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Ecosystem characterisation of Indian coast with special focus on the west coast

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Ecosystem Characterisation of Indian Coast with Special Focus on West Coast

Authors

S. Prasanna Kumar, N. Ramaiah and R.A. Sreepada

CSIR-National Institute of Oceanography (CSIR-NIO)

Dona Paula, Goa-403 004, INDIA

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CREDITS

Name	Affiliation
AUTHORS	
S. Prasanna Kumar	CSIR-National Institute of Oceanography, Goa
N. Ramaiah	CSIR-National Institute of Oceanography, Goa
R.A. Sreepada	CSIR-National Institute of Oceanography, Goa
CO-CONTRIBUTORS	
Priyanka Banerjee	CSIR-National Institute of Oceanography, Goa
Ashwini Pawar	CSIR-National Institute of Oceanography, Goa
Joshua D'Mello	CSIR-National Institute of Oceanography, Goa
Sucharita Chakraborty	CSIR-National Institute of Oceanography, Goa
Sushant Sanaye	CSIR-National Institute of Oceanography, Goa
M. A. Aswini	CSIR-National Institute of Oceanography, Goa
TECHNICAL SUPPORT	
Devanad P. Kavlekar	CSIR-National Institute of Oceanography, Gao
COLLABORATORS	
David Brewer	CSIRO Oceans and Atmosphere Flagship, Australia
Timothy Skewes	CSIRO Oceans and Atmosphere Flagship, Australia
WORKSHOP DELIBERATIONS	
B. Meenakumari	Indian Council of Agriculture Research, New Delhi
B.M. Kurup	Kerala University of Fisheries & Ocean Studies, Kerala
Ajmal Khan	CAS in Marine Biology, Annamalai University, Tamil Nadu
E. Vivekanandan	Central Marine Fisheries Research Institute, Chennai
A.C. Anil	CSIR-National Institute of Oceanography, Goa
V. Ramaswamy	CSIR-National Institute of Oceanography, Goa
K. Sunil Mohamed	Central Marine Fisheries Research Institute, Kochi
M. Dileep Kumar	CSIR-National Institute of Oceanography, Goa
C.K. Murthy	Dept. of Fisheries, Govt. of Karnataka, Bangalore
Chowdula Satya Narayana	Zoological Survey of India, Kolkata
Gangadhara Gowda	College of Fisheries, Mangalore
U.S. Sajeev	Dept. of Fisheries, Govt. of Kerala, Thiruvanthapuram
P.S Rao	CSIR-National Institute of Oceanography, Goa
G. Padmavati	Pondicherry University, Port Blair, Andamans
B.S. Ingole.	CSIR-National Institute of Oceanography, Goa
Sudhir Kumar Das	West Bengal University of Animal and Fishery Sciences
D. Satapathy	College of Fisheries, Rengeilunda, Odisha
Shamila Monteiro	Dept. of Fisheries, Govt. of Goa, Goa
Sachinandan Datta	Reliance Foundation, Mumbai

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FOREWORD

This comprehensive report on "Ecosystem Characterisation of Indian Coast with Special Focus on West Coast" is an outcome of the 'National Experts Workshop on Ecosystem Characterisation of Coastal Waters of India' organised by CSIR-National Institute of Oceanography (CSIR-NIO), Goa, India during 20-22 October 2014 at the behest of the Bay of Bengal Large Marine Ecosystem (BOBLME) supported by the Food and Agricultural Organisation (FAO), Rome. The mandate of this workshop was to come out with a report documenting the review of the ecosystem provinces along the east coast of India delineated during the first ecosystem characterisation workshop organised by BOBLME in Phuket, Thailand, in February 2014, and to demarcate ecosystem provinces along the west coast of India.

While preparing this report, inputs from a large number of national experts from leading government institutions and state fisheries departments, who participated in the workshop, have been taken into consideration in addition to the data and information gathered from the literature by the writing team. This report, being brought out as a result of concerted efforts of my colleagues from CSIR-NIO besides providing in-depth analysis of different provinces along the west coast of India, demarcated during the October 2014 Workshop, also has most relevant information on the ecological assets. This knowledge-base is certain to help not only coastal fisheries and oceanographic research fraternity in the region but also in proactive planning for sustained fisheries resource harnessing and for promulgating policies for conservation of fisheries resources in the region.

I hope that the process that yielded this succinct report will serve as a model for many other regions.

Dr. SWA Naqvi

Director CSIR-NIO

ACKNOWLEDGEMENTS

This Synthesis Report on “Ecosystem Characterisation of Indian Coast with special focus on West Coast” is a culmination of the unstinted facilitation, contribution and a variety of supports from various organisations and experts. We thank them all for helping us accomplishing the requirements and for enabling us to complete this assignment.

The Food and Agricultural Organisation (FAO) provided grants for conducting the National Workshop on Ecosystem Characterisation of Coastal Waters of India. The FAO also provided grants for bringing out this Report. Bangkok based office of the Bay of Bengal Large Marine Ecosystem (BPBLME) coordinated with us for completing the Workshop and Report writing. The Council of Scientific and Industrial Research (CSIR), in particular its International Science and Technology Affairs Directorate (ISTAD) and Planning and Project Directorate (PPD) facilitated with developing and execution of Letter of Agreement between the FAO and CSIR, a mandatory requirement of the FAO. The Indian Council of Agricultural Research (ICAR), Central Marine Fisheries Research Institute (CMFRI), Zoological Survey of India (ZSI), CSIR-National Institute of Oceanography (CSIR-NIO), State Departments of Fisheries from Tamil Nadu, Kerala, Karnataka and Goa provided support by deputing their officers/scientists to be on the Workshop Panel for deliberations and contribution. Universities from West Bengal, Odisha (Berhampur University), Tamil Nadu (Annamalai University), Pondichery (Andaman Campus), Kerala (KUFOS), Karnataka (Karnataka Veterinary, Animal Husbandry and Fisheries Sciences University) and Goa (Goa University) also provided immense support by providing their expert faculties to be in the Workshop Panel. We thank them all for their unstinted support.

Dr S WA Naqvi, Director CSIR-NIO was an inspiration for us in getting this Workshop and the Report accomplished. His strong support is indeed deeply acknowledged. Dr. Chirs O' Brien, Regional Coordinator of BOBLME, Bangkok was instrumental in involving CSIR-NIO by writing the first letter to Director exploring the possibility of holding a National Experts Workshop at Goa and subsequent production of this report. The expert articulations and contextualisation of the Workshop deliberations were handled effectively and in an educative ambience by Drs. David Brewer and Timothy Skewes, FAO Consultants from CSIRO Australia. We thank them all for their kind support.

Constant and proactive guidance as well as timely interventions of Dr. Muraleedharan, BOBLME Office in Bangkok and Mr. K.Venkatasubramanian in the CSIR-PPD, New Delhi helped us to secure the mandatory clearances for the conduct of the Workshop and production of this report in a time bound manner. Mr B Vijayakumar, MoU Desk at CSIR-NIO, Goa helped us immensely with the LoA document. We thank them all and many of our student volunteers and administrative staff who contributed in bringing out this Report.

S Prasanna Kumar, N Ramaiah and R A Sreepada

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ACRONYMS

AS	Arabian Sea
BOBLME	Bay of Bengal Large Marine Ecosystems
BOD	Biochemical Oxygen Demand
CE	Critically Endangered
CF	Contamination Factor
CMFRI	Central Marine Fisheries Research Institute
CSIR	Council of Scientific and Industrial Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DD	Data Deficient
DO	Dissolved Oxygen
EEZ	Exclusive Economic Zone
EICC	East India Coastal Current
EN	Endangered
ENSO	El Niño- Sothern Oscillation
ERL	Effective Range Low
ERM	Effective Range Median
FAO	Food & Agriculture Organisation of the United Nations
FIM	Fall Inter Monsoon
FSI	Fishery Survey of India
GEC	Gujarat Ecology Commission
ICMAM	Integrated Coastal & Marine Area Management
IGBP	International Geosphere-Biosphere Program
IndOBIS	Ocean Biogeographic Information System for assessment & conservation of Indian Ocean biodiversity
IRS	India Remote Sensing Satellite
IUCN	International Union for Conservation of Nature
LC	Least Concern
MPEDA	Marine Products Export Development Authority
NEM	North East Monsoon
NIO	National Institute of Oceanography
NOAA	National Oceanic & Atmospheric Administration
NT	Near Threatened
POM	Post Monsoon
OCM	Ocean Colour Monitor
PrM	Pre Monsoon
SAGE	Center for Sustainability & the Global Environment
SeaWIFS	Sea-Viewing Wide Field-of-View Sensor
SIM	Spring Inter Monsoon
SSH	Sea Surface Height
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SWM	South West Monsoon
VU	Vulnerable
WICC	West India Coastal Current
WRIS	Water Resources Information System
ZSI	Zoological Survey of India

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EXECUTIVE SUMMARY

Bangladesh, India, Indonesia, Malaysia, Maldives, Myanmar, Sri Lanka and Thailand are working together through Bay of Bengal Large Marine Ecosystem (BOBLME) Project to lay foundation for a coordinated programme of action designated for improving the livelihood opportunities of the stakeholders of the region. The first ecosystem characterisation workshop organised by BOBLME was held in Phuket, Thailand in February 2014. Participants from most of BOBLME countries including India attended this Workshop. Although considerable knowledge on the marine environment and resources of the BOBLME region has been gained through this Workshop, it was felt that more information is needed from the east as well as west coasts of India to address the knowledge gaps. In addition, it was also felt that the Indian west coast (Arabian Sea), which was not dealt in Phuket Workshop, should be included as both east and west coasts of India are dynamically linked through circulation and comes under the same monsoonal forcing. In view of the above, a second follow-up Workshop was planned to facilitate an expert-opinion based characterisation and understanding of the ecological systems covering the entire Indian coast to address the knowledge gaps.

With this background, CSIR-National Institute of Oceanography (CSIR-NIO), Goa, India in collaboration with the researchers from CSIRO, Australia organised a 2-Day "National Experts Workshop on Ecosystem characterisation of Coastal waters of India" during 20-22 October, 2014 with the funding from Food & Agriculture Organisation (FAO) through BOBLME Project Bangkok, Thailand. The objectives of the workshop were:

- To conduct an interactive workshop for the Ecosystem characterization of coastal waters of India by pooling together national experts in Fisheries and Oceanography

- Verification of the draft ecosystem characterisation for the east coast of India

- Development of ecosystem characterisation for the west coast of India based on regional ecological/biophysical systems

25 participants from various R&D organisations, academic institutions and departments under Central and State governments involved in fisheries and/or oceanography/marine science research and developmental activities served as National Experts for the Ecosystem Characterisation Workshop. Dr. David Brewer and Dr. Timothy Skewes, Research Scientists from CSIRO, Australia conducted the Workshop. During the 2-Day Workshop, the National experts (i) reviewed the ecosystem provinces of the east coast of India that were demarcated during Phuket Workshop and (ii) deliberated in detail about the ecological characterisation of coastal waters along the west coast of India. The Workshop achieved its set out objectives by collating all the information that was brought to the table during the course of the 2-Day Workshop.

This final report is prepared based on the narratives and the inputs received during the deliberations of the Workshop as well as the information/data gathered from the published literature by the National experts and the writing team. Based on the detailed deliberations on the ecosystem provinces along the east coast of India, the need for a modification in the geographical boundary between NE Indian Shelf/Slope and the Coromandel Shelf/Slope was felt necessary. The main rationale for this modification was to include Krishna and Godavari riverine ecosystems within the NE Indian Shelf/Slope Province. This modification was agreed upon by the National Experts of the Workshop. Accordingly, the boundary between the NE Indian Shelf/Slope and Coromandel Shelf/Slope has been shifted southwards. Included in this report is the verification and adaptation of eleven ecosystem provinces, the national experts adapted through consensus, along the east coast of India which are (1) Ganges Shelf, (2) Ganges Slope, (3) North East (NE) Indian Shelf, (4) North East (NE) Indian Slope, (5) Coromandel Shelf, (6) Coromandel Slope, (7) Sri Lankan Shelf, (8) Sri Lankan Slope, (9) Palk Bay, (10) Gulf of Mannar Shelf, and (11) Gulf of Mannar Slope.

This final report also deals at great details the 5 provinces delineated by the National Experts along the west coast of India based on climatic, geographic, oceanographic, biological and ecological characteristics. These are (1) Kutchch Shelf, (2) Surashtra Shelf, (3) Khambhat Shelf (Inner and Outer), (4) South West Indian Shelf, and (5) West Indian Slope (North-west & South-west).

It is hoped that the vast pool of information provided in this document will be useful for agencies involved in biological resources management, environmental conservation as well as coastal ecosystem health surveillance.

1. Background

Eight countries (Bangladesh, India, Indonesia, Malaysia, Maldives, Myanmar, Sri Lanka and Thailand) connected by the waters and the ecosystem of the Bay of Bengal are working together through Bay of Bengal Large Marine Ecosystem (BOBLME) Project to lay foundation for a coordinated programme of action designated to better the lives of the coastal populations through improved regional management of the Bay of Bengal environment and its fisheries. The BOBLME Project, in collaboration with the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia has initiated a programme on data analysis and interactive workshops with biologists, oceanographers, fisheries scientists and other marine experts to identify and characterise ecosystem provinces within the larger BOBLME. This information is of fundamental importance for executing various activities relating to the management of trans-boundary resources.

The first ecosystem characterisation workshop organised by BOBLME was held in Phuket, Thailand in February, 2014. This workshop focused on the Bay of Bengal was attended by most of the BOBLME countries including India. Though considerable information on its coastal marine environment and resources has been gathered during the Workshop, it was felt that more information is needed along the east coast of India to address the knowledge gaps. In addition, it was also felt that the Indian west coast (Arabian Sea), which was not dealt in Phuket Workshop, should be included as both east and west coasts of India are dynamically linked through circulation and comes under the same monsoonal forcing. In view of the above, a second follow-up Workshop was planned to facilitate an expert-opinion based characterisation and understanding of the ecological systems covering the entire Indian coast to address the knowledge gaps.

Accordingly, a 2-Day "National Experts Workshop on Ecosystem characterisation of Coastal waters of India" was conducted by Council of Scientific and Industrial Research-National Institute of Oceanography (CSIR-NIO), Goa, India in collaboration with CSIRO, Australia during 20-22 October, 2014 with the funding from Food & Agriculture Organisation (FAO) through BOBLME Project Bangkok, Thailand. The objectives of the workshop were:

- To conduct an interactive workshop for the Ecosystem characterisation of coastal waters of India by pooling together national experts in Fisheries and Oceanography.
- Verification of the draft ecosystem characterisation for the east coast of India.
- Development of ecosystem characterisation for the west coast of India based on regional ecological/biophysical systems.

25 participants from various R&D organisations, academic institutions and departments under Central and State governments involved in fisheries and/or oceanography/marine science research and developmental activities served as National Experts for the Ecosystem Characterisation Workshop **(Figure 1).** Dr. David Brewer and Dr. Tim Skewes, Research Scientists from CSIRO, Australia conducted the Workshop. The List of National Experts along with their contact details have been annexed to this Report (**Annexure I**).

The Workshop achieved its set out objectives by collating all the information that was brought to the table during the course of the 2-Day Workshop as well as the information gathered by the National experts and the writing team. During the 2-Day Workshop, the National experts (i) reviewed the ecosystem provinces of the east

Figure 1: Participants of National Experts Workshop held at Goa during 20-22 October, 2014.

coast of India that were demarcated during Phuket Workshop and (ii) deliberated in detail about the ecological characterisation of coastal waters along the west coast of India.

2. Review of Ecosystem Characterisation of Indian Coastal Waters: East Coast of India

The National experts intensely deliberated on the classification of Provinces along the east coast of India based on the regional oceanography, climate setting, riverine systems, biology, fishery and biogeochemical attributes. It was noted that though the physical driver (monsoon) which is common for the entire Indian coast, the responses of the coastal waters of east and west coasts are different. For example, the East India Coastal Current (EICC) flowing pole-ward during spring-summer and towards equator during fall-winter seasons **(Figure 2)** (See Shankar *et al.,* 2002 for details on EICC and circulation) carries along with it low salinity waters of the Bay of Bengal origin and high salinity waters of the Arabian Sea origin respectively. The resulting biological **(Figure 3)** and ecological characteristics of the Bay of Bengal and the Arabian Sea are quite different (see Prasanna Kumar *et al*., 2009 for details on chlorophyll and primary productivity).

The east coast of India sustains relatively rich biodiversity and the 3 important ecosystems along this coast are mangroves, corals, and seagrass. The frequency of occurrence of harmful algal blooms has been reported to be relatively much smaller compared to their global occurrence. On the fisheries front, it was noted that the emergence of large shoals of sardines along the east coast is a recent phenomenon.

A wide variation in the tidal range from micro-tide in the south to macro-tide in the northern shelf of the east coast of India could serve as a parameter for characterisation of the coast.

Another criterion could be the of depth changes such as shelf and slope regions. After an engaging and intense debate over the zonation of east coast of India, it was finally agreed upon that the east coast can be divided into six provinces, such as Ganges Shelf, Ganges Slope, NE Indian Shelf and NE Indian Slope, and Coromandel Shelf and Coromandal Slope. This zonation was based on the geological/geomorphic characteristics such as continental shelf, shelf break and orientation of the coast. In addition, 5 more Provinces (Sri Lankan Shelf, Sri Lankan Slope, Palk Bay, , Gulf of Mannar Shelf, Gulf Mannar Slope) were also

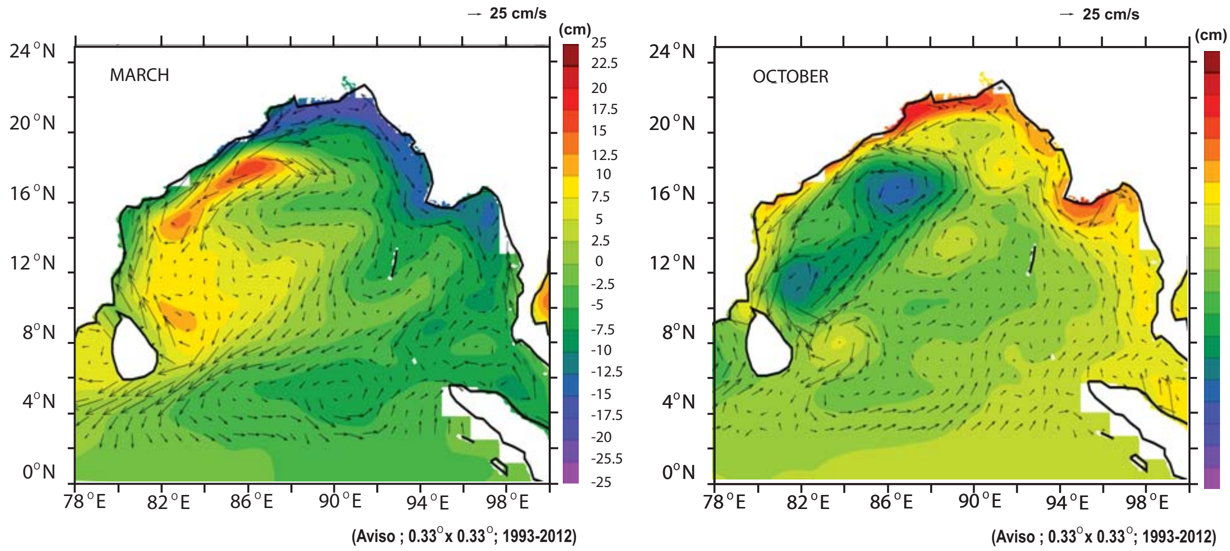

Figure 2: Surface circulations in the Bay of Bengal based on monthly mean climatology of sea level anomaly during the period 1993 to 2012 depicting the seasonal East India Coastal Current (EICC) flowing northward (Left Panel) along the western boundary during spring-summer and soutward (Right Panel) during fall-winter periods (Prasanna Kumar and Narvekar, 2015, Bay of Bengal circulation, unpublished manuscript).

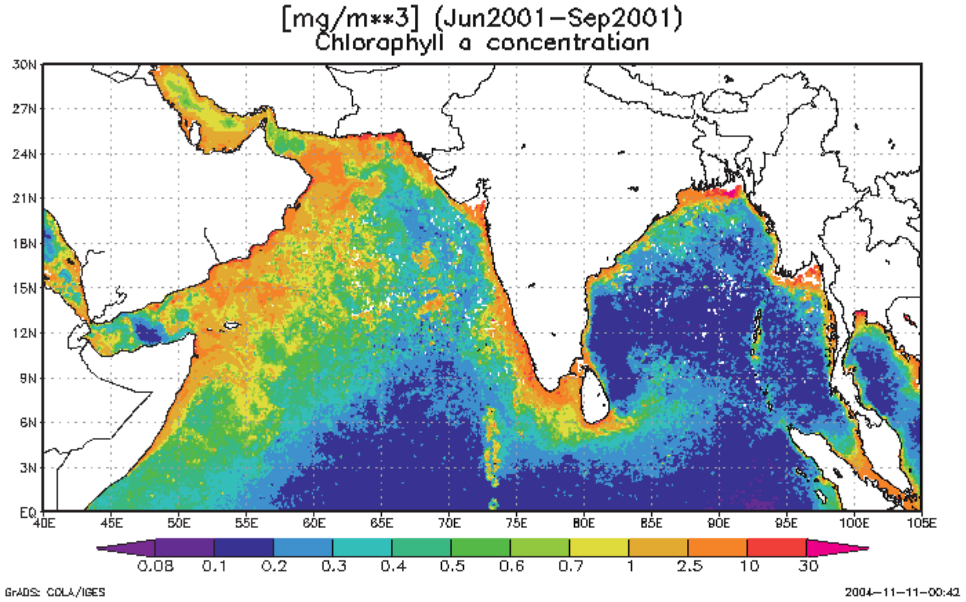

Figure 3: Spatial distribution of chlorophyll pigment concentration (mg/m^3) obtained from SeaWiFS (Map generated from NASA's Giovani http:// reason.gsfc.nasangov/ OPS/Giovanni/ocean.seawifs.2.shtml).

demarcated based on drivers such as depth and ecological biodiversity attributes. However, originally identified boundaries of provinces were not altered in this Workshop.

2.1. A modification in the province along the Coromandel Coast

Based on the detailed deliberations, the need for a modification in the geographical boundary between NE Indian Shelf/Slope and the Coromandel Shelf/Slope (see **Figure 4** for old boundary) was felt necessary. The main rationale for this modification is to include Krishna and Godavari riverine ecosystems within the NE Indian Shelf/Slope Province.

This modification was agreed upon by the National Experts of the Workshop. Accordingly, the boundary between the NE Indian Shelf/Slope and Coromandel Shelf/Slope has been shifted southwards **(Figure 5)**.

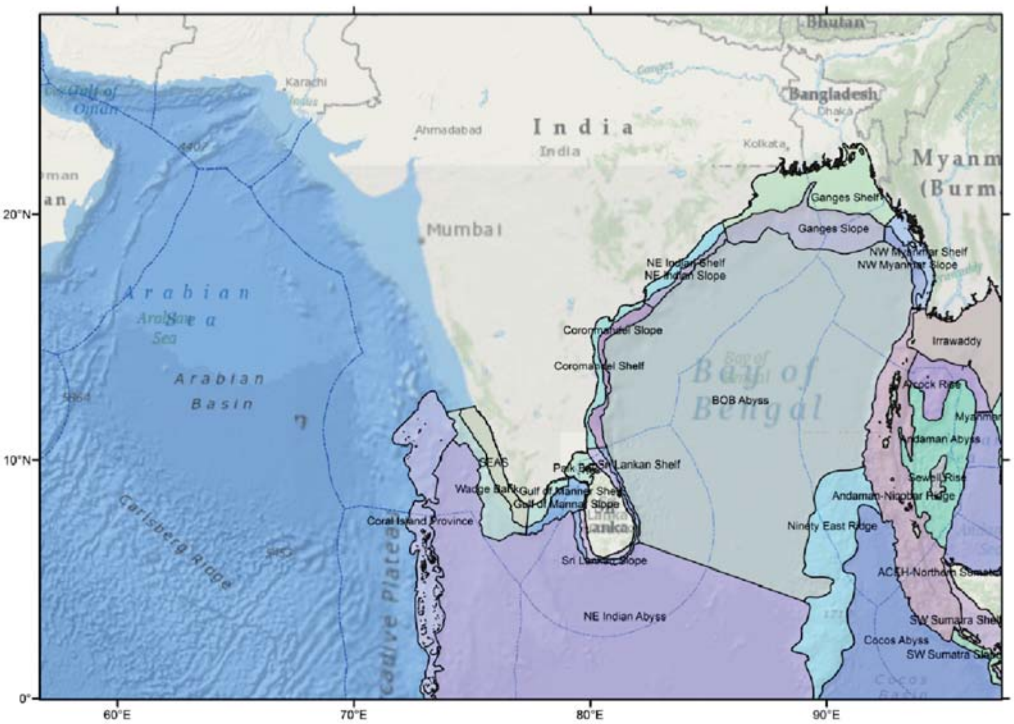

Figure 4: Old boundaries between Coromandel and NE Indian Shelf/Slope (Courtesy: David Brewer)

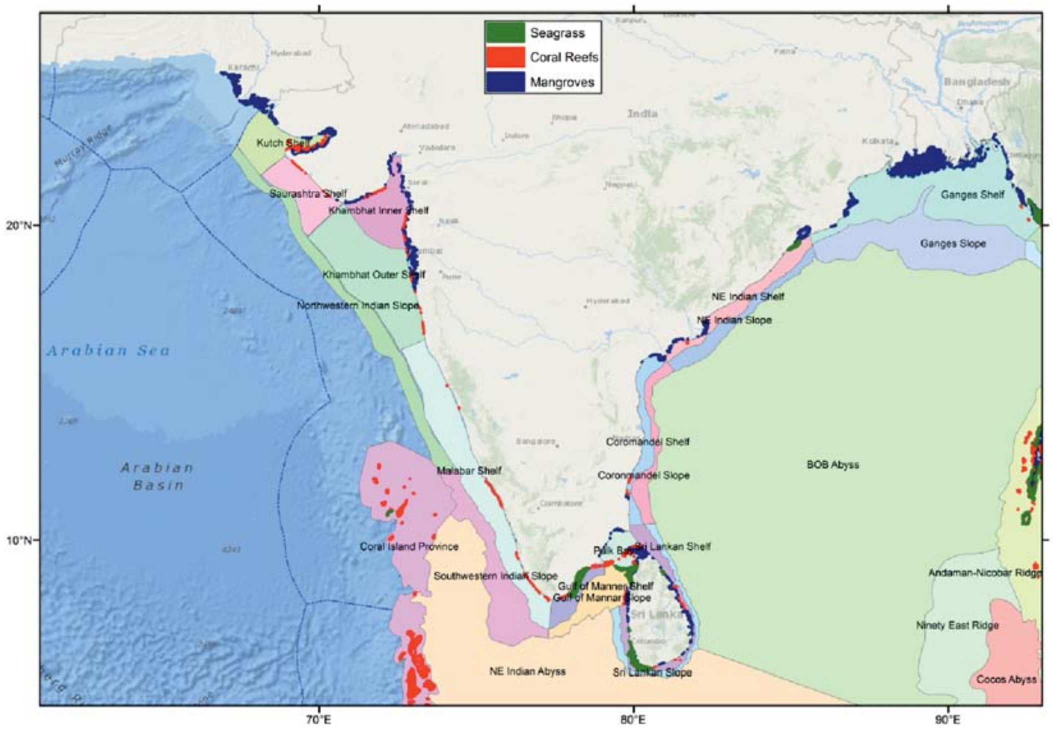

Figure 5: New boundaries between Coromandel and NE Indian Shelf/Slope (Courtesy: David Brewer)

2.2. Final demarcation of ecosystem provinces along the east coast of India

Through consensus, the workshop adapted 11 Ecosystem Provinces along the east coast of India which are listed below and presented in **Figure 5**:

1. Ganges Shelf
2. Ganges Slope
3. North East (NE) Indian Shelf
4. North East (NE) Indian Slope
5. Coromandel Shelf
6. Coromandel Slope
7. Sri Lankan Shelf
8. Sri Lankan Slope
9. Palk Bay
10. Gulf of Mannar Shelf
11. Gulf of Mannar Slope

A detailed account on the basis for delineating the above provinces has been described in the draft report entitled "An ecosystem characterisation of the Bay of Bengal" prepared by CSIRO, Australia (CSIRO, 2014).

3. Ecosystem Characterisation of indian Coastal Waters : West Coast of India

The west coast of India (and the adjoining continental shelf/slope) bordering the eastern Arabian Sea (AS), lies between latitudes 7°N and 25°N. The total length of the coastline is 3010 km (Sanil Kumar *et al.*, 2006). The coastal plain encompassing the states of Kerala, Karnataka, Goa and Maharashtra is narrow with the Western Ghats, rising to an elevation of about 500 m within a distance of 10 to 80 km from the coastline. The plain, however, broadens out and flattens north of 18°N within the state of Gujarat with its large portion of the coastal plain lying within a few metres above the sea level. The continental shelf fringing the coastal plains is narrow in the south (~60 km) and becomes wide to the north (~340 km) except along the Saurashtra coast. The continental slope, on the contrary, widens towards the south (Biswas, 1989). The entire region is a heterogeneous mosaic of different landform features associated with the evolution of the western continental margin of India. The main provinces that have been adapted based on shelf and slope classifications for west coast are presented in **Table 1** and depicted in **Figure 6**.

The following sections of this document describe the general geographical setting of shelf and slope regions along the west coast of India. Furthermore, a detailed description on geomorphology, climate and oceanography,

Table 1: Main provinces along the West coast of India adapted during the Ecosystem Characterisation Workshop held at Goa, India during 20-22 October, 2014.

Sr. No.	Province	Latitude	Average Shelf width
1	Kutchch Shelf	22°N 24.7°N	180 km
2	Saurashtra Shelf	20.5°N-22°N	70-110 km
3	Khambhat Shelf*	16°N- 20.5°N	128-345 km
4	South West Indian Shelf	8°N-16°N	-
5	West Indian Slope**	-	-

* Inner and Outer ** North-west and South-west.

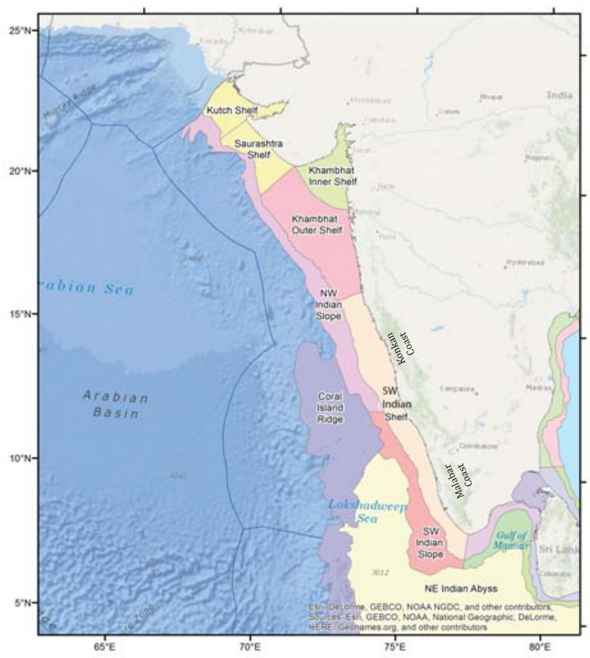

Figure 6: Delineation of five provinces with key ecological features along the West coast of India during the National Experts Workshop (20-22 October, 2014) (Courtesy: David Brewer).

ecological characteristics, fish and fisheries for each of the 5 ecological Provinces has been highlighted.

3.1. General Geographical Setting

3.1.1. Geomorphology

The western continental margin of India is regarded as a volcanic passive continental margin (Corfield *et al*., 2010). The present configuration and the geomorphologic characteristics of the margin is primarily as a result of the breaking-up of the supercontinent Gondwanaland and the volcanic activity related to Reunion hotspot, sea-floor spreading along Carlsberg Ridge and Indo-European continental collision (Norton and Schlater, 1979). The high input of riverine sediments has further modified the basic features of the shelf and slope regions.

The west coast of India is bordered by the Western Ghats to the west that run parallel to the coast for about 1600 km **(Figure 7)**. The Western Ghats (known as Sahyadris) are basaltic provinces that have a scarp-face facing the west and slopes towards the east. They stretch from Tapi River to Cape Comorin. The Nilgiri Hills is the confluence zone of the Eastern and the Western Ghats. Anamudi Peak (2695 m), in the Annamalai Hills, lying south of the Nilgiri hills is the highest point of the Western Ghats. There are several gaps or passes in the Ghats that act as corridors of the western coastal plain to Deccan Province. These are Palghat Gap in Kerala, Thal Ghat Gap in between Mumbai-Nasik and Bhor Ghat Gap between Mumbai-Pune. Southern part of the Palghat Gap is known as the Southern Ghats.

The west coastal plain nested between the Western Ghats and the Arabian Sea is mainly rocky in nature along with the presence of sandy beaches, coastal and sand dunes, mud-flats, lagoons, alluvial tracts along rivers, estuaries alternating with promontories jutting out at irregular intervals **(Figure 8).** The numerous small rivers do not form any delta due to the high-energy conditions. The tidal range varies remarkably between 1 m (southern tip) and 11 m (north).

The outer margin of western continental shelf of India is generally considered to be limited by the 200 m isobath with the shelf break running nearly parallel to the 200 m isobath (Rao and Wagle, 1997). The rifted Indian Shelf is bordered

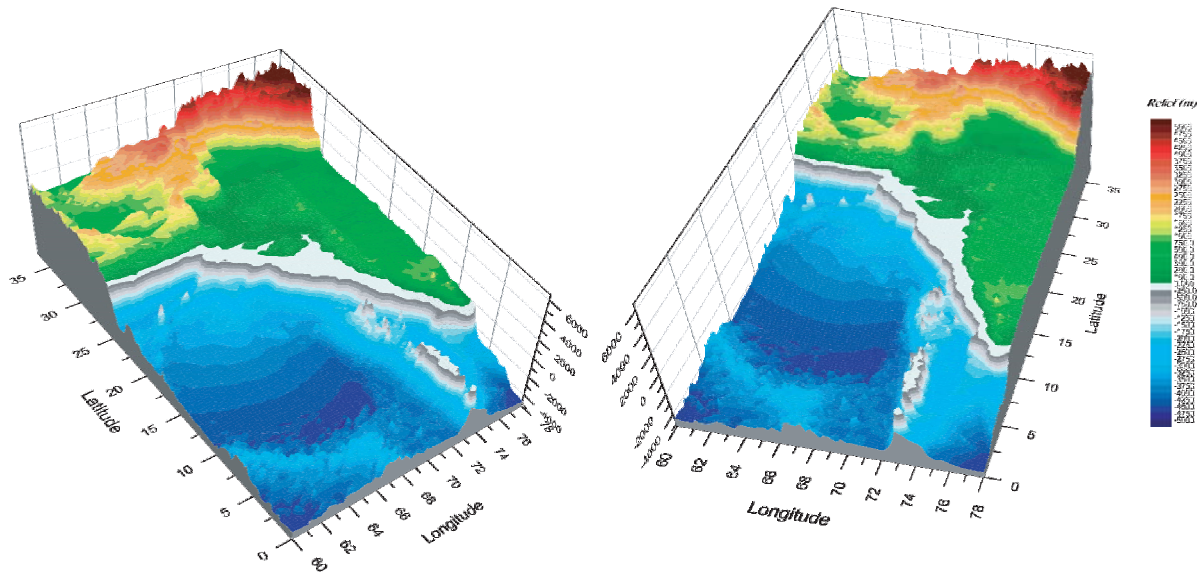

Figure 7: Main relief features of the western continental margin of India and the Indian landmass generated from ETOPO05.

Figure 8: Map depicting the most significant coastal features along the West coast of India (modified from Mukhopadhyay and Karisiddaiah, 2014). The continuous red line indicates 200 m height contour and the dashed red line shows the 200 m depth isobaths. The main features are: A-Archipelago; B-Beach; BR-Beach/Dune ridges; BW-Backwater; C-Cliff; CR-Coral reef; E-Estuary; M- Mangrove; MR- Marshland.

offshore by the Kori-Comorin Rige and the Kori-Comorin Depression (Biswas, 2014). The inner shelf is characterised by smooth topography with a gradient of 1:800. Average depth in the inner shelf varies between 25 m (south) and 60 m (north). Several buried paleo-channels and wave-cut terraces have been reported between the shelves off Daman and off Goa and their probable formation could be date back to the period of lower sea-levels in the Late Pleistocene.

considerably. Sediments from the Indus fan can be seen even southward of 10°N. Maximum sediment depth (exceeding 7 km) is seen northward of the Gulf of Khambhat **(Figure 9)**. In general, the inner shelf is predominantly matted with clayey sediments, while the outer shelf is composed of sandy sediments. The sediments of continental slope are composed of a mixture of terrigenous clay and carbonates **(Figure 9)** (Kessarkar *et al.*, 2003).

