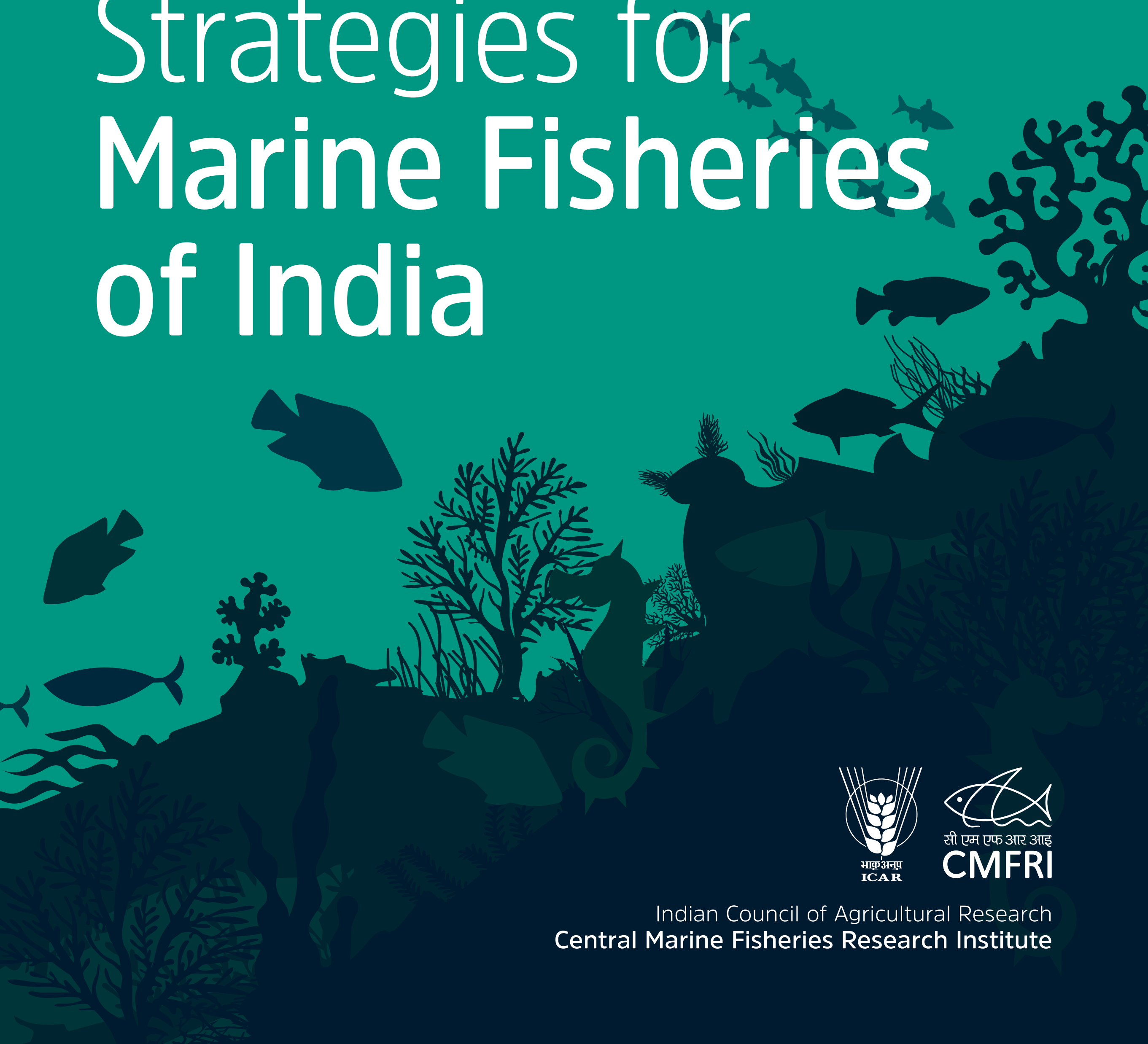
CMFRI Special Publication No.135
ISSN 0972-2351

Impact, Vulnerability and Adaptation Strategies for **Marine Fisheries of India**



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Impact, Vulnerability and Adaptation Strategies for **Marine Fisheries of India**

IVAS–MFI Project Final Report | December, 2019

Gopalakrishnan A., Zacharia P. U. and Grinson George

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Impact, vulnerability and adaptation strategies for marine fisheries of India

Published by
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Design: Blackboard, Kochi
Printed at: PrintExPress, Kaloor, Kochi

Publication, Production & Co-ordination
Library & Documentation Centre, CMFRI

CMFRI Special Publication no.135
ISSN: 0972-2351

Citation: Gopalakrishnan A, Zacharia P. U and Grinson George, 2020. Impact, vulnerability and adaptation strategies for marine fisheries of India: IVAS-MFI final report. CMFRI special Publication No.135. ICAR-Central Marine Fisheries Research Institute, Kochi. 80 pp.

Preface

Scientists at ICAR-CMFRI often encounter questions on the changes in resource abundance and distribution in the coastal waters due to climate change. But, there is lack of coherent studies in northern Indian Ocean to scientifically quantify and predict the impacts of climate variables on fisheries resources. The absence of scientific information becomes a major limitation to policy planners in their attempt to explain the magnitude of climate change impacts on oceans and seas in future and the possible measures that could be adopted to tackle them. Therefore, an effort is made in this document to quantify the future alterations in potential climate variables of the northern Indian Ocean and infer the possible effects it can have on the marine flora and fauna.

This document is meant to address a global audience. Therefore, efforts are made to incorporate globally approved climate change model results in the study to understand the future challenges of marine ecosystems in the northern Indian Ocean. The long-term forecasts on major environmental variables such as Sea Surface Temperature (SST), pH, mean sea level, sea surface salinity, rainfall and chlorophyll were examined for assessing the changes and the plausible effects on the resources. The resulting possible changes on the quantum of production and changes in essential fish habits are deliberated in this special publication. The cascading effects of productivity changes, vulnerability of certain sensitive ecosystems such as the coral reefs and the social/ community impacts of such changes are discussed. Obvious changes registered in the marine resources during the last two decades, future changes with short-term interim breaks for 2030, 2050 and 2080 are also included in this.

All these studies have to be addressed in the organizational or institutional framework of governance existing in the country. Therefore, a dedicated section with recommendations or possible strategies is also presented. There are probable solutions or adaptation strategies for specific challenges. This document can serve as a scientific guideline for effectively implementing it.

I acknowledge the support from Ministry of Environment Forest and Climate Change (MoEF&CC – Govt of India) which enabled us to prepare this document with the active funding support from UNDEP-GEF. I am sure that the third national communication on India's preparedness to climate change will have marine fisheries as a major component. Finally, the effort put up by my colleagues, Drs P.U. Zacharia and Grinson George is greatly acknowledged. As the study was conducted using a small grant with numerous project deadline extensions, several project staff were involved in this compilation and I gratefully remember the service of each and every one of them in this programme. I am sure that humanity is going to survive despite the frequent jolts humans are receiving in the form of disasters and pandemics in the wake of climate change. Scientific initiatives such as this will complement the ongoing efforts in combating such challenges.

A. Gopalakrishnan

Contents

Brief Summary of the Project

1. Project title	Impact, Vulnerability and Adaptation Strategies for Marine Fisheries of India
2. Reporting Period	Dec 2016 – Dec 2019
3. Name of the Institute	ICAR-Central Marine Fisheries Research Institute, Kochi
4. Name of the PI	Dr. A. Gopalakrishnan, Director, ICAR-CMFRI, Kochi. director.cmfri@icar.gov.in
5. Name of the Nodal Officer	Dr. P. U. Zacharia, Principal Scientist & Head-in-Charge, Demersal Fisheries Division
6. Name of the Co-Nodal Officer	Dr. Grinson George, Senior Scientist, Fishery Resources Assessment Division
7. Total Grant (Rs.)	25,30,000/-
8. Grants released so far (as on 31st Dec 2019) Rs.	24,49,040/-

9. Brief of Technical Program

CMIP-5 model was adapted to northern Indian Ocean region and validated using some in-situ measurements collected during the study period. Calibrated and validated model was used for predicting the environmental variables in different RCP scenarios. Further, the data generated was used for assessing the impact and vulnerability of commercially important resources in Indian EEZ. Various secondary data sets generated in different climate change related programmes and marine fisheries census of ICAR-CMFRI was used in this study. Original data from National Marine Fisheries Database of ICAR-CMFRI was used in this study.

10. Summary of achievements :

- In-situ oceanic data collection was done for variables such as chlorophyll, salinity, pH and SST using flurometer, onboard Research Vessel *F. V. Silver Pompano*
- Projections of six oceanographic variables (SST, Precipitation, Chlorophyll, pH, Salinity, Sea level rise) for different RCP scenarios (2.6, 4.5, 6.0 and 8.5) for 2030, 2050 and 2080 were made using CMIP-5 model and possible Impact, vulnerability and adaptation strategies for Indian marine fisheries sector has been assessed
- Documented the impact of changes in oceanographic variables on the catch of vulnerable species of fishes along Indian Ocean during the period 2007-16 based on the inputs received from various climate change related projects at ICAR-CMFRI
- One full length research article was published based on the modeling studies of the project
- Association and partial sponsorship has been done for the event 'The second symposium of SAFARI on Remote sensing for Ecosystem Analysis and Fisheries'

Objectives

a. Assessment of Impact of Climate Change on marine fisheries of India:

- Impact of climatic variations on prioritized marine fisheries and coastal ecosystem
- Predictive modelling for assessing the possible changes in marine fisheries sector during 2030, 2050 and 2080

b. Development of vulnerability indices for marine fisheries of India:

- Assessment of vulnerability of prioritized marine fishes to Climate Change

c. Development of an adaptation framework for marine fisheries of India:

- Formulation of strategies to increase the adaptive capacity of key vulnerable segments of the marine fishery

Impact of climate change on the marine fishery potential of India in economic, social and ecological terms

Introduction

Fisheries sector plays an important role in the socio-economic development of the country. Apart from generating income, employment and providing nutrition to a large section of the economically backward population, it supports a substantial amount of foreign exchange in the form of seafood export. Marine fishery resources are naturally renewable and management of their harvest is necessary for a sustained production from the sea. Towards this, it is very much essential to have reliable and updated knowledge base with information on status of these resources, socio-economic status of fisherfolk and infrastructure facilities existing in fishing villages. In view of the dynamic nature of marine fisheries sector, the policies and interventions need to be reviewed periodically. The marine fisheries census 2005 and 2010 was carried out by CMFRI as the component 'Census on marine fisheries' of the 10th and 11th plan central sector scheme of DAHDF entitled "Strengthening of Database and Geographical Information System for Fisheries Sector" with a budget allocation of ₹163.5 lakhs. Further, the release of the latest census report in 2016 as part of 12th plan is awaited. In this study, we have used data sets from marine fisheries 2010 to illustrate the impact and vulnerability of climate change.

As per the census there were 3,288 marine fishing villages and 1,511 marine fish landing centres in 9 maritime states and 2 union territories. The total marine fisher folk population was about 4 million comprising of 8,64,550 families. Nearly 61% of the fishermen families were under below poverty line (BPL) category. The average family size was 4.63 and the overall sex ratio was 928 females per 1,000 males. Almost 58% of the fishers were educated with different levels of education. About 38% of marine fisherfolk were engaged in active fishing with 85% of them having full time engagement. About 63.6% of those in fishing were engaged in fishing and allied activities. Nearly 57% of the fisher community engaged in fish seed collection were females and 43% were males. Among the marine fishermen households 1,31,012 families were having life saving equipment. In the marine fisheries sector, there were 1,94,490 crafts in the fishery, out of which 37% were mechanized, 37% were motorized and 26% were non-motorized. Out of a total of 1.67,957 crafts fully owned by fishers, 53% were non-motorized, 24% were motorized and 23% were mechanized. Among the mechanized crafts fully owned by fishermen, 29% were trawlers, 43% were gillnetters and 19% were dolnetters.

The erstwhile Department of Animal Husbandry Dairying and Fisheries, Ministry of Agriculture and Farmer's Welfare, Government of India was bestowed with the responsibility of planning the sustainable exploitation of the fishery resources of the Indian EEZ until 2019. Realising the attention needed in the sector, a separate Ministry of Fisheries Animal Husbandry and Dairying was formed in 2019 and there is a separate Department of Fisheries under the Ministry to provide undivided attention to fisheries and aquaculture in the country.

For achieving the primary objective as mentioned in the title, the Department constituted a Working Group to study and revalidate the resource potential of the Indian EEZ and subsequently in 2018 revised estimates were given. The experts of the Working Group convened several meetings and conducted in-depth analysis of available data and arrived at the revised figures of potential for different resources in the Indian EEZ. Their summary of the findings and recommendations are presented as follows.

Summary of Potential Estimates

The potential yield of the Indian EEZ has been revalidated as 53,10,593 t by the present Working Group of Experts for conventional resources and 18,47,775 t for non-conventional resources with a grand total of 71,58,368 t.

The potential for the EEZ up to 200 m depth is estimated at 49,24,016 t whereas the potential for depth zones between 200–500 m had been estimated as 97,421 t. There are oceanic resources of 168063 t other than islands and island resources to the extent of 1,21,053 t.

The estimates for the different depth zones indicated a definite gradient in the density of distribution of the resources from shallow zones to deeper zones. The region within 100 m depth zone being currently fully exploited. There is no scope for further expansion in near shore waters and potential in deeper waters needs to be explored for more production from the sea.

