of December to March; and the Southwest Monsoon (SWM) from the month June to September. These two monsoonal seasons are interspersed by Summer inter-monsoon (SIM) during April and May, and Autumn inter-monsoon (AIM) during October and November *(Wiggert et al., 2005).* The seasonal reversal of winds is due to temperature and air pressure gradient that exist between land and the Arabian Sea. *(Matthias & Godfrey, 2003)* The Sea Surface Temperature (SST) of the Arabian Sea varies in a typical bimodal pattern with peaks during summer-inter monsoon (SIM) (April-May) and Autumn-inter monsoon (AIM) (October- November). On the other hand, during the Southwest Monsoon (SWM) (June-September) and Northeast monsoon (NEM) (December-March), seasons, there is a cooling that results in decrease in SST *(Rao et al., 1989).*

2.5 HYDROGRAPHY OF THE ARABIAN SEA

The Arabian Sea has been reported to be amongst the most unique tropical basins with a highly complex water mass structure *(Tang et al., 2002).* They are strongly influenced by the seasonal monsoonal winds *(Swallow, 1991)* that not only affect the surface currents but also lead to divergent oceanographic phenomena *(Burkill et al., 1993)* ranging from strong upwelling to stratification *(Yoder et al., 1993)*, to formation of fronts and eddies. Due to the Monsoonal winds, the surface water circulation also undergoes seasonal reversal leading to changes in vertical mixing, upwelling, downwelling phenomena, which not only affect the hydrography of the Arabian Sea but also have strong influence on its biological processes. The monsoonal winds enrich the nutrient input into the euphotic layer of the Sea through upwelling, advection, and changes in mixed-layer depth *(Brink et al., 1998),* which induce phytoplankton bloom *(Schott and McCreary, 2001; Shankar et al., 2002; Murtugudde et al., 2007).*

The Arabian Sea experiences strong southwesterly winds during the Southwest Monsoon (June-September) season which leads to upwelling along the western and eastern coastal areas. In the western coast, the Somali current along the coast of Somalia and Oman has been reported to be the one of the most intense seasonal upwelling systems for any coastal areas of the world *(Smith and Codispoti, 1980; Van Veering et al., 1997; Bakun et.al, 1998).* The Somali current also undergoes seasonal changes under the influence of SWM and NEM. During the SWM, the strong winds move the coastal waters northeastward, creating coastal upwelling. The upwelled water is carried offshore by Ekman transport and merges with the water brought to the surface by open-ocean upwelling. Additionally, parallel to the coast of Somalia, a strong and a steady Findlater jet, with an average wind speed of more than 15m/s, also develops during the Southwest monsoon. The resulting wind stress, caused from the jet lead to upwelling in the northwest and convergence and downwelling in the southeast *(Fischer, 2000).* On the other hand, during the NEM, there is a reversal of the Somali Currents, with cooler air causing the Sea surface temperature to decrease, resulting in cooler and denser water that results in deep mixing, bringing abundant nutrients to the surface.

Additionally, the eastern part of the Arabian Sea, off the south west coast of India, also experiences upwelling which promotes primary productivity *(Naqvi et al., 200).* The upwelling is driven by strong southwest monsoonal winds that displace the surface water with the colder deeper nutrient rich subsurface waters, resulting in increased nutrient levels that sustain distinct floral and faunal groups (*Smitha et al., 2008).*

It has been reported that the western and northern Arabian Sea have a very high primary productivity as compared to eastern or central Arabian Sea during the SWM *(Brock et al., 1991; Brock and McClain, 1992; Ittekkot et al., 1992; Antoine et al.,1996).* Though the intense upwelling in the western Arabian Sea is one of the factors accounting for high productivity, yet it cannot be the only factor responsible for the high productivity *(Sen Gupta and Naqvi, 1984).* Additionally, the other well established methods of nutrient supply to the surface layer include – wind induced deep mixing, open-ocean upwelling driven by Ekman pumping and lateral advection *(Luis and Kawamura, 2004; Wiggert et al., 2005)*, mesoscale eddies *(Fisher et al., 2002)*, and fronts especially the Gulf of Aden front that spreads across the Persian Gulf, separating it from the Arabian Peninsula to the Somali Coast (*Belkin et al., 2009).*

Even during the Northeast Monsoon (NEM) season (December to February), the western and northern Arabian Sea have been reported to be having high productivity, although the wind stress during the season is lesser than SWM *(Veldhuis et al., 1997; Dickey et al., 1998).* However, negative heat flux lead to convective overturning *(Kawamiya and Oschlies, 2003),* and deepening and cooling to a depth of ~ 60 m, which brings up nutrients and results in a wintertime bloom and high productivity.