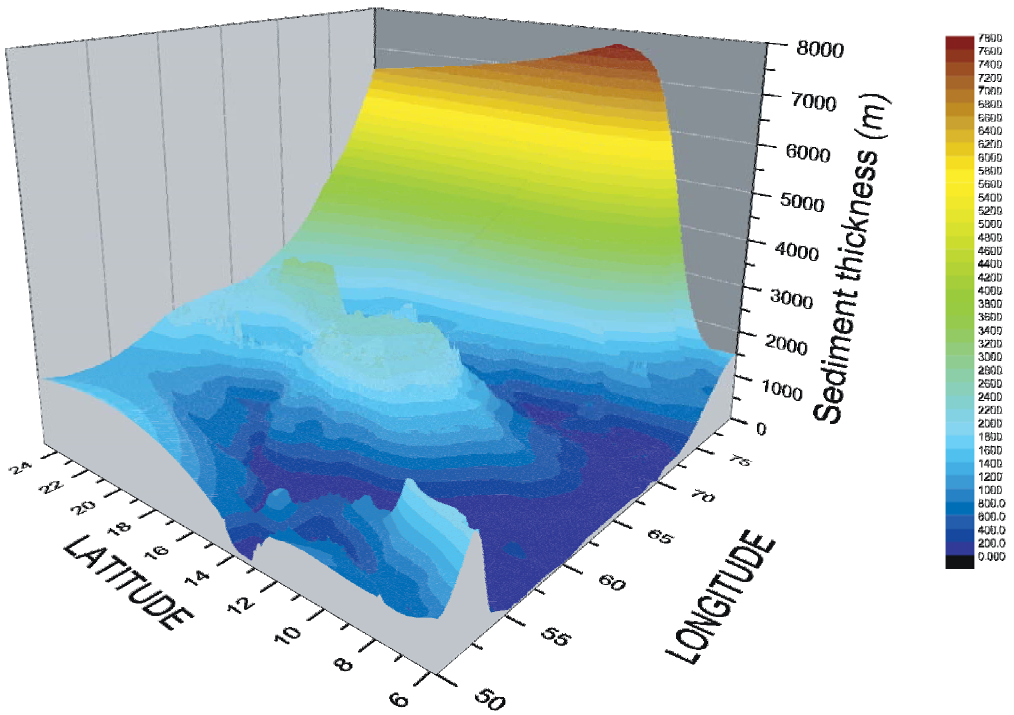

Figure 9: Thickness of sediment (in m) along the western continental margin of India generated by data obtained from NOAA National Geophysical Data Center (Divins, 2003; Geli *et al.*, 2007). Note the Indus Fan between longitudes, 65-70°E and extending up to 8°N.

The outer shelf is uneven dotted with erosional remnants of relict bars having relative relief between 2 and 20 m. A series of submarine terraces parallel to the coast have been formed at depths ranging from 55 to 115 m within latitudes, 11°N to 20°N. These are attributed to coral reef growth and changes in sea-level and wave activity during the Late Quaternary. The continental slope to the north bears testimony to the volcanic activity that led to the formation of the Deccan Trap (Rao and Wagle, 1997).

However, the high input of sediments from the Indus River has altered the slope morphology,

There are series of horsts and grabens formed by faulting that characterise the basement trend of the continental shelf. These are controlled by the 3 main Precambrian orogenic trends over peninsular India (**Figure 10**, left) (Biswas, 1987): (i) The north-south Dharwarian trend running offshore from Kerala to Mumbai, (ii) the east-west Satpura trend from the Gulf of Khambhat dividing India into southern Peninsular block and the northern foreland and (iii) the north-east to south-west Aravali-Delhi trend in the Kutchch-Saurashtra region. There are several sedimentary basins in the shelf region. From north to south these are: Kutchch Offshore Basin, Cambay Basin

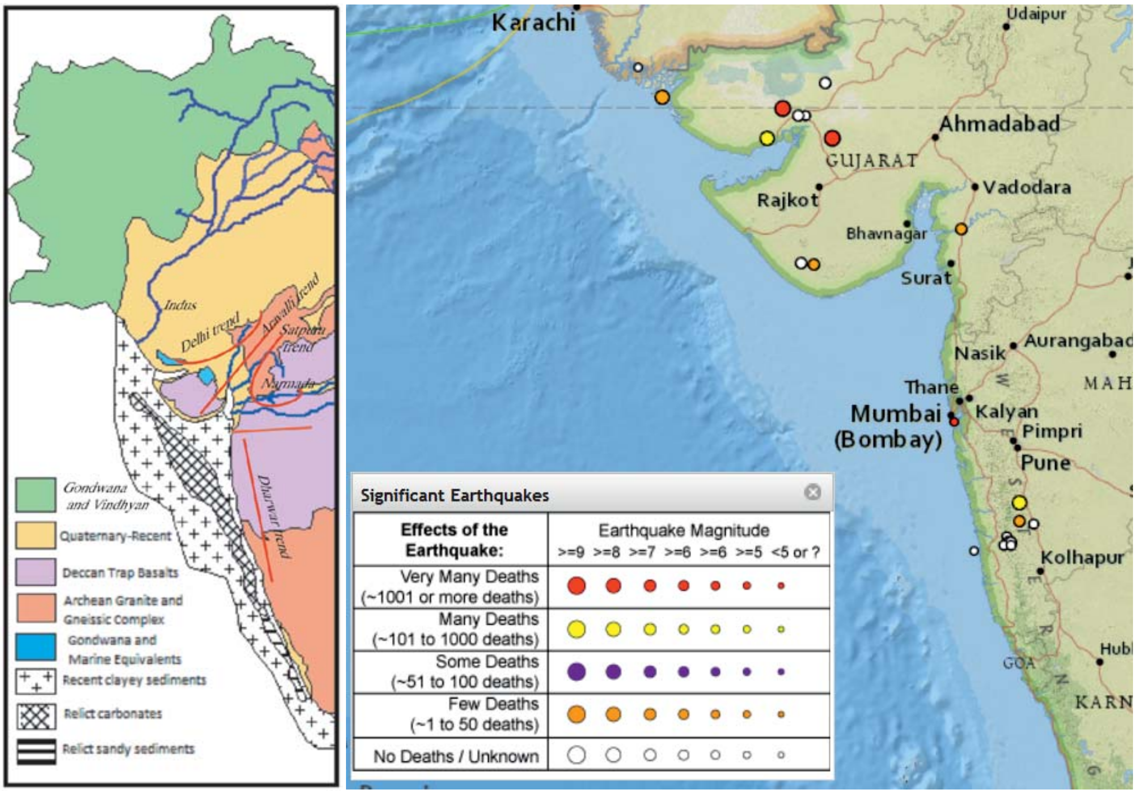

Figure 10: Main geological provinces of the western part of the Indian mainland (left). The fill colors reflect the main rock types (simplified from Geological Survey of India maps) and the symbols indicate the main types of sediments on the continental shelf and slope off the west coast of India (obtained from Kessarkar *et al.*, 2003). The red lines indicate the main structural trends (simplified from Biswas, 1987) and the blue lines are the rivers (right). Map showing locations where earthquakes occurred around west coast of India (obtained from http://www.ngdc.noaa.gov/hazard/earthqk. shtml).

(Khambhat Basin), Saurashtra Basin, Surat Basin, Bombay Offshore Basin (referred together as Northern Basins), the Konkan Basin and the Kerala Basin (Campanile *et al.*, 2008). Most of the earthquakes tend occur near Kutchch and Saurashta regions as they are near the boundary of the Indian plate (**Figure 10**, right). The Makran subduction zone's large earthquakes have generated destructive tsunamis in the past (Berninghausen, 1969). Tsunamigenic waves can occur along the major faults in the east Makran region as well as the western end of the subduction zone. The continental slopes have become unstable due to extensive sedimentation by major rivers. Thick sediments can also trigger tsunami when an earthquake causes the sediments to slide underwater.

3.1.2. Drainage

Due to the eastward slope of the land, most of the major peninsular rivers have their origin in the Western Ghats and drain into the Bay of Bengal. Smaller rivers that cut across the hilly terrain of the Westen Ghats drain into the Arabian Sea. The Indus is the largest river draining into the Arabian Sea. The other two principal rivers are Narmada and Tapi (see **Figure 11**). Except Indus, all other rivers are seasonal and rain-fed. The construction of dams across these rivers has considerably reduced the freshwater discharge as well as sediment input to the coastal and open Arabian Sea.

3.2. Climatology and Oceanography

The Arabian Sea experiences a monsoonal type of climate with a change in the wind pattern and ocean circulation semi-annually (Wyrtki 1973; Schott *et al.*, 2009). There is an upwelling phenomenon along the south-west tip of India in summer (Wyrtki, 1973). Upwelling zones from Cochin to Karwar have also been reported during the south-west monsoon season (Varadachari and Sharma, 1967). The monsoonal winds are stronger from June to September bringing along a lot of precipitation. The monsoonal winds have a

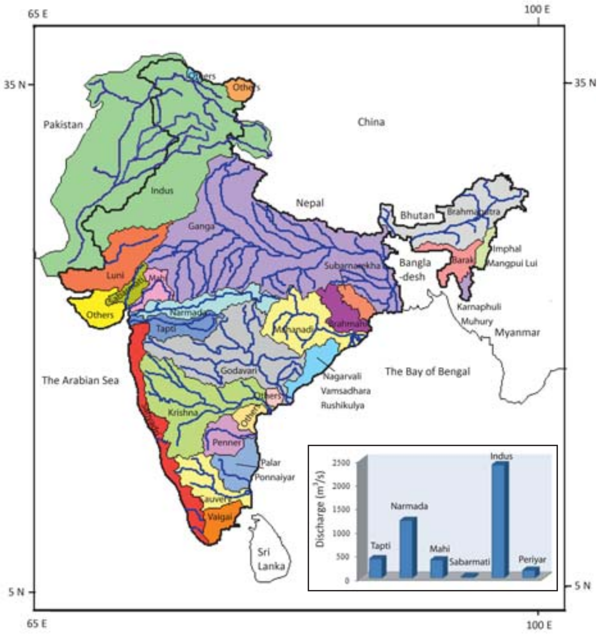

Figure 11: Principal rivers and the drainage basins of India (obtained from Water Resources Information System, WRIS). The right-bottom corner inset shows the average annual discharge of the main rivers that drain into the Arabian Sea (data from www.sage.wisc.edu).

strong narrow, low-level jet which develops in summer. This jet is known as the 'Findlater jet' (Findlater 1969; 1974) blowing from Arabia towards the Gujarat coast. To the north-west of the jet axis, the wind-stress curl is positive and causes open-ocean upwelling, while to the south-east of the jet axis, the wind-stress curl is negative and causes convergence and downwelling. During winter, the cold and dry winds from Asian landmass blow over the Arabian Sea (Tomczak and Godfrey, 1994). There is a loss of surface heat from the ocean due to reduced incoming solar radiation (Schott *et al.*, 2009) as well as heat loss due to enhanced evaporative cooling (Prasanna Kumar and Prasad, 1996). This causes surface densification and subsequent sinking of denser waters drives the convection that brings sub-surface nutrient rich waters to the surface. This process has profound impacts on the productivity (Madhupratap *et al.*, 1996). The two prominent modes of climate variability impacting the Indian Ocean are the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (Saji *et al.*, 1999; Webster *et al.*, 1999).

3.2.1. Air Temperature

The climatology of the air temperature (averaged over the west coast shelf and slope region), is shown in **Figure 12**. The air temperature has a bimodal distribution with peak in March and September, while the coldest temperature has been recorded in January followed by July.

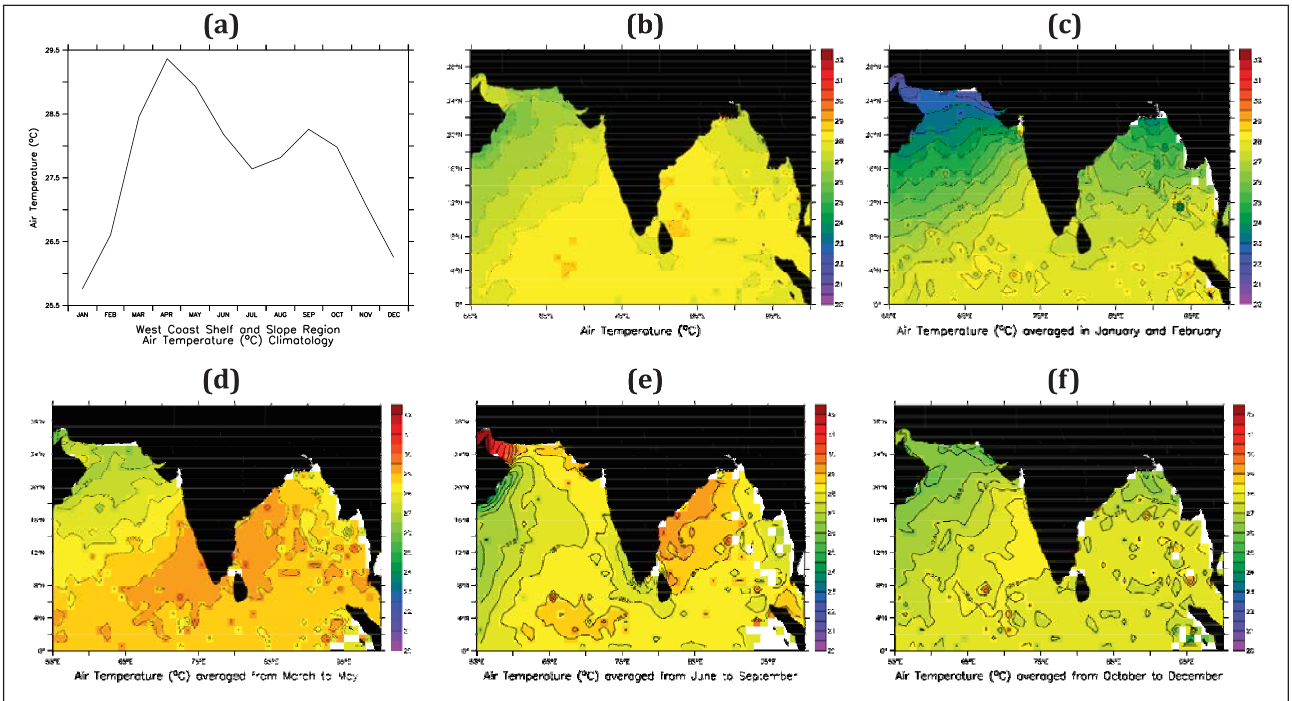

Figure 12: Seasonal cycle of monthly mean air temperature (°C) climatology (1960 to 2012) (a) averaged over the shelf-slope regions of the west coast of India, (b) climatological annual mean, (c) for January and February, (d) for March to May, (e) for June to September, and (f) for October to December.

The air temperature along the west coast of India varies latitudinally with the least in the Kutchch region (26.5 °C) and increased southwards along the coast, having a value of around 28°C along the Malabar coast. Seasonally, the air temperatures are the lowest in winter, with Kutchch and Malabar coasts (southern part of the west coast) recording values of 23°C and 28°C, respectively. The air temperatures from March to May are the highest among the seasons.

3.2.2. Precipitation

The shelf-slope averaged precipitation climatology along the west coast of India shows a peak in June **(Figure 13)**. The region is under the influence of the south-west monsoonal regime, and receives heavy rainfall in the months from June to September. A low-pressure trough forms over India, due to solar heating. At this time of the year, the winds from the Indian Ocean blow towards the west coast of India, where they encounter the orographic feature, the 'Western Ghats'. The moisture laden winds rise along the Ghats and the moisture in the air begins to condense due to the lowering of the temperature with altitude, thus causing high amount of precipitation.

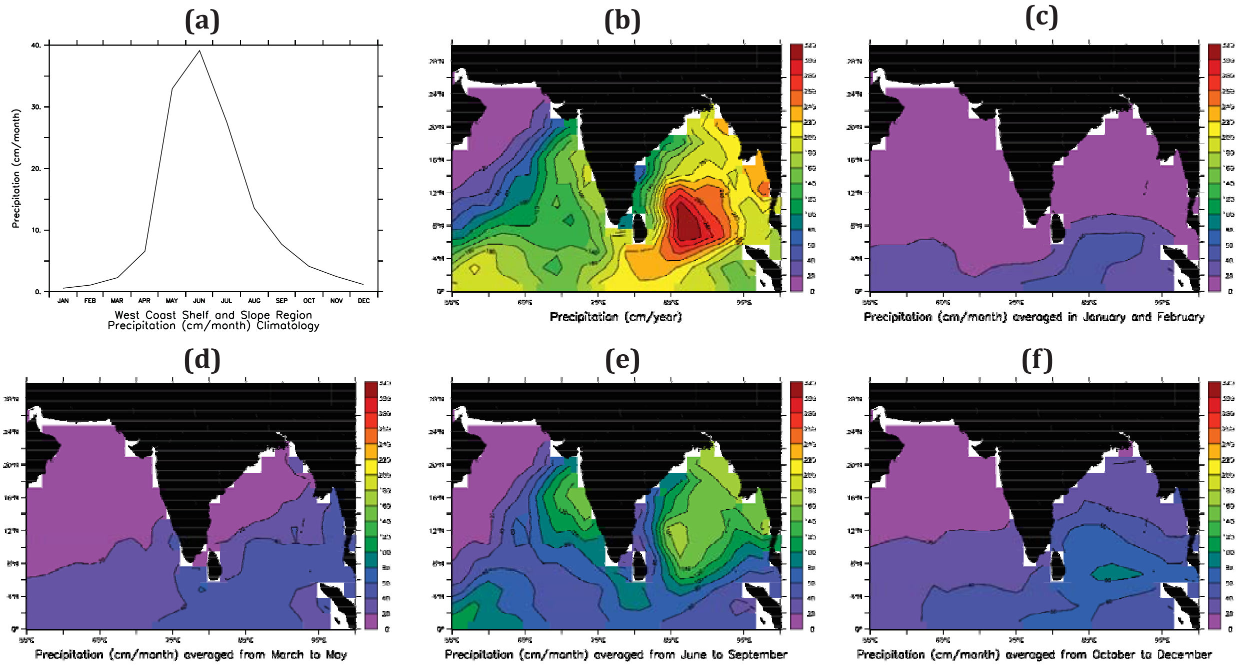

Figure 13: Seasonal cycle of monthly mean precipitation (cm/month) climatology (1960 to 2012) (a) averaged over the shelf-slope regions of the west coast of India, (b) climatological annual mean, (c) for January and February, (d) for March to May, (e) for June to September, and (f) for October to December.

The amount of precipitation due to the orography is relatively more intense along the Konkan and Malabar coasts than along Gujarat coast. The precipitation values are least in the Kutchch region and increases southwards toward the Malabar region (~140 cm/year). There is a region of very high rainfall along 14°N. Seasonally, the least rainfall occurs in winter when winds are dry.

3.2.3. Net Heat Flux

Similar to the air temperature, the net heat flux (averaged over the shelf and slope regions along the west coast of India) shows a bimodal distribution with peaks in March and October and lowest during December followed by June **(Figure 14)**. The loss of heat from the ocean in the December is due to reduced solar insulation combined with enhanced evaporation under cold dry northeast trade winds of continental origin. The net heat flux values are highest off the south-west coast of India with a value of 40 W/m^2.

3.2.4. Cyclones

Though tropical cyclones do occur in the Arabian Sea, their frequency and intensity is relatively

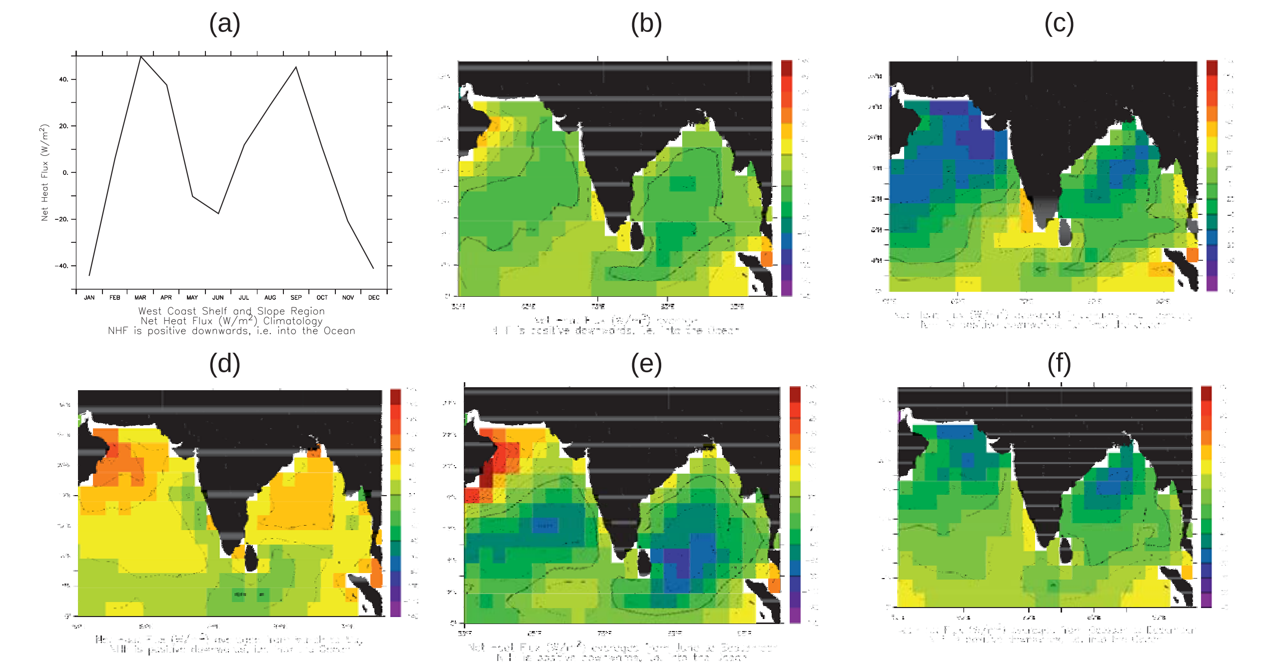

Figure 14: Seasonal cycle of monthly mean net heat flux (W/m^2) climatology (1960 to 2012) (a) averaged over the shelf-slope regions of the west coast of India, (b) climatological annual mean, (c) for January and February, (d) for March to May, (e) for June to September, and (f) for October to December.

smaller compared to those occur in the Bay of Bengal. The number of cyclonic systems that form in the Arabian Sea is in the order of 1 or 2 per year (Evan and Camargo, 2011). Generally, cyclones occur during spring-summer (April-June) and fall-winter (October-December) transitions.

3.2.5. Tsunamis

Instances on the occurrence of tsunamis in the Arabian Sea have been reported. A tsunami that occurred on 28 November, 1945 (http://drgeorgepc.com/TsunamiPotentialMakranSZ.html) has been reported to be the highest. Another tsunami that occurred in October/November 325 B.C. had impacted the fleet of Alexander the Great, which was in the vicinity of the Indus River (Murty and Bapat, 1999).

3.2.6. Winds and Currents

The sea surface winds in the Arabian Sea as well as along the west coast of India experience semi-annual periodicity (**Figure 15**, Left Panel). The strongest winds occur during summer monsoon period (June to September) with an average wind speed of 15 m/s from the south-westerly direction. The wind changes its direction to north-easterly during winter monsoon period (November to February) with an average speed of 5 m/s.

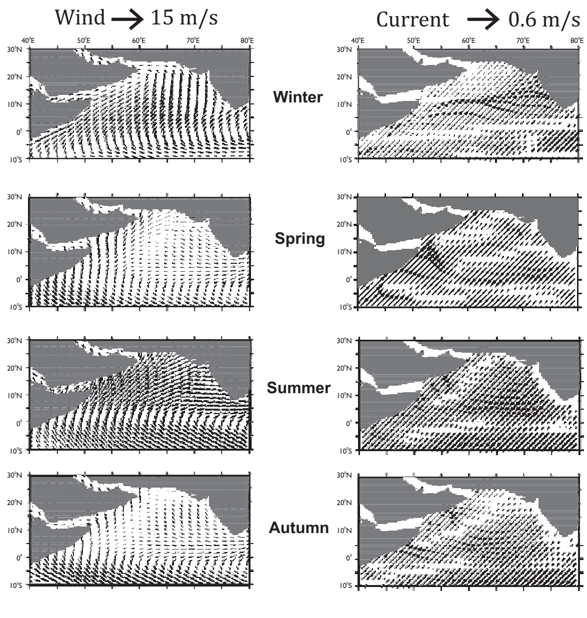

Figure 15: Seasonal cycle of prevailing (left) wind (m/s) and (right) current (m/s) patterns for (from top to bottom) winter, spring, summer and autumn (fall) seasons.

The winds blowing during summer monsoon are oceanic in their origin and are warm and moisture laden. In contrast, the winds blowing during winter monsoon are cold and dry due to their continental origin. Between the summer and winter monsoons, the winds are weak and variable in direction during spring (March-May) and fall (October) intermonsoons.

As the upper ocean current is driven by winds, the surface circulation in the Arabian Sea as well as along the west coast of India, also undergo a semi-annual variability (**Figure 15**, Right Panel). The West India coastal current (WICC) that flows southward during summer monsoon carries high saline waters from the northern Arabian Sea to the southern region. In winter, the WICC changes its direction and flows northward. During winter WICC carries the low salinity waters of the Bay of Bengal along the western shelf of India.

3.2.7. Sea Surface Temperature

The spatial distribution of sea surface temperature (SST) shows a seasonal cycle with warmest temperature during spring (March-May) and coldest during winter (**Figure 16**). The warmest SST occurs during spring along the west coast of India. In winter, the northern half of the west coast experiences winter cooling with cold SST, while its southern half is warm. During summer, the SST along the west coast is cooler particularly towards the southern part due to upwelling.

3.2.8. Sea Surface Salinity

The sea surface salinity (SSS) along the west coast of India exhibits a strong temporal and spatial intra-annual variability with very low saline waters in the southern part during winter and high salinity towards the northern part (**Figure 17**). This is due to the intrusion of low saline waters from the Bay of Bengal towards the southern part of the western shelf which is carried to north by the northward flowing WICC. During summer, the southward flowing WICC carries high saline waters of Arabian Sea towards the south.

3.3. Ecological Characteristics

The monsoonal forcing of the surface layer primarily controls the concentration of nutrients and the levels of phytoplankton biomass along the western continental shelf and slope off India. A reversal in the current direction between the northeast and the southwest monsoons, upwelling during summer monsoon and convective mixing during winter monsoon largely influence the chemical and biological processes.

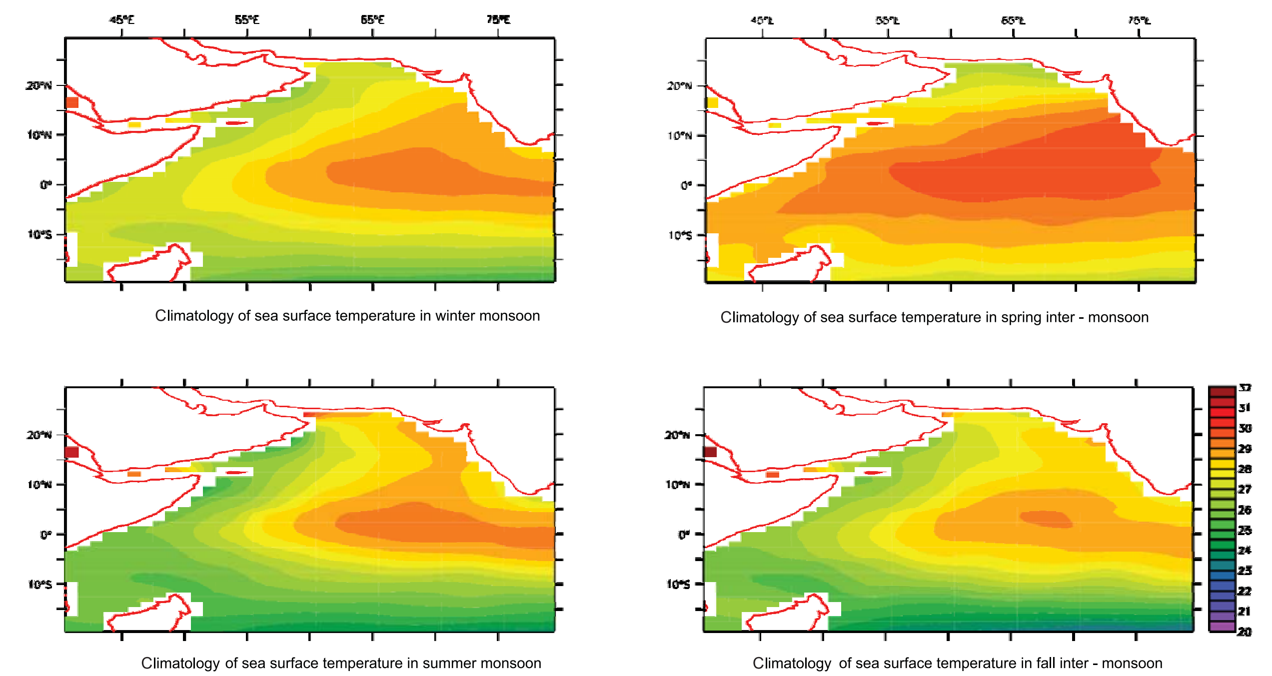

Figure 16: Seasonal cycle of sea surface temperature (°C) in the Arabian Sea during winter (top left), spring (top right), summer (bottom left) and fall (bottom right).

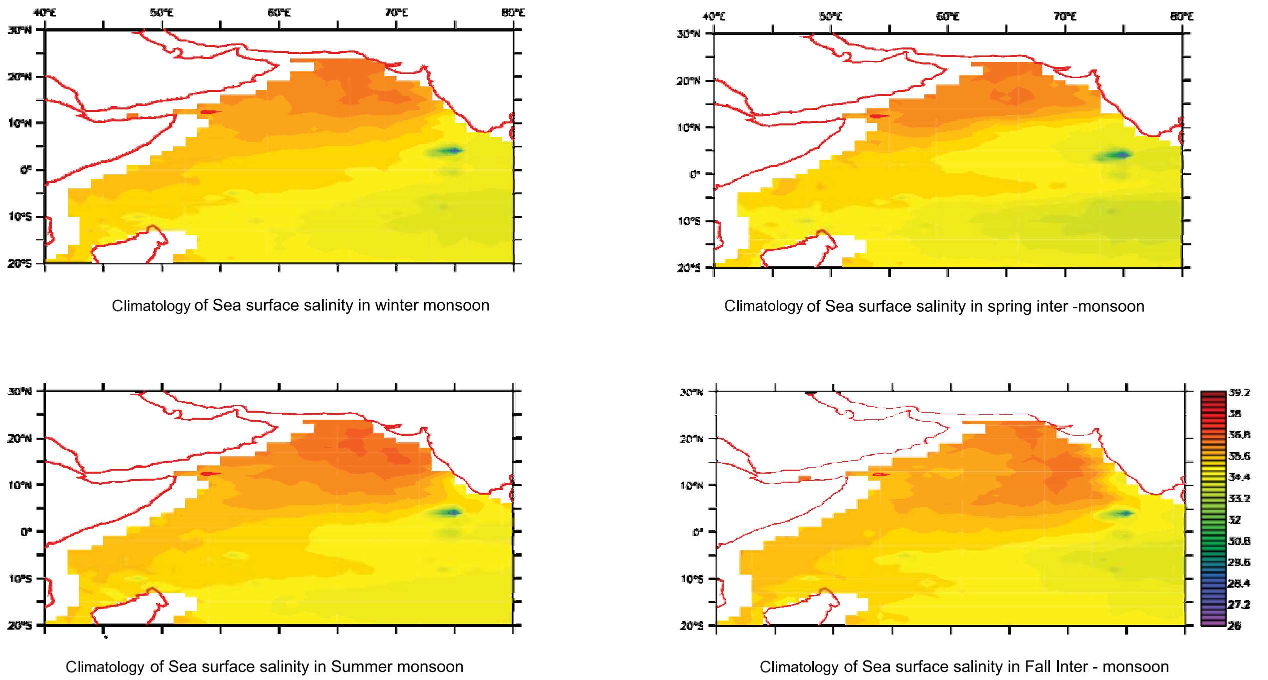

Figure 17: Seasonal cycle of sea surface salinity (psu) in the Arabian Sea during winter (top left), spring (top right), summer (bottom left) and fall (bottom right).

3.3.1. Chemical Characteristics

In a multi-dimensional coastal system where the dynamic processes are rarely in equilibrium, the environmental gradients occur spatially and temporally both on micro and macro-scales. The chemical environment is commonly understood in terms of dissolved oxygen (DO), nutrients (nitrate, phosphate and silicate), metal concentrations and biochemical oxygen demand (BOD). Being influenced by the monsoonal system of winds and currents, the coastal waters of the west coast of India exhibit strong seasonality in the water column chemistry as well.

The dissolved oxygen (DO) in any water body is an important parameter since the existence of aquatic life including fishes intimately depends on its availability. The major sources of DO in water column are photosynthesis and dissolution from atmosphere. The west coast of India experiences the upwelling of oxygen-poor (<0.5 ml/L), nutrient-rich subsurface water during summer. As a consequence, the shelf waters become hypoxic and sulphate-reducing during late summer due to exhaustion of oxygen and even nitrate by heterotrophic microorganisms (Ramasastry, 1957; Banse, 1959; Satry and Myrland, 1960). The summer upwelling begins in May and lasts until October (Darbyshire, 1967; Banse, 1968).

Nitrogenous, phosphorous and silicious nutrients are essential for the photosynthetic production of organic matter and hence nutrient levels in the upper ocean are affected by the utilization by phytoplankton . The spatial distribution of Nitrate-nitrogen (NO_3-N) and Phosphate-phosphorous (PO_4-P) along the western Arabian Sea and along the Shelf of India are depicted in **Figure 18** and **Figure19**, respectively.

3.3.2. Phytoplankton Biomass

The distribution pattern of phytoplankton biomass (chlorophyll *a)* shows strong seasonality similar to the availability of nutrients in the Arabian Sea (Matondkar *et al*. 2006; Jacob *et al*., 2009). The chlorophyll *a* concentrations are the highest during southwest monsoon season (June-September), particularly, in the southern part of the shelf and adjoining offshore regions (**Figure 20**a). This is largely due to coastal upwelling and advection of nutrient-rich waters offshore. An intermediate level of chlorophyll *a* concentration prevail during the fall monsoon (October) and winter monsoon (November-February) (**Figure 20b**). The concentrations of chlorophyll

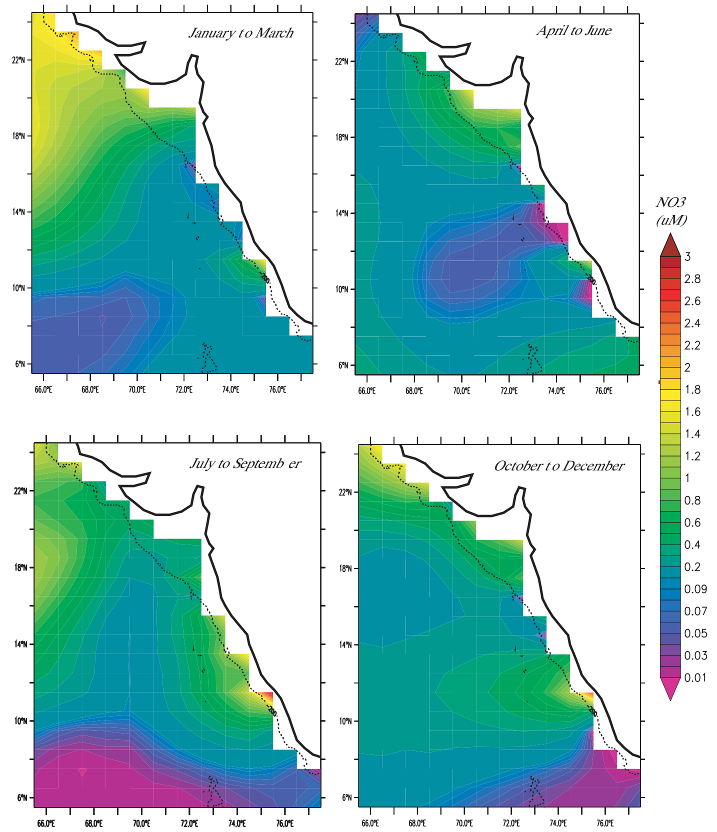

Figure 18: Climatological nitrate-nitrogen (NO_3-N) distribution in the surface waters off the west coast of India (generated from World Ocean Atlas 2013 database). The dashed line shows the 200 m depth contour.