Coastal Resources in India almost reached its peak with the production levels just above 3.5 million metric tonnes, the latest production data of the year 2018 being 3.49 million metric tonnes. When we look into the crafts involved in fishing in Indian Exclusive Economic Zone (EEZ), among the nearly 2.3 lakh vessels in operation in the country; 30% are mechanized vessels harvesting nearly 70% of resources and the remaining motorized (in-board and out-board vessels) as well as non-motorized/ non-mechanized vessels are harvesting only 30% resources. Fishing fleets above optimum level are observed in coastal fishing. Fish from peninsular India is almost plateaued at an annual production level that hovers around 3.5 million metric tons. NITI Aayog, the major planning body in India recommended no further registration of mechanized fishing vessels. The irony is that Lakshadweep and Andaman & Nicobar Islands presently contribute to about 45,000 tonnes of fish catch which is much below the potential of total fish which could be harvested in these Union Territories. The average landing from the islands is however only about 10-15 percent of the estimated fishable potential (Vinay et al, 2017; Dam Roy et al, 2009; CMFRI 2006). Given that the EEZ encompassing the islands is close to half of India's total EEZ, there is substantial untapped potential that could be harnessed by investing more on island fisheries. Most of the island resources are constituted by high value fishes such as tunas and allied species, barracudas, bill fishes, elasmobranchs and squids. The development priorities in fisheries in the islands are quite different from that of the mainland. Islanders are mainly dependent on reef and deep sea resources for their livelihood.

Impact of climate variability on prioritized marine fisheries and coastal ecosystem

Introduction

Climate change is a global issue requiring a global response, which have economic and ecological implications on regional resource management. United Nations Framework Convention on Climate change (1992) defines climate change as "change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". IPCC refers climate change to a change in the state of the climate that can be identified (*e.g.* using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity.

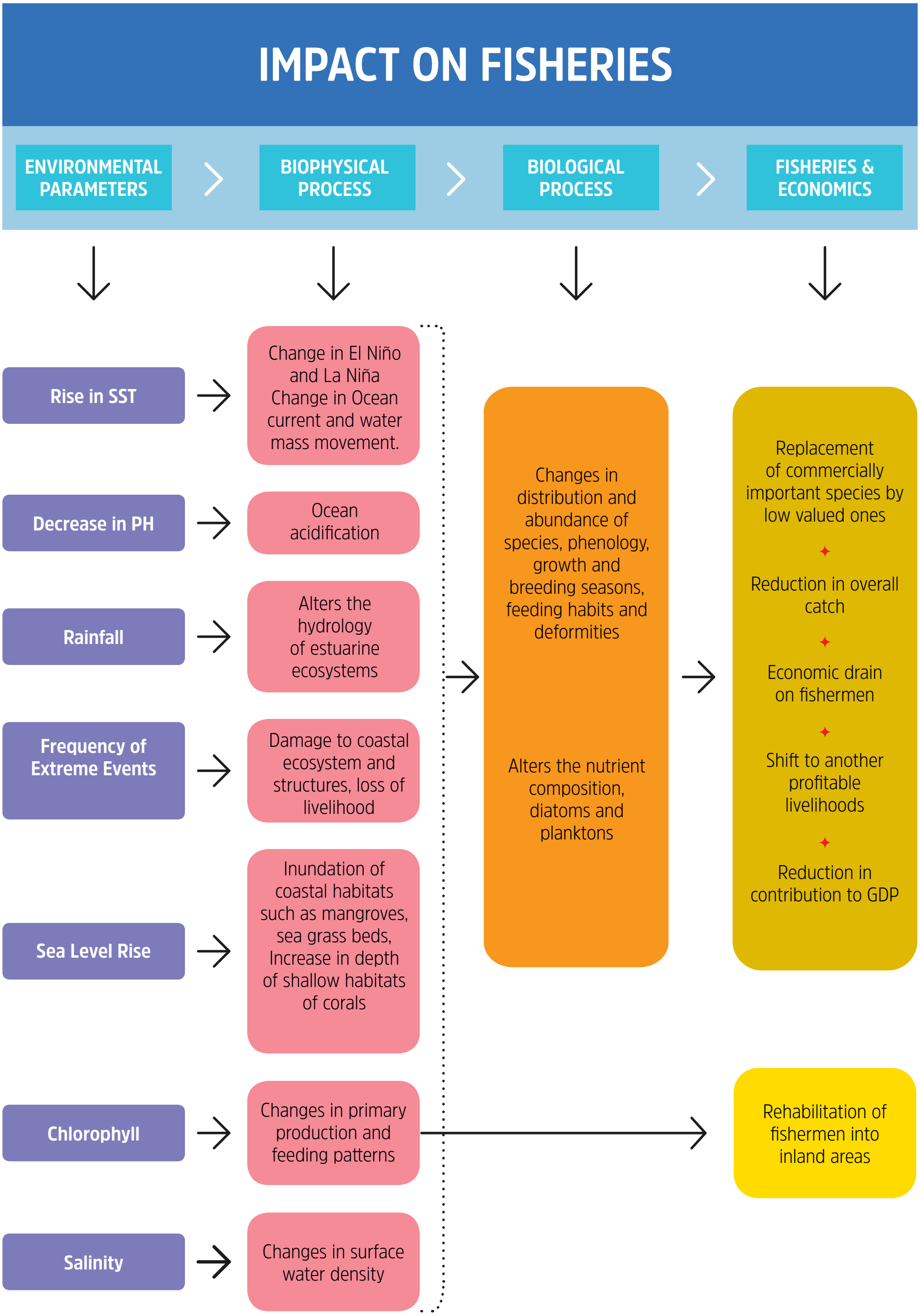
The World Meteorological Organization has attributed the increasing concentrations of greenhouse gases to the increased use of energy and growing economy. The emission of greenhouse gases has increased since the pre-industrial era (level of 280 ppm to the level of 379 ppm CO_2 in 2005), which is a major anthropogenic cause for the climate change and its impacts on the marine fisheries sector (warren et al., 2011). The annual global greenhouse gas (GHG) emission has reached its maximum of 49 (±4.5) $GtCO_2$-eq yr^{-1} in 2010. The GHG emission which was 0.4 $GtCO_2$-eq (1.3%) yr^{-1} during 1970-2000 had increased to 1.0 $GtCO_2$-eq (2.2%) yr^{-1} during 2000-10. Emissions of CO_2 from fossil fuel combustion and industrial processes contributed about 78% of the total GHG emissions increase from 1970 to 2010 (IPCC, 2014). Globally, the ocean warming is largest near the surface, and the upper 75 m warmed by 0.11°C [0.09 to 0.13] per decade over the period 1971 to 2010 (IPCC, 2014). This impact of climate change is well pronounced in fisheries sector.

Varying environmental conditions can induce changes in foraging, growth, fecundity, metamorphosis, endocrine homeostasis and migratory behaviour of fish species. Changes may be at the population and community level due to effects on performance, patterns of resource use, and survival.

Oceanic changes caused by the climate changes seriously affect the fish populations, and the aquatic food web, as each species depends on optimum conditions suitable for their lifecycle. Climate change has direct effects on fish stocks and productivity and indirect through changes in the diet and habitat. Adaptive strategies will become essential for the fisheries for inducing robustness and flexibility to absorb the changes in resource abundance, as well as to avoid negative social and economic impacts.

The Indian Ocean (IO) extends over 30% of the global ocean area and is rimmed by 36 littoral and 11 hinterland nations sustaining about 30% of the world's population. Meridionally, the IO extends from the Gulf of Oman and the head of the Bay of Bengal in the north to 40^{o}S and zonally, from the east and South African coasts in the west to the coastlines of Myanmar, Thailand, Malaysia, and Western Australia in the east. The IO spreads over 74.92 million km^2 (29% of the global ocean area) with an average depth of 3,873 m and a maximum depth of 7,125 m (Java Trench). India is one of the major fish producing countries in the world contributing to about 6.3% of fish production to world production. India with a coastline length of 8129 km and Exclusive Economic Zone (EEZ) of 2.02 million sq. km supports 0.9 million active fishermen population. The total marine production in India during 2015 was 3.49 million tonnes which registered a 6.2% reduction when compared to the total catch (3.72 million tonnes) in 2014. The total contribution of India to global capture fisheries production in 2015 is 4.3% (Shelley, 2015). In India, marine fisheries are very important in sustaining food security, employment and income generation, strengthening rural development and also in providing the essential nutrition supply for the people. Northern Indian Ocean has been identified as one of the 17 climate change hotspots among the world oceans. According to the United Nations Environment Programme (UNEP), India is one of the 27 countries that will face the worst consequences of sea level rise caused by thermal expansion of ocean water due to global warming.

The impacts of climate change on fisheries and aquaculture occur as a result of both gradual atmospheric warming along with associated physical and chemical changes of the aquatic environment. Climate change is likely to affect already vulnerable fisheries and ocean-dependent communities through less stable livelihoods, changes in the availability and quality of fish for food, and rising risks to their health, safety and homes. It has been predicted that there would be a decrease in landed fish value of 21% and a total annual loss of USD 311 million by 2050 over 2000 values, and a significant loss in fisheries-related jobs of almost 50% in 14 West African countries. Overall, rising temperatures are predicted to reduce catches of main fish species by 40% by 2050 (FAO, 2017)


IMPACT ON FISHERIES
ENVIRONMENTAL PARAMETERS
BIOPHYSICAL PROCESS
BIOLOGICAL PROCESS
FISHERIES & ECONOMICS
Rise in SST
Change in El Niño and La Niña Change in Ocean current and water mass movement.
Decrease in PH
Ocean acidification
Rainfall
Alters the hydrology of estuarine ecosystems
Frequency of Extreme Events
Damage to coastal ecosystem and structures, loss of livelihood
Sea Level Rise
Inundation of coastal habitats such as mangroves, sea grass beds, Increase in depth of shallow habitats of corals
Chlorophyll
Changes in primary production and feeding patterns
Salinity
Changes in surface water density
Changes in distribution and abundance of species, phenology, growth and breeding seasons, feeding habits and deformities
Alters the nutrient composition, diatoms and planktons
Replacement of commercially important species by low valued ones
Reduction in overall catch
Economic drain on fishermen
Shift to another profitable livelihoods
Reduction in contribution to GDP
Rehabilitation of fishermen into inland areas

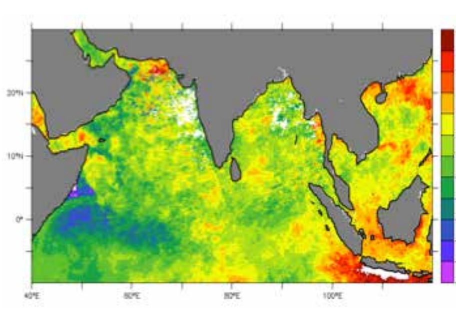
Environmental variables and recent changes

Sea Surface Temperature (SST)

Rates of increase in SST are highest near the surface of the Ocean (>0.1°C per decade in the upper 75m from 1971 to 2010) and decrease with with depth (0.015°C per decade at 700m). The surface layers of the three ocean basins (Indian, Atlantic and Pacific oceans) have warmed, with the Indian Ocean (0.11°C per decade) warming faster than the Atlantic (0.07°C per decade) and Pacific (0.05°C per decade) Oceans. This is consistent with the depth-averaged (0 to 700 m) temperature trend observed from 1971 to 2010. The total SST change for the coastal boundary systems for the last 60 years along the western Indian Ocean accounts to 0.60^{o}C and along the eastern Indian Ocean accounts to 0.552^{o}C (IPCC, 2014).

Average Sea Surface Temperature in the Bay of Bengal was found to be 28.39^{0}C (1970-1979), 28.86^{0}C (1980- 1989), 29.31^{0}C (1990-1999) and 29.39^{0}C during 2000-2010. The trends of forty years (1970-2010) of SST registered a maximum of 31.91^{0}C during 1973 (April) and minimum of 14.35^{0}C during 1999 (December) with an average of 28.39^{0}C. Trend analysis during the study showed that, SST is increasing over the period (Hossain, 2015). Fluctuations in regional temperature induced by climate change can affect growth, maturity, spawning time, egg viability, food availability, mortality, and spatial distribution of marine organisms (Ottersen et al., 2001; Perry et al., 2005; Nye et al., 2009).

Increase in temperature will reduce the amount of dissolved gases in liquid, and decrease with leads to expansion of the low oxygen zones in water. Over a range from 0 to 15^{o}C, dissolved



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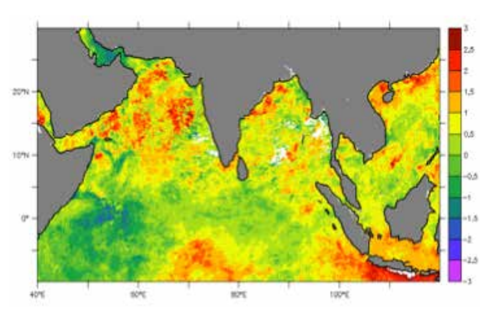


July 2015

Fig 2. SST anomaly for the Indian Ocean (MODISA) oxygen concentration in seawater is related approximately linearly to temperature, and will decline by about 6% per one degree rise. By the end of the century low oxygen zones will expand to more than 50% of their present volume as a result of increase in SST and rising CO_2 concentrations. Oxygen availability and variations in oxycline depth affects fish schooling behaviour to a greater extend (Brierley et al., 2009).

Rising sea surface temperatures (SST) can enhance near-surface stratification inhibiting vertical mixing, a critical process for introducing nutrients into the euphotic zone where sufficient light is available for photosynthesis (Roxy et al. 2016).

pH (Ocean acidification)

The increased uptake of CO_2 by oceans since the beginning of the industrial era has resulted in acidification of the ocean. The pH of ocean surface water has decreased by 0.1 units, corresponding to a 26% increase in acidity, measured as hydrogen ion concentration. Surface ocean pH has decreased by approximately 0.1 pH units since the beginning of the Industrial Revolution, with pH decreasing at the rate of 0.0013 and 0.0024 pH units yr^{-1} globally (IPCC, 2014).

The pH in the Bay of Bengal has fallen by 0.2 units between 1994 (pH 7.95) and 2012 (Rashid et al., 2013).

Ocean acidification resulting from human emissions of carbon dioxide has already lowered and will further lower pH of surface ocean water. This decrease in pH will have more deleterious effect on calcifying and calcareous organisms. The consequent decrease in calcium carbonate saturation with decreasing pH threatens calcareous marine organisms. The main carbonate minerals produced by marine calcifers include calcite and aragonite, the production and stability of which is affected by the amount of CO_2 in seawater, which is also partially determined by SST (Guinotte et al., 2008).