2.6 BIOLOGICAL SIGNIFICANCE OF THE ARABIAN SEA

The biological significance of Arabian Sea can be well interpreted from that fact that it has been reported to be one of the most productive oceanic zones *(Madhupratap et al., 1996)* of the world, and the occurrence of phytoplankton blooms has been a constant phenomenon over a major region of the northern Arabian Sea. It has been categorized as a class I highly productive ecosystem (with productivity >300 g Cm^{-2} yr^{-1}) amongst the large marine ecosystems of the world *(UNEP Report, 2009).* More than 330 species of corals, 500 species of molluscs, 200 species of crabs, 20 species of marine mammals and more than 1,200 species of fish are found in the Arabian Sea LME *(Fouda et al., 1998).*

The primary productivity of Arabian Sea is strongly influenced by the monsoon regime, which causes significant seasonal variations in marine productivity *(Baars et al., 1998, Desai & Bhargava, 1998).* During the southwest monsoon, strong southwesterly winds blow across the Arabian Sea, producing intense upwelling along the Oman and Somalia coasts. This is the most intense large-scale seasonal coastal upwelling system in the world *(Bakun et al., 1998)*, making the Arabian Sea one of the most productive regions of the world's ocean *(Codispoti, 1991).* In summer, the strong southwest monsoon causes intense upwelling in the western Arabian Sea, while in winter, the surface cooling in the north results in enhanced vertical mixing. In both these cases the photic zone gets nutrients from below which results in high primary productivity *(Madhuparatp et al., 1996)*.

As the phytoplankton productivity drives the oceanic biological pump, it has the potential to affect global atmospheric CO_2 levels *(Sarmiento and Orr, 1991)*. It is in this regard that the Arabian Sea has a global significance being one of the potent sinks for atmospheric CO_2. And any disruption in its seasonal productivity cycle, either by thermal stratification of its water layers due to rising SST, shifts in marine biota including the phytoplankton, or acidification is bound to have a catastrophic effect.

Numerous studies have already been done which highlight the impact of climate change and developmental work being done along the coastal areas of Arabian Sea. The mangrove forest along the Indus Delta, which constitutes the largest arid climate mangrove forest of the world is fast disappearing *(Saifullah, 1997)*. Besides, the impacts are also being shown by the pristine corals, which are getting limited in their occurrence. The large scale coastal developmental work, dredging, land reclamation, overexploitation, pollution and recreational activities *(Pilcher & Alsuhaibany, 2000; Pilcher et al., 2000; Wilson et al., 2002)*, along with rising SST have already caused extensive damage to reefs throughout the Arabian Sea. Bleaching events in 1996 and 1998 led to near-complete mortality of the reefs in Bahrain, Qatar, Saudi Arabia and the United Arab Emirates *(Pilcher et al., 2000)*. The reefs of the Lakshadweep islands were reported to have lost between 43–87% of the live coral cover during the 1998 bleaching event, whereas in the Gulf of Kutch less than 30% of the corals were destroyed *(Pet-Soede et al., 2000)*. Additionally, episodic occurrences of fish-kills in some localities due to occurrence of harmful algal blooms caused by the growing pollution *(Abbani et al., 1990)* have also increased in recent years.

2.7 NEED TO ASSESS THE IMPACT OF CLIMATE CHANGE IN ARABIAN SEA

In today's era of 'global warming', with 0.8°C increase in global temperature in the last century *(IPCC, 2007*), there is a serious threat to the marine ecosystems, *(Behrenfeld et al., 2006; Ji et al., 2007; Halpern et al., 2008)*, with shifting habitats and dwindling marine biota across the world. Arabian Sea, being a one of the large marine ecosystems of the world, with unique and endemic species of corals and mangroves dinoflagellets etc., is also experiencing the impact of climate change which needs to be quantified in terms of change in phytoplankton biomass and their productivity. It is in this regard that the present study was carried out to highlight the changing state of Arabian Sea climatic condition in terms of its rising SST across decades, changing pattern of wind speed and on phytoplankton biomass and the resulting productivity.