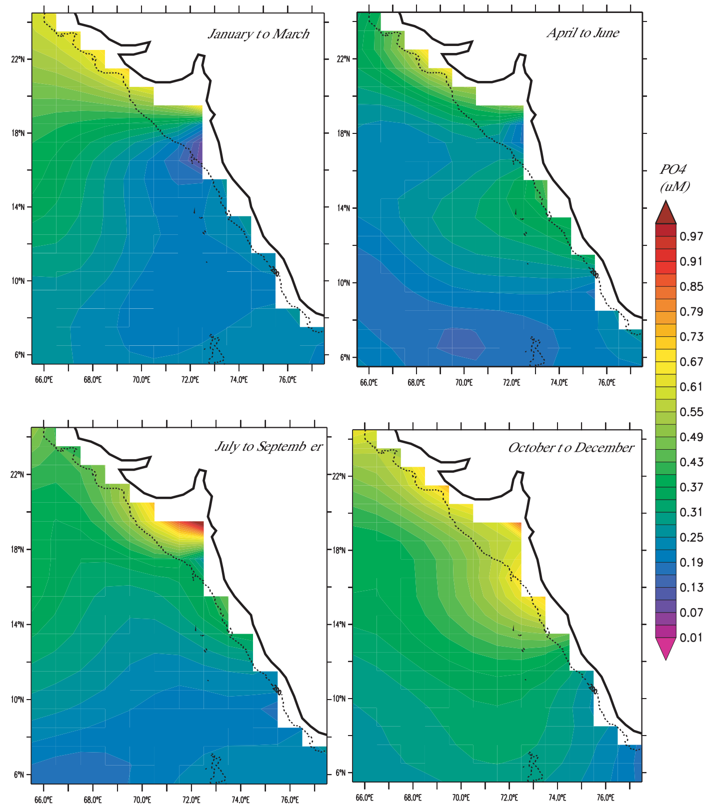

Figure 19: Climatological Phosphate-phosphorous (PO_4-P) distribution in the surface water off the west coast of India (generated from World Ocean Atlas 2013 Database). The dashed line shows the 200 m depth contour.

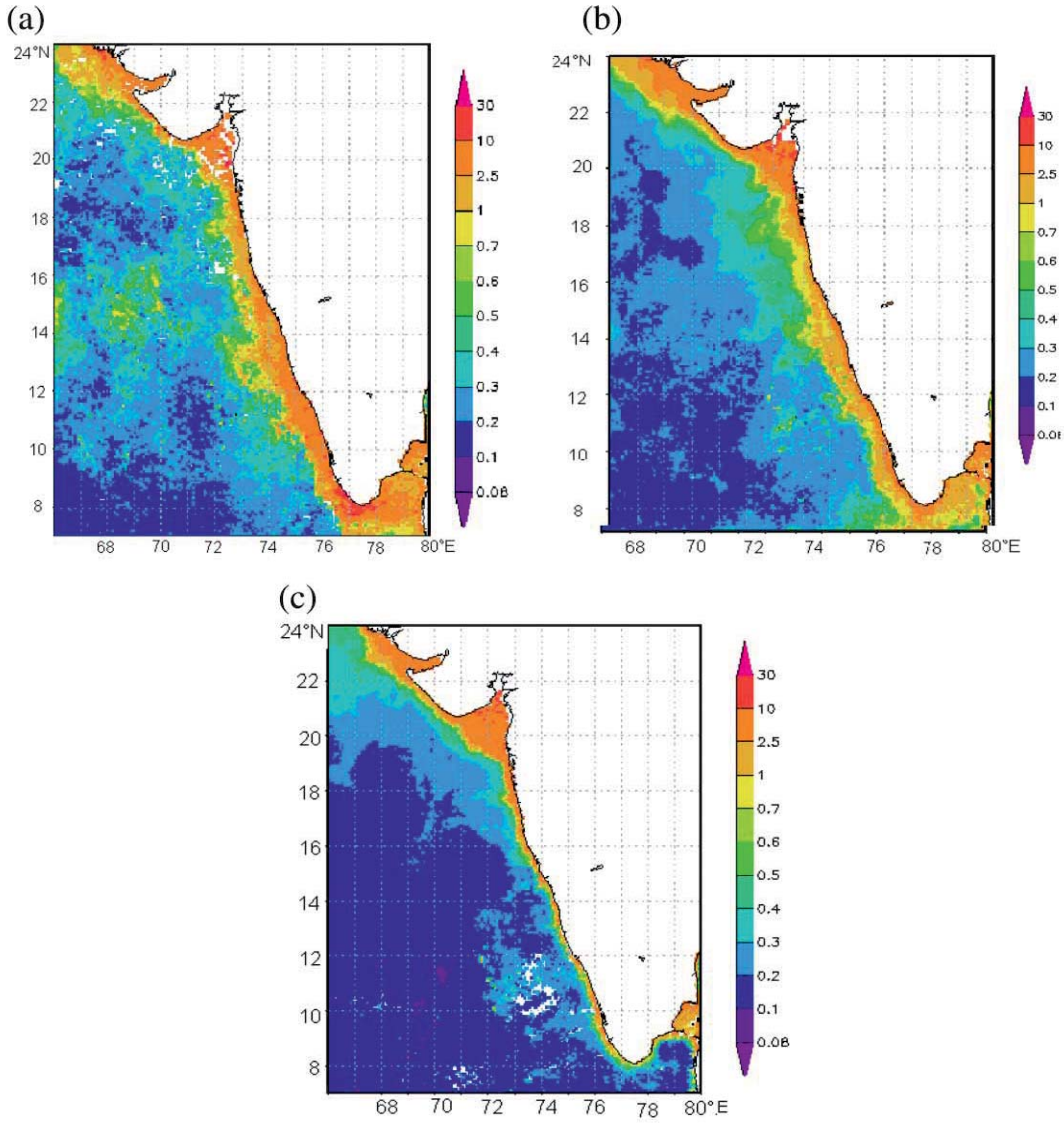

Figure 20: Setellite (SeaWiFS) derived monthly average chlorophyll *a* pigment concentration (mg/m^3) during (a) September 2003 (southwest monsoon), (b) October 2003 (fall intermonsoon), and (c) April 2004 (spring intermonsoon), Imageries are from Jacob et. al. (2009).

a are the least during spring intermonsoon (April-May) (**Figure 20c**).

3.3.3. Zooplankton

The community of zooplankton, small invertebrates feeding on phytoplankton with little or no self controlled locomotion, includes an array of organisms with varying size from the microscopic protozoans of a few microns to some jelly fishes with tentacles, several meters long. Zooplankton plays an important role in the marine food chain as intermediate link between phytoplankton and fish. The major groups of zooplankton species recorded from Indian waters are presented in **Table 2**.

3.4. Fish and Fisheries

India is endowed with a long coastline of about 8129 km, an exclusive economic zone (EEZ) of 2.02 million sq. km and a continental shelf of 468,000 sq. km **(Figure 21).** It has extremely diverse coastal and marine ecosystems on account of unique geomorphologic and climatic variations. The coastal and marine habitats include gulf waters, creeks, tidal flats, mud flats, coastal dunes, mangroves, marshes, wetlands, seaweed and sea grass beds, deltaic plains, estuaries, lagoons and coral reefs.

Western coast of India is relatively more productive in terms of fisheries (CMFRI, 2011). This is because off Maharastra and Gujarat, the

Table 2: Major zooplankton groups recorded from Indian seas (Source: Venkataraman and Wafar, 2005).

Zooplankton Group	No. of Species	Zooplankton Group	No. of Species
Tintinnida	<1000	Cirripedia	36
Hydrozoa	212	Mysidacea	75
Scyphozoan	34	Cumacea	31
Cubozoa	5	Euphausiacea	25
Siphonophora	116	Decapoda-Macrura	243
Ctenophore	12	Brachyura	705
Chaetognatha	30	Anamura	162
Copepods	<1925	Fish (eggs & larvae)	2456
Ostracoda	< 120		

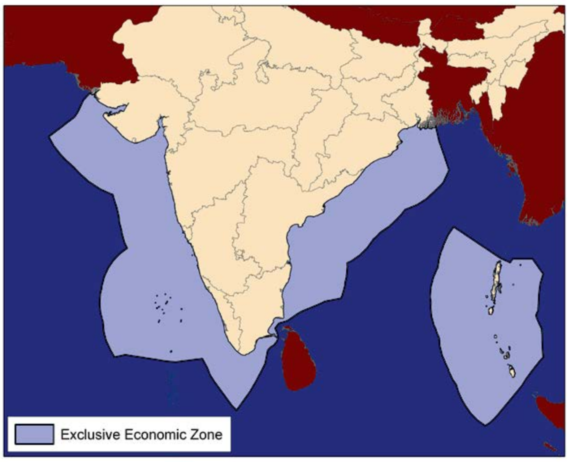

Figure 21: Exclusive economic zone (EEZ) of India (Source: GADM, 2014).

shelf extends in such a manner that 180 nautical miles within 200 m depth contour enabling extended fishing depths. Marine fisheries sector contributes significantly to the India's economy and has long been recognised as an important source of occupation and livelihood opportunity for the coastal communities. There are five maritime states *viz*., Gujarat, Maharashtra, Goa, Karnataka and Kerala; one union territory, Daman and Diu, and one group of islands, Lakshadweep group of island off the west coast of India.

3.4.1. Marine Fisheries Resources

Estimates of potential fishery resources from the Exclusive Economic Zone of India (EEZ) are about 3.5 to 4.7 million tonnes (Desai *et al*., 1990; Sudarsan *et al*., 1990; CMFRI, 2014). Recent trends in annual marine fish landings show that the catches fluctuate between 2.2 and 2.8 million tonnes. During 2004, the marine fish production was estimated to be 2.81 million tonnes, of which 63% came from the west coast and the rest from the east coast (FAO, 2004, India has a significant marine fisheries sector that has long been recognised as an important source of occupation and livelihood opportunities for the coastal communities of the country providing an employment to about 14.5 million people (Livestock Census, 2003). Marine resources of five states and Union Territory/Island are presented in **Table 3.** The distribution of fishermen population and fishing crafts used for the fishery at different Provinces along the west coast of India are depicted in **Figure 22** and **Figure 23**, respectively (CMFRI, 2010; FSI, 2008).

3.4.2. Marine Fish Production

For global fish trade purposes, the west coast of India has been categorized under Western Indian Ocean Fishing Area 51 by FAO and contributed about 4.5 million tonnes of total fish production of India during 2012 (FAO, 2014). India ranks seventh in marine capture fish producing countries and witnessed a growth rate of 15.1% during the years 2003-2012 (FAO, 2014). Marine fish production of west coast of India (five

Table 3: Marine fishery resources of States/Union territories along west coast of India (Source: CMFRI, 2010).

State/ Union territories	Approximate coastal length (km)	Continental Shelf area (X1000 Sq. km)	No. of Landing Centres
Gujarat	1600	184	121
Diu and Daman	27	-	5
Maharashtra	720	112	152
Goa	104	10	33
Karnataka	300	27	96
Kerala	590	40	187
Lakshadweep Islands	132	4	10
Total	**3473 (42.72%)**	**377 (71.13%)**	**604 (40%)**
India total	**8129**	**530**	**1537**

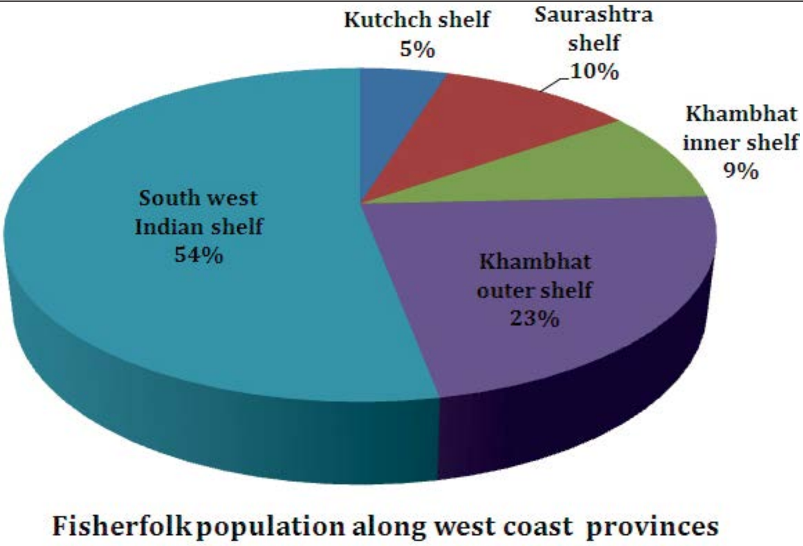

Figure 22: Distribution of fisherfolk population in different provinces of west coast of India.

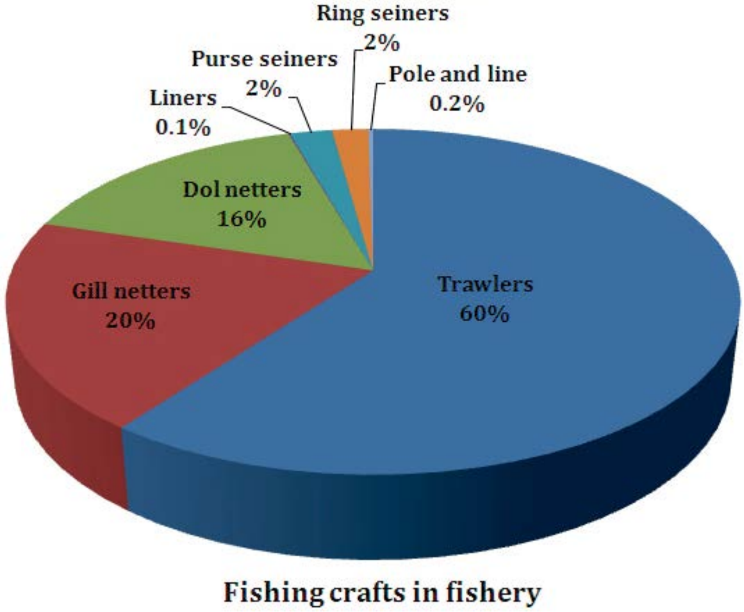

Figure 23: Distribution of fishing crafts employed in fishery along the west coast of India.

maritime states) from year 1985 to 2011 is shown in **Figure 24**, while the group/species-wise fish landing is given in **Table 4.** Landings data suggest that Gujarat (because of the longest coast line) and Kerala (due to upwelling driven short food chain mediated shoal-forming anchovies, oil sardine and mackerel fishes) are top producers since the inception of data collection (CMFRI, 2014).

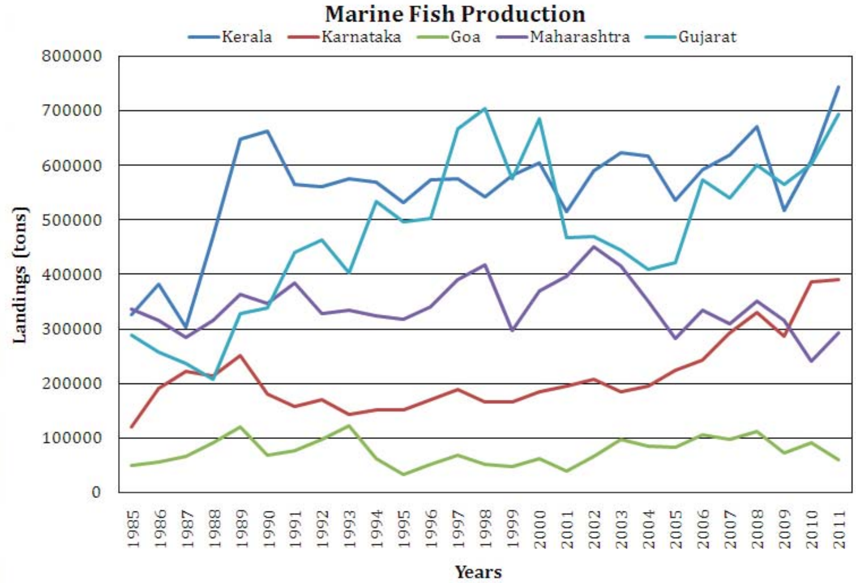

Figure 24: Marine fish production from west coast of India during 1985-2011 (Source: CMFRI, 2014).

4. Ecosystem Characterisation of provinces along the West Coast of India

In this section, the ecosystem characterisations of each of the five provinces as delineated in **Figure 6** and presented in **Table 1** are described in detail.

4.1. Kutchch Shelf

The Kutchch Shelf is the northernmost province defined along the west coast of India. The western end of the shelf shares its border with Pakistan coast.

4.1.1. Biophysical Drivers

Geomorphological Features: The Kutchch Shelf is a graben formed by submergence of the landmass. It has rifted along the Aravali trend. The basin is characterised by uplifted highlands and plains (Biswas, 1987). This lies entirely bordering the Kutchch district of Gujarat. Inspection of topographical maps and satellite images show that the region comprises of a mosaic of coastal features such as spits, beaches, bars, creeks, beach ridges, swales, mudflats, saline flats, dunes (both stable and active), chennier ridge/plain, mangrove swamps, tidal channels etc. The most prominent feature in this region is the saline wetland known as the Rann of Kutchch. This region remains submerged underwater during the monsoon period, but forms a glistening white salt surface following the retreat of monsoon. To the west of the Rann of Kutchch is the lower Indus deltaic plain which is crisscrossed by numerous tidal creeks **(Figure 25)** and is matted with mangroves (Schwartz, 2005). Sandy beaches and dunes are prominent along the northern part of the Gulf of Kutchch, while the southern part has mudflats with a number of cliffed rocky islands. The coast here is adorned with coral reefs and mangroves.

The shelf off the Kutchch region is wide at the southern end (~160 km) and comparatively narrow in the northern part (<100 km) with the shelf break occurring between 117 and 154 m. The average depth of the Gulf of Kutchch is about 30 m. At the mouth of the Gulf, east-west aligned shoals are conspicuous that channelise the tidal flow from the Gulf head (Chauhan, 1994). This is a macro-tidal region experiencing mixed semi-diurnal tide with the tidal range increasing from 3

Table 4: Group/species-wise marine fish landings (in tonnes) along the west coast of India, during 1980 and 1998-2001 (Source: FAO, 2003).

Group	Marine Fish landings (in tonnes)				
	1980	1998	1999	2000	2001
Anchovies, etc.	40,025	68, 487	54,308	54,987	64,249
Barracudas	501	9, 903	9 926	350	382
Bombay-duck	114, 855	144, 774	146, 591	133,156	142,944
Brown seaweeds	-	16 000	16, 000	16 000	16 000
Butterfishes, pomfrets	37, 143	15, 200	14, 897	10,417	8,093
Carangids	4,336	21, 426	22, 589	5,679	5,909
Cephalopods	10, 954	86, 337	84, 793	85,939	103,903
Clupeoids	14,442	70, 487	63, 435	36,678	32,823
Croakers, drums	93,643	233,160	280, 556	235,744	214,665
False trevally	4,368	7,995	5, 503	4,623	5,992
Flatfishes	9,178	17,460	12,840	24,709	11,271
Flying fishes	31	57	102	114	47
Frigate and bullet tunas	-	6,152	12,722	13,101	7,031
Giant tiger prawn	-	167,904	168, 942	145, 857	136, 443
Goatfishes	5, 363	7,061	7,186	8,457	14,748
Green seaweeds	-	60 000	60,000	60, 000	60,000
Hairtails, scabbard fishes	38, 829	58, 595	92,334	100, 570	93,970
Halfbeaks	644	1 312	1 928	1 650	1,474
Indian mackerel	40,455	142,669	138,086	62,026	29,938
Indian oil sardine	157,881	110,288	122,254	277,842	287,628
Indo-Pacific king mackerel	-	13,965	12,003	13,150	43,112
Indo-Pacific sailfish	-	-	-	8	-
Jacks, crevalles	7,622	52,315	51,741	22,808	31, 418
Kawakawa tuna	-	12,376	16,757	17,255	851
Kelee shad	7,138	3,077	3,076	3,896	6,458
Lizard fishes	9,329	12,012	11,539	4,029	2,671
Longtail tuna	-	3,805	2,275	2,342	258
Marine crabs	-	369	394	6,193	8,009
Marine crustaceans	11,070	12,658	11,272	11,047	8,853
Marine fishes	108,463	264,758	288,658	293,193	335,781
Marine molluscs	-	2,718	1,217	815	547
Marlins, sailfishes, etc.	-	1,557	1,188	1,303	407
Mullets	2,585	5,760	6,104	6,799	6,004
Narrow-barred Spanish mackerel	-	19,921	17,123	18,759	27,650
Natantian decapods	209,003	97,570	90,957	90,734	86,882
Percoids	19,800	52,230	53,600	58,297	40,053
Pike-congers	17,198	5,820	5,414	5,236	4,831
Pompanos	-	2,533	2,329	12	11
Pony fishes	8,878	9,115	8,934	4,551	6,951
Red seaweeds	-	24,000	24,000	24,000	24,000
Sea catfishes	36,147	36,082	38,432	31,467	45,850
Sea squirts	-	-	-	95	-
Seer fishes	19,391	-	-	-	-
Sharks, rays, skates, etc.	26,810	33,418	34,088	37,060	34,036
Skipjack tuna	-	831	5,707	5,878	21,789
Streaked seer fish	-	67	58	64	-
Threadfins, tassel fishes	1,958	1,544	2,780	2,243	2,817
Tuna-like fishes	18,884	4,931	-	-	-
Unicorn cod	897	1,113	458	1,123	2,095
Wahoo	-	14	12	13	-
Wolf-herrings	10,539	10,201	4,663	6,813	10,038
Yellowfin tuna	-	2,772	1,547	1 ,596	7,324
Total Landings	**1088,360**	**1932,799**	**2011,318**	**1948,678**	**1996,206**

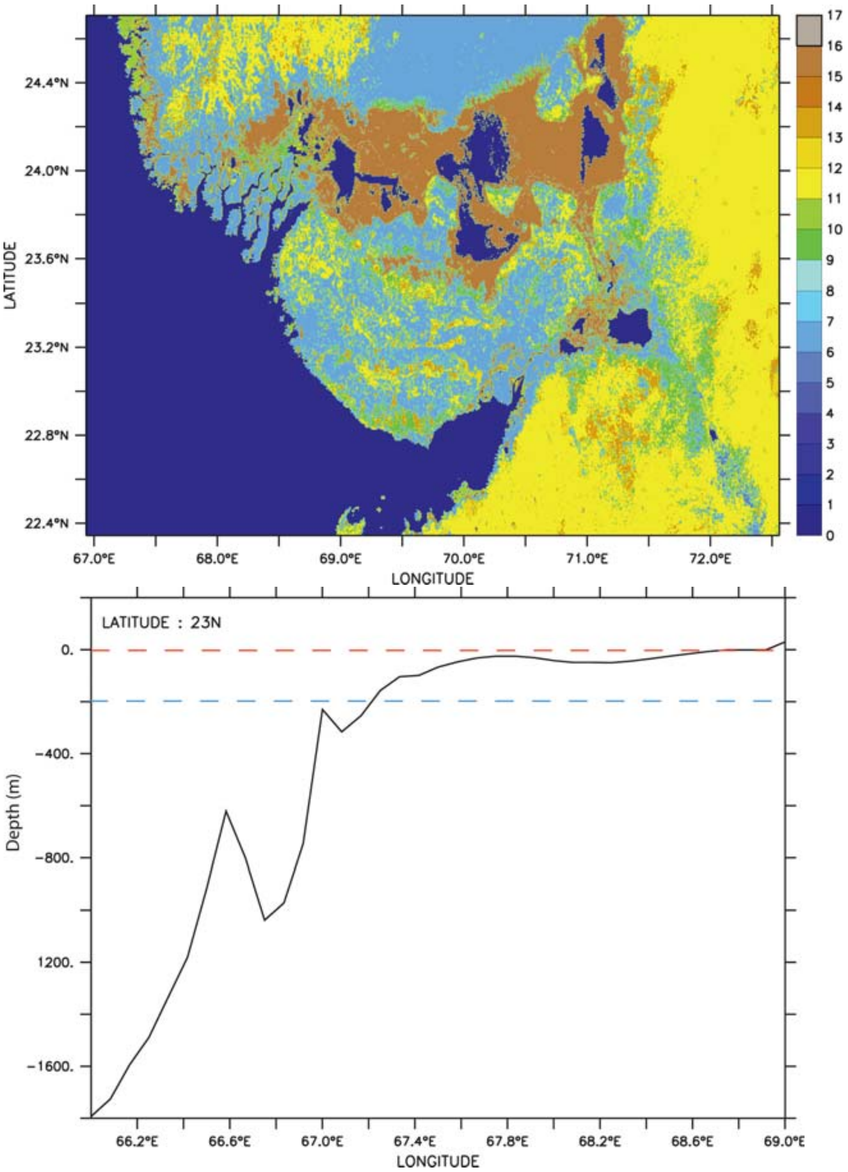

Figure 25: (Top) Land cover map in and around Kutchch derived from International Geosphere-Biosphere Program (IGBP). (Bottom) Depth section off the continental shelf along 23°N. The red and blue dashed line indicates 0 m and 200 m depth levels, respectively. See **Table 5** for different land cover categories .

Table 5: Land cover classification scheme as defined by International Geosphere-Biosphere Program (IGBP).

Value	Description
1	Evergreen Needle leaf Forest
2	Evergreen Broadleaf Forest
3	Deciduous Needle leaf Forest
4	Deciduous Broadleaf Forest
5	Mixed Forest
6	Closed Shrublands
7	Open Shrublands
8	Woody Savannas
9	Savannas
10	Grasslands

Value	Description
11	Permanent Wetlands
12	Croplands
13	Urban and Built-0Up
14	Cropland/ Natural Vegetation Mosaic
15	Snow and Ice
16	Barren or Sparsely Vegetated
17	Water Bodies
18	Interrupted Areas
19	Missing Data

m at the mouth of the Gulf to almost 7 m at the head due to the shape of the Gulf. The coastal waters of northern part of the Gulf of Kutchch is highly turbid with the suspended sediment concentrations reported to be >670 mg/l (Ramaswamy *et al.*, 2007). This is due to the resuspension and mixing of the bottom sediments by the tidal currents. The southern part of the Kutchch region is relatively clear with suspended sediment concentration of <10 mg/l. This marked north-south difference in suspended matter is the result of the east-west flow of the strong tidal current. The main source of sediment to the Kutchch region is from Indus River as testified by the dominance of chlorite and illite with very little contribution of sediments derived from the weathering of the Deccan Trap (Ramaswamy *et al.*, 2007). At the head of Gulf of Kutchch, the composition of sediments is a mixture of those derived from the Indus River as well as from Rann of Kutchch.

Climate: The air temperature in the Kutchch region shows a bimodal character (**Figure 26a**) with a double peak, one in May and another in September. The precipitation in the Kutchch region peaks in the month of June (**Figure 26b**), while the evaporation peaks in the month of December (**Figure 26c**). Winter is the period when the cool and dry winds from the land cause a high amount of evaporation in the North Arabian Sea of which Kutchch is a part. Values of net heat flux are higher from February to June (**Figure 26d**). The values then decrease and become negative attaining the minimum in December. The high amount of evaporation causes heat loss from the ocean, during this period.

Oceanography: The sea surface temperature (SST) in the Kutchch region is the highest during spring intermonsoon (SIM) (~29°C) and is lowest during northeast monsoon (NEM) (**Figure 27a**) due to low insulation and high evaporation. The resulting cold and denser surface waters undergo convective mixing and lead to the deepening of the mixed layer. The vertical profiles of temperature also show distinct seasonality with very shallow isothermal layer in SIM and deep isothermal layer in NEM (**Figure 27b**). The spatial distribution of SST (**Figure 27 c-f**) also shows a strong seasonality with warmer surface waters during SIM (**Figure 27d**) followed by SWM (**Figure 27e)**. The coldest SST was in NEM

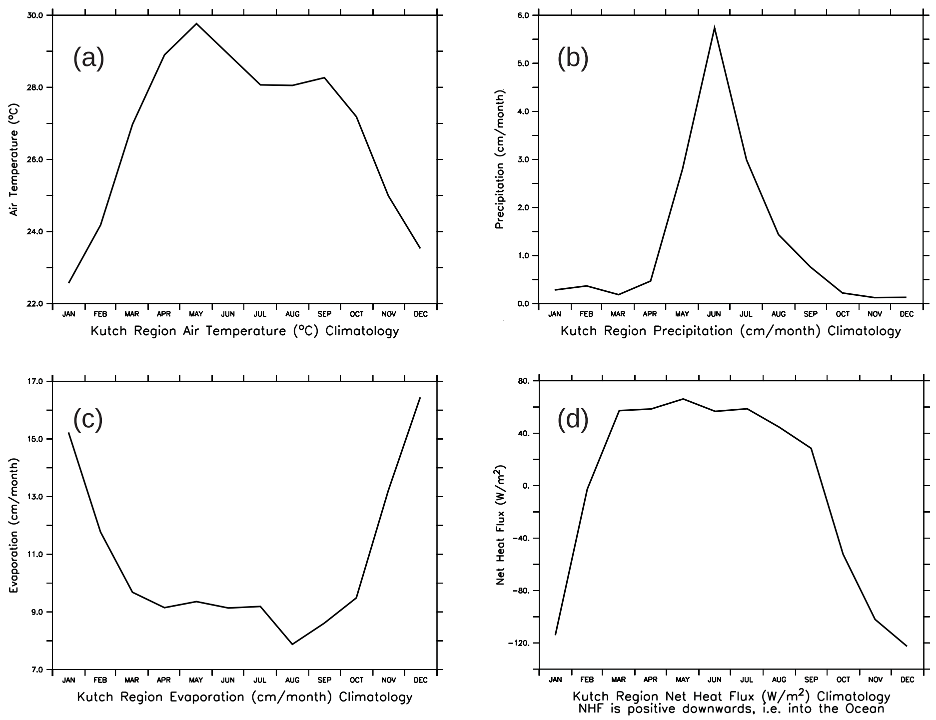

Figure 26: Monthly climatology showing evolution of (a) air temperature (⁰C) (b) precipitation (cm/month) (c) evaporation (cm/month) and (d) net heat flux (W/m^2) for Kutchch region.

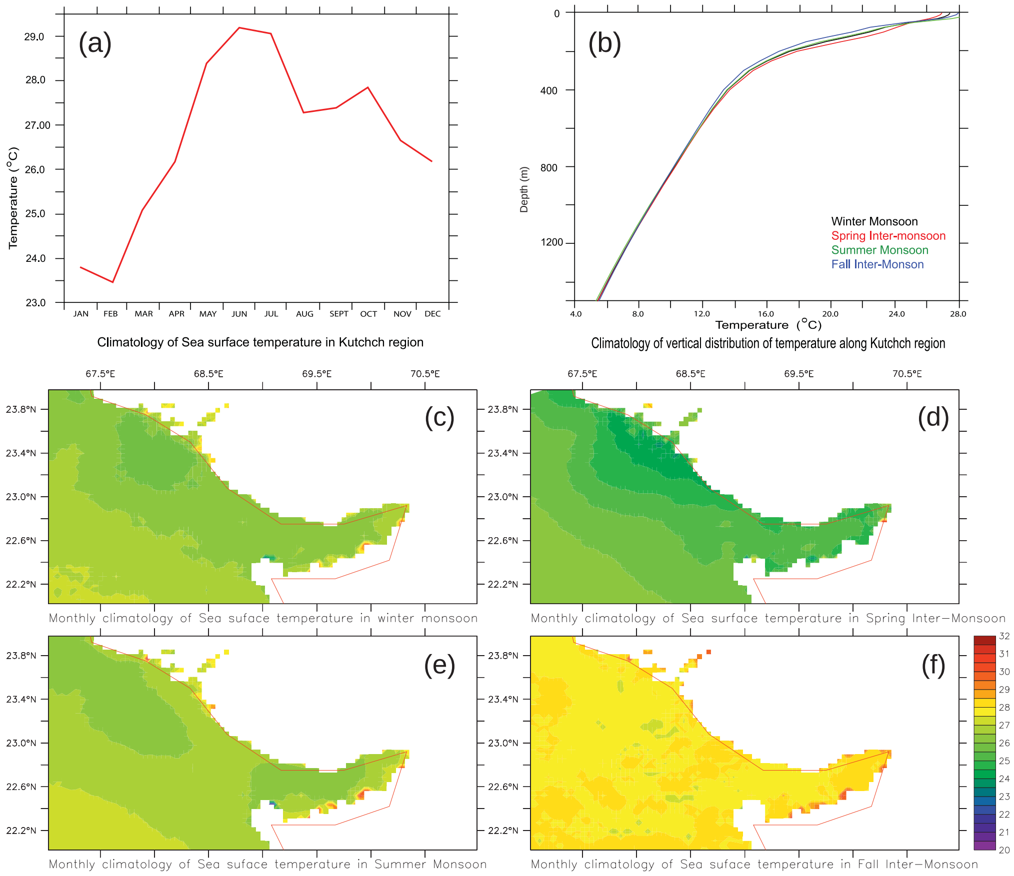

Figure 27: Time series showing evolution climatological (a) SST, (b) vertical variation of temperature during four seasons, and horizontal pattern of SST variation for the Kutchch region for NEM, SIM, SWM and FIM are shown in (c), (d), (e) and (f), respectively.

with lowest values hugging the coast (**Figure 27c**) followed by FIM (**Figure 27f**).

The sea surface salinity (SSS) increases up to 36.8 psu during SWM and is low during SIM and fall intermonsoon (FIM) varying between 36.30 and 36.20 psu (**Figure 28a**). During SWM, sea surface height (SSH) is around 22 cm and the same varies between 26 and 30 cm during the SIM and FIM (**Figure 28c**). Okha Port situated in the Kutchch region experiences a mixed semi-diurnal tide (**Figure 28 d**) with amplitude of 7 m due to the funnel shape of the region.

4.1.2. Ecological Assets

Water and Sediment Chemistry: During the NEM, the enhanced evaporation due to the passage of cold, dry north-easterly air mass leads to the cooling and deepening of the surface layer. This sets up a convective cell and entrains nutrients from the subsurface layer into the surface mixed layer. Concentrations of nitrate-nitrogen increase from <1 µmol/L during the spring intermonsoon to >5 µmol/L during July-August. This is accompanied by an increase in silicate (>12 µM) and phosphate (above 3 µM) concentrations leading to increased biological production during NEM.

Phytoplankton Biomass and Abundance: Several studies have been conducted for understanding the abundance and seasonal distribution of marine phytoplankton along the West coast of India. The studies by Das and Roy (2013) showed well-marked variations in the abundance of phytoplankton off Kandla.

In the northern most regions of the Arabian Sea, the magnitude of concentration of chlorophyll *a* is controlled by nutrient availability rather than light. The distribution of phytoplankton and chlorophyll concentration along Gulf of Kutchch (Navlakhi, Kandla, Okha, Jamnagar, Sikha,

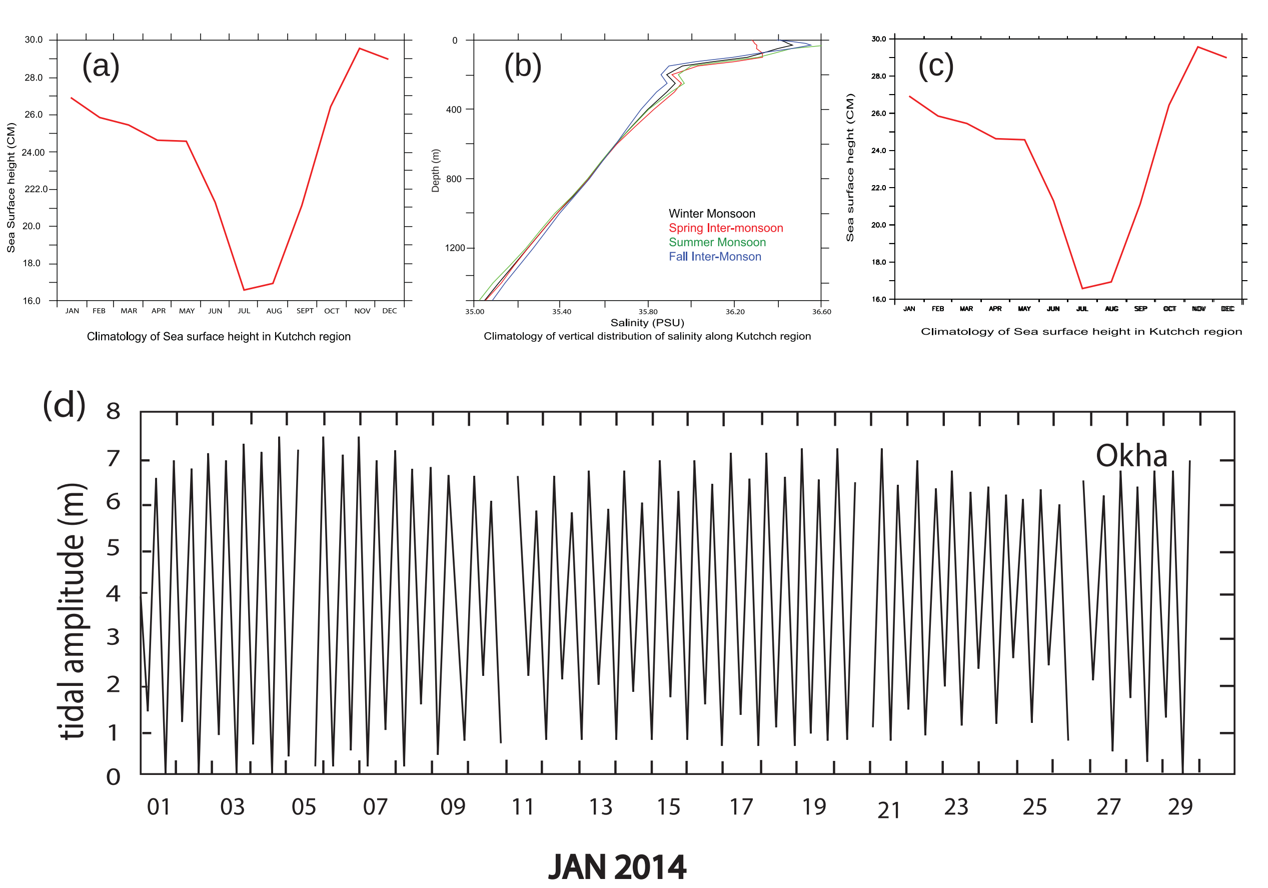

Figure 28: Seasonal cycle of (a) climatological SSS (a), (b) time evolution of climatological vertical profiles sea surface salinity (SSS) for the four seasons, (c), seasonal cycle of the climatological SSH (c) and (d) variation of tidal amplitude at Okha, a port in the Gulf of Kutchch during the month of January, 2014.