Sea Level Rise (SLR)

Intergovernmental Panel on climate change (IPCC) 2013 report says that the average rate of global sea level rise during 1901 to 2010 was 1.7 mm yr^{-1} [1.5 to 1.9], and 2.0 mmyr^{-1} [1.7 to 2.3] between 1971 and 2010, and 3.2 mm yr^{-1} [2.8 to 3.6] between 1993 and 2010. Globally, on an average the mean Sea Level Rise from a period of 1901 to 2010 is 0.19 m (0.17 to 0.21 m) (IPCC, 2013).

Unnikrishnan et al. (2006) studied the SLR for Mumbai, Kochi and Vishakhapatnam and showed a SLR of 0.78, 1.14 and 0.75 mm yr^{-1} respectively. In another study Unnikrishnan and Shankar (2007) estimated SLR for the northern part of Indian Ocean. The estimated trend in stations such as Mumbai and Kochi in the Arabian Sea and Vishakhapatnam in the Bay of Bengal is between 1.06 -1.75 mm yr^{-1}, with an average rise of 1.29 mm yr^{-1}.

An increase in mean sea level will affect waves, currents and bottom pressure in the near shore region. In general, an increase in mean water depth will be accompanied by an increase in mean wave height, resulting in a more severe wave attack on the coast and a greater wave induced littoral drift.

Rising sea levels will lead to submergence of important coastal habitats such as mangrove forests, sea grass beds and salt marshes which in turn affect the diversity of benthic invertebrates such as tiger prawns or mud crabs (Badjeck et al., 2010). These coastal ecosystems usually act as buffer for changes in environmental parameters and protect the shores from the extreme events such as storm surges, high waves *etc*., (Gitay et al., 2002; IPCC, 2013). Existing wetlands such as peat lands are major deposits of carbon, thus degradation of these ecosystems will release significant amount of Green House Gases.

Sea Surface Salinity (SSS)

Ocean salinity changes are an indirect but potentially sensitive indicator of a number of climate change processes such as precipitation, evaporation, river runoff and ice melt. Ocean salinity varies regionally and is dependent on the balance between precipitation and evaporation. Evaporation dominated regions such as Atlantic and western Indian Oceans have elevated salinity while areas having increased precipitation such as North Pacific, North Eastern Indian Ocean and Eastern pacific have relatively low salinities (Hoegh-Guldberg et al., 2014).

Combined effect of the temperature and salinity changes is an overall reduction of the surface density, resulting in an increased vertical stratification and changes in surface mixing. Changes in salinity also disrupt the osmoregulation of marine species. Decrease in salinity would reduce the buoyancy. Eg: Buoyancy would be too low for cod eggs to remain floating, due to reduction in density which occurs as a result of changes in salinity (Tsukamoto et al., 2008).

Rainfall (Pr)

The Indian monsoons are related with the El Niño and La Niña. The warm phase (El Niño) is associated with weakening of the Indian monsoon, while the cold phase (La Niña) is associated with the strengthening of the Indian monsoon (Kumar et al., 2010).

Studies on change of rainfall pattern over India by Indian Meteorological Department identified changes in the frequency of days of rainfall with different intensities at various geographical regions of India. Significant change/turning points are also detected in the southwest monsoon rainfall. Reports also indicated a reduction in frequency of moderate rainfall events (5 mm $\leq$daily rainfall$<$100 mm) during the period 1951–2010 over the monsoon core region of India (Guhathakurta et al., 2015).

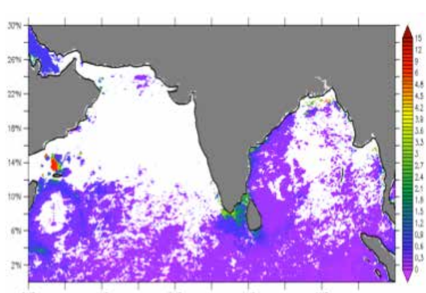
Chlorophyll (*Chl*)

Changes in chlorophyll composition, which are the primary producers will affect the fish species composition and catch availability. These are influenced by the availability of nutrients in the ocean.

Any trend in primary production change can have greater implications for ecosystem processes, and biogeochemical cycling. Downward trends in primary production over the upwelling areas can be detrimental to the marine food webs and the fishing industry (Roxy et al, 2016).

The decadal seasonal analysis of chlorophyll concentration in the Arabian Sea and the Bay of Bengal has been studied by Shah et al, 2017. It was observed that there has been an increase in chlorophyll concentration in both AS and BOB from 1980 to 2000's with respect to a gradual increase in SST. The chlorophyll values ranged between 0.5 to 1.3 mg m^{-3} in 2000's which was 0.4 to 0.9 mg m^{-3} in 80's. The chlorophyll values in BOB which was 0.2 to 0.5 mg m^{-3} in 80's have increased to 0.5 to 0.7 mg m^{-3} in 2000's (Shah et al., 2017).

Singh and Chaturvedi in 2010 has studied the chlorophyll variation in the Arabian Sea and the Bay of Bengal. Results concluded that the Arabian Sea was found to be higher in chlorophyll concentration compared to Bay of Bengal. Highest chlorophyll concentrations were found in northern Bengal near the river mouths during monsoon seasons. This is due to the heavy nutrient discharge from the rivers during monsoon season. Phytoplankton blooms in the Bay of Bengal during winter was attributed to the upwelling driven by Ekman pumping. Reduced chlorophyll concentrations in the Bay of Bengal was attributed to the increased SST, strong stratified layer which could not be easily broken by weaker winds over BOB, thus leading to a reduced nutrient availability (Singh and Chaturvedi, 2010).



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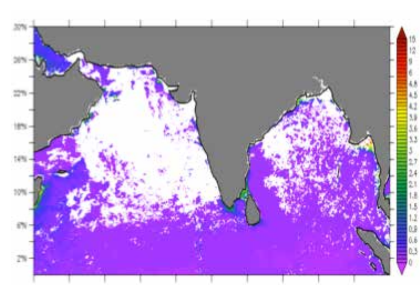


July 2015

Fig 3. Chlorophyll concentration along Indian Ocean during July in 2016 compared to July 2015

Impacts on marine fisheries and ecosystem

Most marine fishes are adapted to a narrow range of temperature related to their metabolic activities and food availability. An increase in SST of 1ºC will increase the metabolic activity by 10%. These changes in metabolic activity will induce changes in distribution and abundance in fish stocks (Zacharia et al., 2016). Metabolic rates of most marine and aquatic animals which are cold-blooded (poikilotherms) are strongly affected by external environmental conditions, especially temperature. The optimum conditions of thermal tolerance for marine organisms is at midrange and poorer growth is observed at temperatures which are too high or too low. Many macro physiological studies show that natural levels of spatial and temporal environmental variation have great impact on the physical condition of individual marine organisms and species. Organisms that are transferred into conditions different from those to which they have been adapted, function poorly compared with related organisms previously adapted to these new conditions (Osovitz and Hofmann, 2007).

Changes in diet composition

Changes have been observed in the diet composition of Indian mackerel (*Rastrelliger kanagurta*) as an impact of climate change. The diet study during 1960-1961 showed a diet dominant in zooplankton and copepods. But this composition has been found to change to a diet dominant in phytoplankton consisting of *Coscinodiscus* sp. in 2011-2014. It was assumed from the results that an increase in phytoplankton in surface waters as an effect of increased SST lead to change in the available food (Supraba et al., 2016).

Changing chlorophyll compositions in the ocean is observed to have induced changes in the diet composition of marine fishes. Extension of distributional ranges of phytoplankton and its associated zooplankton in the North Sea owing to atmospheric changes such as increased wind circulation, oceanic flow and higher SST lead to a change in migratory pattern of horse mackerel (*Trachurus trachurus*) based on the food availability. This led to an increased catch of mackerel from 40 kt in 1982 to 300 kt during the period 1990 to 1994 (Reid et al., 2001).

Fish availability and catch composition depend on the availability and extend of distribution of phytoplankton. Reports from FAO says that 20% of the world tuna catch accounts from Indian Ocean, especially the most economically valuable big eye tuna, making it the second largest supplier to world markets. It is evident that large-scale distributions of these dominant species of tunas in Indian Ocean are associated with the phytoplankton availability and abundance.

Changes in chlorophyll concentration of the oceans induce changes in overall fish catch. This has been observed off Mumbai coast. The studies on fish landings and chlorophyll concentration indicated that during the period 2008-10 there was an overall increase of chlorophyll concentration leading to increased fish catch and further during the period to 2012 a gradual decrease in fish catch was seen owing to reduced chlorophyll concentration (Azmi et al., 2015)

Shifts in spawning seasons

Sea Surface Temperature anomalies greater than summer maxima seems to impact the spawning of many marine fishes. Fish species tend to shift their spawning seasons to cooler months in order to avoid the temperature anomalies. The threadfin breams which are short lived, fast growing and highly fecund species is seen to have a shift in spawning season when SST exceeds 29°C. Data on the spawning of *Nemipterus japonicus* indicate that during the warm months (April- September) of 1981-1985, there occurred 35.3% spawners which were reduced to only 5.0% during 2000-2004 for the same months. It was also observed that the percentage of spawners increased to 95% during October-march (coolest months) in 2004 which was only 65% during 1985 for the coolest month (Rao, 2011).

Changes in metabolic activities

Study conducted on *Plectropomus loepardus* revealed that the standard oxygen consumption (minimum or resting) increased 11% per 1°C over the temperature range from 24°C to 33°C and maximum oxygen consumption peaked at 30°C and the same was 16.7% lower for the fishes subjected to 33°C irrespective of the population (Pratchett et al., 2017).

In case of coral grouper when newly fertilized embryos were subjected to increase in temperature, the mortality was negligible at 29.5°C and the mortality rates increased with an increasing temperature, finally all embryos died within 6 hours at 33.9°C. The fish also exhibited declines in spontaneous swimming speeds at temperatures greater than 27°C (Pratchett et al., 2017).

Changes in distribution of marine species

In relation to climate change, marine species either extends their distributional boundary or shows a latitudinal shift. Catfishes that were earlier distributed between 8°N and 14°N latitudes (southwest and southeast coasts of India) showed a reduction in catch from 35,000t to 7,800t as the SST in southern latitudes exceeds 29°C. The same way the catch increased from 16,000t to 42,500t in the northwest and northeast coasts of India for the same period as the SST in the northern latitudes ranged between 27°C and 28.5°C (Rao, 2011).

False Trevally, a commercially important fish of India, was usually found along the Rameshwaram coast of southeast India and also at depths ranging from 15 to 90 meters. But during the past decade the catch of this species declined as they moved to other coasts including the east coast of Sri Lanka (Rao & Vivekanandan, 2008).

The tropical coastal and small pelagic fishes such as the oil sardine, *Sardinella longiceps* and the Indian Mackerel, *Rastrelliger kanagurta*, that form the major share of the Indian marine catch, was found to have a restricted distribution between latitudes 8ºN and 14ºN and longitude 75ºE and 77ºE (Malabar upwelling zone along the southwest coast of India) when the SST ranged between 27ºC and 29ºC. Now catch of these two species has been found to have increased between 14ºN and 22ºN latitudes but without any reduction in catch from the Malabar upwelling zone indicating that this is a distributional extension and not distributional shift (Rao, 2011).

Impacts on primary productivity

Phytoplankton is the primary producer of the ocean on which all other trophic level is built upon. Any change in phytoplankton composition will alter the feeding pattern of zooplankton and small fishes which in turn will affect the higher trophic levels. These changes can lead to changes in availability of fish species, catch composition etc. *Chl-a* has been used as a measure to identify the presence of phytoplankton. *Chl-a* concentration above 0.2 mgl^{-1} indicate the presence of sufficient fish food to sustain a viable commercial fishery. Climate change also affects the size of cells and timing of plankton blooms, which is the primary producer, with direct impact on recruitment success and population sizes (Walther et al., 2002).

Low levels of surface nutrients limit phytoplankton growth. Climate warming inhibits mixing of sea water, reducing the upward nutrient supply and lowers the productivity (Doney 2006). Ocean acidification can also affect processes related to photosynthetic activity, including increased rates of phytoplankton growth, primary production, and release of extracellular organic matter, as well as shifts in cellular carbon to nitrogen to phosphorus (C:N:P) ratios (Riebesell et al., 2007; Bellerby et al., 2007; Fu et al., 2007; Hutchins et al., 2009)

Sea Surface Temperatures (SST) and primary production are directly correlated. Shah et al. (2017) studied the relationship between chlorophyll and SST in the Arabian Sea and Bay of Bengal. Results showed that the increase in SST was comparatively much higher in the Arabian Sea than in the Bay of Bengal during the period 1980-2000. the Arabian Sea showed a positive relationship between chlorophyll and SST during 1980's and inverse relationship in 2000. This had been attributed to the increased tolerance limit of phytoplankton to changing SST and nutrient availability. Increase in SST leads to change in species composition of phytoplankton as species tolerant to higher temperatures expand their range, which will induce a change in carbon export and food availability to higher tropic levels.

Increase in SST will lead to rapid growth, early maturing and short life span of phytoplankton or algae. These changes in growth pattern of planktons which are primary producers may not coincide with the feeding patterns of aquatic biota. Experimental studies on algae; *Chaetoceros calcitrans* shows that the growth rate increases at elevated temperatures and also a reduction in life span. The maximum cell density on the sixth day of the study at 29ºC was $650x10^3$cells ml^{-1} but when cultured at 24ºC the maximum cell density reached only $510x10^3$cells ml^{-1} even on the seventh day. All micro algae died on day 10 at 29ºC and on day 12 at 24ºC revealing reduced life span and early death at higher temperatures (Vivekanandan, 2010).