Mundra and Mandvi regions) during November are depicted in **Figure 29 (a)** and **Figure 29 (b),** respectively. According to study of Das and Roy (2013), high phytoplankton concentration along this coast is ascribed to winter convection process which brings nutrient rich subsurface waters to the photic zone and is therefore responsible for the high productivity of this area. The coastal boundary and processes of open ocean of Arabian Sea are influenced by upwelling during summer and cooling during winter which brings in high amount of nutrients into the upper surface enhancing the primary productivity. The overall phytoplankton abundance and

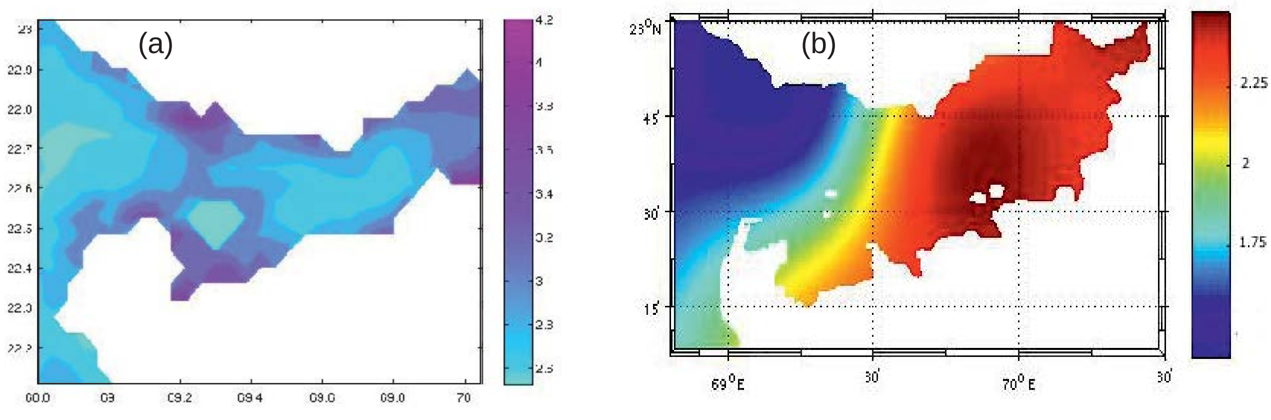

Figure 29: Spatial distribution of surface (a) chlorophyll *a* concentration from MODIS Aqua dataset during November and (b) phytoplankton from model simulation during November (Source: Das and Roy, 2013).

chlorophyll *a* concentrations from Gulf of Kutchch are listed in **Table 6**. Maximum and minimum phytoplankton abundance recorded in the surface waters in this Province is $9.41x10^6$ cells/L and $1.01x10^4$ cells/L, respectively. The surface chlorophyll *a* concentrations varies from 0.2 to 4.3 mg/m^3.

Table 6: Phytoplankton abundance (cell counts) and concentrations of chlorophyll *a* from Bhuj and Jamnagar areas within the Gulf of Kutchch Province.

Region	Area	Phytoplankton Abundance (cells/L)		Surface Chl *a* (mg/m^3)		Study Period	References
		Min	Max	Min	Max		
Bhuj	Jakhau-Babber Sanghi-Kharo & Medisinthodi Creek (N=3)	$2.44x10^5$	$9.41x10^6$	-	-	1999-2000	Saravanakumar *et al*. (2008)
	Kotdi creek off Tunda –Wandh (N=13)	$5.75\underline{+}2.59x10^4$	1.72			April 2008	NIO (2010)
	Mundra	$1.82x10^4$	$1.89x10^5$	0.5	1	1981-2008	NIO (2010)
	Kandla	$1.45x10^4$	$6.75x10^4$	0.4	1.1		
Jamnagar	Okha	$1.28x10^4$	$4.12x10^5$	0.2	4.3		
	Vadinar	$1.19x10^4$	$1.39x10^5$	0.3	1.4		
	Sikka	$1.01x10^4$	$1.22x10^5$	0.2	1.6		
	Bedi	$7.5x10^4$	$2.25x10^5$	1	1		
	Navlakhi	$1.31x10^4$	$1.45x10^5$	0.6	2.2		

Table 7: Zooplankton biomass and density reported from different areas within the Gulf of Kutchch Province (SIM-Spring intermonsoon; SWM-Southwest monsoon; FIM-Fall intermonsoon).

Area	Season	Biomass (ml/100m^3)			Density (Nos./100 m^3)		Reference
		Min	Max	Mean	Min	Max	
Interior Gulf	SIM	1.96	130.79	41.45	$3.5x10^4$		Paulinose *et al.* (1998)
	SWM	0.59	185.5	40.67	$3.4x10^4$		
	FIM	2.16	149.5	31.40	$7.2x10^3$		
Karumbhar	-	-	-	-	$1.6x10^5$	$2.9x10^5$	ICMAM (2002a)
Pirotan Island	-	-	-	-	$1.2x10^5$	$2.8x10^5$	
Mangra-Kandla	-	-	-	-	$1.8x10^5$	$9.1x10^5$	
Okha	-	-	-	-	$4.9x10^5$		
Mundra	-	-	-	-	$9.0x10^5$		
Mandvi	-	-	-	-	$4.0x10^5$		
Sangi-Kharo Creek	-	-	-	-	$3.0x10^6$	$1.8x10^7$	
Medi-Sinthodi Creek	-	-	-	-	$3.9x10^6$	$2.1x10^7$	

Zooplankton Biomass and Density: Variations in zooplankton biomass and density in the Gulf of Kutchch region are presented in **Table 7**. The density of zooplankton as reported by Paulinose *et al*. (1998) for this province is in the range of $7.2x10^3$ to $3.5x10^4$ Nos./100m^3, while biomass varied widely with the lowest (0.59 ml/100 m^3) and the highest (185.5 ml/100 m^3) values occurring during monsoon season. Studies by Integrated Coastal & Marine Area Management

(ICMAM, 2002a) indicate that the lower zooplankton density ($1.2x10^5$ Nos/100 m^3) and higher density ($9.1x10^5$ Nos/100 m^3) occur off Pirotan Island and off Mundra, respectively (**Table 7**). Lowest ($3.0x10^6$ Nos./100m^3) and highest ($21x10^6$ Nos./100m^3) zooplankton density values during Summer and winter, respectively have been recorded in Babber Creek by Sarvanakumar *et al*. (2007). Sudden swarms of few zooplankton groups have been attributed to such a high density during winter (Saravanakumar *et al*., 2007). Furthermore, higher population density with the dominance of copepods has been reported by Rajagopalan et al. (1992) and Paulinose et al. (1998).

Density of fish eggs during Premonsoon and Postmonsoon seasons has been reported in the range of 35–454/100m^3 and 8-3177 eggs/100m^3, respectively (George *et al*., 2011).

4.2. Saurashtra Shelf

4.2.1. Biophysical Drivers

Geomorphological Features: The Saurashtra region lying on the Saurashtra Peninsula is a Horst in between the Kutchch, Khambhat and the Narmada rift basins (Biswas, 1987). It is tilted to the southwest. Presence of sandy beaches are seen between Dwarka and Diu, while cliffs and shore platforms between Veraval, Diu and beyond Jaffrabad have been documented (Mukhopadhyay and Karisiddaiah, 2014). The shelf off the Saurashtra coast is greatly narrow with the shelf break varying between 80 and 150 m (Rao and Wagle, 1997). The continental shelf is moderately sloping with a steep shelf break **(Figure 30)**. Smectite derived from the weathering of Deccan Trap region is the principal clay mineral in the inner shelf region. Sediments at the outer shelf region are dominated by illite and chlorite-which are derived from the Indus river and transported by the southerly current.(Ramaswamy and Nair, 1989).

Climate: The climatology of the air temperature in the Saurashtra region shows a bimodal regime with two peaks, one in May and another in September **(Figure 31)**. The air temperature decreases to a minimum in January due to the blowing of cold land winds. The precipitation in the Saurashtra region also shows a peak in the month of June coinciding with the southwest monsoon period. The evaporation climatology in the Saurashtra region shows a high value in the month of December. This is the period when the

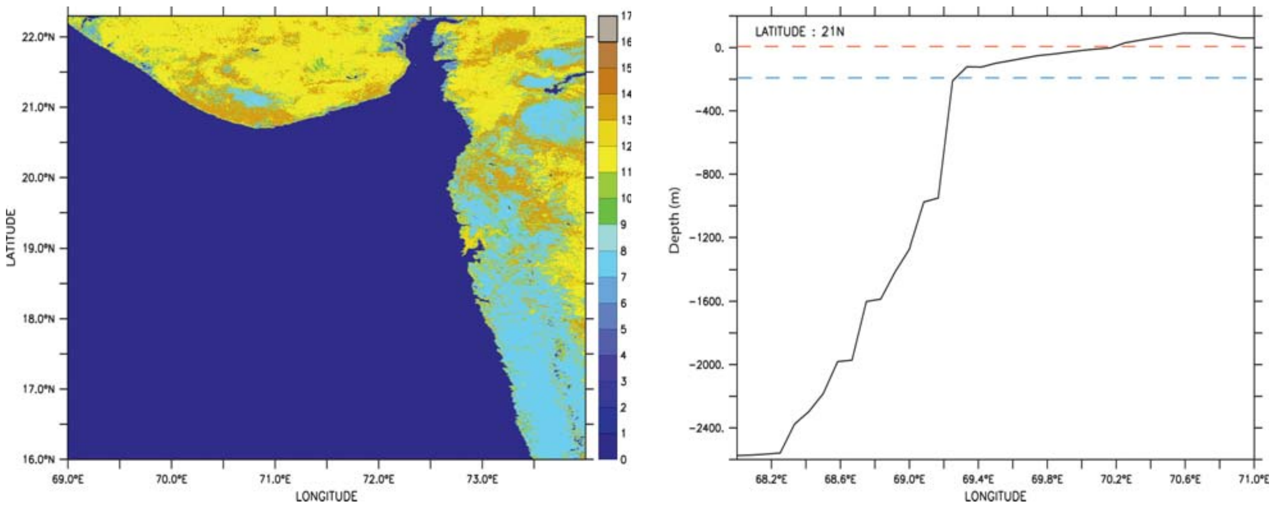

Figure 30 : Land cover map in and around Saurashtra and Gulf of Khambhat (Left Panel) and depth section off the continental shelf along 21 N (Right Panel) for different land cover as per the classification Scheme of International Geosphere - Biiosphere Program (Table 5). See Table 5 for the categories. The red and blue dashed lines indicate 0 m and 200 m depth contours, respectively.

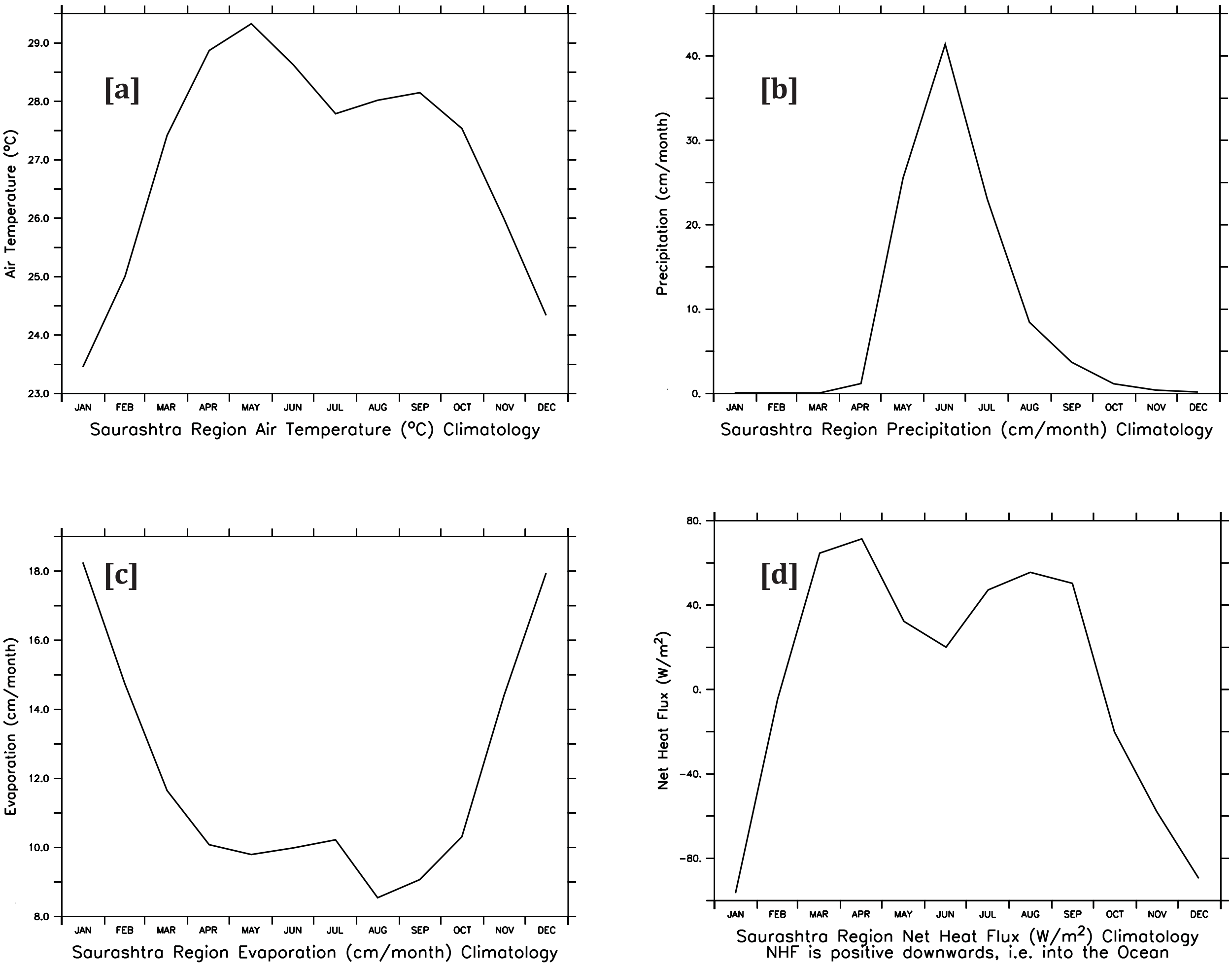

Figure 31 :Monthly climatology showing evolution of (a) air temperature (ºC) (b) precipitation (cm/month) (c) evaporation (cm/month) and (d) net heat flux (W/m^2) for Saurashtra region.

cool dry land winds cause a high amount of evaporation in the North Arabian Sea of which Saurashtra is a part. The net heat flux shows a bimodal peak, one in April and another in September. The increase in evaporation during the southwest monsoonal months causes the decrease in the net heat flux. During the month of January, the dip in net heat flux is at its maximum. The high amount of evaporation causes a loss of heat from the ocean, during this period.

Oceanography: The high SST values during SIM and FIM hover around (28-29 °C) and the low SST occurs during the SWM (<28 °C) (**Figure 32**). High salinity is seen during August (SWM) (~36.65) and low salinity was in March (~36.0 psu) (**Figure 33**).

Strong coastal currents prevail during summer monsoon, while intense winter cooling and convective mixing occurs in this region during winter. This helps to inject nutrients from subsurface to surface (Prasanna Kumar and Prasad, 1996) which supports high phytoplankton growth. The tidal amplitude at Veraval is between 3 and 4 m.

4.2.2. Ecological Assets

Water and Sediment Chemistry: The Saurashtra region comes under the domain of winter convection with the sinking of surface water mass. The shelf off Saurashtra experiences intense denitrification although productivity is lower compared to other parts of the Arabian Sea (Naqvi, 1991). Nitrite concentration at the secondary nitrite maxima is more than 2 µM. It has been proposed that sinking of water mass during NEM may facilitate injection of large quantities of dissolved organic carbon which may

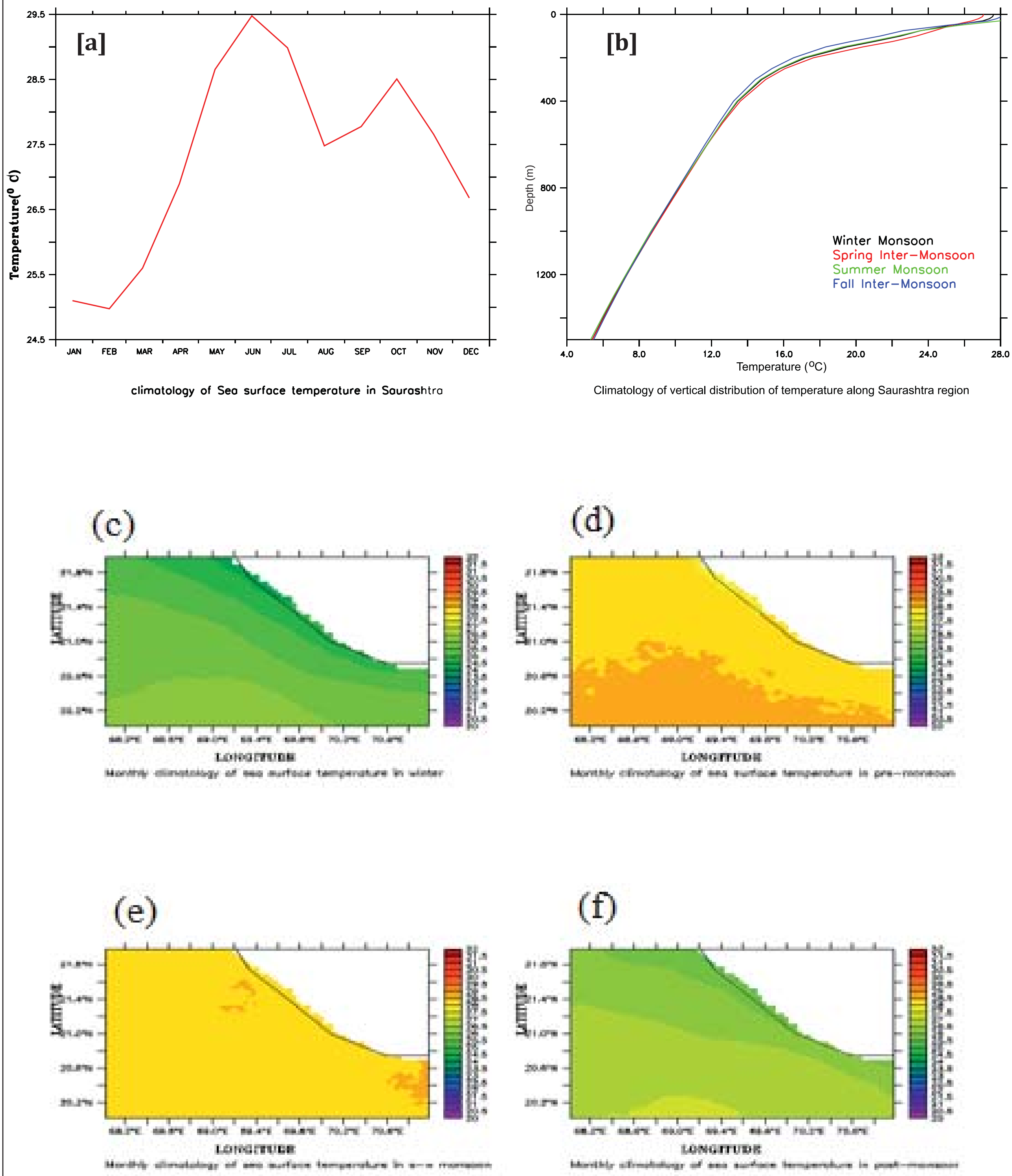

Figure 32: Time series measurements showing evolution of climatological (a) SST, (b) vertical variation of temperature during four seasons. The horizontal pattern of SST variation along Saurashtra Shelf and offshore for NEM, SIM, SWM and FIM are shown in (c), (d), (e) and (f), respectively.

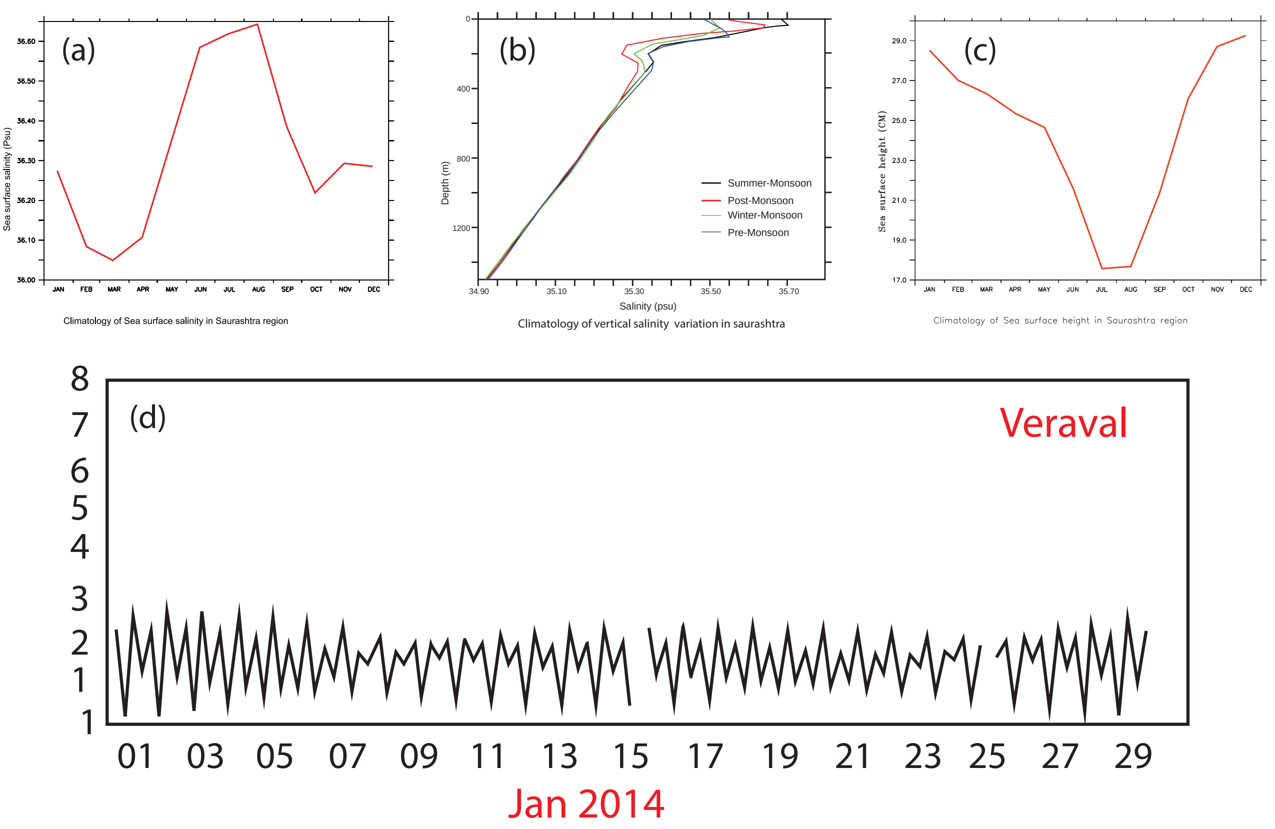

Figure 33:. Seasonal cycle of (a) SSS, (b) time evolution of climatological vertical profiles of SSS for the four seasons, (c) seasonal cycle of climatological SSH and (d) variation of tidal amplitude at Veraval, a port in the Saurashtra, during the month of January 2014.

explain why this region has most intense denitrification, in spite of having much lower primary production in the euphotic layer.

The sediments of Saurashtra shelf are characterised by somewhat intermediate concentrations of different metals compared to Mumbai or Gulf of Kutchch. Mean concentrations of Pb, Cd, Cr, Cu, Ni and Co in sediments are 14.1, 0.2, 123, 60, 93 and 39.0 mg/kg of dry wt of sediment, respectively (**Figure 34**). Contamination Factor (CF) values indicate moderate contamination for most of these metals. However, comparison of these metal concentrations with Effective Range Low (ERL) and Effective Range Median (ERM) values imply that, except Ni, all other heavy metals are below ERM. Therefore, Ni concentration might be lethal to marine organisms in this region. In case of Cu and Cr, the concentrations vary between ERL and ERM and for Pb and Cd concentrations are lower than the ERL.

Phytoplankton Biomass and abundance: The coastal area between Kodinar and Veraval along the Saurashtra coast is a hotspot of mega industries and Diu is seasonal tourist town. Thus, anthropogenic activities as well as environmental characteristics affect the distribution of phytoplankton and concentrations of chlorophyll *a* pigment along different regions. The range of chlorophyll *a* concentrations recorded in this Province during NEM, SIM, SWM and FIM, respectively are 1.28-1.30, 1.09-1.12, 1.19-1.23 and 1.16-1.19 mg/m^3 (**Table 8**).

Zooplankton Biomass and Density : In general, the Saurashtra Shelf is more productive as for as secondary and tertiary production levels are concerned. Off Dwaraka and Veraval, minimum and maximum biomass reported by Padmavati and Goswami (1996) are 10 and 40 ml/100m^3. Similarly, the zooplankton density has been reported to be in the range of 9.9x10^3- 4.3 x 10^4 Nos./100m^3. In another study (NIO, 2011), the

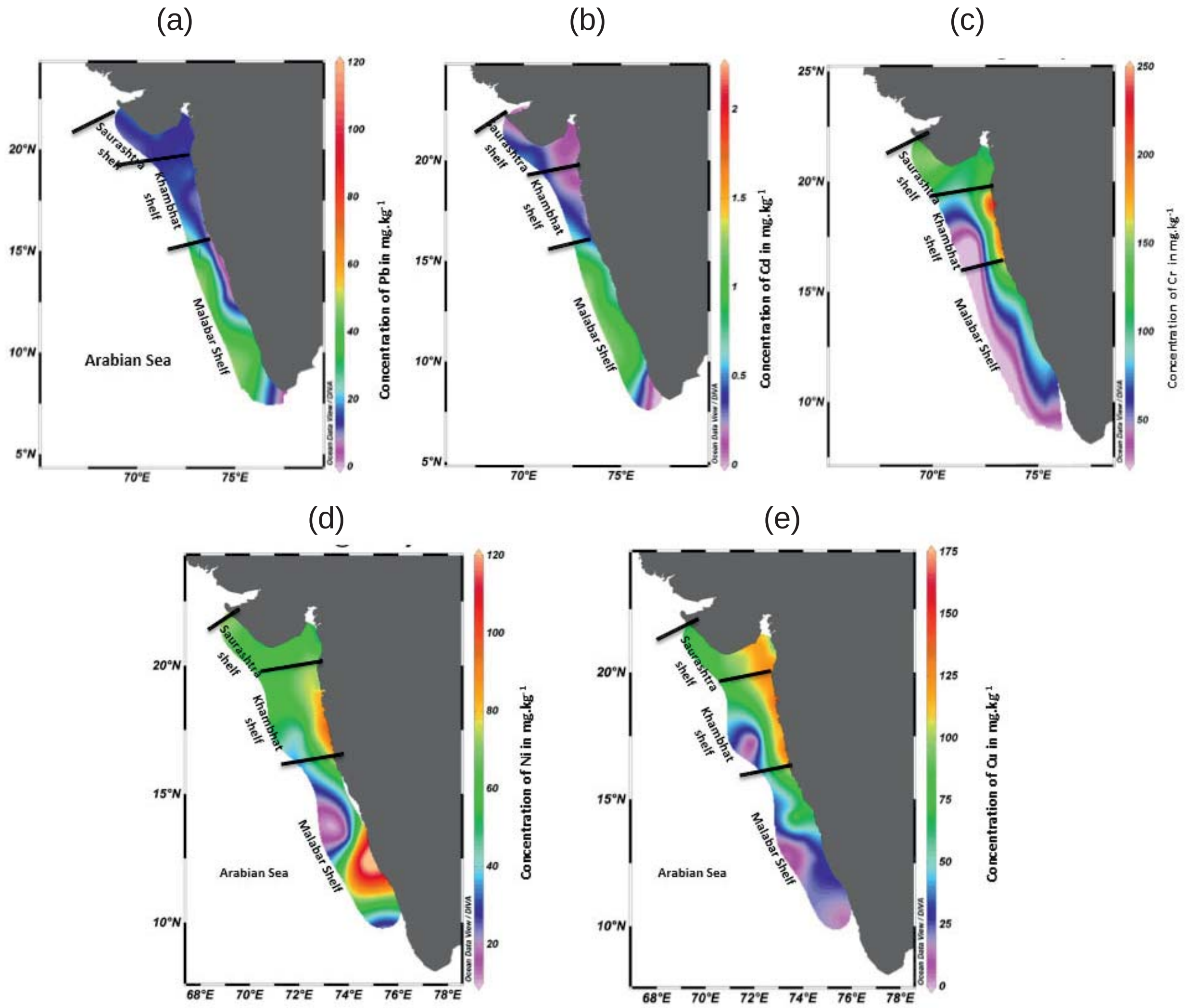

Figure 34: Distribution of concentrations of (a) Pb, (b) Cd (c) Cr, (d) Ni, and (e) Cu in the sediments (mg/kg dry wt.) from western continental shelf of India.

Table 8 : Phytoplankton abundance and biomass (chlorophyll *a*) recorded frm different areas within the Saurashtra Province.

Samling site	Phytoplankton Abundance (cells/L)		Surface Chl *a* (mg/m³)		Study Period	References
	Min	Max	Min	Max		
Gojiness-Bhogat (N=15)	$87.43 \pm 47.6 \times 10^2$		1.23 ± 0.5		March, 2010	NIO (2011)
Dwarka			1.10±0.02	1.30±0.08	November 2007–October 2008	Bhadja and Kundu (2012)
Mangrol	-	-	1.12±0.04	1.30±0.01		
Veraval	-	-	1.12±0.02	1.28±0.01		
Sutrapada	$1.46 \pm 0.6 \times 10^5$	$6.64 + 3.6 \times 10^5$	2.5±1.58	3.85±1.16	October, 1995 and February 1996	NIO (1996)
Kodinar	-	-	1.09±0.02	1.28±0.02	November 2007 – October 2008	Bhadja and Kundu (2012)

minimum and maximum biomass and density recorded respectively were 110-780 ml/100m^3 and 1.2 x 10^5-2.5 x 10^6 Nos./ 100m^3 (NIO, 2011) (see **Table 9**).

Table 9: Zooplankton biomass and density along Saurashtra Shelf during Fall inter-monsoon season.

Regions	Area	Depth (m)	Biomass (ml/100m^3)			Density (Nos./100m^3)			Reference
			Min	Max	Mean	Min	Max	Mean	
Jamnagar	Off Dwarka (n=2)	110	20	-	-	1.9×10^4	3.2×10^4	-	Padmavati and Goswami (1996)
Junagad	Off Veraval (n=4)	50-90	10	40	-	9.9×10^3	4.3×10^4	-	
Jamnagar	Gojiness -Bhogat (n=15)	6-21	110	780	321	1.2×10^5	2.5×10^6	8.9×10^5	NIO (2011)

4.3. Khambhat Shelf (Inner and Outer)

4.3.1. Biophysical Drivers

Geomorphological Features: The northern part of the Gulf of Khambhat forms the Cambey graben filled with tertiary sediments. It is formed by the northern continuation of the Dharwar trend across the Narmada Rift valley. Southwards, it is situated on the east-west aligned Narmada rift valley (Biswas, 1987). It is a funnel shaped extension of the ocean that tapers to a width of only 5 km at the Gulf head region. The depth of the Gulf ranges between 18 and 27 m. The tides are mixed semi-diurnal in nature with high tidal range exceeding 10 m in the head of the Gulf [Unnikrishnan *et al.*, 1999] giving rise to large inter-tidal expanses. The coastline at the head of the Gulf is highly indented owing to the presence of numerous creeks and estuaries. Large expanses of mudflats and saltflats border the coastline. The sediment in the zone between Khambhat and Bharuch is alluvial. The ecosystem comprise of mangrove and coral reefs. Major rivers such as Narmada, Tapi, Mahi, Sabarmati and Setrunji along with several minor ones drain into the Gulf. Although, these rivers carry high sediment load, the high energy environment prevent the delta formation in this region. Towards the south in the Konkan region, the coastline is rocky with pockets of sandy beaches and intertidal mudflats. Sediments in this region are derived from the Deccan Trap basalts. Wave-cut platforms are present in Harihareshwar and Murud Janjira. Mangroves are present in Thane Creek and Malvan Coast. Corals, seaweeds and mangroves are abundant in Malvan Marine Sanctuary (Mukhopadhyay and Karisiddaiah, 2014).

The continental shelf is widest in the north (more than 300 km) and narrows considerably to the south (around 60 km) **(Figure 35)**. The depth of the shelf break varies between 130 m off

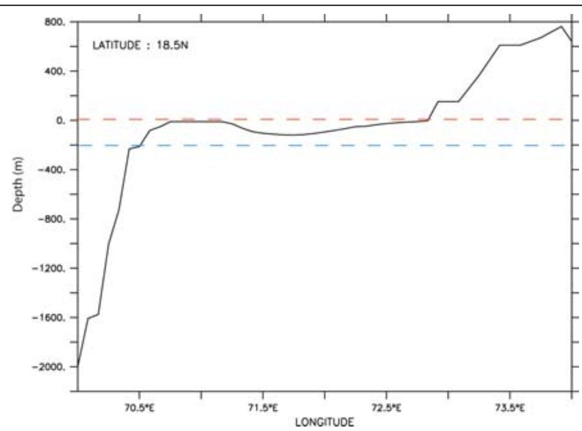

Figure 35: Depth section across the continental shelf off the Khambhat region along 18.5°N. The red and blue dashed line indicates 0 m and 200 m depth contours, respectively.

Ratnagiri and about 90 m off Tarapur. The inner shelf off the Gulf of Khambhat has sand banks at depth of ~8-30 m and sand waves at depth of ~60 m. About 7 to 8 rows of submerged sand ridges are found in the middle and outer shelf at water depths between 75 and 100 m off the coast of Mumbai (Rao and Wagle, 1997). The sediments in the inner shelf consist of those derived from the Narmada and Tapi Riverine systems with predominance of smectite **(Figure 36)**. However, lack of cross-shelf transport does not permit the sediment to cross over. The sediment in the outer shelf is of Indus-derived with dominance of illite (Ramaswamy and Nair, 1989).

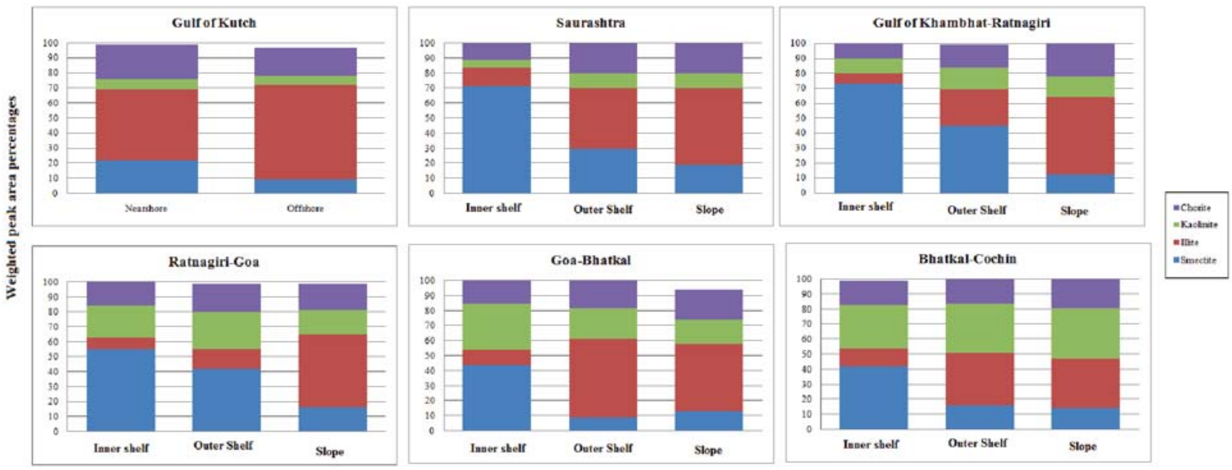

Figure 36: Clay mineral distribution along the western continental shelf and slope off India generated from Rao and Rao (1995).