Impacts on corals

Corals are seen to have greatly affected by changes in environmental conditions. It primarily affects the growth and reproduction of corals, which are home to many species of marine organisms. Coral reefs provide habitat for a highly diverse ecosystem and short-term extreme water temperatures can cause the symbiotic algae (zooxanthellae) in corals to perish, resulting in coral "bleaching". Bleaching usually occurs when temperatures exceed a threshold of about 0.8 to 1°C above mean summer maximum levels which prevails for at least four weeks (Hoegh-Guldberg et al., 1999). Rise in SST induce a state of thermal stress in corals which will be evident as coral bleaching. Temperature anomalies would also lead to quicker embryo development, reduced egg and sperm production and incomplete fertilization cycles in corals.

Ocean acidification reduces the ability of corals to secrete their exoskeletons that are made of calcium carbonate. This leads to coral exoskeletons which have reduced strength that will be more vulnerable to physical disturbances such as storm surges and high speed winds. Rise in sea level increases the depth of water column resulting in death of zooxanthellae due to reduced light penetration. Increased frequency of severe storms and heavy rainfall leads to physical damage with a reduced time for recovery. These changes in coral ecosystems will eventually affect the reef associated fish species.

Heat stress event in 1998 led to a decline in the coral cover across the Western Indian Ocean by an average of 37.7%. Responses to the anomalously warm conditions in 1998 varied between sub-regions, with the central Indian Ocean islands (Maldives, Seychelles, Chagos, and Lakshadweep) experiencing major decreases in coral cover directly after the 1998 event (from 40 to 53% coral cover in 1977–1997 to 7% in 1999–2000) (Ateweberhan et al., 2011). Similar decreases in coral cover were observed in coral reefs lining the islands of southern India and Sri Lanka (45% in 1977–1997 to 12% in 1999–2000) (IPCC, 2014).

Report by Rashid et al. in 2013 stated that the pH level reduction rate for the Bay of Bengal is around 0.0083 units per year which will have a negative impact for the biodiversity of the Bay of Bengal. The study revealed that pH of BOB has fallen by 0.2 units than in 1994. A map on the global ocean acidification scenario of 2095 showed that the pH level of sea water in the Bay of Bengal will be less than 8.0 in 2050 and below 7.8 in 2095. It was also reported that the current pH of North Indian Ocean where the Bay of Bengal is situated is in the range 7.9 to 8.25 with an average of 8.068. The study also focused on the calcareous marine organisms of Bay of Bengal, examined the chemical composition of shells and oysters. Results indicated that the chemical composition of shells and oysters were reduced by 17% (range varied from 7-22% from standard composition of those species) (Rashid et al., 2013).

In India, major reef areas exist in the Gulf of Kutch, the Lakshadweep, Gulf of Mannar, and the Andaman and Nicobar islands. The Gulf of Kutch reefs showed an average of 11% bleached coral with no apparent bleaching-related mortality. Also the corals associated with the lagoon reefs of Lakshadweep experienced 82% bleaching and 89% of the coral cover in the Gulf of Mannar reefs. Bleaching-related mortality was high 26% in Lakshadweep and 23% in Gulf of Mannar (Arthur 2000).

Studies by Krishnan et al., 2013 showed that a decrease in number of rainy days and amount of rainfall received lead to increase in SST during April 2010. These led to partial or complete bleaching of corals in the North Bay, Tarmugli and Chidiyatapu islands of Andaman. During the year 2011, the island received considerable amount of rainfall and there was a decrease in SST that lead to recovery of 54% of bleached corals in North Bay, 81% and 86% respectively in Tarmugli and Chidiyatapu respectively. It was seen that during the recovery of the corals from bleaching the abundance of fishes especially belonging to families Chaetodontidae, Pomacentridae, Acanthuridae and Scaridae also increased (Krishnan et al., 2013).

Indian corals found along the Gulf of Mannar, Gulf of Kachchh, Palk Bay, Andaman Sea and Lakshadweep Sea have experienced 29 widespread bleaching events in 1989 and intense bleaching from 1998 to 2002 attributing to increased SST which was higher than the maximum temperature during summer months (Vivekanandan et al., 2009).

Impacts on coasts and coastal communities

There has been a considerable increase in the risk of life of coastal fishermen due to increased events of storm surges and high speed winds. Coastal erosions caused by Sea Level Rise (SLR) pose serious threat to coastal infrastructure and livelihoods.

Fluctuations in fish stocks also have major economic consequences for the livelihood of fishermen community that in turn affect the economy of the country. Fishing communities which are dependent on local resources of just a few species become more vulnerable to fluctuations in stocks, in the context of climate change.

Small scale fisheries sector comprising of artisanal and subsistence fishers will be the most vulnerable one as low and irregular income from fishing activities shall lead to poor adaptability to the economic effects.

Most of the coastal ecosystems are very rich in diversity and are very helpful in mitigating the impacts of any perturbation. Ecosystems such as coastal wetlands and mangroves are very important in buffering the effects of climate change such as Sea Level Rise, protecting the coastal ecosystems from high speed winds, fluctuations in salinity, controlling the amount of nutrients reaching the ocean and storm surges. Rising sea surface temperature and sea level rise due to thermal expansion could affect the fish distribution and lead to the destruction of significant portion of mangrove ecosystem. Further, destruction of mangroves would diminish their critical role as natural buffers against tropical cyclones resulting in loss of lives and livelihoods. Again degraded wetlands are the primary source of greenhouse gas emissions. Reduction in area and diversity of coastal wetlands and mangroves will increase vulnerability of coastal communities to erosion and sea level rise.

The vulnerability atlas of India, 2006 by BMTPC, shows that 8.5% of total land in India is vulnerable to cyclones, 5% of land is vulnerable to floods and 1 million houses are vulnerable to other allied damage annually. Between 1877-2005, total 283 cyclones (among those 106 severe cyclones) occurred in a 50 km wide strip on the east coast whereas comparatively less severe cyclones occurred on west coast (total 35 cyclones). In 19 severe cyclonic storms death was greater than 10,000. The super-cyclone of 1999 wreaked havoc in coastal Odisha claiming more than 30,000 human lives. Similarly in July 2005, the city of Mumbai received an unprecedented 944 mm of rainfall in a 24-hour period, resulting in the most devastating floods in recent history leaving more than 500 people dead, mostly in slum settlements.

Extreme events related to intense rainfall include floods, cyclones and storm surges and the increase in the intensity or frequency of these can even damage brackish water aquaculture. India has already witnessed many catastrophic events such as cyclones ('Nisha' in coastal Tamil Nadu (2008), 'Aila' in West Bengal (2009), 'Laila' in Andhra Pradesh (2010), 'Thane' in Tamil Nadu (2012), 'Phailin' in Odisha (2013)) and floods as a part of sea level rise or Tsunamis. These events damages the coastal infrastructure and even many coastal ecosystems such as mangroves, sea grass beds and even manmade ecosystems like aquaculture farms by changes in salinity or even submergence (Zacharia et al., 2016).

During the last three decades there has been an overall reduction in land area of estuarine island system (around 86 km^2) in the Sunderbans and Sagar island have suffered major loss by erosion and submergence as the sea level rise near the island account for 3.14 mm yr^{-1}, with an aerial loss of 30 km^2 (Hazra et al., 2002).

Coasts are more vulnerable to erosion with rising sea level. It is estimated that the erosion due to sea level rise in Kerala is 7,125 m^3yr^{-1}, with an erosion rate of 0.3×10^6 m^3yr^{-1}. It has also been expected that the erosion potential would increase by 15.3% by 2100 (Shyam & Manjusha, 2015).

This section dealt with the impacts of various oceanographic parameters on Indian marine fisheries sector. The SST increases at a rate of 0.1°C per decade will further impact various climatic parameters of the ocean. These impacts are well pronounced with respect to Indian marine fisheries (reduction in marine catch of India by 6.2% during 2015). Extreme events such as cyclones, storm surges, and loss of area due to inundation are increasing yearly. Future projections on climate change need to be done for developing appropriate adaptation strategies so that marine fisheries sector will be sustained.

Impacts of change in oceanographic variables on the catch of vulnerable marine fishes of the northern Indian Ocean for the decade 2007-2016

Climate change cause alteration of ocean conditions including water temperature, ocean currents and coastal upwelling (Bakun, 1990; IPCC, 2007; Diaz and Rosenberg, 2008) and affect the marine fisheries productivity. Alteration of such changes in ocean conditions affect primary productivity, species distribution, community and food web structure that have direct and indirect impacts on distribution and productivity of marine organisms. Distribution of fishery landings and potentially the distribution and magnitude of fishing effort (Malin et al., 2012).

The change in temperature patterns have directly influenced the physiological functions such as growth, reproduction, spawning, and recruitment of fishes (Chowdhury et al., 2010). Also the primary and secondary production, fish distribution and its abundance and phenology, i.e., timing of life-cycle events such as spawning are also affected by change of temperature (Harvell et al., 1999; Beaugrand et al., 2002; Edwards and Richardson, 2004; Perry et al., 2005; Lehodey et al., 2006; Bruno et al., 2007; Reid et al., 2007). Another important oceanographic variable influencing fish distribution and productivity is chlorophyll and is often considered as an index of biological productivity in an oceanic environment. Chlorophyll concentrations above 0.2 mg/cu m indicate the presence of sufficient planktonic life to sustain a viable commercial fishery (Butler et al. 1988) in an oceanic environment.

Precipitation is an important climate factor that plays a major role in the spawning and larval cycles of many fish and shellfish species, especially along the northern Indian Ocean region (Zacharia et al., 2010). This region has been identified as one of the 17 climate change hotspots among the world oceans. These areas will warm faster than 90% of the world oceans, with high implications on the Indian marine fisheries. Many of the commercially important fishes including demersal, pelagic and crustaceans found in Indian Ocean region has been identified as vulnerable by Zacharia et al. (2016) and they had developed a zone wise vulnerability indexing of marine fishes of India. Vulnerability of a species is considered as the extent to which abundance or productivity of a species in a region could be impacted by climate change and decadal variability (Hare et al., 2016).

Though reports are available on the distribution of fishes with change in various oceanographic parameters, the study on the impact of SST, Chl and precipitation on the catch of vulnerable (vulnerable in the Indian Ocean region) species of fishes of Indian Ocean region is lacking. In order to have a better understanding, the Indian Ocean region has been divided in to four zones and from these four zones, species with high vulnerability index were chosen for the present study. Vulnerable species are selected based on the scientific criteria developed by ICAR-CMFRI as below:

Zone-wise vulnerability index of marine fishes of India

Vulnerability assessment of important marine species was done using the scientific criteria developed by ICAR-CMFRI (Zacharia *et al*, 2016) as

Vulnerability, V= (E+S)-A

Where Exposure (E) is the projected magnitude of change in the physical environment due to climatic variations and defines the nature and degree to which a species is exposed to climatic variations,

Sensitivity (S) indicates the extent, to which a species is affected due to its life history traits influenced, either adversely or beneficially, by anthropogenic activities,

Adaptive capacity (A) is the ability of a species to adjust successfully to climate or environmental change.

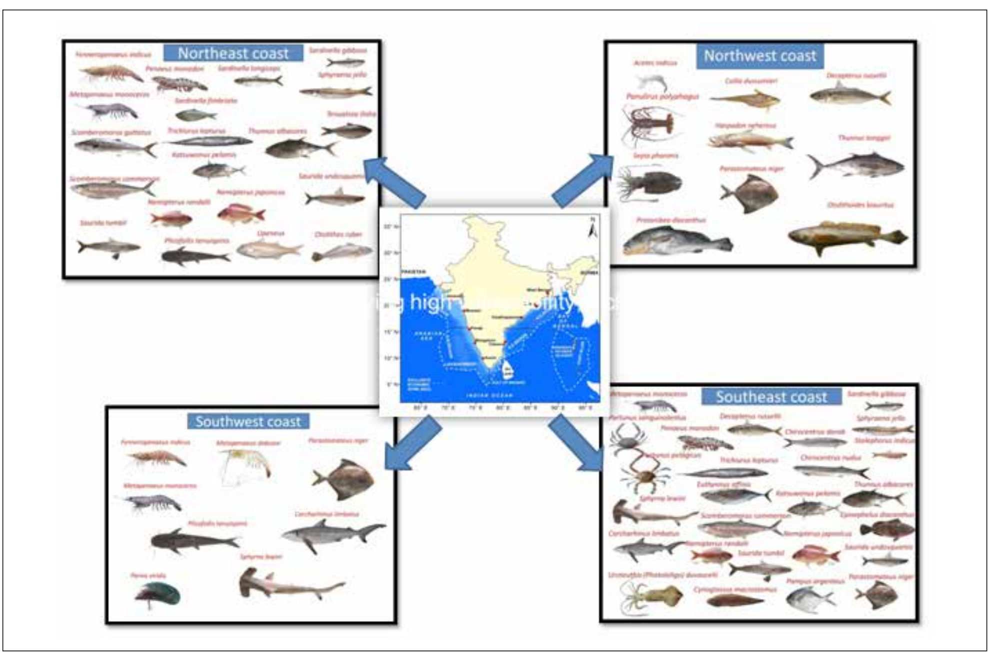


Fig 4. Zone-wise vulnerability index of marine fishes of India

Zone wise vulnerability index of marine fishes of India has been accordingly developed, which shall favour for sustainable fisheries management. Vulnerable species identified are classified based on the locations-northeast coast, northwest coast, southwest coast and southeast coast.

We correlated the catch data of six species of vulnerable as well as commercially important fishes such as *Pampus argentus, Parastomateus niger, Rastrelliger kanagurta, Katsuwonus pelamis, Nemipteurus japonicus, Thunnus albacares* of Indian Ocean region with the oceanographic parameters such as sea surface temperature, chlorophyll and rainfall. The species were chosen according to its status of vulnerability index (high) along the respective zone of the Indian Ocean region. Correlations were made to have a better understanding of the relation between various oceanographic parameters and fish catch.

The data were sorted zone-wise for Sea Surface Temperature (SST), Precipitation (Pr) and Chlorophyll (Chl) and the monthly anomaly of each parameter for 10 years were calculated for all the four zones comprising the coastal states of Kerala, Karnataka, Goa, Tamil Nadu, Gujarat, Maharashtra, West Bengal, Orissa, and Andhra Pradesh. Available fish catch data in National Marine Fisheries Database in the Fishery Resources Assessment Division (FRAD) of the Central Marine Fisheries Research Institute (CMFRI), Kochi was tabulated and standardized CPUE were calculated for each species.

Materials and methods

The study was conducted in the Northern Indian Ocean, which is designated conventionally as an area between 0º-30ºN and 50º-100ºE. Available fish catch data for the decade 2007 to 2016 with the FRA Division of CMFRI, Kochi was tabulated and to have standardized landings by fishing effort, standardized CPUE were calculated for each species (Daniel et al. 2017).

Environmental data of Sea Surface Temperature, Precipitation and Chlorophyll for a period of ten years from 2007 to 2016 were retrieved from various data sets of NOAA Optimum Interpolation (OI) SST V2, NCEP, COARDS', CPC Merged Analysis of Precipitation and NCEP Reanalysis respectively. Standardized monthly anomalies of oceanographic parameters were calculated by subtracting the climatological monthly cycle from the data (Plisnier et al. 2000; Suarez et al. 2004).

Standardized CPUE values of four vulnerable species from four zones were correlated (Pearson correlation) with SST, chlorophyll and rainfall and the Pearson correlation coefficient (r) was estimated.

Results and Analysis

The highest and lowest anomaly of Sea Surface temperature, Precipitation and Chlorophyll concentration for various coastal states along the northern Indian Ocean during the decade 2007 to 2016 are summarized in the table below:

Table 1. Anomalies of various oceanographic variables for the coastal states along the Indian Ocean

Coastal state	Highest anomaly			Lowest anomaly		
	SST	Pr	Chl	SST	Pr	Chl
Gujarat	2.959 Jun 2014	18.77 Aug 2007	1.55434 Jul 2009	4.607 Jan 2014	3.735 Mar/ May 2010	1.2017 Jul 2014
Maharashtra	2.12 Jun 2016	11.82 Jun 2015	2.903 Jul 2008	2.64 Feb 2008	4.488 Feb 2010	0.477 May 2009
Goa	1.87 May 2016	14 Jun 2016	0.84587 Jul 2009	1.482 Jan 2015	4.869 Feb 2007	0.2505 Jun 2016
Karnataka	1.791 May 2016	22.09 Jun 2016	1.2863 Aug 2014	1.357 Aug 2010	6.576 Feb 2010	0.1931 Apr 2012
Kerala	1.96 May 2016	11.52 Jun 2013	1.592 Jul 2016	1.62 Aug 2010	6.03 Mar 2007	0.45 Apr 2016
Tamil Nadu	1.883 Apr 2010	10.66 Nov 2015	0.317693 Aug 2012	2.011 Jan 2014	4.233 Jan 2015	0.2421 Mar 2007
Andhra Pradesh	1.963 Jun 2014	7.293 Oct 2013	0.59002 Jul 2009	2.53 Jan 2015	4.976 Feb 2010	0.2351 May 2012
Orissa	2.461 Jun 2014	15.44 Jul 2015	1.36813 Jul 2009	3.97 Jan 2012	5.85 Nov 2013	1.0334 Jun 2012

The highest anomaly for increase in SST within the decade 2007-2016 was observed during June 2014 along the coast of Gujarat (with an SST anomaly value of 2.959) and the highest anomaly for decrease in SST was also observed along the Gujarat coast (-4.607) during the month of January 2014. The correlation of various oceanographic parameters with CPUE of fish catch shows varying trends along the four different zones of the northern Indian Ocean region. These changes which might have occurred due to the complex interactions of oceanic, physical, chemical and biological processes that tend to induce variations in fish stocks (Solanki et al., 2003).

The CPUE of *R. kanagurta*, one of the major species along the Indian Ocean region (Vivekanandan et al., 2005) showed a significant negative correlation ($p<0.05$) ($r=-0.232083$, $r=-0.2711704$ respectively for Kerala and Karnataka coasts) with change in SST over the southwest zone. Previous reports on seasonal analysis of the catch data of *R. kanagurta* along the Indian Ocean region show a positive correlation of the catch with SST till 2010 (Kizhakudan et al. 2014). However, such an increase in catch of *R. kanagurta* with change in SST was not observed in the present study. Similarly, the CPUE of *R. kanagurta* along the coast of Goa (southwest zone) showed a similar trend of decrease with increase in SST, though statistically not significant. In the northwest zone, comprising the coasts of Gujarat and Maharashtra, the SST had an insignificant positive correlation ($p>0.05$) ($r=0.1006$) with the CPUE of *P. argentus* and *P. niger* ($p>0.05$) ($r=0.0635$). Whereas, the CPUE of *P. niger* showed an insignificant negative correlation in the coast of Maharashtra along the similar zone with change in SST. Along the South East zone, comprising the coast of Tamil Nadu, the *P. niger*, *T. albacares* and *K. pelamis* showed an insignificant positive correlation ($p>0.05$) with change in SST.

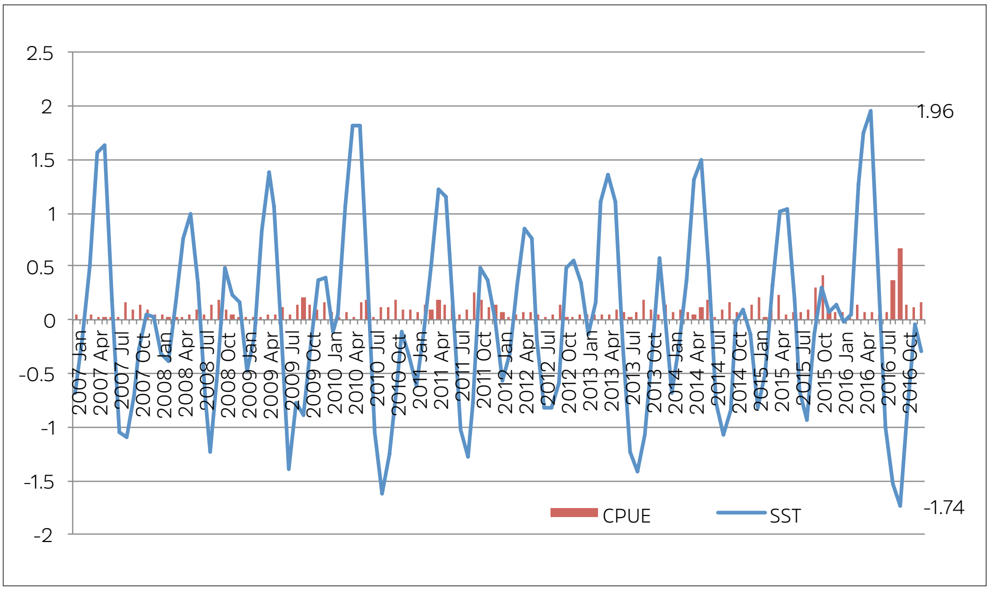


Fig 1. Variation of CPUE of *R. kanagurta* with SST along Kerala

In the case of Pr, the highest anomaly within the decade was observed during June 2016 along the coast of Karnataka (with a Pr anomaly value of 22.09) and the highest anomaly value for decrease in Pr was also observed along the coast of Karnataka with an anomaly value of–6.576.

The CPUE of *R. kanagurta* showed a negative correlation with change in Pr along the coasts of Karnataka and Goa, however, a significant negative relationship ($p<0.05$) ($r=-0.1814553$) was observed with Pr along the coast of Goa in the South West zone. However, in the coasts of Kerala, an insignificant positive correlation was observed for the CPUE of *R. kanagurta* with Pr.

Another selected species of our study *P. niger* showed an insignificant ($p>0.05$) negative correlation with change in Pr along the southwest and southeast zones, comprising the coasts of Kerala, Karnataka and Tamil Nadu. Whereas in the northwest zones comprising the coasts of Gujarat and Maharashtra, the CPUE of *P. Niger* showed both positive and negative correlation with change in the Pr, though, not statistically significant ($p>0.05$). The CPUE of *P. argentus* showed an insignificant

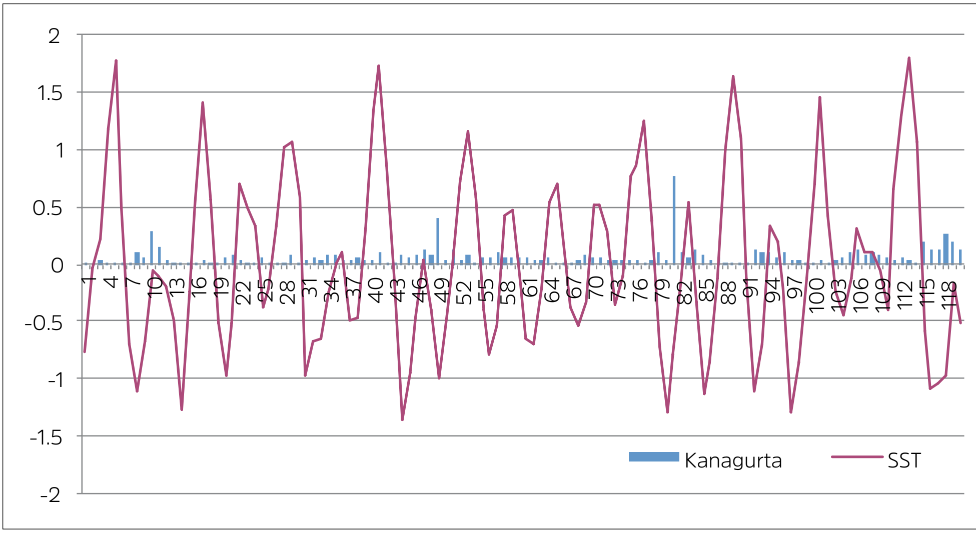


Fig 2. Variation of CPUE of *R. kanagurta* with SST along Karnataka

($p>0.05$) positive correlation with change in Pr along the northwest zones comprising the coasts of Gujarat and Maharashtra. The CPUE of *N. japonicus* showed an insignificant ($p>0.05$) negative correlation, whereas, the CPUE of *T. albacares* and *K. pelamis* showed insignificant ($p>0.05$) positive correlation along the northeast zone comprising the coast of AndhraPradesh. However, the CPUE of *T. albacares* and *K. pelamis* showed an insignificant ($p>0.05$) negative correlation with Pr along the southeast zone comprising the coast of Tamil Nadu.

The anomaly for increase in Chl within the decade of 2007-2016 was observed along the coast of Maharashtra during July 2008 with an anomaly value of 2.903 and the highest anomaly value for decrease in Chl was observed along the Gujarat coast with an anomaly value of -1.2017.

The Chl had a significant positive correlation with the catch of two important fish species such as *P. niger* ($p<0.05$) ($r=0.2027$) and *R. kanagurta* ($p<0.05$) ($r=0.2753$) in the southwest zone of the Indian Ocean region. Hoyer et al. (2002) found a linear relationship between chlorophyll-a and the nutrient content of sea water and pointed out that nutrient level of seawater is a significant factor for increase in fish catch in a particular region of the ocean. This positive relationship of *P. niger* and *R. kanagurta* may also be associated with the Malabar upwelling and the associated nutrient and chlorophyll availability of the ocean water along the southwest zone of the Indian Ocean region. However, in our study species such as *P. argentus, T. albacares* and *N. japonicas* showed an insignificant ($p>0.05$) negative correlation with change in Chlorophyll concentration in the northwest, south east and northeast zones.

Thus the present study demonstrated that all the oceanographic variables chosen for the study has influenced the change in the catch of various fish species selected. It has already been reported that change in environmental conditions strongly influence the spatial distributions

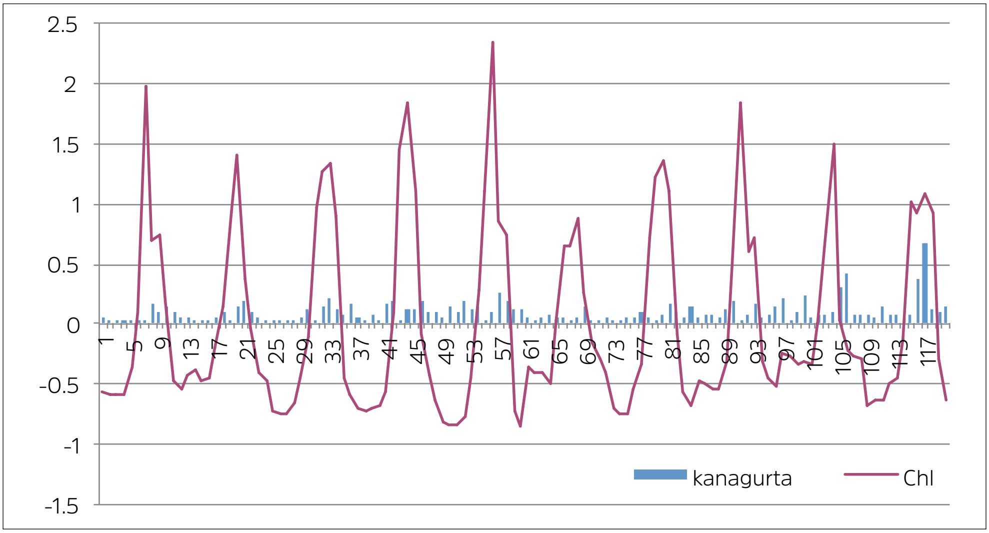


Fig 3. Variation of CPUE of *R. kanagurta* with Chlorophyll along Kerala

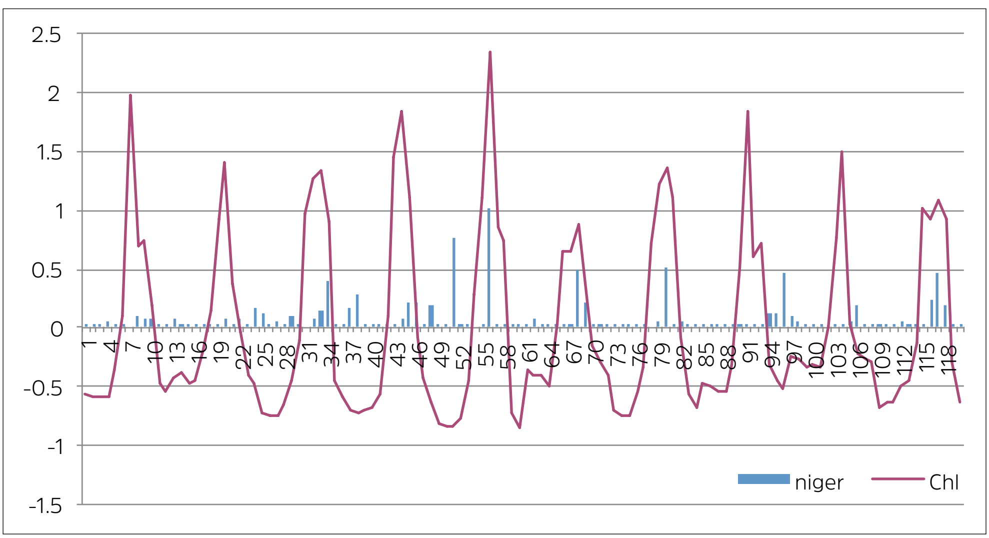


Fig 4. Variation of CPUE of *P. niger* with SST along Kerala

of marine fishes and fish capture (Pörtner, 2010). The present study is a preliminary study on the catch of selected vulnerable species of fishes along the Northern Indian Ocean region with change in oceanographic parameters. The drop in CPUE has become a severe concern nowadays. The understanding of the status of fisheries catch of vulnerable species is of utmost important for the management of fishery resources and also to take proper mitigation measures to reduce the impact of climate change on Indian marine fisheries.