Climate:

(a) Inner Khambhat: The climatology of the air temperature in the Inner Khambhat region shows a bimodal character with two peaks, one in May and another in September **(Figure 37)**. The air temperature falls in January due to the cold continental winds from the north. The precipitation in the Inner Khambhat region shows a peak in the month of June. This is the period of the south-west monsoon. The evaporation climatology in the Inner Khambhat region shows a high value in the month of December. This is the period when the cool dry land winds blow causing a high amount of evaporation in the North Arabian Sea of which Inner Khambhat is a part. The net heat flux shows a bimodal peak in April and September. Indices of net heat flux decrease in the south-west monsoonal months and in January. The south-west monsoonal months show an increase in evaporation causing the net heat flux decrease. Maximum dip is seen during January. The high amount of evaporation causes a loss of heat from the ocean, during this period.

(b) Outer Khambhat: The climatology of the air temperature in the Outer Khambhat region is similar to that of inner Khambhat with two peaks, one in April and the other in September **(Figure 38)**. During January, the air temperature is the coldest due to reduced incoming solar radiation and due to the prevalence of cold dry winds from the north. The highest precipitation occurs in the month of June associated with the south-west monsoon. In contrast, the evaporation was the highest in the month of January. This is the period when the cool dry continental winds blowing over the Arabian Sea, especially in the north, leading to high amount of evaporation in the North Arabian Sea of which Outer Khambhat is a part. The net heat flux shows a bimodal peak, one in April and another in August. The high amount of evaporation causes a loss of heat from the ocean, in the winter.

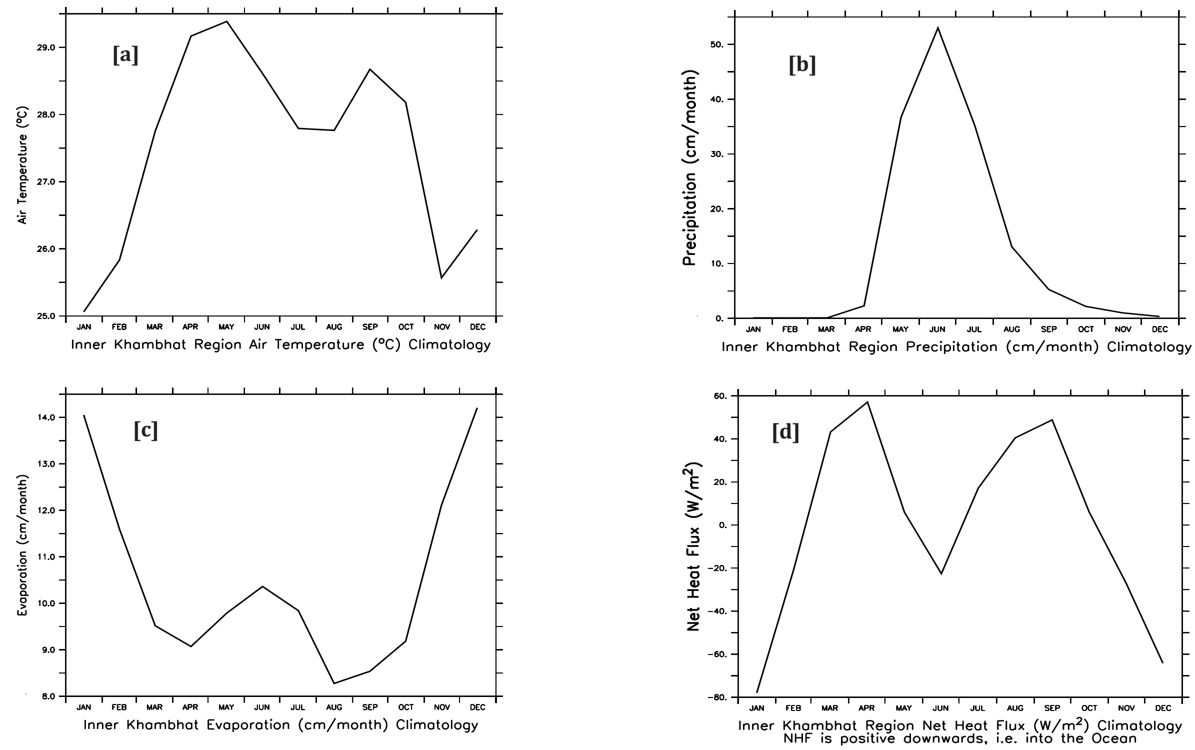

Figure 37: Monthly climatology showing evolution of (a) air temperature (°C) (b) precipitation (cm/month) (c) evaporation (cm/month) and (d) net heat flux (W/m^2) for inner Khambhat region.

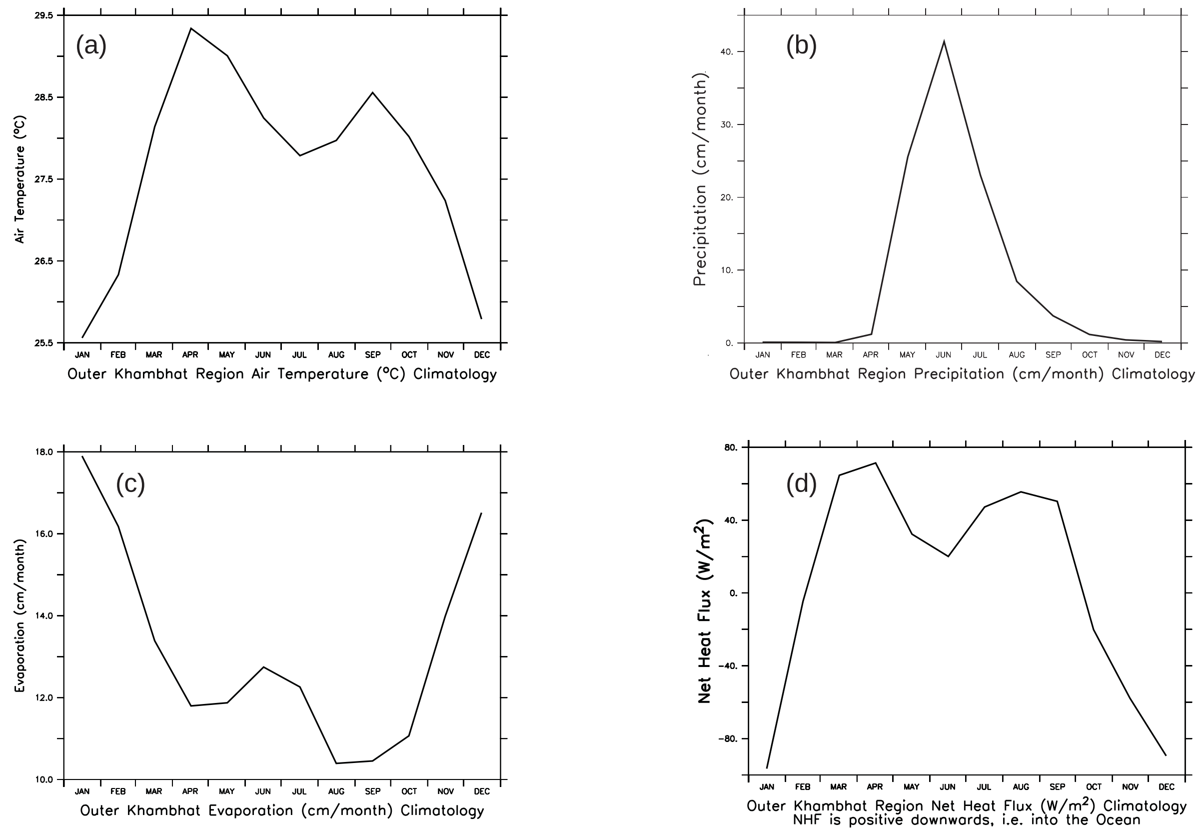

Figure 38: Monthly climatology showing evolution of (a) air temperature (°C) (b) precipitation (cm/month) (c) evaporation (cm/month) and (d) net heat flux (W/m^2) for Outer Khambhat region.

Oceanography: The maximum recorded value of SST in both Inner and Outer Khambhat regions is in the range of 28 to 31°C which is during SIM (**Figure 39**).

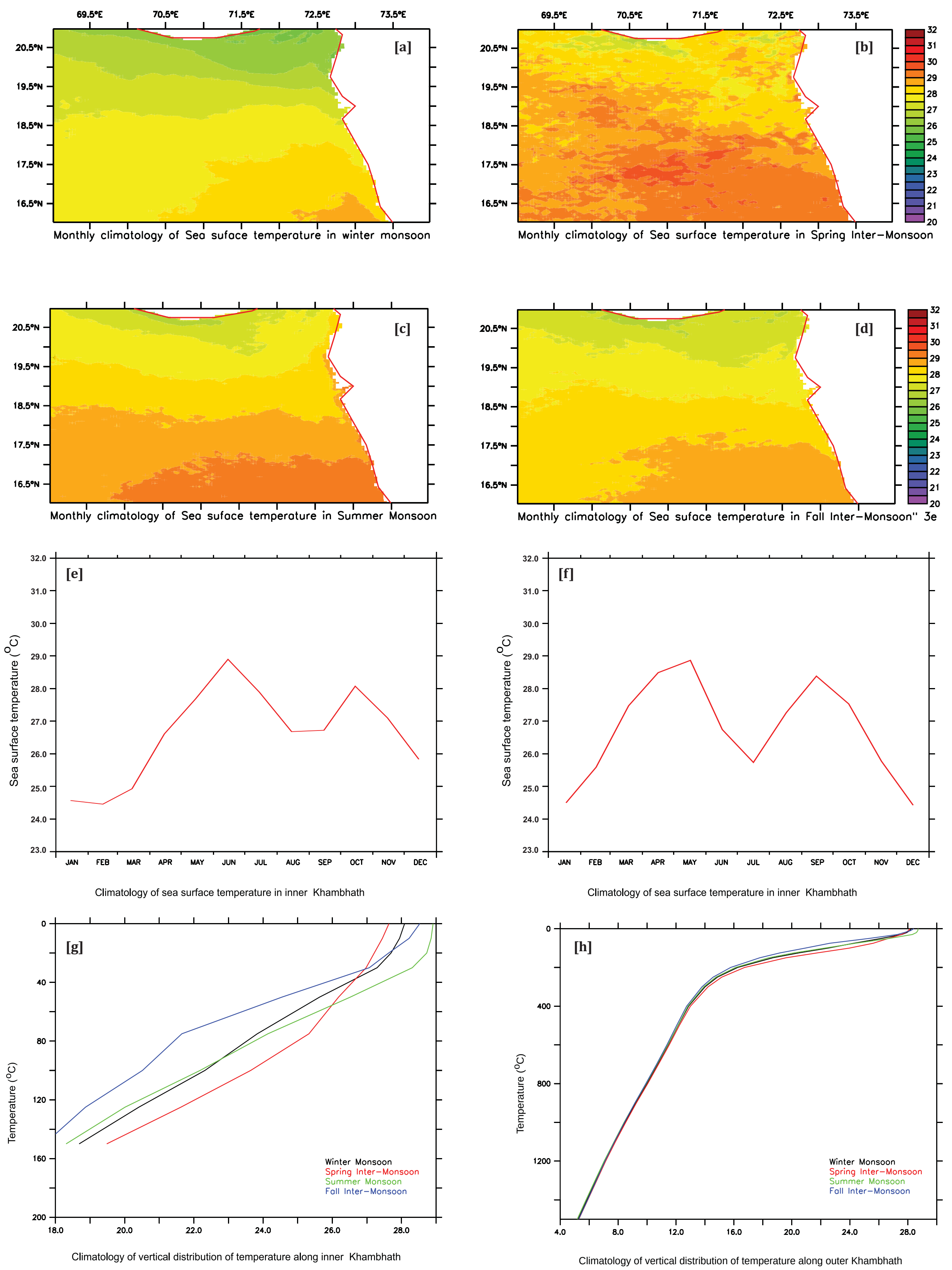

Figure 39: SST variation along Gulf of Khambhat during (a) NEM (b) SIM (c) SWM and (d) FIM. Time evolution of SST for (e) Inner Khambhat and (f) Outer Khambhat. Depth-wise variation of temperature in (g) Inner Khambhat and (h) Outer Khambhat.

Oceanography: The maximum recorded value of SST in both Inner and Outer Khambhat regions is in the range of 28 to 31°C which is during SIM (**Figure 39**).

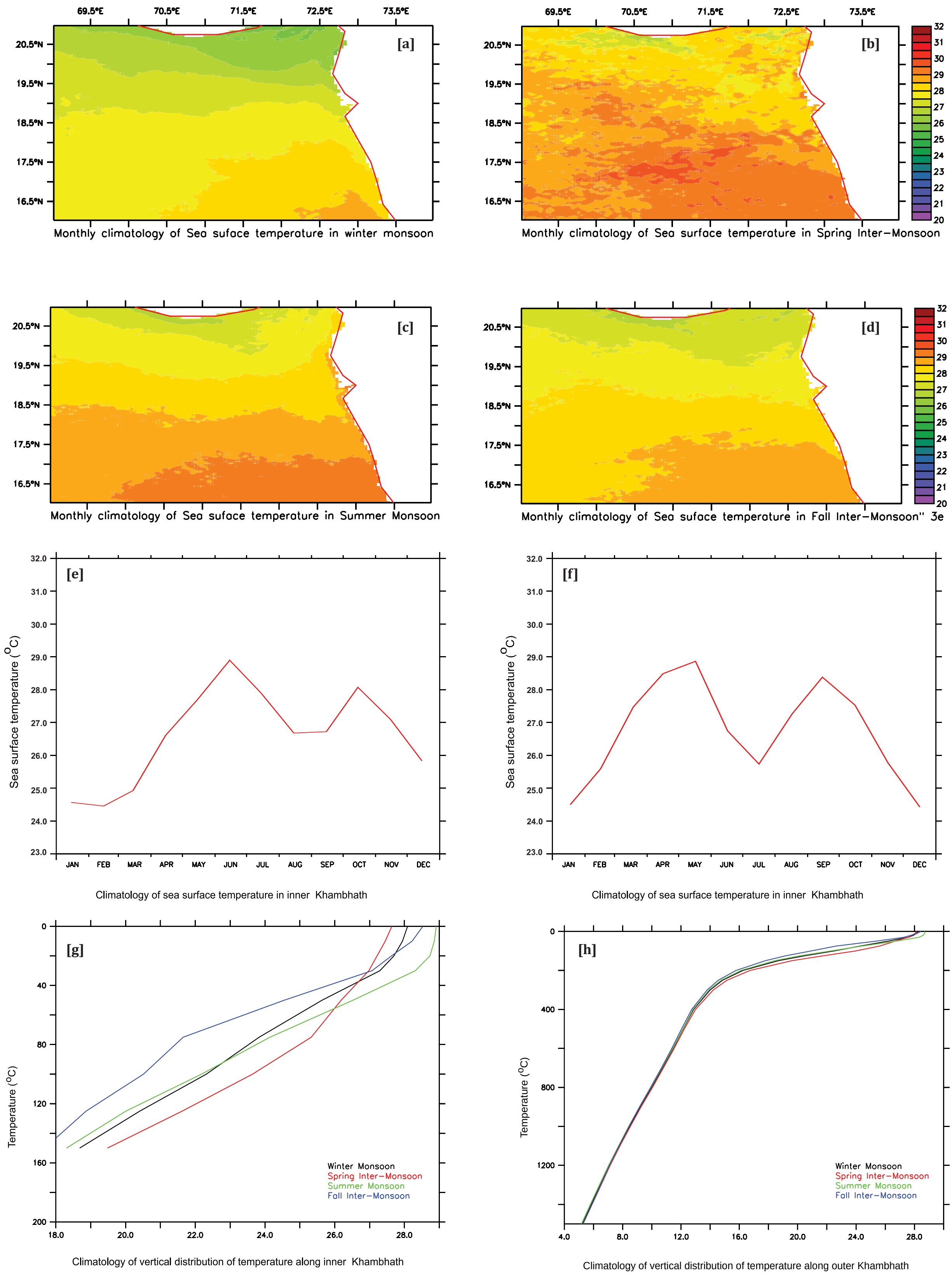

Figure 39: SST variation along Gulf of Khambhat during (a) NEM (b) SIM (c) SWM and (d) FIM. Time evolution of SST for (e) Inner Khambhat and (f) Outer Khambhat. Depth-wise variation of temperature in (g) Inner Khambhat and (h) Outer Khambhat.

The minimum SST is recorded during the NEM time in both regions with a value of 27 to 28.5°C. The highest value of SSS (36.2 psu) has been recorded during SWM, while low SSS has been recorded during FIM. The SSH minimum has ben observed during the SWM and maximum in SIM and NEM. The tidal amplitude at Mumbai Port located within the Khambhat region was about 5 m (**Figure 40**).

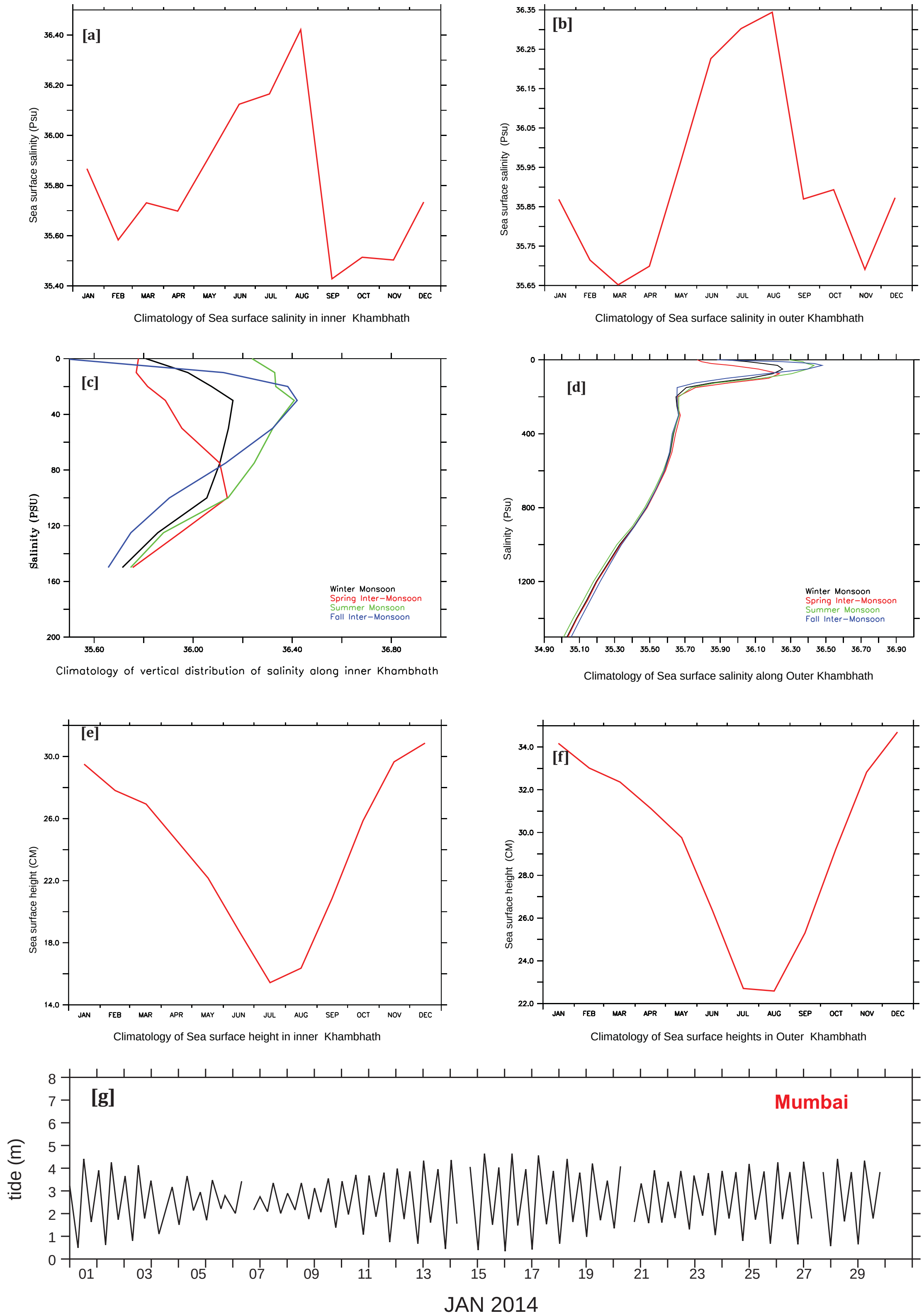

Figure 40: Time series showing evolution of SSS for (a) Inner Khambhat and (b) Outer Khambhat region. Vertical variations of SSS for (c) Inner Khambhat and (d) Outer Khambhat. Time evolution of SSH for (e) Inner Khambhat and (f) Outer Khambhat. The tidal amplitude at Mumbai Port (g) within the Gulf of Khambhat.

4.3.2. Ecological Assets

Water and Sediment Chemistry: The region north of 20°N experiences winter convection during the northeast monsoon time. This leads to formation of vertically homogenous cool coastal waters. The intensity of the winter convection is at its maximum in the shelf region due to shallow water. This leads to build up of nitrate concentrations (Goes *et al.*, 1992). The nitracline is around 80 m. The shelf region is characterised by stratification during summer monsoon and the surface nitrate concentration is less than 0.5 µM. The nitracline varies between 60 m in the inner shelf and deepens to about 80 m in the outer shelf. The high silicate concentration during the summer time is ascribed to river (mainly Narmada and Tapi) and weathering inputs (Sharma and Subramanian, 2008). Denitrification is most intense off the outer shelf of Gulf of Khambhat with the nitrite concentration increasing to >3 µM at the secondary nitrite maxima (Naqvi, 1991).

Average concentrations of trace metals such as Pb, Cd, Cr, Cu, Ni and Co in sediments have been reported to be 13.36, 119.2, 80.8, 172.5, 0.21 and 42.3 mg/kg dry wt, respectively. The elevated concentrations of some of the heavy metals are due to industrial discharges.

Phytoplankton Biomass and Abundance:

(a) Inner Khambhat: The Shelf of Inner Khambat is characterised by many small islands, wetlands, fringing mangroves and rivers/rivulets. The north-south length of shelf is approximately 115 km with rocky beaches being common from Mahua to Gopnath and, not so common between Ghogha and Bhavnagar. The Gulf is intercepted by many inlets of sea and creeks formed by major rivers such as Narmada, Tapi, Mahi, Sabarmati, Shetrunji (ICMAM, *2002b*). The entire coast in general, and the shore from Bhavnagar Creek to Sonrai Creek, in particular is subjected to high erosion owing to loose soil along the banks. They are also affected by strong currents, tidal movements and monsoonal waves. Thus, Gulf receives nutrient load from respective rivers and also the waste-waters from larger towns and cities as well as effluents from small-scale industries (Jaiswar *et al.* 2011). According to a study carried out off Bhavnagar, Bhavnagar Creek, Sonarai Creek and Malcolm Channel, the highest concentrations of Chlorophyll *a* were recorded in Sonarai creek with a of 4.6±4.9 mg/m^3 and 1.0±0.38 mg/m^3, respectively during SIM and FIM. The highest phytoplankton counts during the same period were 1.7±2.3x10^5 cells/L and 5.2±5.8x10^4 cells/L. Results of this study and few other studies are carried out at Dahej and Daman region along the Gulf are listed in **Table 10.**

(b) Outer Khambhat: The Outer Shelf of Khambhat consists of shelf area off the districts of

Table 10: Reported ranges of phytoplankton density and biomass (chlorophyll *a*) from different areas within the Inner Shelf of Gulf of Khambat.

<table>
<tr><th rowspan="2">Region</th><th rowspan="2">Area</th><th colspan="2">Phytoplankton Abundance (cells/L)</th><th colspan="2">Surface Chl a (mg/m³)</th><th rowspan="2">Study Period</th><th rowspan="2">Reference</th></tr>
<tr><th>Min</th><th>Max</th><th>Min</th><th>Max</th></tr>
<tr><td rowspan="4">Rajkot</td><td>Sonrai Creek (N=2)</td><td>3.75±2.4x10³</td><td>1.72±2.3x10⁵</td><td>0.2±0.0</td><td>4.6</td><td rowspan="4">1996-2007</td><td rowspan="4">Jaiswar et al. (2011)</td></tr>
<tr><td>Bhavnagar Creek (N=2)</td><td>1.35±0.63x10³</td><td>1.3±0.5x10⁴</td><td>0.3±0.12</td><td>0.7±0.21</td></tr>
<tr><td>Malcolm Channel (N=3)</td><td>1.65±1.0x10³</td><td>1.19±0.2x10⁴</td><td>0.3±0.35</td><td>0.75±0.35</td></tr>
<tr><td>Off Bhavnagar (N=2)</td><td>1.10±0.5x10³</td><td>1.28±0.7x10⁴</td><td>0.2±0.42</td><td>1.1±0.42</td></tr>
<tr><td>Vadodara</td><td>Dahej (N=16)</td><td colspan="2">1.69±2.63 x10⁵</td><td>0.31±0.2</td><td>2.07</td><td>Jan 2012 and March 2012</td><td>NIO (2012)</td></tr>
<tr><td>Surat</td><td>Off Daman & Damanganga (N=13)</td><td colspan="2">23.2±18.8x10³</td><td>1.32±1.28</td><td>1.36</td><td>Jan 2006 and April 2006</td><td>NIO (2006)</td></tr>
</table>

Mumbai, Raigad and Ratnagiri. Available data on chlorophyll *a* and phytoplankton abundance in Khambhat outer shelf is provided in **Table 11**. On the basis of these data the highest average phytoplankton abundance along this shelf is 8.94±6.64x10^4cells/L off Girgaon area of Mumbai. The highest average concentration of surface chlorophyll *a* of 18.04 mg/m^3 was also recorded in Gorai creek off Mumbai.

Table 11: Reported ranges of phytoplankton density and biomass (chlorophyll *a*) concentrations from different areas within the outer shelf of Gulf of Khambhat.

Region	Area	Phytoplankton Abundance (cells/L)		Surface Chl *a* (mg/m³)		Study Period	Reference
		Min	Max	Min	Max		
Mumbai	Dahanu Creek	-	-	3.30±1.03		Nov. 2008 – Oct. 2009	Kadam and Tiwari [2012]
	Versova Creek	-	-	2.20	15.79	-	CMFRI [2013]
	Mahim Creek	-	-	1.73	16.26	-	
	Gorai Creek	-	-	3.89	18.04	-	
	Girgaon Beach	8.94 ± 6.64x10^4		7.08±5.26		June 2013	NIO [2014]
Raigad	Dharamtar Creek (N=5)	2.89±2.29x10^5		1.94±0.22		Sept.1984- Nov. 1985	Tiwari and Nair. [1998]
Ratanagiri	Vashisthi Estuary (N=7)	6.17± 4.42x10^4	7.41±4.53x10^4	0.9±0.5	2.74± 1.49	March 2007 and Dec. 2007	NIO [2007]

Zooplankton Biomass and Density:

(*a*) *Inner Khambhat*: Zooplankton biomass varied widely among the four estuaries within the inner Khambhat region with a minimum in Mindola estuary (1.35 ml/100m^3) and maximum in Ambika estuary (7.43 ml/100m^3) (**Table 12**). Similarly, the density also showed a large variation (Nair *et al.*, 1981). Zooplankton production ranged from a minimum density of 1.5 x 10^6 Nos./100m^3 at Piram Island to a maximum density of 3.9x 10^7 Nos./100m^3 at Mahuva (ICMAM, 2002b).

Table 12: Zooplankton biomass (ml/100m³) and density (Nos./100m³) recorded along Khambhat Inner Shelf.

Region	Area	Biomass (ml/100m³)			Density (Nos./100m³)			Reference
		Min	Max	Mean	Min	Max	Mean	
Gulf of Khambat	Mahuva	-	-	-	11.75x1 0^6	39.0x 10^6	-	ICMAM [2002b]
	Alang	-	-	-	6.0x10^6	13.8x 10^6	-	
	Piram island	-	-	-	1.5x10^6	6.5x 10^6	-	
	Aliya island	-	-	-	4.5x10^6	4.8x 10^6	-	
	Auranga estuary	3.33	5.45	4.46	1.1x10^3	2.75x 10^5	7.4x10^4	Nair et al. [1981].
	Ambika estuary	1.80	7.43	5.3	1x10^2	1.7x10^5	6.2x10^4	
	Purna estuary	2.21	6.29	4.25	1.3x10^3	1.3x10^5	5.2x10^4	
	Mindola estuary	1.35	5.47	4.81	7.0x10^2	1.3x10^5	6.0x10^4	

(b) Outer Khambhat: The zooplankton biomass and density (in terms of numbers) in the out

Khambhat also showed large variation (**Table 13**). Kadam and Tiwari, (2012) recorded zooplankton biomass in the range of 12.50 to 120.80 ml/100 m^3 and a density in the range of 1.2 to 11.8 $x10^5$ Nos./ 100m^3 off Dahanu coast. In contrast, zooplankton biomass as low as 0.01 ml/100m^3 off Mumbai has been reported by Gajbhiye *et al.* (1984) during premonsoon district) during pre-monsoon and found that zooplankton biomass to be in the range of 5.3–28.3 ml/100m^3. Off Ratnagiri, the zooplankton biomass was to be in the range of 20–50 ml/100m^3 (Madhupratap et al., 1990). Various reported values of zooplankton biomass and density from within the province of Khambat outer shelf are listed in **Table 13**.

Table 13: Zooplankton biomass and density along Khambhat Outer Shelf (PrM=Pre-monsoon; M= Monsoon; PoM=Post-monsoon).

Regions	Area	Depth (m)	Season	Biomass (ml/100m³)			Density (Nos./100m³)			Reference
				Min	Max	Mean	Min	Max	Mean	
Thane	Dahanu sea (n=3)	5-26	PoM	65.40	120.80	80.94	$4.7x10^5$	$1.2x10^6$	$8.4x10^5$	Kadam and Tiwari (2012)
	Dahanu creek (n=2)		PoM	12.50	64.30	29.62	$1.2x10^5$	$6.2x10^5$	$3.8x10^5$	
Mumbai	Malad creek	12-15	PrM	0.01	13.2	3.4	70	$3.7x10^4$	-	Gajbhiye *et al.* (1984)
	Thal (n=9)	4-12.5	PrM	9.61	15.09	12.12	$9.7x10^3$	$4.4x10^5$	$5.7x10^4$	Nair *et al.* (1983)
			M	12.71	27.57	21.25	$7.0x10^3$	$2.4x10^5$	$6.4x 10^4$	
			PoM	25.1	43.95	35.38	$1.2x10^4$	$2.4x10^5$	$8.2x10^4$	
	Off Mumbai (n=15)	15-20	PrM	4	64	20	$1.2x10^5$	$7.0x10^5$	$2.0x10^5$	Nair and Ramaiah (1998)
			M	2	78	23	$6.7x10^3$	$2.2x10^5$	$4.2x10^5$	
			PoM	60	290	87	$5.9x10^4$	$2.0x10^5$	$1.0x10^5$	
	Off Girgaon (n=13)	10-25	M	3.51	22.06	10.23	$1.2x10^3$	$5.3x10^4$	$1.2x10^4$	NIO (2014)
			PoM	5.91	232.24	63.63	$2.0x10^3$	$7.8x 10^5$	$3.4x10^5$	
Raigad	Dharamtar creek (n=5)	8-11	PrM	1.41	26.63	13.11	$3.0x10^3$	$2.4 x 10^5$	$3.5x10^4$	Tiwari and *Nair* (1993)
			M	1.17	135.33	42.83	$1.2x10^4$	$1.8x 10^6$	$2.9x10^5$	
			PoM	1.12	81.75	20.96	$6.2x10^3$	$1.2x10^5$	$7.2x10^4$	
Ratnagiri	Jaigad to Rajapur (n=32)	5-20	PrM	5.3	28.3	12.27	-	-	-	Nair *et a*l. (1980)
	Off Ratnagiri	-	PoM	20	50	30	-	-	-	Madhupratap *et al.* (1990)

season. It appears that zooplankton do attain sizable biomass during the productive postmonsoon season. Biomass values as high as 290 ml/100m^3 have been recorded by Nair and Ramaiah (1998) during postmonsoon season. Minimum zooplankton density (70 Nos./100m^3) has been reported by Gajbhiye *et al.* (1984) during premonsoon season, while maximum density (3.4x 10^5 Nos./100m^3) has been reported by during postmonsoon season (NIO, 2014).

Tiwari and Nair [1993] reported lowest zooplankton biomass (1.12 ml/100m^3) during postmonsoon season, while highest biomass (135.33 ml/100m^3) during monsoon season from Dharmtar Creek. They also reported minimum zooplankton density (3.0$x10^3$ Nos./100m^3) during premonsoon season, while maximum (1.7$x10^6$ Nos./100m^3) during monsoon season. Nair *et al.* [1980] studied zooplankton distribution from Jaigad to Rajapur (Ratnagiri

4.4. South West Indian Shelf

4.4.1.Biophysical Drivers

Geomorphological Features: The South west Indian Shelf Province includes the coast and shelf region off the states of Goa, Karnataka and Kerala. Evidences of both emergence and submergence are available along the coasts of these states. The Karnataka Plain is about 8-25 km wide. This forms the narrowest part of the coastal plain. The description of this province is given from north to south **(Figure 41)**. The northern part of the region has cliffy coastline with raised platforms with evidences of submergence.

The beaches along south west Indian shelf undergo seasonal changes in morphology. The coast of Karnataka is marked by the presence of linear beaches, estuaries, spits, mudflats, shallow lagoons and belts of mangroves (Schwartz, 2005).

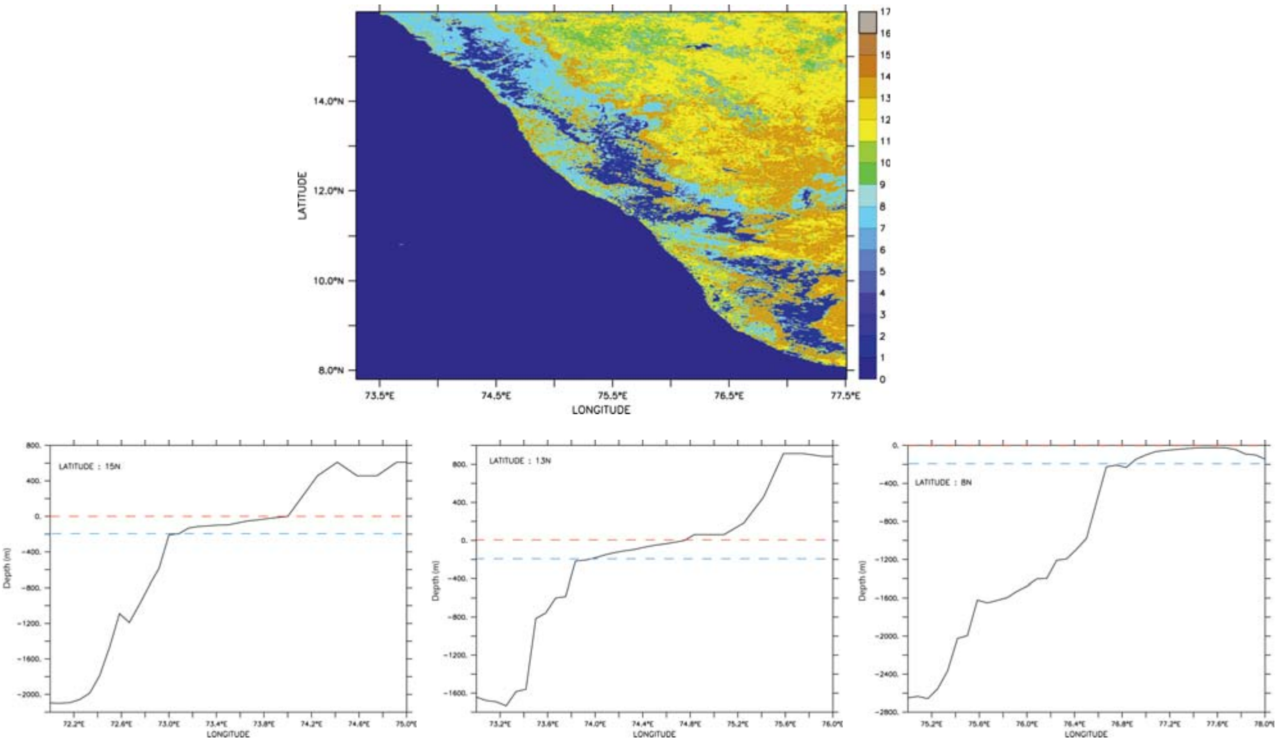

Figure 41: Land cover map in and around the Malabar Coast derived from International Geosphere-Biosphere Program (Top). Depth section off the continental shelf along 15°N, 13°N and 8°N (Bottom) . The red and blue dashed line indicate 0 m and 200 m depth contours, respectively. See **Table 5** for the different land cover classification.