Predictive modelling for assessing the possible changes in marine fisheries sector during 2030, 2050 and 2080

Global warming and the consequent changes in climate patterns have potential impacts on marine fisheries of India. Marine and coastal ecosystems are extremely vulnerable to variations in oceanographic parameters due to climate change. The Conference of Parties (COP) of UNFCC receives the outputs of the Intergovernmental Panel on Climate Change (IPCC) and uses IPCC data and information as a baseline on the state of knowledge on climate change in making science based decisions. IPCC was established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988 to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts. 195 countries are now members of the IPCC, which reviews and assesses the most recent scientific, technical and socio-economic information produced world wide relevant to the understanding of climate change. Significant Assessment Reports were brought out as 1st AR on 1990 (lead to UNFCC formation), 2nd AR on 1995 (lead to adoption of Kyoto protocol), 3rd AR on 2001, 4th AR on 2007 (lead to Nobel Peace Prize), 5th AR as 4 parts in 2013 and 2014, while 6th AR is expected on 2020. IPCC also prepares and publishes Special Reports, Methodology Reports, Technical papers and Supporting Material. The Nobel Peace Prize 2007 was awarded jointly to Intergovernmental Panel on Climate Change (IPCC) and Albert Arnold (Al) Gore Jr. "for their efforts to build up and disseminate greater knowledge about man-made climate change and to lay the foundations for the measures that are needed to counteract such change". Many factors have to be taken into account when trying to predict how future global warming will contribute to climate change. The amount of future greenhouse gas emissions is a key variable. Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems (IPCC, 2014) and degradation of biodiversity, coastal erosion, agricultural productivity and mortality of marine organisms (Natasha, 2015). Limiting climate change would require substantial and sustained reductions in greenhouse gas emissions which, together with adaptation, can limit climate change risks (IPCC, 2014).

The marine science community regularly uses climate change projections released by the Intergovernmental Panel on Climate Change (IPCC) to make qualitative and quantitative projections of marine ecosystem responses to environmental changes (Anne et al., 2013). Observations and theory have indicated that marine fishes frequently undergo shifts in distribution, altered patterns of species richness, ecosystem function and consequential changes in marine goods and services in response to changing environmental factors (Miranda et al., 2015). Most of the previous studies on impact, vulnerability and adaptation strategies of marine fisheries and ecosystem relative to climate change are based on remote sensing data. General circulation model and Earth system model output studies are now being carried out for historical as well as future projection of oceanographic variables for better analysis of impact studies and adaptation planning. Each variable: sea surface temperature, sea surface salinity, precipitation, chlorophyll concentration, pH and sea level rise can be studied for separate predictive analysis, by taking multi model or suitable model outputs of each variable and analyzing the possible changes, causes and their impacts of marine and coastal ecosystems and formulating possible adaptation planning. Our study provides a quantitative and general evaluation of the predictive changes of oceanographic variables and their trend (in all RCP scenarios for better and worst condition analysis) for an overall understanding of changes and their effects in Indian Ocean.

Representative Concentration Pathways (RCPs)

The necessity of scenario is that there are many climate modeling teams around the world, if they all used different metrics, made different assumptions about baselines and starting points, then it would be very difficult to compare one study to another. In the same way, models could not be validated against other different, independent models, and communication between climate modeling groups would be made more complex and time-consuming. Scenarios provide a framework by which the process of building experiments can be streamlined (Wayne, 2013). In the past climate projections for India have relied on the CMIP3 models, based on special report on emission scenarios (SRES) published by the Intergovernmental Panel on Climate Change (IPCC) (Chaturvedi et al., 2012). SRES scenarios were used in the Third Assessment Report (TAR) and Assessment Report Four (AR4), while in 2007 IPCC released an improved scenario called Representative Concentration Pathways (RCPs) and is used in IPCC Fifth Assessment Report (AR5). Detailed description of each RCP scenarios: RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5, is provided in table 1 (IPCC expert meeting report, 2007; Wayne, 2013). RCP contains a set of starting values and the estimated emissions up to 2100, based on assumptions about economic activity, energy sources, population growth and other socio-economic factors. Modellers download the database sets to initialize their models. Each RCP contains the same categories of data, but the values vary a great deal, reflecting different emission trajectories over time as determined by the underlying socio economic assumptions (Wayne, 2013). RCPs provide a quantitative description of concentrations of the climate change pollutants in the atmosphere over time, as well as their radiative forcing in 2100 (for example, RCP 6 achieves an overall impact of 6 watts per square meter by 2100). Radiative forcing, expressed as Watts per square meter, is the additional energy taken up by the Earth system due to the enhanced greenhouse effect. More precisely, it can be defined as the difference in the balance of energy that enters the atmosphere and the amount that is returned to space compared to the pre-industrial situation.

Table 1. Description of RCP scenarios

RCP Scenarios	Description
RCP 2.6	Radiative forcing reaches 3.1 W/m2 before it returns to 2.6 W/m2 by 2100. To reach such forcing levels, ambitious greenhouse gas emissions reductions would be required over time.
RCP 4.5	Radiative forcing is stabilized shortly after year 2100, consistent with a future with relatively ambitious emissions reductions.
RCP 6.0	Radiative forcing is stabilized shortly after year 2100, which is consistent with the application of a range of technologies and strategies for reducing greenhouse gas emissions.
RCP 8.5	This RCP is consistent with a future with no policy changes to reduce emissions. Characterized by increasing greenhouse gas emissions that lead to high greenhouse gas concentrations over time.

CMIP5 (Coupled Model Intercomparison Project Phase 5)

RCP based climate projections are available from many climate models under the Coupled Model Inter-comparison Project Phase 5 (CMIP5). CMIP5 coordinated by the World Climate Research Program (WCRP) has produced a multi-model dataset designed to advance our knowledge

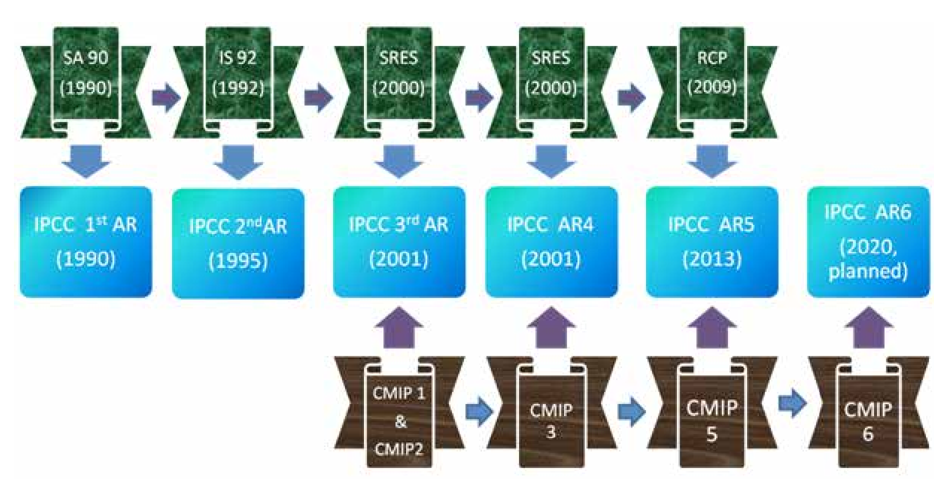


Figure 1a History of scenarios and CMIPs and their contributions to IPCC Assessment Reports (ARs)

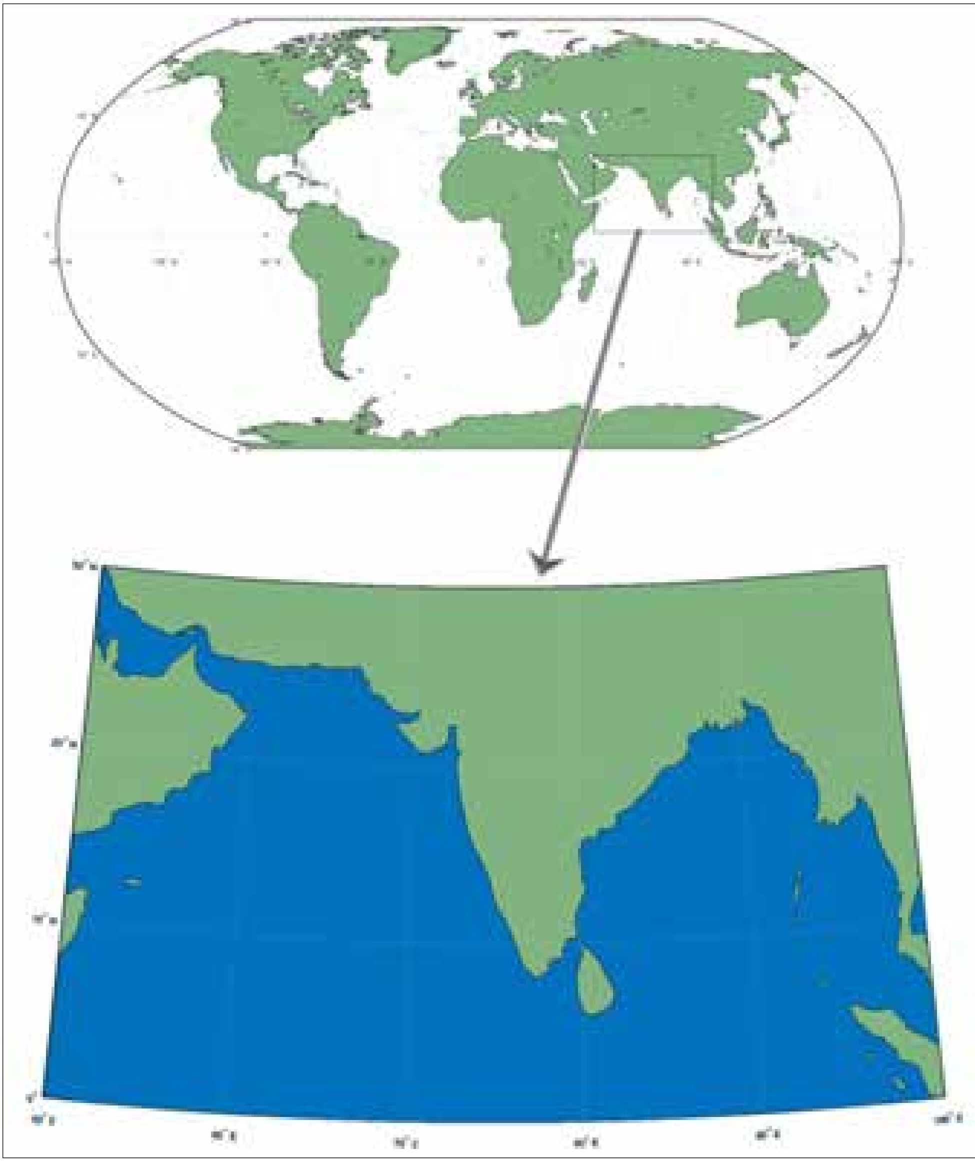
of climate, its variability and change through the application of global models of the climate system (Emori et al., 2016). It provides a community-based infrastructure in support of climate model diagnosis, validation, and inter-comparison, documentation and data access, with a participation of 25 modelling groups with 52 models. The dataset has been analysed by the scientific community worldwide to produce the results that underlay the IPCC Fifth Assessment Report and continues to be available for further analyses (Emori et al., 2016).

Changes in oceanographic variables have the potential to substantially alter fish breeding habitats, food supply and abundance in fish populations (Vivekanandan et al., 2010). The fluctuations in the physical, chemical and biological oceanographic conditions have a profound influence on the periodic and seasonal migration of fishes also affects the availability, behaviour and distribution of commercial fishes (Natasha, 2015). So, it reveals high importance for assessing the possible changes in oceanographic variables in future and how it will affect the marine sector and ecosystems. In this chapter, we analyse the projections, possible causes and impacts for six oceanographic variables for Indian Ocean in 2030, 2050 and 2080 based on a suitable CMIP5 model in all RCP scenarios. The major oceanographic variables considered for the study under different RCP scenarios (RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5) are: Sea surface temperature (SST), Chlorophyll concentration (Chl), Sea surface salinity (SSS), Precipitation (Pr), pH and Sea level rise (SLR).

This section contains the findings of the full length paper published out of the project as climatic projections of Indian ocean during 2030, 2050 and 2080 with implications on fisheries sector (Akhiljith et al. 2019)

Study Area

The oceans and the atmosphere are tightly linked and forms the most dynamic component of the climate system in which oceans play a fundamental role in controlling the climate. They play a key role in the global carbon cycle, serving as a major heat and carbon sink, transferring heat around the world and thereby driving the climate and weather systems. The growing ocean acidification, sea level increase, and changes in temperature and currents, all of which in turn impact the health of marine species, ecosystems, and our coastal communities. Of the three major oceans, the Indian Ocean is the third largest and warmest ocean in the world. On the west side of the Indian Ocean is the Arabian Sea, and on the east side is the Bay of Bengal and is landlocked to its north by Asian land mass and is a closed ocean in comparison to the other oceans of the world. The changes in Indian Ocean has great importance in regional and global climate, our study is mainly focused on Indian Ocean in between latitude 0^0-30^0 North and longitude 50^0-100^0 East. Indian Ocean SST anomaly has significant impacts on the rainfall variability in central, eastern and southern African regions (Goddard et al., 1999) and variability of monsoons in Asia and Australia (Yoo et al., 2006). Boreal summer surface air temperature over south China and northeast China is remotely influenced by the Indian Ocean Basin warming (Hu et al., 2011). Indian Ocean



strongly interacts with the surrounding land masses resulting in the well-known monsoons or seasonal cycles of southern Asia, east Africa and northern Australia (CLIVAR, 2006). The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) points out that 90% of the heat resulting from global warming during the last four decades has been accumulated in the oceans (Roxy et al., 2014). The unique closed geography of the Indian Ocean has important implications for the oceanic circulation physics and consequently for climate and the biogeochemistry of the ocean. It cannot transport heat gained in the tropics to the higher northern latitudes as the Pacific and Atlantic do (CLIVAR, 2006).

Methodology

CMIP5 models provide the opportunity to investigate the role of various oceanographic variables on past and projected future climates (Ibnu et al., 2017). The variables selected for the study: Sea Surface Temperature (SST), Chlorophyll Concentration (Chl), Sea Surface Salinity (SSS), Precipitation (Pr), pH and Sea Level Rise (SLR) are based on the impacts that could be related to the climate change (Zacharia et al., 2016; Vivekanandan et al., 2010; Zacharia et al., 2016; Jena and Grinson, 2017; Roxy et al., 2016; Sharad and Vijay, 2012).

For future projection analysis, options exist to either select the multi model mean (Chaturvedi et al., 2012) or select a most apt model that adress the constraints. MIROC-ESM-CHEM model developed by Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology and MPI-ESM-MR model developed by Max Planck Institute for Meteorology (Germany) are the two best models that are commonly used in studies (Ibnu et al., 2017; Roxy et al., 2016; Lu and Tianjunzhou, 2014; Chaturvedi et al., 2012). Based on the comparison of two models, for analyzing possible changes of the selected six variables for 2030, 2050 and 2080 in all RCP scenarios MIROC-ESM-CHEM model is best suited. The methodology of study is shown in figure 2a. Dataset of MIROC-ESM-CHEM model from CMIP5 is examined and global data of each variable for all RCP scenarios are extracted for the Indian Ocean region in between latitude 0^0-30^0North and longitude 50^0-100^0 East. The average change of variables in 2030, 2050 and 2080 in all RCP scenarios were compared with the reference year 2015.

Salinity at level 1 out of 44 levels was used as sea surface salinity in this study and sea level rise is based on sea surface height above geoid. Precipitation is the rainfall flux over ice free ocean over sea, computed as the total mass of liquid water falling as liquid rain into the ice-free portion of the ocean divided by the area of the ocean portion of the grid cell. Chlorophyll concentration and pH are projected in yearly between 2010-2100 whereas SST, SSS, SLR and Pr are projected in each month (Jan-Dec) for 2030, 2050 and 2080. Since all the variables selected showed unique variations in AS and BoB, spatial analysis of these variables were performed, and for better analysis, our study area was further divided into four regions such as, Northern Arabian Sea (NAS), Southern Arabian Sea (SAS), Northern Bay of Bengal (NBoB) and Southern Bay of Bengal (SBoB).

Results & Analysis

CMIP5 model based projections for 2015, 2030, 2050 and 2080 for all RCP scenarios for the variables SST, SSS, SLR, Pr, Chl and pH in Indian Ocean are discussed further. RCP 2.6 provides the better scenario as ambitious greenhouse gas emission reductions required over time and

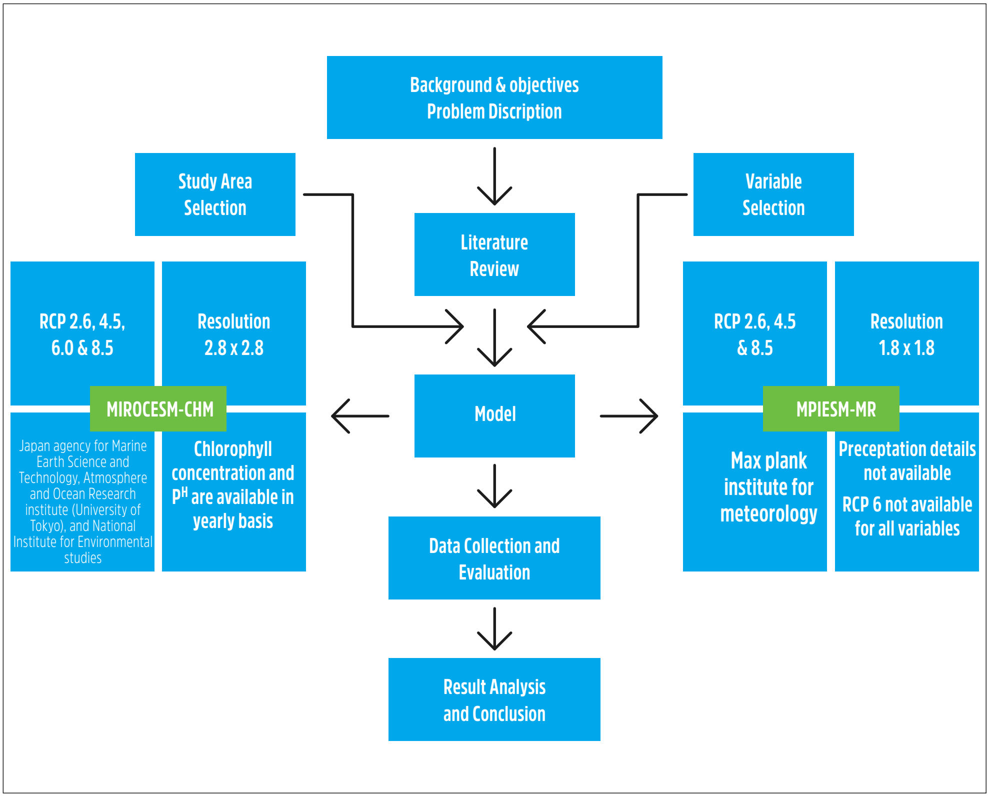


Fig. 2 Methodology of study

RCP 8.5 provides the worst scenario, where no policy changes to reduce the emissions, RCP 4.5 and 6.0 represents the moderate scenarios. For the analysis of each variable, it would be better to consider the possible variations in RCP 2.6 and 8.0 in three time slices.

Sea Surface Temperature (SST)

Monthly projections of SST is shown in Fig 3.1a, indicating a continuous rise in SST in 2030, 2050 and 2080 in all RCP scenarios. In each of the three time slices, RCP 2.6 generally experiences the least warming, whereas RCP 8.5 is associated with the highest warming, with RCP 4.5 and RCP 6.0 representing the moderate warming scenarios. From Fig 3.1a, we can infer the monthly variations of SST in 2030, 2050 and 2080 for each RCP scenarios. For example, in the month of April, as per RCP 2.6 SST increases to 0.54°C by 2080 when compared to 2015 whereas, SST increases to 2.4°C in RCP 8.5. As per our latest scenario projection, in RCP 2.6, SST will increase to 0.69°C by 2080 compared to 2015 whereas, an increase of 1.42°C in RCP 4.5, 1.54°C in RCP 6.0 and 2.6°C in RCP 8.5 were observed. SST in Indian Ocean will increase by 0.69°C by 2080, 0.60°C by 2050 and 0.43°C by 2030 relative to the reference year 2015 in RCP 2.6 scenario whereas, respective change in RCP 8.5 scenario shows a rise of 2.6°C by 2080, 1.3°C by 2050 and 0.59°C in 2030. Vivekanandan et al. (2009a) pointed out that, the surface temperature of the Indian Seas has increased by 0.03°C to 0.18°C per decade during 1950-2005 and based on UKMO HadCM3 model, he also pointed out an increase in sea surface temperature in the Indian Ocean by about 3.0°C during 2000 to 2099. In another study, a region wise increase in SST over the last 40 years, *i.e.* by 0.602°C along northeast India, by 0.597°C along northwest India, by 0.690°C along southeast India and by 0.819°C along southwest India was reported by Jena and Grinson (2017).

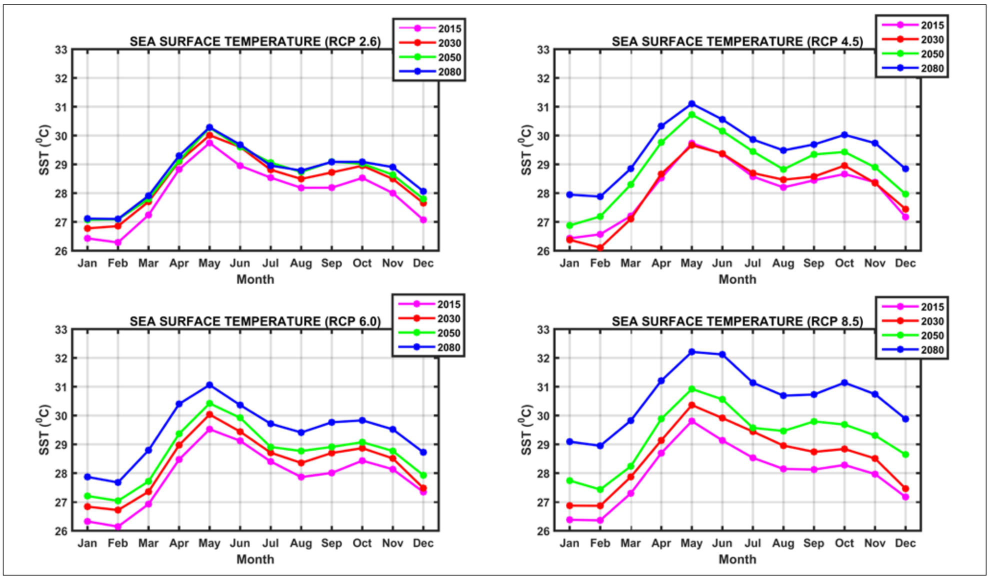


Fig. 3.1a Sea surface temperature projection for different RCP scenarios

Fig 3.1b shows the spatial variations of SST in AS and BoB in 2015, 2030, 2050 and 2080 for four RCP scenarios. In each scenario and in three time slices (2030, 2050 and 2080), SST shows an increasing trend in all the four regions analysed. SST shows higher values in BoB compared to AS, and among that, SAS and SBoB shows rise in trend compared to NAS and NBoB. It was observed that, on comparing the RCP 2.6 and RCP 8.5 scenarios in 2080, the four regions reaches an SST of 30-32°C, whereas, on comparing it with RCP 2.6, only SAS and SBoB reaches the above range of temperature increase.

Sea Level Rise (SLR)

Fig 3.2a shows the projected change in sea level rise based on CMIP5 model in 2030, 2050 and 2080 in four RCP scenarios. In each of the three time slices, SLR shows a rising trend in all RCP scenarios, in which RCP 2.6 shows a minimum rise in each time slice, whereas, RCP 8.5 shows maximum rise. Our study projects that in RCP 2.6, sea level may rise to 12.7 cm by 2080, 7.27 cm by 2050 and 2.64 cm by 2030 compared to 2015, whereas, in RCP 8.5 scenario, the sea level may rise to 19.1 cm by 2080, 9.37 cm by 2050 and 5.23 cm by 2030. IPCC has projected

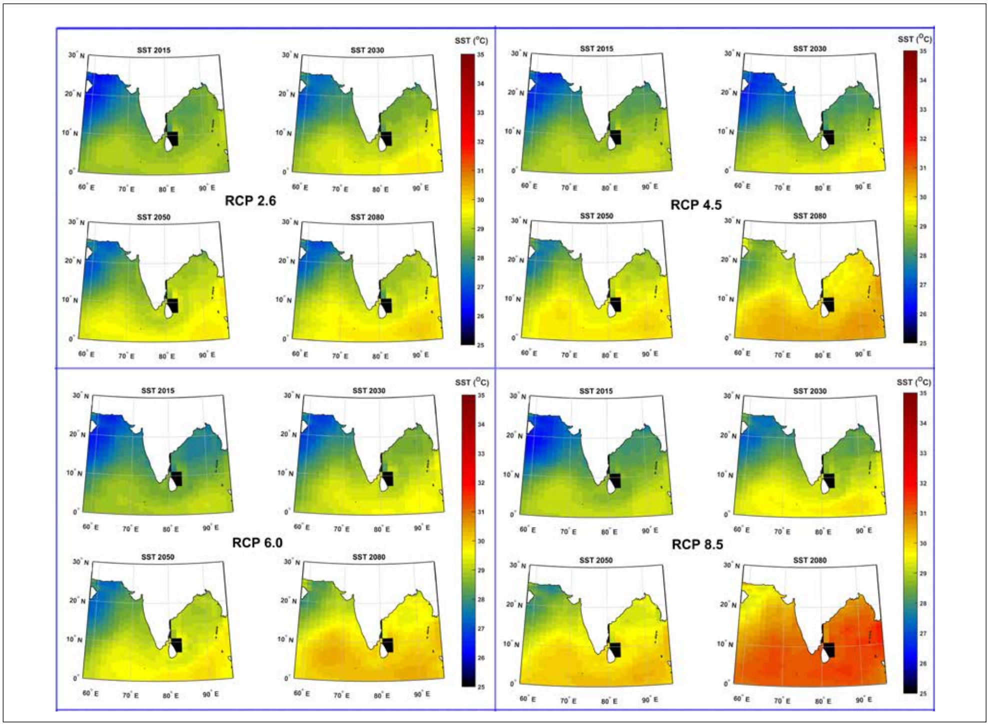


Fig. 3.1b Sea surface temperature spatial projection for different RCP scenarios

that the global annual sea level may rise 8 to 25 cm by 2050 (Vivekanandan, 2009). It has been reported that, the historic SLR for Cochin (southwest coast) is about 2 cm in the last one century. However, the rate of increase is accelerating, and it is projected that, it may rise at the rate of 5 mm per year in the coming decades.