There are few islands off the coast of Karnataka of which St. Mary's Island (~4 km off Malpe) is the most important one. The main rivers draining into the Arabian Sea, in this region are Mandovi, Zuari, Kali, Gangavali, Aganashini, Sharavathi, Mulki and Gangolli. These rivers form estuaries which are aligned with sandbars.

The north-west to south-east trending Kerala coastline is more or less straight. North Kerala coast and south Kerala coast (between Trivandrum and Kollam) are predominantly characterised by rocky promontories and lateritic cliffs interspersed with beaches. Kovalam and Varkala cliffs are two important examples of cliffs on Tertiary sediments in south Kerala. The central part (Alleppey-Ponnani stretch) is of recent alluvium (Chattopadhyay, 2010). Development of barrier bars and spits are important features in the Kerala coast aided by the southwesterly direction of the waves during summer monsoon which leads to alongshore drifts of the sediments. These barrier features protect Kerala coastline from erosion and has resulted in formation of backwaters and lagoons behind the sand bars and spits (**Figure 42**).

Figure 42: Lake and Backwater Ecosystem of Kerala (Malabar Coast) obtained from Google Earth image.

In addition to these barriers and spits, a unique feature of the Malabar coast is the presence of mudbanks. These are areas of calm waters that form along certain parts of the coast during the southwest monsoon period, when the wave activity is very high. Hence, the formation of mudbanks along some parts of the coast during southwest monsoon period also protects the coast from erosion. Out of the 570 km long coastline, about 420 km of the coastline is safeguarded by these barriers, while severe erosion has plagued the southern part of Kerala coast [Schwartz, 2005]. These are areas that have muddy bottoms and absorb the wave energy during the southwest monsoon period leading to churning of the bottom sediments in a thick suspension. Following the cessation of southwest monsoon the mud settles down (Gopinathan and Qasim, 1974).

The continental shelf has width varying between 60 and 185 km off Goa to about 110 km off Bhatkal in Karnataka to about 60 km off Cochin with the depth contours running almost parallel to the coast (Rao and Wagle, 1997). Placer deposits in river beds, beaches and continental shelf off Kerala are of economic importance. The inner shelf north of Quilon is composed by clay and biogenic carbonate sands between Quilon and Cape Comorin. The lower supply of sediments by the rivers south off Quilon has resulted in calcareous sediments. Wedge Bank characterised by flat and wide shallow bottom is present south of Quilon. Smectite dominate the inner shelf and Kaolinite and illite dominate the clay fraction both in the outer shelf and the slope of the region (Rao and Rao, 1995). This indicates that the sediments have been primarily derived from the Gneissic Province of the Western Ghat that runs between Goa and Cochin.

Climate: The climatology of the air temperature in the Southwest Indian Shelf shows a bimodal character (**Figure 43**). There are two peaks, one in May and another in September. The air temperature drops in July. Besides, there is a decrease of air temperature in December due to the winter, when the sun is over the southern hemisphere. The precipitation in the Southwest Indian sgelf shows a peak in the month of June. This is the period of the south-west monsoon. The monsoonal winds blow towards the Indian subcontinent and encounter the Western Ghats, which cause the moisture-laden winds to rise, undergo condensation and cause precipitation. The evaporation climatology in the Souuthwest Indian Shelf shows a high value in the month of

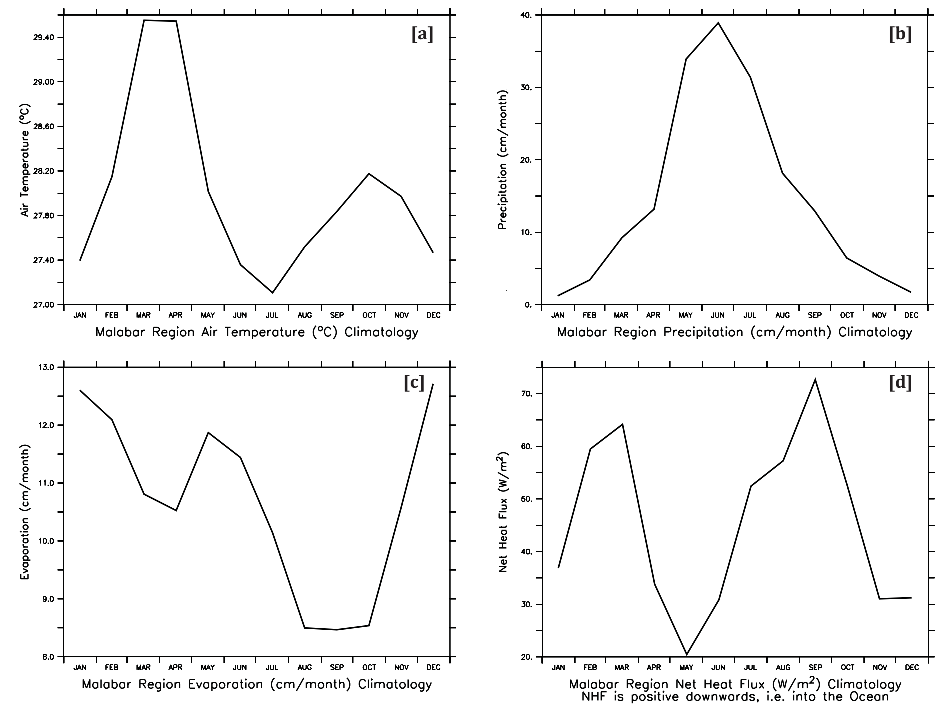

Figure 43: Mothly climatology showing evolution of (a) air temperature (^{0}C) (b) precipitation (mm/month) (c) evaporation (mm/month) and (d) net heat flux (W/m^2) for South west Indian Shelf region.

December and in May. The wind speed increases in strength during May. The net heat flux shows bimodal peaks in March and September. There is a dip in May and in November. The high amount of evaporation causes a decrease in the net heat flux during May.

Oceanography: In the Southwest Indian shelf, the SST varies from 28–30 °C all other seasons except SWM period (**Figure 44**). During the SWM

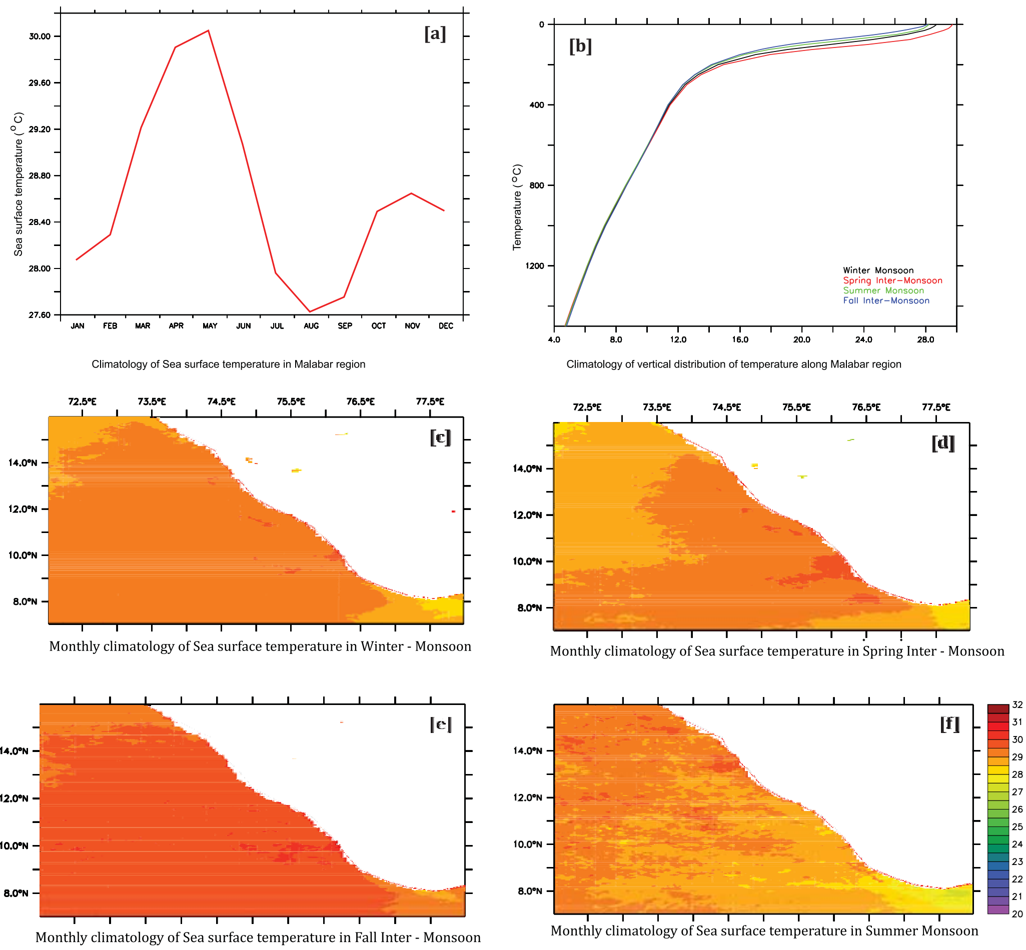

Figure 44: Temporal evolution of SST in the South west Indian Shelf region (a) season-wise vertical profile of SST (b). Spatial distribution of SST along the Malabar Coast during (c) NEM (d) SIM (e) SWM and (f) FIM.

period, the SST reduces to 27.6 °C as this coast experiences seasonal upwelling driven by summer monsoon. The surface salinity along this coast is the highest during SIM and early SWM (35.30 psu) and lowest in January (31.12 psu) (**Figure 45**). During winter monsoon, the West India coastal current (WICC) carries low salinity Bay of Bengal waters into this shelf region (Prasanna Kumar *et al.*, 2004)

The SSH undergoes an annual cycle with minimum and maximum recorded in this region is around 28-34 cm and 60 cm in SWM and NEM periods, respectively. (**Figure 45**). Marmugao and Kochi are two major ports located adjacent to the South West Indian Shelf where the tidal amplitude vary between 1-2 m.

4.4.2. Ecological Assets

Water column chemistry : The Southwest Indian Shelf is influenced by seasonal upwelling during the south west monsoon and downwelling during the northeast monsoon periods. Accordingly, concentrations of nutrient and dissolved oxygen (DO) are modulated by these phenomena in this South West Indian Shelf. As upwelling intensifies, an oxygen level <0.5 ml/L shrouds the entire continental shelf off the west coast of India (Naqvi *et al.*, 2000), making this region the largest coastal hypoxic system in the world. During the peak of the SWM, denitrifying conditions develop.

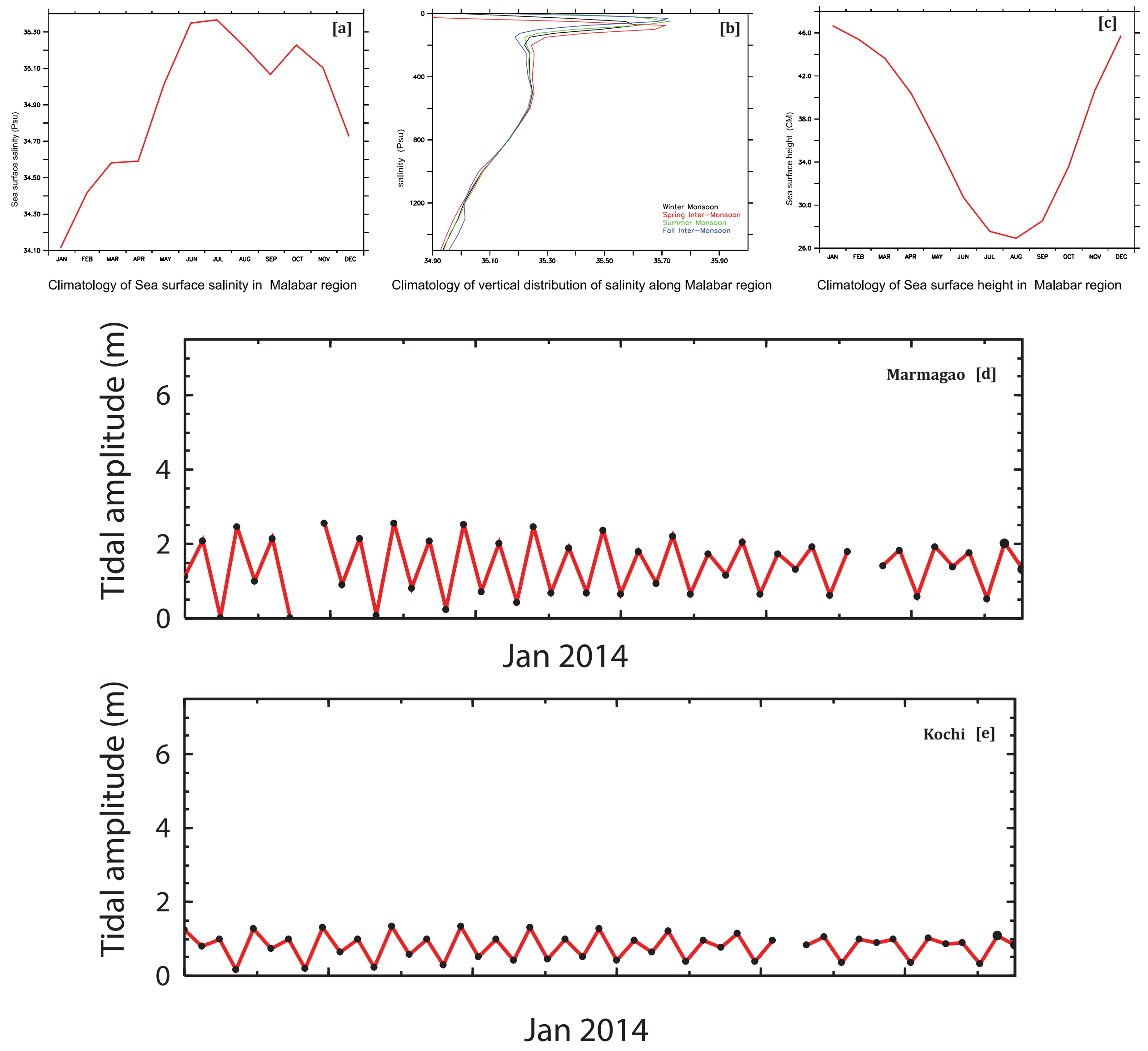

Figure 45: Time evolution of (a) SSS along South west Indian Shelf, (b) season-wise vertical distribution of SSS, (c) time evolution of SSH and time variation of tidal amplitude for (d) Marmugao and (e) Kochi Ports.

Reported rates of denitrification are from 5 nmol L^{-1} d^{-1} (Devol, 2006) to 1 µmol L^{-1} d^{-1} (Naqvi *et al.*, 2006). During the late SWM, anoxic conditions take over (Naqvi *et al.*, 2009). An important process along the Southwest Indian Shelf during the NEM period is the intrusion of the Bay of Bengal water, a mechanism of maintaining inter-basin hydrographic balance in the northern Indian Ocean. Consequently, an enhancement of upper layer nitrate concentration in excess of 0.5 µM also takes place. However, the influence of Bay of Bengal water decreases as one progresses towards the north and a fall in the nitrate levels is also seen (Prasanna Kumar *et al.*, 2004). Around 15ºN, there is another region of local nitrate increase to >0.5 µM. This is probably from the discharges by Mandovi and Zuari rivers. The second important process is the coastally-trapped downwelling Kelvin wave that deepens the thermocline and suppresses the nitracline. This is most pronounced during the late NEM and results in low nutrient concentrations.

Phytoplankton Biomass and Abundance: As noted above, upwelling during south west monsoon and down-welling during northeast monsoon periods influence biological productivity characteristics in the Southwest Indian Shelf. With enriched nutrient concentrations during southwest monsoon, the phytoplankton biomass increases. The overall general picture of phytoplankton abundance and chlorophyll *a* concentrations suggest a greater primary productivity during the July-October period (**Table 14**). The reported values of maximum phytoplankton abundance ($1.15x10^6$ cells/L) from Mandovi estuary and the minimum phytoplankton abundance ($2.23x10^3$ cells/L) off Vengurla can be considered as maximum and minimum abundance values, respectively, for this Province.

Table 14: Overview of phytoplankton abundance and biomass (Chlorophyll *a*) along the South west Indian Shelf at different locations.

Region	Area	Phytoplankton Abundance (cells/L)		Surface Chl *a* (mg/m³)		Study Period	Reference
		Min	Max	Min	Max		
Sindhudurg	Vengurla (N=18)	$2.23 \pm 0.6x10^3$		4.86 ± 1.19		Oct. 2012	NIO (2013)
Goa	Mandovi estuary (N=187)	$1.42 \pm 0.88x10^4$		1.95±1.6	5.76±3.1	May 2007-Nov. 2007	Parab et al. (2013)
	Mandovi estuary (N=1-5)	$2.63x10^5$	$1.15x10^6$	20.46±2.2	43.63	Jan. 2005	Bhaskar et al. (2011)
	Mandovi, Cabo and Zuari (N=3)	$1.07 \pm 0.29x10^4$		2.55 ± 0.33		22 Months	Kumari and John (2003)
	Zuari	$1.02x10^5$	$3.7x10^5$	3.97	11.44	April and Sept. 2002	Matondakar et al. (2007)
	Off Goa	-	-	5.60		Oct.- Nov. 1999	Gopinathan et al. (2001)
Karnataka	Karwar (N=9)	$0.94x10^4$		2 .22		Dec. 2011	NIO (2012)
	Netravati and Gurupura Estuary (N=3)	$16.94x10^3$	$28.64x10^3$	1.67 (N=1)	4.87 (N=1)	June 2010–May 2011, Dec. 2005-January 2006	Shruthi and Rajshekar (2013) Harnstorm et al. (2009).
	Tadadi (N=18)	$79.63 \pm 43.95x10^2$		2.88 ± 1.83		Dec 2010	NIO (2011)
Kerala	Off Kerala (N=3-5)	-	-	2.25	8.49	Jan. to October	Manjusha et al. (2013)
	Cochin backwater (N=9)	$3.3 \pm 2.3x10^4$	$6.2 \pm 2.70x10^4$	5.9± 2.7	17.4±14.6	April – Oct. 2003 and Jan. 2001 - Dec. 2002	Madhu et al. (2007) Selvaraj et al. (2003)

Similarly, the chlorophyll *a* concentrations of 43.63 mg/m³ from Mandovi estuary and 1.61 mg/m³ in Netravati and Gurupur Estuary might signify its range for this Province. Along Kerala coast, all biological processes are very profoundly influenced by monsoonal upwelling and river runoff [Gopinathan *et al*. 2001]. Indeed the chlorophyll *a* concentrations are far greater in this region within the province. The seasonal average chlorophyll *a* concentration during 1988-2006 period ranged from 0.51 - 0.61 mg/m³ (premonsoon) 1.15 - 4.01 mg/m³ (monsoon) and 0.7 -3.1 mg/m³ (postmonsoon). Long-term variability of surface chlorophyll a concentration derived through composite satellite imageries by George *et al*. (2012) is shown in **Figure 46** and the satellite image of chlorophyll *a* concentration along Kerala coast during an algal bloom is depicted in **Figure 47**.

Zooplankton Biomass and Density: As a consequence of intense upwelling and a rapid

Progression of Chlorophyll *a* in three coastal states

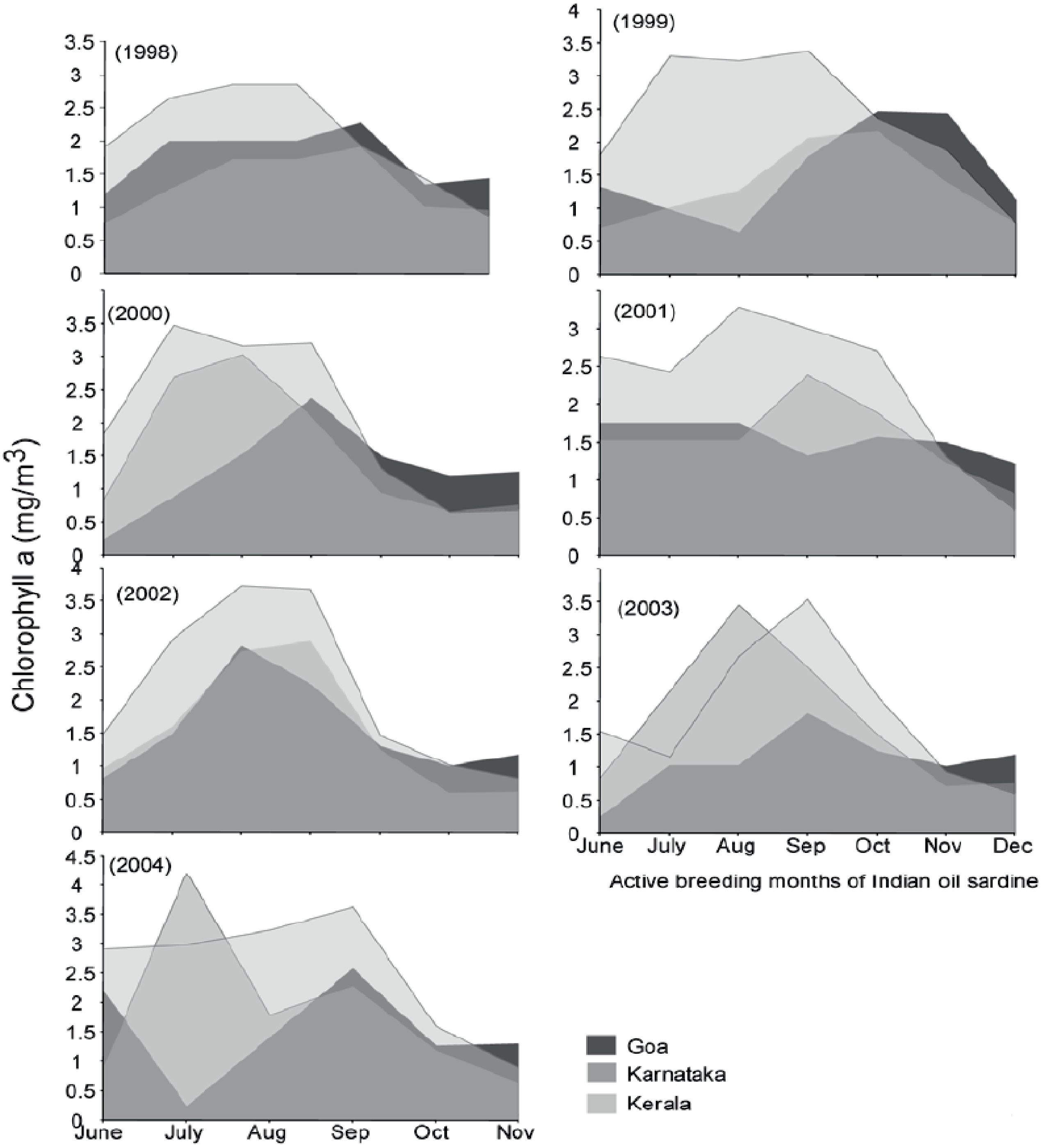

Figure 46: Remotely sensed chlorophyll *a* in three states of South west Indian Shelf from 1998- 2004 (Source: Gorge *et al.*, 2012).

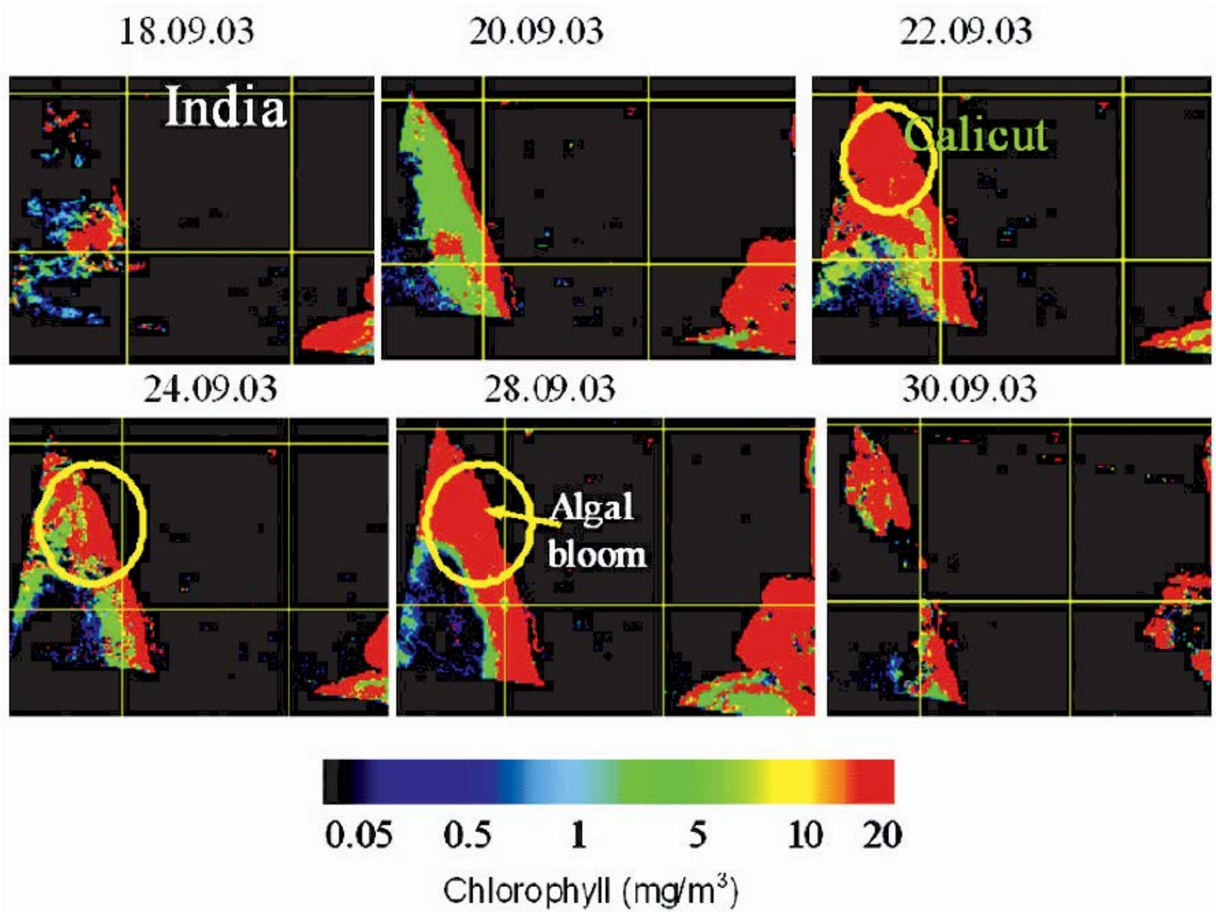

Figure 47: IRS-P4 OCM derived chlorophyll images during algal bloom phases in September off Kerala coast (Source: Sarangi and Mohammed, 2011).

build-up of chlorophyll *a* biomass, the secondary productivity in this province is very substantial (**Table 15**). For instance Madhupratap *et al.* (1992) reported average biomass of zooplankton of 17 ml/100m^3 and density of 8.5x10^4 Nos./100m^3 during monsoon season. According to NIO report (NIO, 2013) zooplankton biomass and density, respectively ranges from 5.5 to 31.7 ml/100m^3 and from 1.1x10^4 to 8.3x10^4 Nos./100m^3 during postmonsoon season. A seasonal study of zooplankton along Goa coast by PrabhuKonkar (2008) documented that the lowest (40 ml/100m^3) and the highest (210 ml/100m^3) biomass values occur during post-and premonsoon seasons, respectively. Zooplankton density recorded in the same study is in the range of 3.8x10^5 - 1.5x10^7 Nos./100m^3. Along Uttara Kannada coast (Karnataka), zooplankton biomass ranged from 1.11 to 12.0 ml/100m^3 and density from 19 to 4.0x10^4 Nos./100m^3 (NIO, 2011; NIO, 2012). Along Dakhshina Kannada coast, the biomass and density are reported to be in the range of 40-50 ml/100m^3 and 5.6x10^5-1.0x 10^7 Nos./100m^3, respectively [PrabhuKonkar, 2008]. From Kerala coast Jayalakshmi *et al.* (2011) reported biomass in the range of 16-90 ml/100m^3 during monsoon season.

4.5. West Indian Slope (North-west and South-West)

4.5.1.Biophysical Drivers

Geomorphological Features: Contrary to the continental shelf, the western continental slope is narrow in the north and wide to the south. The huge accumulation of sediments of Indus River has

Table 15: Zooplankton biomass and density recorded along South west Indian Shelf (PrM=Pre-monsoon; M= Monsoon; PoM=Post-monsoon)

Regions	Area	Depth (m)	Season	Biomass (ml/100m³)			Density (Nos./100m³)			Reference
				Min	Max	Mean	Min	Max	Mean	
Malabar Shelf	Goa, Karnataka, Kerala	Coastal (n=8)	M	17			8.5×10^4			Madhupratap et al. (1992)
Sindhudurg	Vengurla (n=18)	10-16	PoM	5.5	31.7	14.38	1.1×10^4	8.3×10^4	2.7×10^4	NIO (2013)
Goa	-	-	-	75	100	-	-	-	-	Goswami [1996]
	N=3	30-100	PrM	210	460	-	5.9×10^5	3.0×10^6	-	Prabhukonkar (2008)
			M	100	370	-	3.4×10^5	1.5×10^7	-	
			PoM	40	430	-	3.7×10^5	1.3×10^6	-	
North Goa	Mandovi (n=36)	7-12	Annual	1	90	14	1.0×10^3	2.6×10^6	1.6×10^5	Padmavati and Goswami (1996)
	Zuari (n=36)			2	190	20	4.0×10^3	1.0×10^6	1.5×10^5	
Uttar Kannada	Karwar (n=15)	6-45	PrM	8.19	39.95	22	6.0×10^3	2.8×10^4	1.1×10^4	NIO (2012)
			PoM	5.80	44.03	22.69	7.0×10^3	4.0×10^4	1.7×10^4	
	Tadadi (n=18)	7-36	PrM	1.11	15.62	6.55	19	312	102	NIO (2011)
			PoM	12.0	51.5	32.41	882	4.0×10^3	2.3×10^3	
Dakshina Kannada	Manglooru (n=9)	5-15	PoM	4	38	-	-	-	-	Devassy et al. (1987)
	Manglooru (n=3)	30-100	PrM	50	700	-	8.1×10^5	1.2×10^6	-	Prabhukonkar (2008)
			M	40	710	-	1.4×10^6	1.0×10^7	-	
			PoM	50	130	-	5.6×10^5	5.0×10^6	-	
Karnataka	-	-	-	150	200	-	-	-	-	Goswami [1996]
Kerala	-	-	-	100	150	-	-	-	-	
	Off Kochi/ Trivendram (n=6)	10-100	M	16	90	52	-	-	-	Jayalakshmi et al. (2011)

significantly modified the slope morphology to the north of the Kathiawar. Accordingly, bottom of the slope is shallow near the Indus mouth (Chauhan *et al.,* 1993) varying from less than 1500 m depth in the north to more than 2500 m depth in the south. The burial of the surface features by Indus sediment have resulted in steeply sloping, but smooth slope off the Kutchch region. However, southwards, the slope surface is gentle and uneven (Chauhan *et al*., 1993). Deep terraces and structural benches are located off Saurashtra and Mumbai. Evidences of topographic highs are found in the sector between Goa and Cochin, while signs of slumping are present off Goa-Ratnagiri region (Rao and Wagle, 1997). The sediment in the continental slope is composed of clayey silts with carbonate (Rao and Wagle, 1997).

Climate: The climatology of the air temperature in this Province shows a bimodal character (**Figure 48**). There are peaks in April and also in September. The air temperature falls in July. Besides, there is a decrease in January due to the winter, when the sun is over the southern hemisphere, and also due to the blowing of cold dry land winds. The precipitation in the slope region shows a peak in the month of June coinciding with the south-west monsoon period. The evaporation over the West Indian Slope region shows a bimodal character, with peaks during June and December. The major peaking in December is due to the dry continental winds blowing causing a high amount of evaporation in the Northern Arabian Sea. The net heat flux shows a bimodal peak in March and September. There is a dip in the month of July and negative values in the month of January. The high amount of evaporation causes a loss of heat from the ocean, in the winter.

Oceanography: High SST values show around 29 to 30 °C in the SIM and NEM time and comparatively low values of 28-26 °C are seen

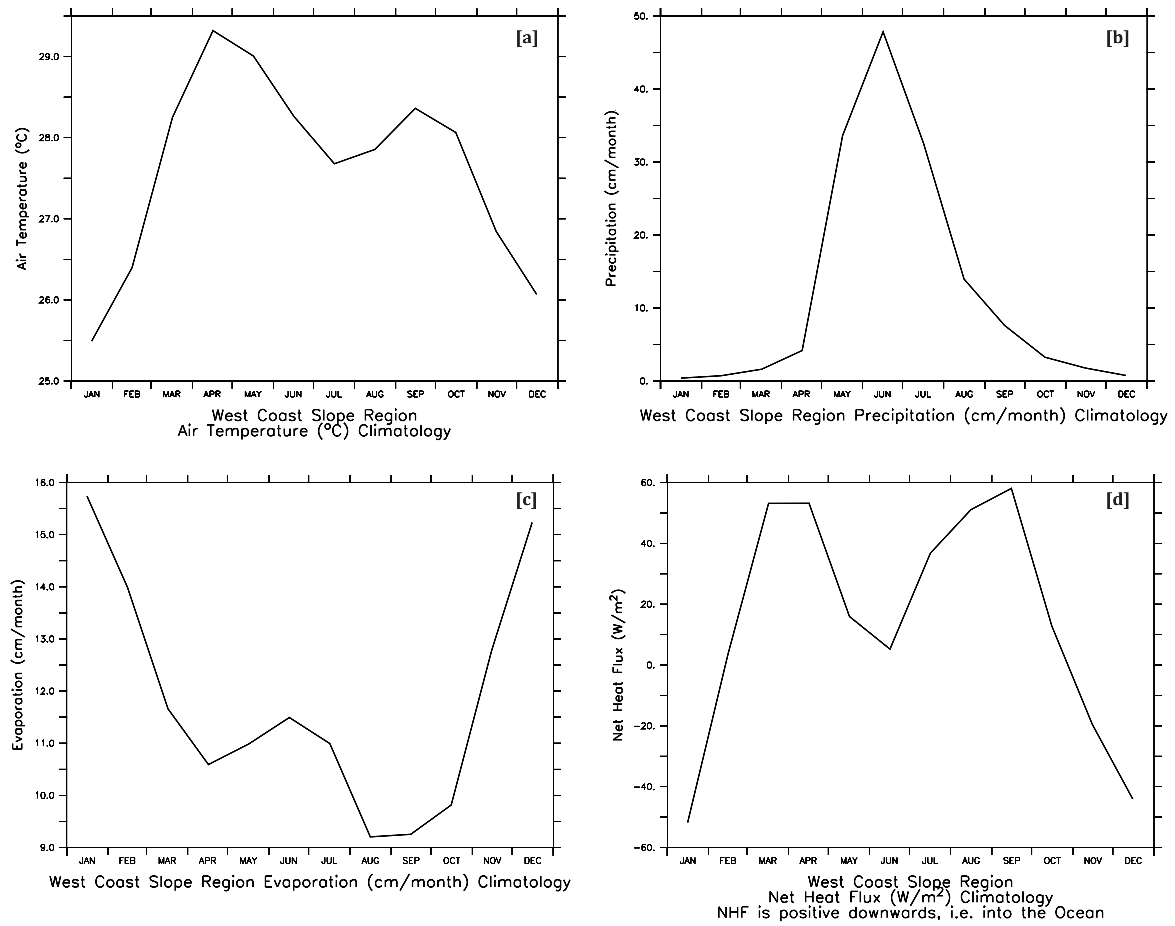

Figure 48: Monthly climatology showing evolution of (a) air temperature (ºC) (b) precipitation (cm/month) (c) evaporation (cm/month) and (d) net heat flux (W/m^2) for the west Indian slope region.

during the SWM time (**Figure 49**). High SSH during the SIM (around 34 cm) and in low SSH during the SWM (around 26-22cm) have been recorded (**Figure 50**).

4.5.2. Ecological Assets

Zooplankton Biomass and Density

North-west Indian Slope : The Northwest

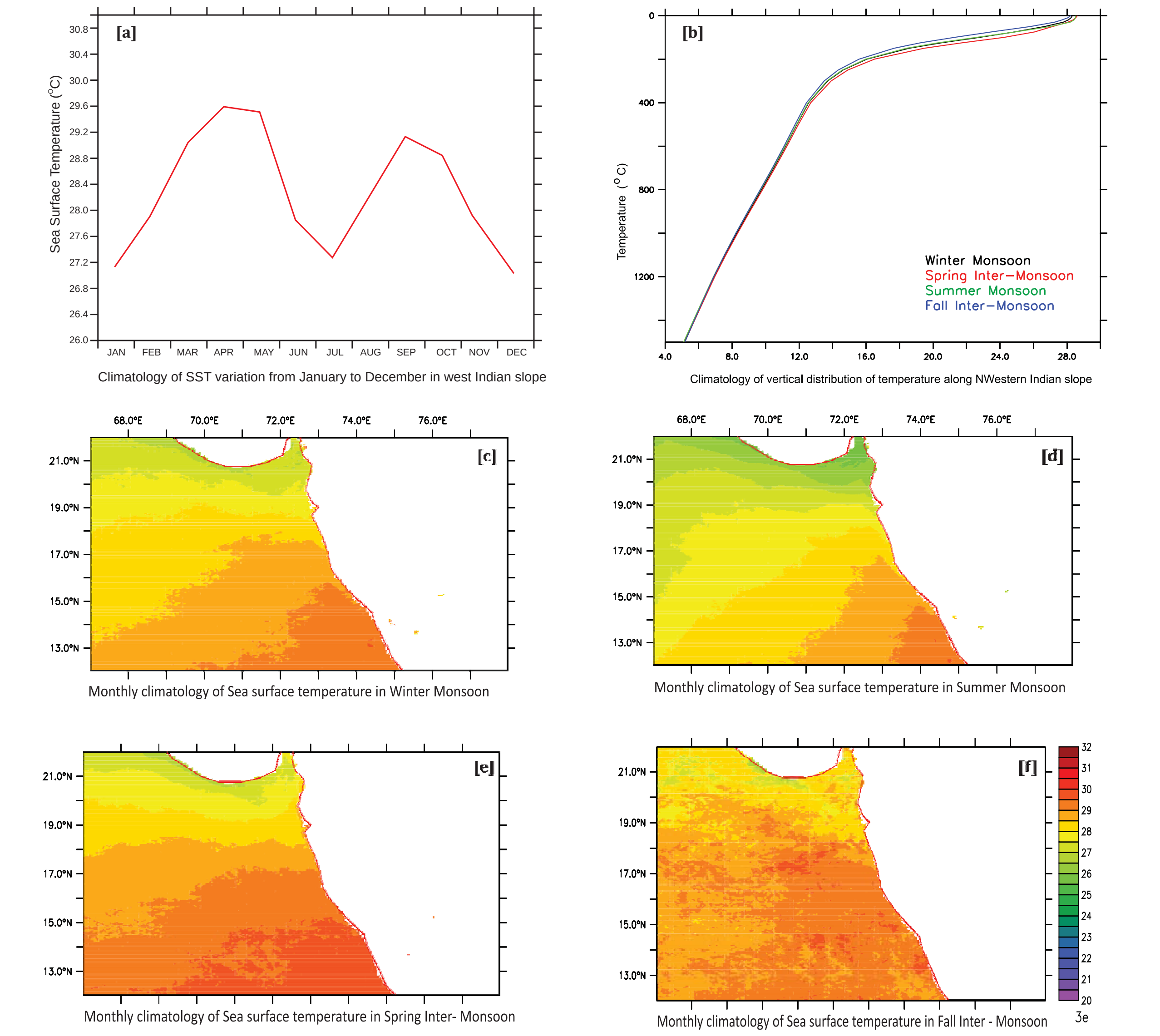

Figure 49: Temporal evolution of SST in the North west Indian Slope region (a) season-wise vertical profile of SST (b). Map of SST variation along the North eastern Arabian Sea during (c) NEM (d) SIM (e) SWM and (f) FIM.

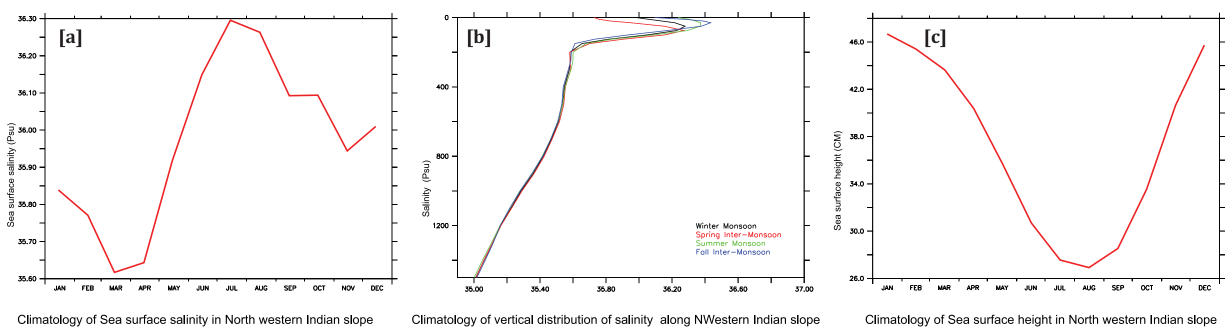

Figure 50: Time evolution of SSS along northwest Indian Shelf (a) season-wise vertical distribution of SSS (b) and time evolution of SSH (c).

Indian Slope Province that covers the area having water depth > 200m off Karnataka, Goa, Maharashtra and Gujarat coast. Few sporadic studies have been conducted in this Province (**Table 16**). Zooplankton sampling via vertical hauls have been carried out mostly for the upper 200m water column. Vijayaraghavan *et al.* (1982 reported zooplankton biomass of 3.2 - 19.2 ml/100m3*)* and density of 1.3x104-1.0x105 Nos./100m3 off Goa during post-monsoon. During the same seasone, Krishnakumari and Nair (1988) reported the mean zooplankton biomass values of 20.18, 30.74, and 77.18 ml/1003 for the slope waters off Goa, Maharashtra and Gujarat, respectively. During monsoon season , zooplankton biomass and values observed to be in the range of 5 - 40 ml/100m3 and 5.0 x103 - 5.0x104 Nos. /100m3, respectively (Achuthankutty *et.al.*, 1992).

Table 16: Zooplankton biomass and density recorded along North West Indian Slope (PrM=Pre-monsoon; M= Monsoon; PoM=Post-monsoon).

Region	Depth	Season	Biomass (ml/100m³)			Density (Nos./100m³)			Reference
			Min	Max	Mean	Min	Max	Mean	
Off Goa	200 m to surface (n=21)	PoM	3.2	19.2	8.76	1.3×10^4	1×10^5	4.2×10^4	*Vijayaraghavan et al.* (1982)
Off Goa	200 m to surface (n=3)	PoM	-	-	20.18	-	-	-	Krishnakumari and Nair, (1988)
Off Maharashtra	200 m to surface (n=9)	PoM	-	-	30.74	-	-	-	
Off Gujarat	200 m to surface (n=6)	PoM	-	-	77.18	-	-	-	
Off Karnataka, Goa, Maharashtra, Gujarat	200 m to surface (n=30)	M	5	40	-	5×10^3	5×10^4	-	*Achuthankutty et al.*, (1992)

South-west Indian Slope : Only few studies on zooplankton have been carried out from this sub-province of West Indian Slope. Zooplankton biomass in the range of 5 - 10 ml/100m3 and average density of 5 x 103 Nos./100m3 have been reported by Achuthankutty *et al.*(1992) (**Table 17**) Whereas, studies by Madhupratap *et.al.* (1992) have reported average biomass of 60 ml/100m3 and density of 6.6x104 Nos./100m3 during monsoon season. Seasonal and diurnal

Table 17: Zooplankton biomass and density recorded from South West Indian Slope during monsoon season.

Regions	Area	Biomass (ml/100m³)			Density (Nos./100m³)			Reference
		Min	Max	Mean	Min	Max	Mean	
Off Kerala	200 m to surface (n=10)	5	10	-	-	-	5.0×10^3	Achuthankutty et al. (1992)
South Western Indian Slope	200 m to surface (n=7)	60			6.6×10^4			Madhupratap et al. (1992)

distribution of zooplankton has been carried out along major islands of Lakshadweep. Achuthankutt *et al.* (1989) reported the lowest zooplankton biomass (13 ml/100m3)and density (3.0 x104 Nos./100m3) in lagoon area of Kalpeni Island and maximum biomass (3.3 ml/1003) and density (5.8 x 105 Nos./100m3) in surrounding waters of Agatti Island. Suresh and Mathew (1997) reported minimum density (6.3 x103 Nos./100m3) during day time and maximum density (5.8 x 105 Nos./10m3) during night time along Kavaratti Island. Most recently, Sanu et al. (2014) recorded seasonal variation in zooplankton distribution along Kavaratti Island and reported variation in the density in the range of 1.5 x104 - 1.5 x 105 Nos./100m3.

5. Bioresource Potential and Biodiversity of West Coast of India

5.1. Overview of Marine Fisheries

Five maritime states (Gujarat, Maharashtra, Goa, Karnataka and Kerala) one Union Territory (Daman and Diu), and one archipelago of islands (the Lakshadweep) occupy the west coast of India. About 15 million coastal people depend on fishery resources (Livestock Census, 2003; **Table 18**). Marine fish landings data suggest that Gujarat and Kerala are top producers (**Table 19**), mostly due to their rich marine resources (CMFRI, 2014). Landings of different resources from year 1985 to 2011 are presented in **Figure 51 to Figure 54**.

5.1.1. Marine Fisheries of West Coast of India

The number of living fish species might be close to around 28,000 in the world. According to Venkataraman and Wafar (2005), their number in Indian waters is around 2500 (west and east coast, Lakshadweep Islands and Andaman and Nicobar Islands). Number of fish species inhabiting along west coast of India might vary between 400 and 600 with higher species around Lakshadweep Islands (Jones and Kumaran, 1980; Talwar and Kacker, 1984, Venkataraman and Wafar, 2005). Major food finfish species reported from the west coast of India and their IUCN Status are listed in **Annexure II**.

5.1.2. Shellfish Fishery along the West Coast of India

Altogether, 254 species of crabs belonging to 120 genera under 24 families have been recorded along west coast of India (Venkataraman and Wafar, 2005). 243 species of marine shrimps and prawns and 26 species of lobsters have been documented from Indian marine waters of which 55 species of shrimps and prawns are commercially important (Venkataraman and Wafar, 2005). Beleem et al. (2014) reported 80 species of marine crabs from Gujarat coast comprising of Kutchch Shelf, Saurashtra Shelf, Khambat Inner Shelf and northwest part of North Western Indian slope, out of which 22 species are recorded from Gulf of Kutchch (Kutchch Shelf). Chhapgar (1957) reported 81 species of crabs

Table 18: Distribution of fishermen population in States/Union Territories along West coast of India (Source: CMFRI, 2010; FSI, 2008).

State/Union Territories	Fishing villages	Fishermen families	Traditional fishermen families	Fisherfolk population
Gujarat	247	62, 231	59, 469	336,181
Diu and Daman	11	7374	7181	40,016
Maharashtra	456	81, 492	74203	386,259
Goa	39	2189	2147	10,545
Karnataka	141	30, 713	28533	167,429
Kerala	222	118, 937	116321	610,165
Lakshadweep Islands	10	5338	-	34,811
Total	**1,126**	**308,274**	**287,854**	**1585,406**

Table 19: Marine fish production of five states along west coast of India (Source: CMFRI, 2014).

Year	Marine Fish Production (in ton nes)				
	Gujarat	Maharashtra	Goa	Karnataka	Kerala
1985	287715	335809	48850	118654	325534
1986	256245	315218	54401	189231	382791
1987	236935	285208	65677	220575	303286
1988	207363	315244	91168	212411	468808
1989	327264	362330	119866	251012	647526
1990	337677	345724	66505	178334	662890
1991	440587	384162	75623	156654	564161
1992	462741	327695	96333	169086	560742
1993	403070	333003	121998	142369	574739
1994	533680	323828	61761	149699	568034
1995	496417	316462	31321	148941	531646
1996	502157	339148	50972	169068	572055
1997	665904	390067	66154	187758	574774
1998	703099	415741	50530	164710	542696
1999	574876	297032	46463	165098	580773
2000	684328	368222	61867	182914	604113
2001	467124	3959 66	36938	193680	514139
2002	468254	449599	64986	207288	589519
2003	444105	415094	95890	184075	623293
2004	408982	350712	83147	192816	616839
2005	421873	282375	81601	224041	536215
2006	571459	334451	105539	240888	591902
2007	538245	308761	97162	291813	619255
2008	598813	350984	110508	330060	670095
2009	564621	315937	71391	285659	517720
2010	601079	241054	89442	385761	608281
2011	692702	291791	58438	390178	743122

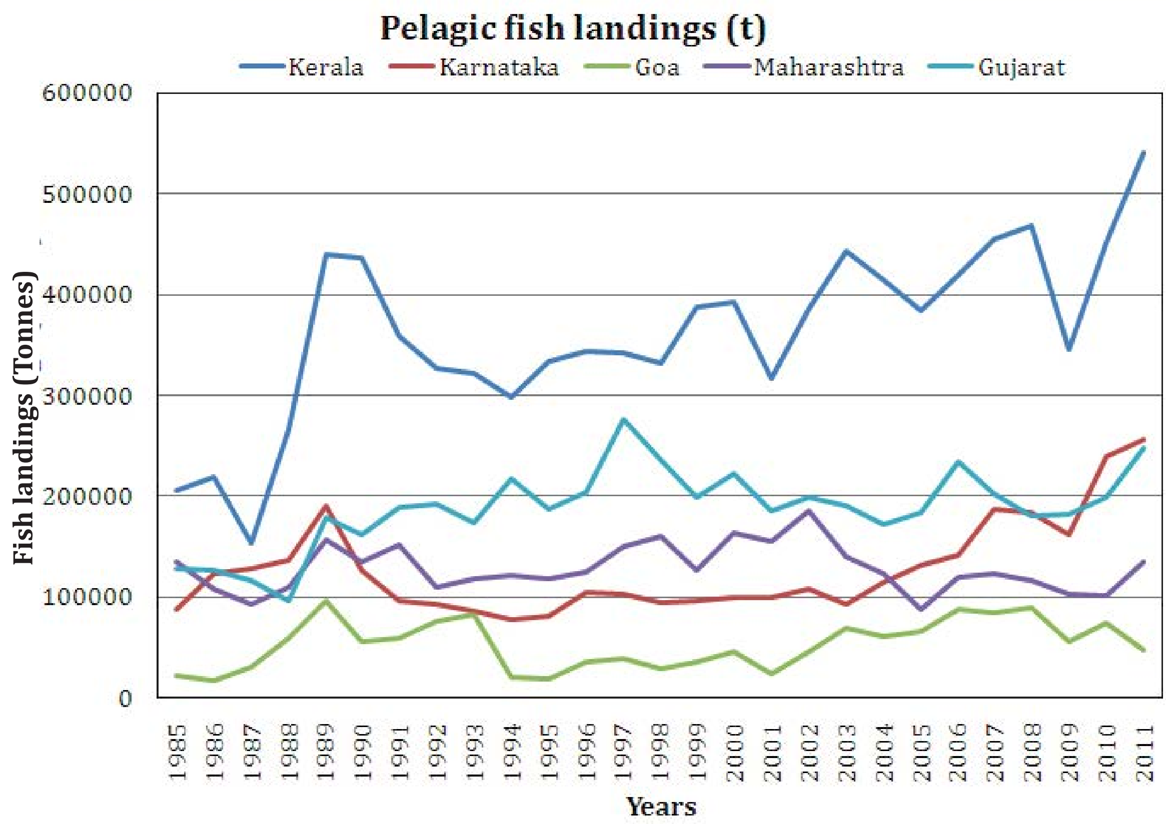

Figure 51: Pelagic fish landings during the years 1985-2011 along the West coast of India (Source: CMFRI, 2014).

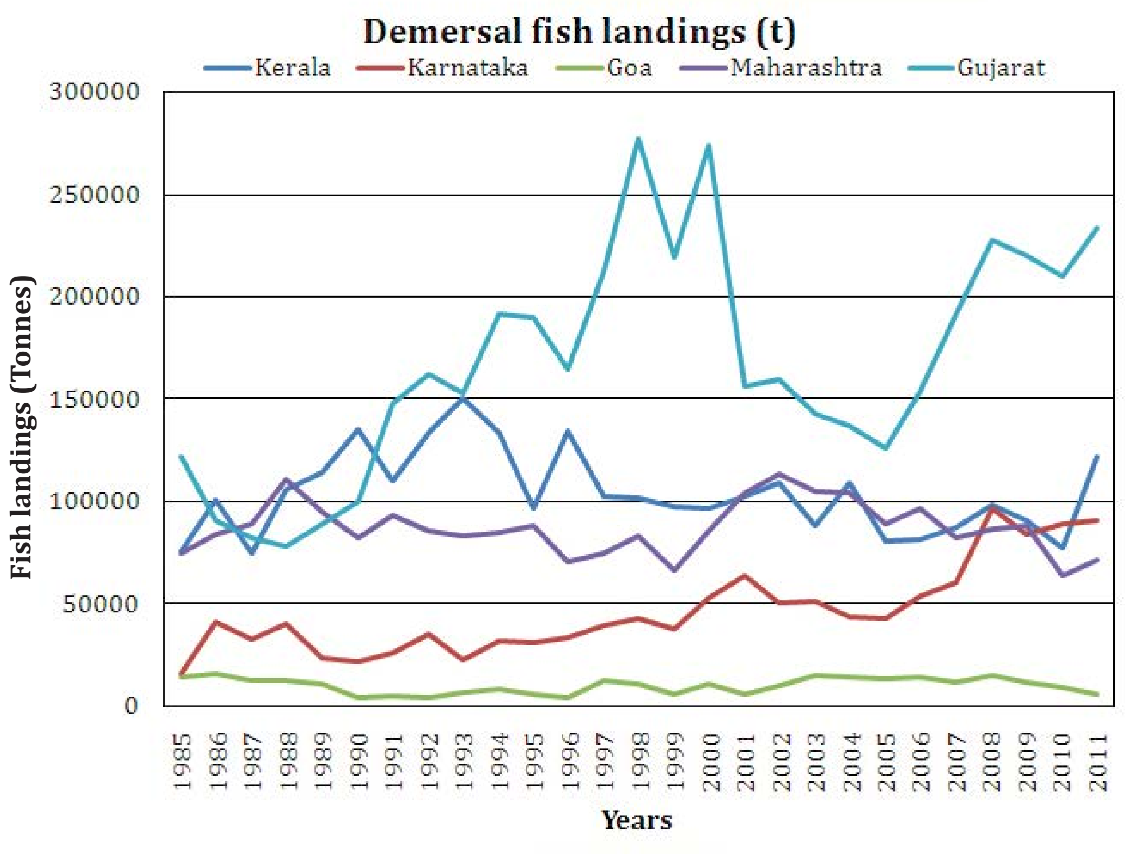

Figure 52: Demersal fish landings during the years 1985-2011 along the West coast of India (Source: CMFRI, 2014).

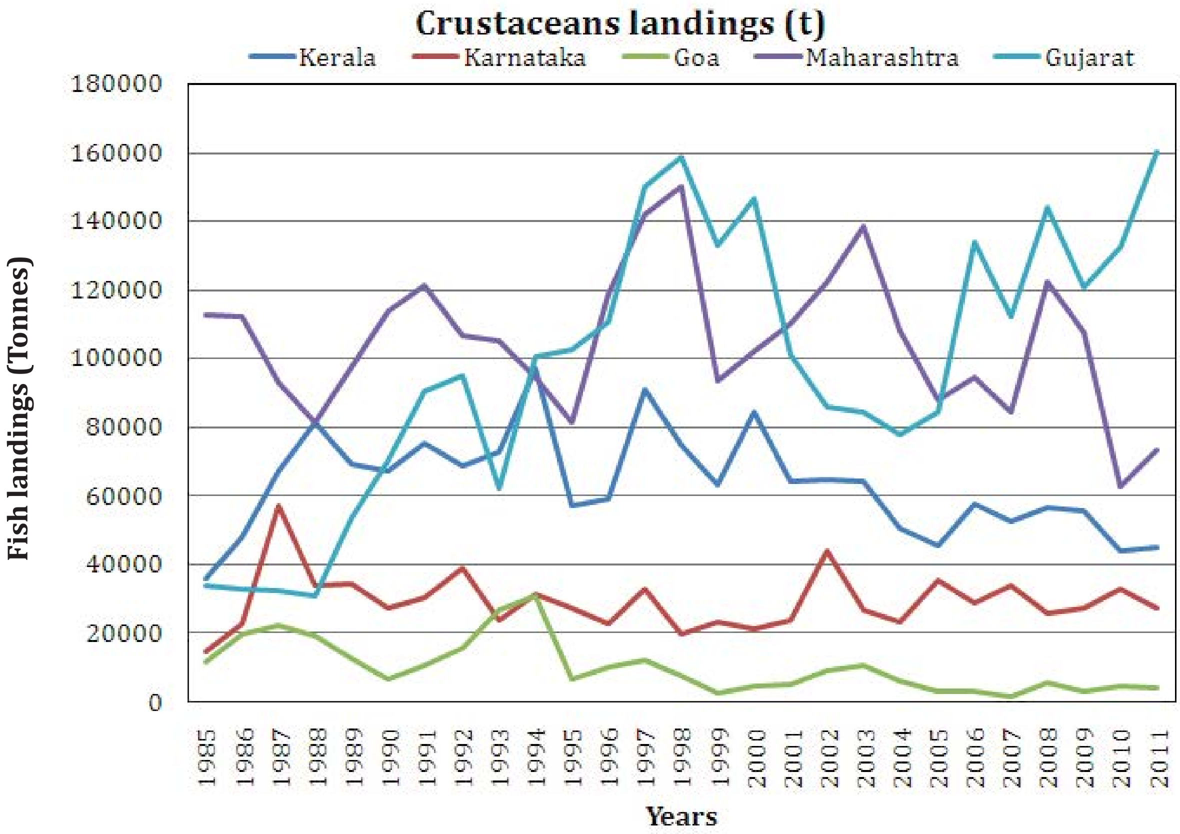

Figure 53: Landings of Crustaceans during the years 1985-2011 along the West coast of India (Source: CMFRI, 2014).

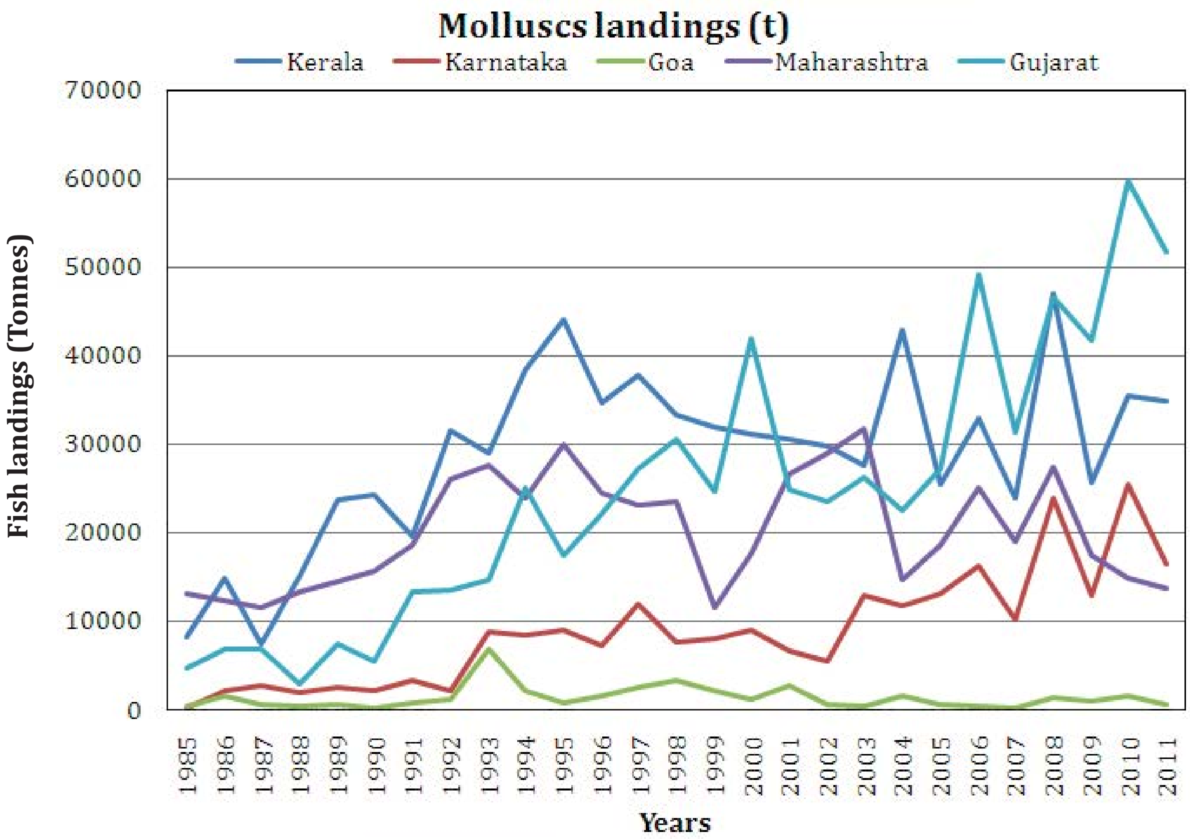

Figure 54. Landings of Molluscs during the years 1985 to 2011 along West coast of India (Source: CMFRI, 2014).

along erstwhile Bombay state comprising of Maharashtra, Goa and Karnataka states. These species are probably reported from Khambat Inner Shelf, Khambat Outer Shelf and North West part of Malabar Shelf. Coral Island province supports 41 species of marine crabs along reef flats (Meiyappan and Kathirvel, 1978; Rao *et al*., 1989).

Cephalopod Fishery along the West Coast of India: Cephalopods (squids, cuttlefishes and octopuses) are commercially exploited all along the Indian coast. Out of 80 species of cephalopods recorded from Indian waters, only 15 are of commercially important [Meiyappan and Mohamed, 2003; Venkataraman and Wafar, 2005]. During year 2013-14, India exported about 68,577 and 87,437 tonnes of frozen cuttlefish and squids valued at US $ 230 and 290 Million, respectively (MPEDA, 2014). Along the west coast, the contribution of the North West Provinces (Kutchch Shelf, Saurashtra Shelf, Khambat inner and Outer Shelf and North Western Indian slope) to the all India cephalopod landings substantially increased from 13% (1961-70) to 45% (1991- 2000), whereas landings from the South West provinces (Malabar Shelf and South Western Indian slope) decreased from 54% to 41% (Meiyappan and Mohamed, 2003). Cuttlefishes are more dominant in this region and contributed about 51% of cephalopod landings. Among squids, *Loligo duvauceli* dominates the landings along Northwest coast of India. In contrast, Siboga squid, *Doryteuthis sibogae* dominantes the squid catches along southwest provinces. Sujitha and Shobha (2006) reported annual landings of cephalopods at Veraval and Mangrol landing centres (Saurashtra Shelf) during 1996-99 have been estimated at 3911 and 1030 tonnes, respectively. Landings of different groups of molluscan fishes during the year 2011-12 are shown in **Figure 55**.

Bivalve Fisheries along West Coast of India: Among Bivalve molluscs, oyster, clams, mussels and pearl oysters are more important in India. Fishery of pearl oysters is now not in existence and cultured pearl production is carried out along east coast of India. The annual average production of clams, oysters and marine mussels in India is about 57,000 tonnes, 18,800 and 14,900 tonnes, respectively (Mohamed, 2013).

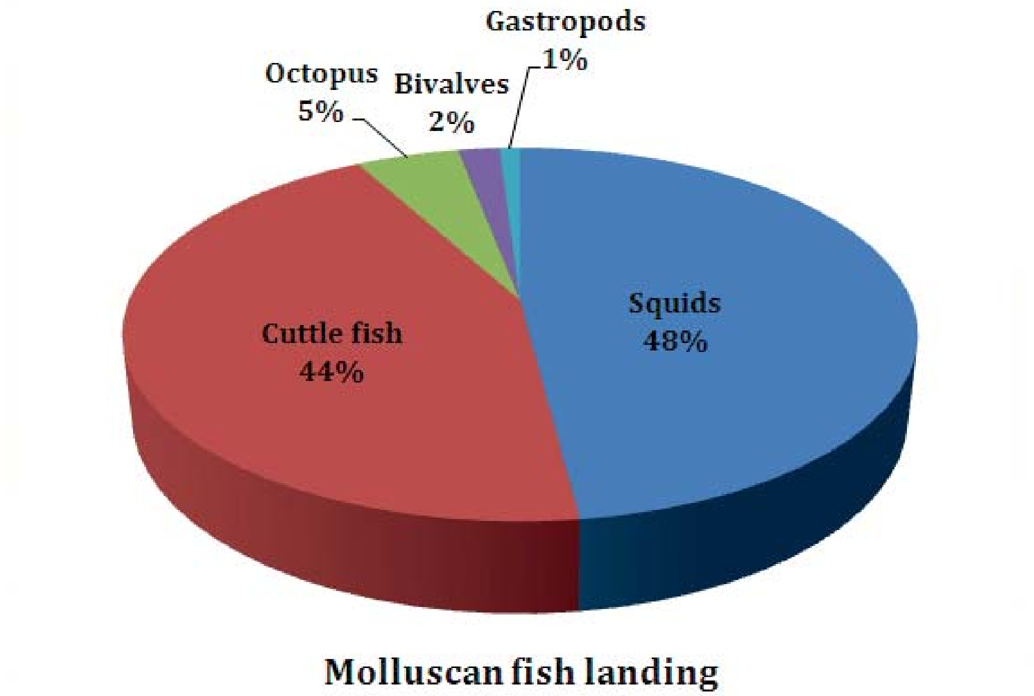

Figure 55: Landings of different groups of molluscs in India during 2011-12 (Source: CMFRI, 2014).

Province-wise standing stock estimates of bivalve molluscs along five maritime states is shown in **Figure 56**.

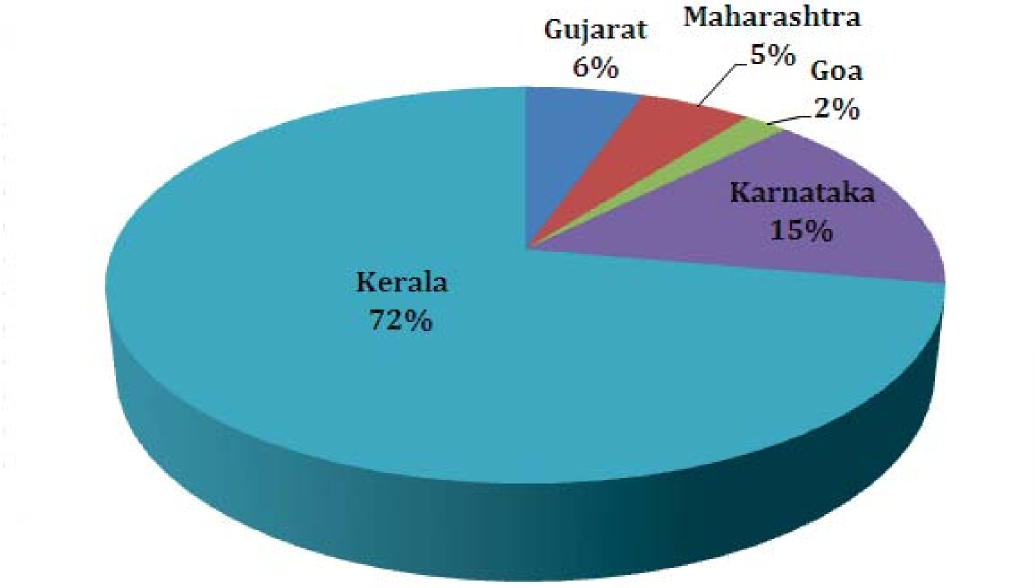

Figure 56: Standing stocks of bivalve molluscs in five maritime states along West coast of India (Source: CMFRI, 2014).

5.2. Other Marine Faunal and Floral Biodiversity

5.2.1. Marine Mammals

Interactions between marine mammals and fisheries have occurred for centuries and have increased in frequency and intensity during the last decades (DeMaster *et al.*, 2001). Major adverse ecological impacts of fisheries are closely related to the bycatch issue and mortality due to bycatch is one of the major adverse ecological impacts of fisheries on marine ecosystems (Lewison *et al.*, 2004). IndOBIS, the primary OBIS dataset for the Indian EEZ, lists 51 point-occurrence records of marine mammals and sea turtles (Chavan and Achuthankutty, 2011). Indian sea supports a habitat for 25 species of cetaceans and out of which, five are Mysticeti (Baleen whales) and the rest are Odontoceti, which includes Delphinidae, Physeteridae, Kogiidae, Ziphiidae, Phocoenidae and Platanistidae (Kumaran, 2002).

Province-wise diversity of sea mammals is presented in **Annexure III**. Thirteen species of sea mammals are reported from Kutchch Shelf area mainly from Gulf of Kutchch by Zoological Survey of India (Singh, 2003). As per IUCN Red List, four species are Least concern (LC), four species are 'Data deficient (DD)', one species i.e. *Sousa chinensis* is 'Near-threatened (NT)', two are 'Vulnerable (VU)' and two are 'Endangered (EN)'. Most common species of Dolphins are *Delphinus delphis*, *Neophocaena phocaenoides* and *Dugong dugon*.

Marine mammals are more common in coastal and offshore waters of Malabar Shelf and South Western Indian Slope (Afsal et al., 2008). Ahmed and Shiledar (2013) reported a dead sperm whale, *Physeter macrocephalus* (VU) from Talashil, Maharashtra. Yousuf et al. (2008) reported *S. longirostris, D. capensis, S. chinensis* and *N. phocaenoides* from Manglooru, Karnataka. Along Kerala coast, there are six species of marine mammals included in Threatened list of species, this includes 02 Endangered (EN), 02 Vulnerable (VU) and 01 Near- threatened (NT). Species richness and abundance is greater in South Western Arabian Sea off Karnataka and Kerala coasts (**Figure 57**) [Afsal *et al.*, 2008]. According to Tripathy (2002), Spinner Dolphin (*Stenella longirostris*), Indo-Pacific Humpback dolphin (*Sousa chinensis*), Bottlenose dolphin (*Tursiops truncatus aduncus*) and Cape dolphin (*D.*

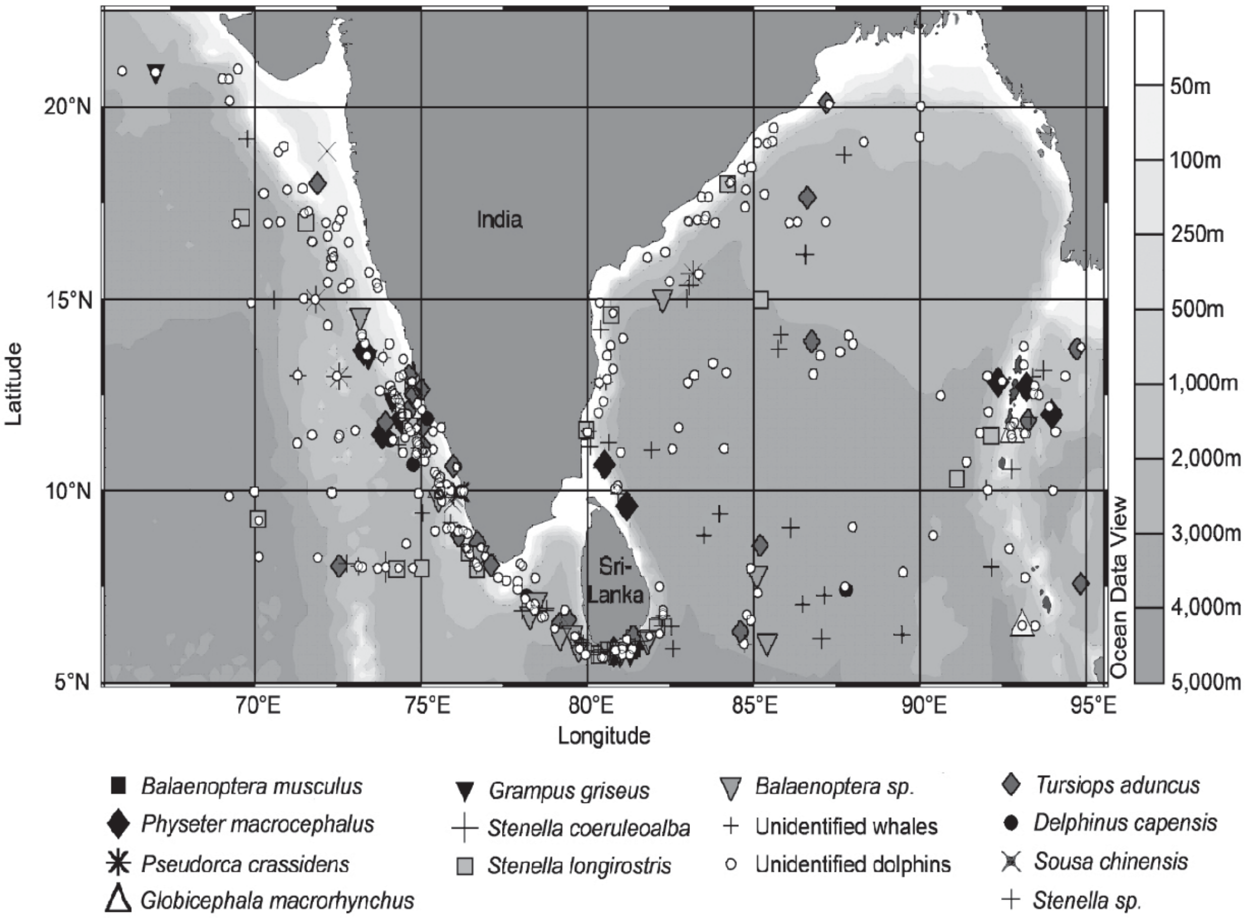

Figure 57: Cetacean Observations of the Indian EEZ (Source: Afsal *et al*., 2008).

delphinus) are most common marine mammals reported along the Coral Island province (Lakshadwep Islands). Pillai (1981) reported the occurrence of Cuvier's Beaked whale (*Ziphius cavirostris*) from Minicoy Island of Lakshadweep. Some sightings of marine mammals along the Indian coast are shown in **Figure 58** and **Figure 59**.

All marine mammals are protected under Indian Wildlife (Protection) Act, 1972 Finless porpoise, *Neophocaena phocaenoides* and *S*ea cow, *Dugong dugon are* listed in Schedule I, while sperm whale, *Physeter macrocephalus* finds in Schedule II List of the Act.

5.2.2. Marine Turtles

All turtle species are protected by Indian Wildlife Act, 1972 under Schedule I and thereby declared their consumption, trade, hunting and injury as prohibited activities. Conservation status of turtle species as per IUCN Red List of threatened species is provided below. According IUCN Red list of threatened species, Hawksbill turtles are critically endangered, while Green turtles are listed in endangered category. Species diversity of sea turtles along west coast of India has been listed in **Table 20**. Turtle nesting sites reported along Indian coast Turtle nesting sites reported along Indian coast is shown in **Figure 60**.

5.2.3. Seagrass Habitats

Seagrasses are grass-like flowering plants that live completely submerged in marine and estuarine waters. These plants are evolved from terrestrial plants and have roots, leaves, flowers and seeds and make their food through process of photosynthesis. Seagrasses and seaweeds, i.e other marine macro-algae are completely different in many ways. Seagrasses have complete root and other tissue specific system like terrestrial plants. On the other hand, macroalgae have a strong holdfast which assist them for anchoring to any hard substratum. Seagrasses

Figure 58: Hump back dolphin, *Sousa chinensis* spotted off Dona Paula, Goa (Photo credit: Sushant Sanaye).

Figure 59: A view of dead whale washed ashore at Tambaldeg, Sindhudurg (Maharashtra) (Photo credit: Sushant Sanaye).

have chloroplast in their leaves which help in photosynthesis with help of sunlight and also capability of extracting nutrients and minerals from sediments through roots. On the other hand, the macroalgae have ability to take nutrients and minerals directly from seawater through diffusion.

waters, mostly associated with coral reefs (Jagtap, 1991; Venkataraman and Wafar, 2005; Manikandan *et al.*, 2011). 11 and 13 species of seagrasses, respectively, have been reported from Palk Bay and Gulf of Mannar. These include *Halophila ovalis*, *Halodule pinifolia*, *Syringodium isoetifolium*, *Thalassia hemprichii*, *Cymodocea*

Table 20: Biodiversity of marine turtles along west coast of India (Source: Halpin *et al.*, 2009). (EN=Endangered; CE= Critically endangered; VU=Vulnerable)

Family	Turtle Species
Chelonidae	Green Turtle *(Chelonia mydas)* (EN) Hawksbill turtle (*Eretmochelys imbricata)* (CE) Olive Ridley Turtle (*Lepidochelys olivacea*) (VU)
Dermocheliidae	Leatherback Turtle (*Dermochelys coriacea*) (VU)

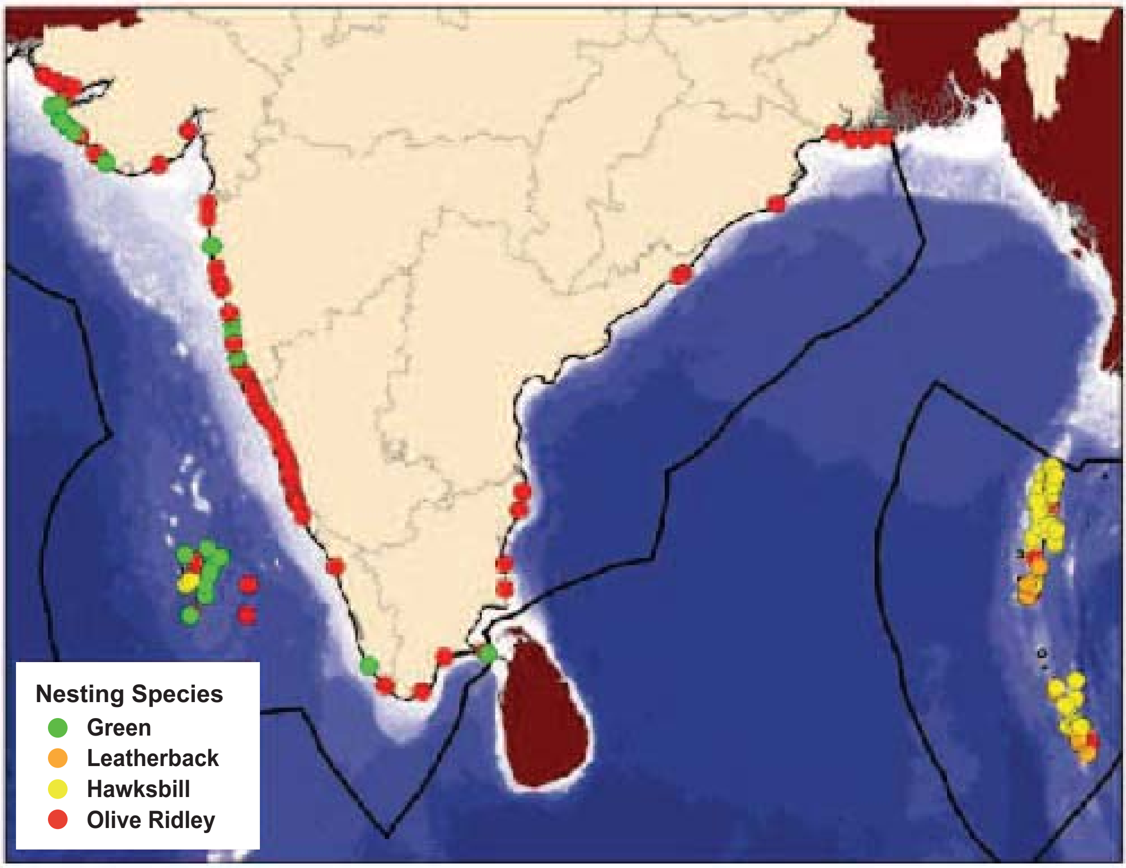

Figure 60: Nesting sites of sea turtles along Indian coast (Source: Halpin *et al.*, 2009).

In India, seagrass habitats are mainly limited to mudflats and sandy regions in lower intertidal zone to the depth of ~10-15 m along the ocean shore and in the lagoons around islands [Jagtap *et al.*, 2003]. 15 species of seagrasses belonging to seven genera are reported from Indian marine *serrulata*, *Enhalus acoroides* (Jagtap, 1991; Kannan et al., 2009; Manikandan *et al.*, 2011) of which *C. serrulata* was most dominant. 9 species of seagrasses have been reported from Andaman and Nicobar Islands (Venkataraman and Wafar, 2005).

Seagrass species such as *Cymodocea* sp and *Syringodium isoetifolium* occur only in small patches at south west coast of India from Trivandrum to Cape Comorin at southwest part of Kerala. Jagtap (1991) reported only two species of seagrasses i.e. *Halophila ovalis* and *H. beccarii* along Goa coast and same species has also been reported from Maharashtra, Karnataka and Kerala coasts. Although no mention about the occurrence of seagrass species were has been made in the inventory of biological diversity of Gujarat state by Gujarat Ecology Commission (GEC, 1996). However, Jagtap and Untawale (1981) reported *H. ovalis* from Okha, Dwaraka areas of Gujarat state. Eight species of seagrasses have been reported from Lakshadweep Islands (Venkataraman and Wafar, 2005).

Major Seagrass Habitats in Coral Island Province: According to Jagtap and Inamdar (1991) total seagrass cover in coral islands (Lakshadwep group of islands) is around 112 ha with max area at Minicoy island (40 ha) while minimum at Agathi (0.5 ha). Jagtap (1987) reported average biomass of Lakshadweep island seagrasses to be 720 g/m^2 during 1984-87. Depth range of seagrass habitat is presented in **Table 21.**

Distribution, diversity and ecological status of seagrasses along west coast of India are presented **Annexure IV**.

Table 21: Depth range of occurrence of seagrass in Coral Island Province (Source: Nobi and Dinesh Kumar, 2014).

Islands/habitat	Seagrass occurrence depth (m)	Average depth (m)
Kavaratti	1-10	0.5-2.0
Agathi	1-10	0.5-2.0
Kadamath	1-10	0.2-4.0
Bangaram	1-8	0.1-2.5
Thinnakkara	1-8	0.1-1.5

5.2.4. Seaweed Resources

Marine macroalgae or seaweeds are of both ecological and commercial importance. These are large diversified group with size ranging from single cell such as *Chlamydomonas* to several meters in length i.e. *Macrocystis* (Deshmukhe *et al*., 2001). Marine algae are classified into four classes based upon their pigmentation as well as morphological characters; these classes include Chlorophyta (green algae), Phaeophyta (brown algae), Rhodophyta (red algae) and Cynophyta (bluegreen algae). Seaweeds are harvested and mainly used for production of agar, alginates and seaweed liquid fertilizers.

About 20,000 species of marine algae are reported over the world, the recent systematic account by Oza and Zaidi (2000) listed 844 species from 217 genera from Indian coasts including islands. Rhodophyta is most abundant group with 434 species, while Chlorophyta with 216 species, Phaetophyta with 191 species and Cynophyta with species (Venkataraman and Wafar, 2005). Distribution of the numbers of marine algal species along west coast of India is provided in **Table 22**. Also, seaweed resources along the west coast of India based on published literature are presented in **Table 23**. Intertidal belt of seaweeds with rocky substratum and washed-off seaweeds along shore of Gojiness-Bhogat, Saurashtra Shelf is shown in **Figure 61**.

5.2.5. Mangrove Ecosystems

Mangrove ecosystems are of great importance for ecological, environmental and socioeconomic factors. According to Jagtap *et al*. [1993] India has a mangrove cover of 3150 km^2 and over 80% of

Table 22: Distribution of marine algae along west coast of India (Source: Untawale *et al*., 1989; Ambiye and Untawale, 1992; Deshmukhe *et al*., 2001; Venkataraman and Wafar, 2005).

West Coast Province s	State/Union Territory	No. of Species
Kutchch Shelf	Gujarat	
Saurashtra Shelf	Gujarat	
Khambhat Shelf	Gujarat, Maharastra	361
	Goa	75
South West Indian Shelf	Karnataka	39
	Kerala	20
	Lakshadweep Islands	89
West Indian Slope (North-west)	Angria Bank (Maharashtra)	57
	Cora divh, Sessostris and Bassas-de-Pedro banks, Karnataka	72

Table 23: Seaweed resources of west coast of India based on published literature (Source: Deshmukhe et al., 2001; Subba Rao and Mantri, 2006)

West Coast Province	State/Union Territory	Annual Yields in tonnes (fresh weight)	Reference
Kutchch Shelf	Gulf of Kutchch	19000	Chauhan and Krishnamurthy (1968)
	Gulf of Kutchch	100250	Desai (1969)
	Hanumandandi to Vumani (Okha)	650	Bhandari and Trivedi (1975)
	Adatra reef	60	Sreenivasa Rao *et al.* (1964)
Saurashtra Shelf	Saurashtra coast	282-608	Chauhan and Marih (1978)
Northern Part of Khambat Outer Shelf and Malbar Shelf	Konkan coast, Maharashtra	315	Chauhan (1978]
	Entire Maharashtra coast	20000	Untawale *et al*. (1979)
	Entire Goa coast Goa	2000	Dhargalkar [1981]
	Dona Paula to Chapora,	255	Untawale *et al*. [1983]
	Karnataka	Negligible	Agadi [1981]
	Kerala	1000	Chennubhotla *et al.* (1988)
Coral Island Province	Lakshadweep islands	3645-7598	Subbaramaiah *et al*. (1979)
		4955-10077	Muthuvelan *et al*. (2001)

which occurs along east coast and in Andaman Islands, while more recently Venkataraman and Wafar (2005) reported 4827 km^2 of mangrove cover of which only 23% present at west coast of India. Altogether, 69 species of mangroves belonging to 25 families and 43 genera have been reported from Indian coast. Changes in mangroves from 1993 to 2012 are presented in

Figure 61: Intertidal belt of seaweeds with rocky substratum (top panel) and washed off seaweeds along shore of Gojiness-Bhogat, Saurashtra shelf (bottom panel). (Photo credit: Sushant Sanaye).

Table 24. Mangrove species reported from west coast of India are presented in **Table 25**. Along west coast rich mangrove habitat can be observed along Gujarat coast in Gulf of Kutchch and Gulf of Khambat which is approximately 80% of total mangrove cover of west coast and 23% that of India (Singh *et al*., 2012). Jagtap (1993) reported 370 km^2 of mangrove cover in Gujarat which is now increased in last two decades due to declaration of Marine National Park in Gulf of Kutchch in 1983. Though mangrove cover is more in Gujarat state (1058 km^2), species diversity is limited to nine species, on the other hand species diversity is more in Maharashtra, Goa, Karnataka and Kerala states. Example of mangrove forest was shown in **Figure 62.** Satellite imagery of Gulf of Kutchch, showing mangrove forests is depicted in **Figure 63**.

Table 24: Changes in mangrove cover along west coast of India from 1993 to 2012 based on published literature.

State	**Area (km^2)**		
	1993 [Jagtap *et al*., 1993]	1999 (Forest Survey of India)	2012 (Singh *et al*., 2012) (Forest Survey of India)
Gujarat	370	1031	1058
Maharashtra	210	108	186
Goa	20	5	22
Karnataka	50	3	3
Kerala	-	-	6
Daman & Diu	-	-	1.56
Total	**650 (20%)**	**1137 (23%)**	**1276.56 (27%)**
India Total	**3140**	**4871**	**4662.56**

Table 25: Distribution of mangroves along the west coast of India.

West coast Province	**Major region of mangrove formation**	**Present area (km^2)**	**No. of species**	**Status**	**References**
Kutchch shelf	Gulf of Kutchch	861.38	9	Recovering	Patel et al. (2014)
Saurshtra Shelf	Porbandar, Junagad, Amreli	4.41			
Khambat inner shelf	Gulf of Khambat	94.32	5		
	Surat, Navsari, Valsad	37.72			
Khambat outer shelf	Raigad and Ratnagiri districts, Maharashtra· Manori	210	20	Degraded	Jagtap et al. (1993); Kulkarni *et al*. (2010); Kaladharan and Ashokan [2012]; Singh et al. (2012); Suma and Gowda, (2013)
South west Indian shelf	Mandovi and Zuari estuaries complex (Goa)	20	18	Degraded	
	Haladi, Kolar and Chakra estuaries, Kundapur, Ud upi (Karnataka)	3	10-15	Degraded	
	Kollam, Kumarhon, Kunhimangalam, Kannur (Kerala)	17	19	Totally degraded	
Coral island province	Minicoy island (Lakshadweep)	Negligible	3	In the process of formation	Nasser et al. (1999)

Figure 62: Mangrove vegetation along Zuari estuary, Goa (Photo credit: Sushant Sanaye).

Figure 63: Satellite imagery of Gulf of Kutchch showing mangrove cover (in red colour) (Source: Jagtap and Nagale, 2007).

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ANNEXURE - I

List of National Experts (and their affiliation) participated in Ecosystem Characterization Workshop held at Goa during 20 - 22 October, 2014

Sr. No.	National Expert	Designation	Official Address	Contact details
1	Dr. Padmavati	Assistant Professor	Pondichery University Port Blair, Andamans	padma190@rediffmail.com 91-9933247796
2	Mr. Sachinandan Datta	Thematic Expert (Fisheries)	Reliance Foundation Navi Mumbai	duttasachi@gmail.com duttasachi@yahoo.co.in 91-7710016717
3	Dr. Sudhir Kumar Das	Professor	West Bengal University of Animal and Fishery Sciences, West Bengal	dashsudhirkumar@gmail.com dashsudhirkumar@rediffmail.com 91-9433565224
4	Dr. Satpathy	Dean	Fisheries College, Rengelunda, Berhampur	dircof2012@gmail.com 91-9861077340
5	Dr. Gangadhara Gowda	Professor	KVAFSU College of Fisheries, Mangalore	deanfisheries@gmail.com 91-9480571370
6	Dr. Ajmal Khan	Professor	CAS in Marine Biology Annamalai University, Port Novo, Tamil Nadu	seyedajmal@gmail.com 91-9443023854
7	Dr. B.M. Kurup	Vice-Chancellor	Kerala Fisheries & Ocean Studies, Pannangad, Kerala	vckufos@gmail.com 91-9447644566
8	Dr. Shamila Monteiro	Director of Fisheries	Directorate of Fisheries, Panaji Goa	dir-fish.goa@nic.in 91-9326125026
9	Dr C K. Murthy	Joint Director of Fisheries	Directorate of Fisheries Govt. of Karnataka Bangalore	dfkarnataka@rediffmail.com 91-80-2286 4681
10	Dr Sunil Mohamed	Principal Scientist	Central Marine Fisheries Research Institute (CMFRI), Kochi, Kerala	ksmohamed@gmail.com ksmohamed@vsnl.com 91-9447056559
11	Dr. Chowdula Satya Narayana	Research Scientist	Zoological Survey of India, Kolkata, West Bengal	chowdula_narayana@rediffmail.com 91-9433325559
12	Dr. E. Vivekanandan	Emeritus Scientist	CMFRI, Chennai	evivekanandan@hotmail.com 91-9444238648
13	Dr B. Meenakumari	DDG (Fishery)	ICAR, Krishi Bhavan, New Delhi	meenakumarib@gmail.com 91-9650934444
14	Dr. Sajeev	Additional Director of Fisheries	Directorate of Fisheries, Govt. of Kerala, Thiruvananthapuram- 33	fisheriesdirector@gmail.com fishdirvkbn@sancharnet.in 91-9496007020
15	Dr. David Brewer	Research Group Leader	CSIRO Oceans & Atmosphere, Brisbane Queensland, Australia	david.brewer@csiro.au Phone: +61 7 3833 5900 Mobile: 0427 722 782
16	Dr. Timothy Skewes	Principal Scientist	CSIRO Oceans and Atmosphere Flagship, Precinct, Brisbane Queensland, Australia	tim.skewes@csiro.au Phone: +61 7 3833 5963 Mob: 0419 382 697
17	Dr. A.C. Anil	Chief Scientist	CSIR-National Institute of Oceanography, Goa	acanil@nio.org +91-9423819755
18	Dr. S. Prasanna Kumar	Chief Scientist	CSIR-National Institute of Oceanography, Goa	prasanna@nio.org +91-9423059971
19	Dr. B.S. Ingole	Chief Scientist	CSIR-National Institute of Oceanography, Goa	baban@nio.org +91-9421241506
20	Dr. N. Ramaiah	Chief Scientist	CSIR-National Institute of Oceanography, Goa	ramaiah@nio.org +91-9420897437
21	Dr. M. Dileep Kumar	Chief Scientist	CSIR-National Institute of Oceanography, Goa	dileep@nio.org +91-9404434053
22	Mr. R.A. Sreepada	Senior Scientist	CSIR-National Institute of Oceanography, Goa	sreepada@nio.org +91-9422063172
23	Dr. P S Rao	Chief Scientist	CSIR-National Institute of Oceanography, Goa	psrao@nio.org +91-9422063936
24	Dr. C U Rivonkar	Professor	Dept. of Marine Sciences, Goa University, Goa	curivonker@unigoa.ac.in urivonker@gmail.com +91-832 6519352
25	Dr. V. Ramaswamy	Chief Scientist	CSIR-National Institute of Oceanography, Goa	rams@nio.org +91-9890181194

ANNEXURE - II

Checklist of marine finfishes recorded from the West coast of India

FAMILY: RHINCODONTIDAE (Whale sharks)
Rhincodon typus (VU) (I)
FAMILY: ORECTOLOBIDAE (Carpet/Nurse sharks)
Chiloscyllium indicum (NT)
FAMILY: STEGOSTOMATIDAE
Stegostoma fasciatum (VU)
FAMILY: ODONTASPISIDAE (Sand tiger shark)
Carcharias taurus (VU)
FAMILY: LAMNIDAE (Thresher & Mackerel sharks)
Alopias vulpinus (VU)
FAMILY: SCYLIORHINIDAE
Atelomycterus marmoratus
FAMILY : CARCHARHINIDAE
Carcharhinus brevipinna (NT)
C. limbatus (NT)
C. dussumieri (NT)
C. macloti (NT)
C. melanopterus (NT)
C. sorrah (NT)
Galeocerdo cuvier (NT)
Rhizoprionodon acutus (LC)
R. oligolinx (LC)
Scoliodon laticaudus (NT)
FAMILY : SPHYRNIDAE (Hammer head sharks)
Eusphyra blochii (NT)
Sphyrna mokarran (EN)
FAMILY: HEMIGALEIDAE
Hemipristis elongata (VU)
FAMILY : PRISTIDAE (Saw fishes)
Anoxypristis cuspidata (EN) (I)
FAMILY : RHINOBATIDAE (Guitar fishes)
Rhinobatos lionotus (DD)
Rhina ancylostoma (VU)
Rhynchobatus djiddensis (VU) (I)
Glaucostegus halavi (DD)
FAMILY: TORPEDINIDAE (Electric rays)
Narcine brunnea
N. timlei (DD)
FAMILY: RAJIDAE (Skates)
FAMILY: DASYATIDAE (Sting rays)
Dasyatis zugei (NT)
Himantura bleekeri
H. imbricata (DD)
H. uarnak (VU)
Pastinachus sephen (DD)
FAMILY: GYMNURIDAE
Gymnura poecilura (NT)
FAMILY : MYLIOBATIDAE (Eagle rays)
Aetobatus narinari (NT)
Aetomylaeus maculatus (EN)
FAMILY : MOBULIDAE (Manta/Devil rays)
Mobula mobular (EN)
Manta birostris (VU)
FAMILY: CLUPEIDAE (Shads,Sardines)
Ilisha elongata
Tenualosa ilisha
T. toil
Nematalosa nasus
Sardinella fimbriata
S. longiceps (LC)
FAMILY: PRISTIGASTERIDAE
Opisthopterus tardoore
Pellona ditchela
FAMILY: CHANIDAE
Chanos chanos
FAMILY : ENGRAULIDAE (Anchovies)
Colia dussumieri
C. reynaldi
Stolephorus indicus
S. commersonni
Thryssa dussumieri
T. hamiltonii
T. mystax (LC)
T. malabarica
T. setirostris
FAMILY : CHIROCENTRIDAE (Wolf herring)
Chirocentrus dorab
C. nudus
FAMILY : ELOPIDAE (Ten pounders)
Elops machnata (LC)

FAMILY : MEGALOPIDAE (Tarpons)
Megalops cyprinoides (DD)
FAMILY : MURAENIDAE (Morray eels)
Gymnomuraena zebra
Gymnothorax eurostus
G. favagineus
G. flavimarginatus
G. javanicus
G. meleagris
G. pictus
G. thyrsoideus
G. undulatus
Congresox talabonoides
Muraenesox cinereus
FAMILY: SYNBRANCHIDAE
Monopterus albus (LC)
FAMILY: OPHICHTHIDAE
Pisodonophis cancrivorus
Lamnostoma polyophthalma
FAMILY : ARIIDAE (Sea catfishes)
Arius arius (LC)
A. caelatus
A. dussumieri
A. jella
A. maculates
A. thalassinus
Osteogeneiosus militaris
Sciades sona
FAMILY: PLOTOSTIDAE
Plotosus canius
P. lineatus
FAMILY : SYNODONTIDAE (Lizard fishes)
Saurida tumbil
FAMILY : HARPADONTIDAE
(Bombay duck)
Harpadon nehereus
FAMILY : BREGMACEROTIDAE
Bregmaceros macclellandi
FAMILY : BATRACHOIDIDAE
Batrachus grunniens
Colletteichthys dussumieri
FAMILY : CHAUNACIDAE
Chaunax pictus
FAMILY : EXOCOETIDAE
Exocoetus volitans
FAMILY : BELONIDAE
Strongylura strongylura
S. leiura
S. incisa
Tylosurus crocodilus
FAMILY : CYPRINODONTIDAE
Aphanius dispar (LC)
FAMILY : FISTULARIIDAE
(Hairtailed, Flute mouths, Cornet fish)
Fistularia petimba
FAMILY : SYNGNATHIDAE
(Seahorses,Pipefishes)
Hippocampus kuda (VU) (I)
H. trimaculatus (VU) (I)
H. histrix (VU) (I)
H. camelopardalis (DD) (I)
Ichthyocampus carce (LC) (I)
Microphis cuncalus (LC) (I)
Syngnathoides biaculeatus (DD) (I)
Hippichthys cyanospilos (I)
Trachyrhamphus serratus (I)
FAMILY : LATIDAE
Lates calcarifer
Psammoperca waigiensis
FAMILY : SERRANIDAE
Aethaloperca rogaa (DD)
Cephalopholis argus (LC)
C. boenak (LC)
C. formosa (LC)
C. miniata (LC)
C. sonnerati (LC)
Chelidoperca maculicauda
Diploprion bifasciatum
Epinephelus areolatus (LC)
E. bleekeri (NT)
E. coeruleopunctatus (LC)
E. coioides (NT)
E. chlorostigma
E. diacanthus (NT)
E. erythrurus (DD)
E. fasciatus (LC)
E. faveatus (DD)
E. flavocaeruleus (LC)
E. lanceolatus (VU)
E. longispinis (LC)

E. sexfasciatus (DD)
E. tauvina (DD)
E. tukula (LC)
Plectropomus areolatus (VU)
Plectranthias alcocki
Pseudanthias squamipinnis
Variola louti (LC)
FAMILY : PRIACANTHIDAE (Bulleyes, Big-eyes)
Priacanthus hamrur
FAMILY : APOGONIDAE (Cardinal fishes)
Apogon aureus
Apogon hyalosoma
Apogon kiensis
Apogon multitaeniatus
Apogon pseudotaeniatus
Apogon thermalis
Apogon quadrifasciatus
Rhabdamia gracilis
FAMILY: HAEMULIDAE
Diagramma pictum
Plectorhinchus chubbi
P. gibbosus (LC)
P. orientalis
P. schotaf
P. vittatu s
Pomadasys argyreus
P. furcatus
P. jubelini
P. maculatus
FAMILY : LACTARIIDAE
Lactarius lactarius
FAMILY : RACHYCENTRIDAE
Rachycentron canadum
FAMILY : EPHIPPIDAE
Ephippus orbis
FAMILY : SCORPAENIDAE
Dendrochirus zebra
Minous monodactylus
Pterois antennata
P. miles
P. mombasae
P. russelli
P. volitans
Scorpaenopsis gibbosa
FAMILY : ECHENEIDAE (Remoras)
Echeneis naucrates
FAMILY :CIRRHITIDAE
Cirrhitus pinnulatus
Paracirrhites forsteri
FAMILY: PEMPHERIDAE
Pempheris molucca
P. sarayu
P. schwenkii
P. vanicolensis
FAMILY: CICHILIDAE
Etroplus suratensis
E. maculatus
FAMILY : PINGUIPEDIDAE
Parapercis pulchella
FAMILY : ANTENNARIIDAE
Antennarius striatus
FAMILY : PLATYCEPHALIDAE
Grammoplites scaber
Platycephalus crocodilus
P. indicus
FAMILY : CARANGIDAE
Atropus atropos
Atule mate
Alepes para
Carangoides caeruleopinnatus
C. chrysophrys
C. malabaricus
C. sexfasciatus (LC)
C. praeustus
Caranx ignobilis
C. heberi
C. melampygus
Decapterus russelli (LC)
Elagatis bipinnulata
Gnathanodon speciosus
Megalaspis cordyla
Parastromateus niger
Scomberoides commersonianus
S. lysan
S. sanctipetri
S. tol
Trachinotus blochii
T. baillonii
FAMILY : CORYPHAENIDAE
Coryphaena hippurus
FAMILY : MENIDAE
Mene maculata
FAMILY : LEIOGNATHIDAE
Leiognathus elongatus
L. equulus
L. fasciatus
L. splendens
Photopectoralis bindus

	FAMILY : CHAUNACIDAE *Chaunax pictus* **FAMILY : EXOCOETIDAE** *Exocoetus volitans* **FAMILY : HEMIRAMPHIDAE** *Rhynchorhampus georgii* **FAMILY : BELONIDAE** *Strongylura strongylura* *S. leiura* *S. incisa* *Tylosurus crocodilus* **FAMILY : CYPRINODONTIDAE** *Aphanius dispar* (LC) **FAMILY : FISTULARIIDAE** **(Hairtailed, Flute mouths, Cornet fish)** *Fistularia petimba*
FAMILY : MURAENIDAE (Morray eels) *Gymnomuraena zebra* *Gymnothorax eurostus* *G. favagineus* *G. flavimarginatus* *G. javanicus* *G. meleagris* *G. pictus* *G. thyrsoideus* *G. undulatus* *Congresox talabonoides* *Muraenesox cinereus* **FAMILY: SYNBRANCHIDAE** *Monopterus albus* (LC)	
FAMILY: OPHICHTHIDAE *Pisodonophis cancrivorus* *Lamnostoma polyophthalma*	**FAMILY : SYNGNATHIDAE** **(Seahorses,Pipefishes)** *Hippocampus kuda* (VU) (I) *H. trimaculatus* (VU) (I) *H. histrix* (VU) (I) *H. camelopardalis* (DD) (I) *Ichthyocampus carce* (LC) (I) *Microphis cuncalus* (LC) (I) *Syngnathoides biaculeatus* (DD) (I) *Hippichthys cyanospilos* (I) *Trachyrhamphus serratus* (I) **FAMILY : LATIDAE** *Lates calcarifer* *Psammoperca waigiensis*
FAMILY : ARIIDAE (Sea catfishes) *Arius arius* (LC) *A. caelatus* *A. dussumieri* *A. jella* *A. maculates* *A. thalassinus* *Osteogeneiosus militaris* *Sciades sona*	
FAMILY: PLOTOSTIDAE *Plotosus canius* *P. lineatus* **FAMILY : SYNODONTIDAE** **(Lizard fishes)**	**FAMILY : SERRANIDAE** *Aethaloperca rogaa* (DD) *Cephalopholis argus* (LC) *C. boenak* (LC) *C. formosa* (LC)
C. miniata (LC) *C. sonnerati* (LC) *Chelidoperca maculicauda* *Diploprion bifasciatum* *Epinephelus areolatus* (LC) *E. bleekeri* (NT) *E. coeruleopunctatus* (LC) *E. coioides* (NT) *E. chlorostigma* *E. diacanthus* (NT) *E. erythrurus* (DD) *E. fasciatus* (LC) *E. faveatus* (DD) *E. flavocaeruleus* (LC) *E. lanceolatus* (VU) *E. longispinis* (LC) *E. maculatus* *E. malabaricus* (NT) *E. merra* (LC) *E. sexfasciatus* (DD) *E. tauvina* (DD) *E. tukula* (LC) *Plectropomus areolatus* (VU) *Plectranthias alcocki* *Pseudanthias squamipinnis* *Variola louti* (LC)	*P. maculatus* **FAMILY : LACTARIIDAE** *Lactarius lactarius* **FAMILY : RACHYCENTRIDAE** *Rachycentron canadum* **FAMILY : EPHIPPIDAE** *Ephippus orbis* **FAMILY : SCORPAENIDAE** *Dendrochirus zebra* *Minous monodactylus* *Pterois antennata* *P. miles* *P. mombasae* *P. russelli* *P. volitans* *Scorpaenopsis gibbosa* **FAMILY : ECHENEIDAE (Remoras)** *Echeneis naucrates* **FAMILY :CIRRHITIDAE** *Cirrhitus pinnulatus* *Paracirrhites forsteri* **FAMILY: PEMPHERIDAE** *Pempheris molucca* *P. sarayu* *P. schwenkii* *P. vanicolensis*

ANNEXURE III

Checklist of marine mammals recorded from West coast of India (Source: Afsal *et al.*, 2008).

Species	IUCN Red List status	Kutchch Shelf	Saurashtra Shelf	Khambat Inner Shelf	Khambat Outer Shelf	Malabar Shelf	South Western Indian Slope	North Western Indian Slope	Coral Island Province
DELPHINIDAE									
Delphinus delphis	LC	P	P	P	P	P	P	P	NR
D. capensis	NA	?	NR	NR	NR	P	P	P	P
Globicephala macrorhynchus	DD	P	NR	NR	NR	P	P	P	NR
Grampus griseus	NA	NR	NR	NR	NR	P	P	P	NR
Orcinus orca	DD	P	NR	NR	NR	P	P	P	NR
Peponocephala electra	LC	P	NR	NR	NR	NR	NR	P	NR
Pseudorca crassidens	DD	P	NR	NR	NR	?	P	P	?
Sousa chinensis	NT	P	P	P	P	P	NR	NR	P
Steno bredanensis	LC	NR	NR	NR	NR	P	NR	NR	NR
Stenella longirostris	DD	NR	NR	NR	P	P	P	P	P
Tursiops truncatus	LC	P	NR	NR	NR	P	NR	NR	P
PHOCOENIDAE									
Neophocaena phœaenoides	VU, I	P	NR	NR	NR	P	P	P	NR
PHYSETERIDAE									
Physeter macrocephalus	VU, II	NR	NR	NR	P	P	P	P	NR
Kogia breviceps	DD	P	NR	NR	NR	?	P	P	NR
Kogia simus	DD	NR	NR	NR	NR	P	P	P	NR
ZIPHIIDAE									
Ziphius cavirostris	LC	NR	NR	NR	NR	NR	P	NR	?
BALAENOPTERIDAE									
Balaenoptera edeni	DD	NR	NR	NR	NR	P	P	P	NR
B. physalus	EN	NR	NR	NR	NR	R	P	P	NR
B. musculus	EN	P	NR	NR	P	P	P	P	NR
Megaptera novaeangliae	LC	P	NR	NR	NR	NR	NR	P	NR
BALAENIDAE									
Eubalaena glacialis	EN	NR	NR	NR	NR	NR	P	NR	NR
E. australis	LC	P	NR	NR	NR	NR	P	NR	NR
DUGONGIDAE									
Dugong dugon	VU, I	P	NR	NR	NR	P	NR	NR	?

ANNEXURE IV

Seagrass distribution along West coast of India (Source: Jagtap and Untawale, 1981; Jagtap, 1987; Jagtap, 1991; Ansari *et al*., 1991; Jagtap and Inamdar, 1991; GEC, 1996; Kaladharan and Ashokan, 2012).

Species	IUCN Red List Status	Population trend	KutchchS helf	Saurashtra Shelf	Khambat Inner Shelf	Khambat Outer Shelf	Malabar Shelf	South Western Indian Slope	North Western Indian Slope	Coral Island Province
Hydrocharitaceae										
Thalassia hemprichii	LC	Stable	NR	NR	NR	NR	NR	NR	NR	P
Halophila ovalis	LC	Stable	P	R	P	P	P	NR	NR	P
H. beccarii	VU	Decreasing	NR	NR	NR	NR	P	NR	NR	NR
H. ovata	LC	Stable	R	NR	R	NR	NR	NR	NR	P
Enhalus acoroides	LC	Decreasing	NR	NR	NR	NR	R	NR	NR	P
Cymodoceaceae										
Cymodocea serrulata	LC	Stable	NR	NR	NR	NR	P	NR	NR	P
C. rotundata	LC	Stable	NR	NR	NR	NR	NR	NR	NR	P
Halodule uninervis	LC	Stable	R	NR	NR	NR	NR	NR	NR	P
Syringodium isoetifolium	LC	Stable	NR	NR	NR	NR	P	NR	NR	P

ECOSYSTEM CHARACTERISATION OF INDIAN COAST WITH SPECIAL FOCUS ON WEST COAST

Report by
CSIR-NIO for BOBLME (FAO)

Bangladesh, India, Indonesia, Malaysia, Maldives, Myanmar, Sri Lanka and Thailand are working together through the Bay of Bengal Large Marine Ecosystem (BOBLME) Project to lay the foundations for a coordinated programme of action designed to better the lives of the coastal populations through improved regional management of the Bay of Bengal environment and its fisheries.

The Food and Agriculture Organization (FAO) is the implementing agency for the BOBLME Project.

The Project is funded principally by the Global Environment Facility (GEF), Norway, the Swedish International Development Cooperation Agency, the FAO, and the National Oceanic and Atmospheric Administration of the USA.

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