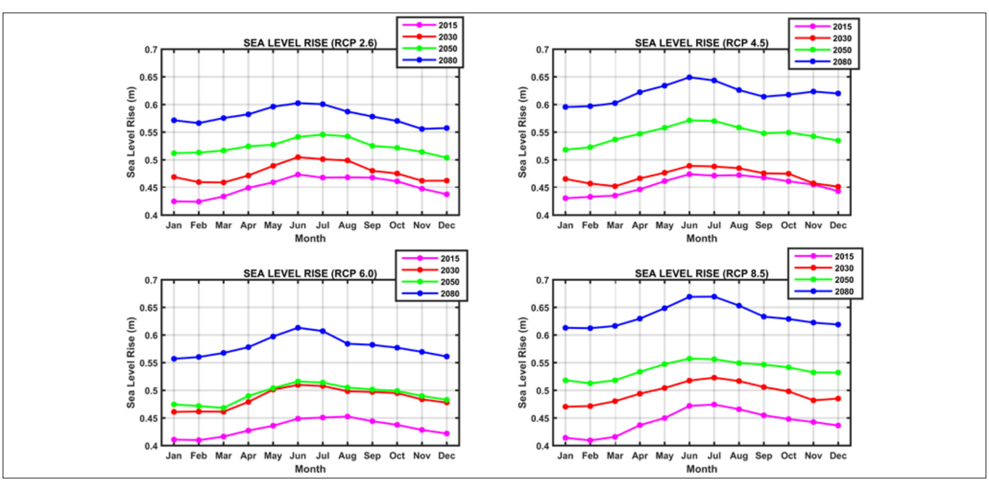


Fig.3.2a Sea level rise projection for different RCP scenarios

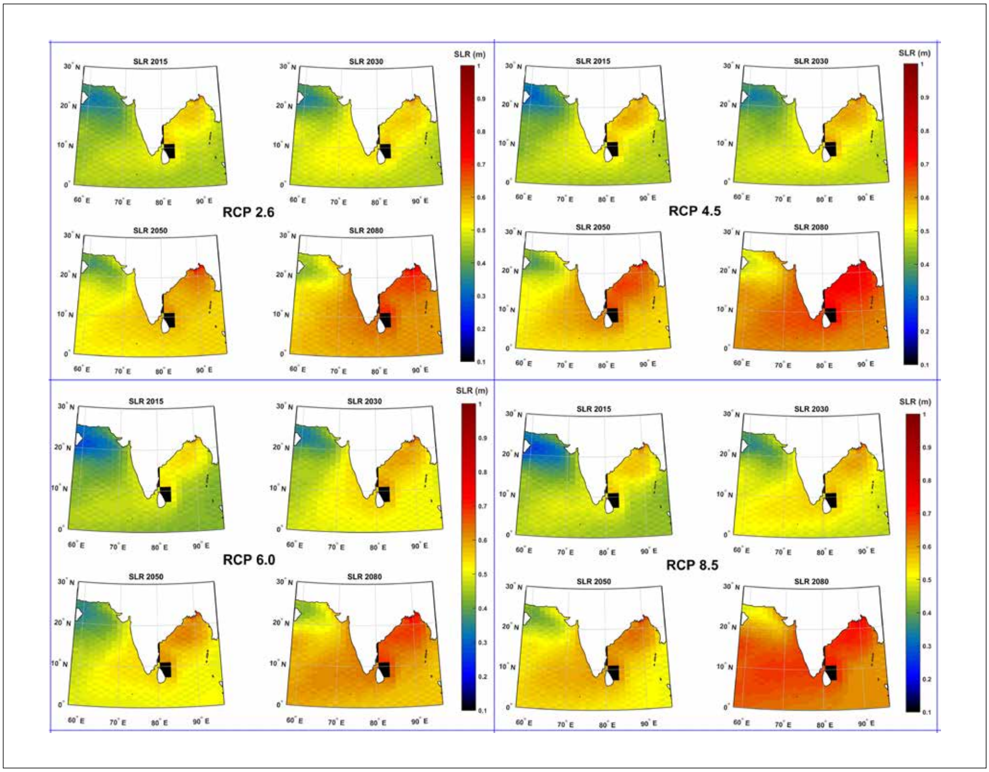


Fig. 3.2b Sea level rise spatial projection for different RCP scenarios

Sea level rise estimates for the Indian coast are between 1.06-1.75 mm per year, with a regional average of 1.29 mm per year, these estimates are consistent with the 1–2 mm per year global sea-level rise estimates reported by the IPCC (Zacharia et al. 2016). Fig 3.2b shows the variations of SLR in AS and BoB in 2015, 2030, 2050 and 2080 for four RCP scenarios. NBoB experiences higher rise in sea level compared to other three regions. In each scenario, significant gradual rise in sea level occurs from 2015 to 2080 in all four regions in which NBoB and SAS shows prominent rise. NAS exhibit least variation in rise compared to other three regions.

Sea Surface Salinity (SSS)

Monthly projections for SSS is shown in Fig 3.3a, indicating that SSS shows an overall decreasing trend in 2030, 2050 and 2080. Probabilistic monthly estimation of SSS for each RCP scenarios were plotted here for 2030, 2050 and 2080, which were useful to analyze the changes in SSS relative to the effect of other factors such as precipitation and SST. Though future projections of salinity studies are scarcely reported, studies deals with salinity effects on regional zones of ocean are of very significant. Our study provides a general view of the trend of Indian Ocean SSS in future three time slices in four scenarios. The study projects that, SSS will decrease to 0.49 psu by 2080, 0.39 psu by 2050 and 0.34 psu in 2030 compared to 2015 in RCP 2.6

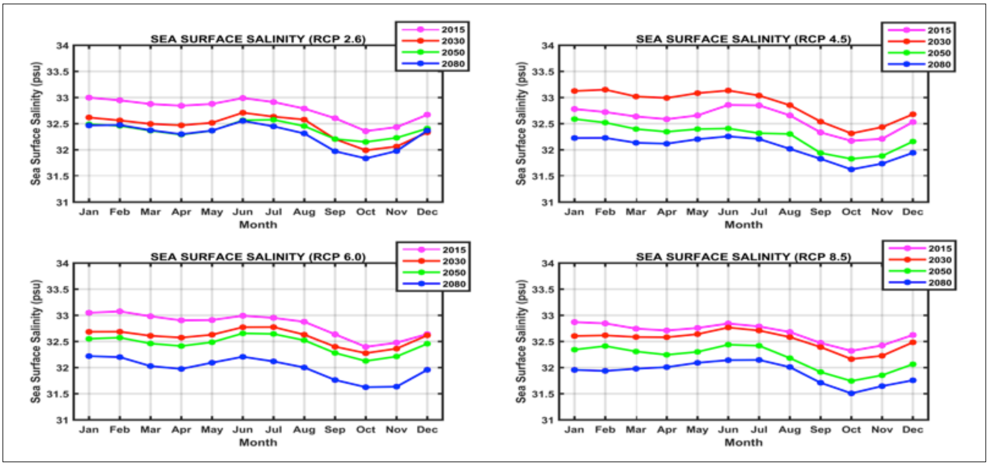


Fig. 3.3a Sea surface salinity projection for different RCP scenarios

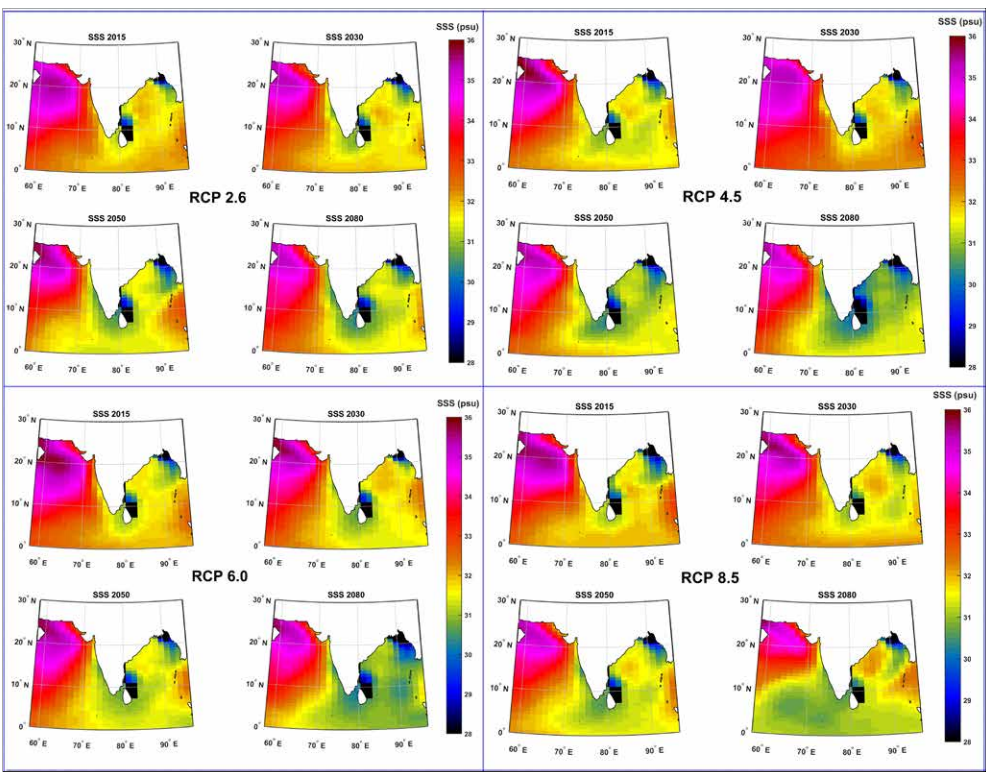


Fig. 3.3b Sea surface salinity spatial projection for different RCP scenarios

scenario, whereas, it may fall to 0.75 psu by 2080, 0.49 psu by 2050 and 0.14 psu by 2030 in RCP 8.5 scenario.

Fig 3.3b shows the variations of SSS in AS and BoB in 2015, 2030, 2050 and 2080 for four RCP scenarios. SSS shows higher values in NAS compared to the other three regions but it shows a decreasing trend from 2015 to 2080 in all scenarios. Unlike in AS, SSS in BoB was found to be low. While comparing RCP 2.6 and 8.5 scenarios of 2080, a gradual decline of SSS was observed in RCP 8.5 in SBoB and SA.

Precipitation (Pr)

Fig 3.4a shows the projected change in monthly precipitation based on CMIP5 model in 2030, 2050 and 2080 in four RCP scenarios. Realistic projection of precipitation is a challenging task in earth system model simulations. As rainfall flux has variations in each season, monthly analysis of data gives a clear picture of information than annual change. There are no significant variations in the general pattern of rainfall over the seasons but variation occurs in the amount of precipitation or extreme precipitation events in 2030, 2050 and 2080. Jena et al. (2016) pointed out that, the MIROC-ESM-CHEM model could best capture the average rainfall intensity as well as the monsoon rainfall peak month (MRPM) of all-India rainfall. Our study projects that in RCP 8.5 scenario, the Pr shows an increase of 0.26 mm/day by 2080, 0.28 mm/day by 2050 and a fall of 0.194 mm/day by 2030 compared to 2015 mean precipitation, whereas, in RCP 2.6 scenario, the Pr shows a change in rise of 0.6 mm/day by 2080, 0.26 mm/day by 2050 and 0.16 mm/day by 2030. Fig 3.4b shows the variations of Pr in AS and BoB in 2015, 2030, 2050 and 2080 for four RCP scenarios. Higher rate of precipitation occurs in SAS and SBoB compared to NAS and NBoB while NAS shows the least variation in precipitation. Precipitation shows no gradual trend of increase or decrease, however, the southern regions get the maximum amount of precipitation.

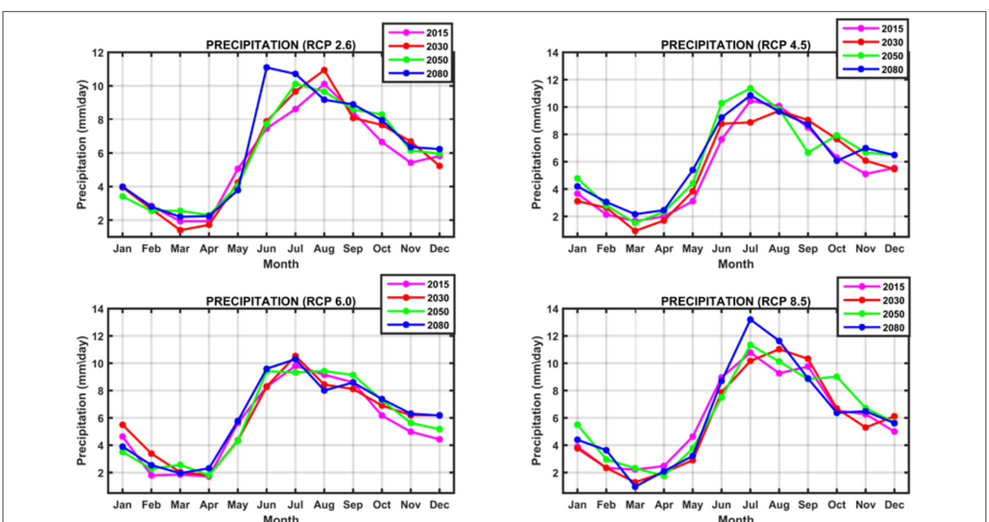


Fig.3.4a Precipitation projection for different RCP scenarios

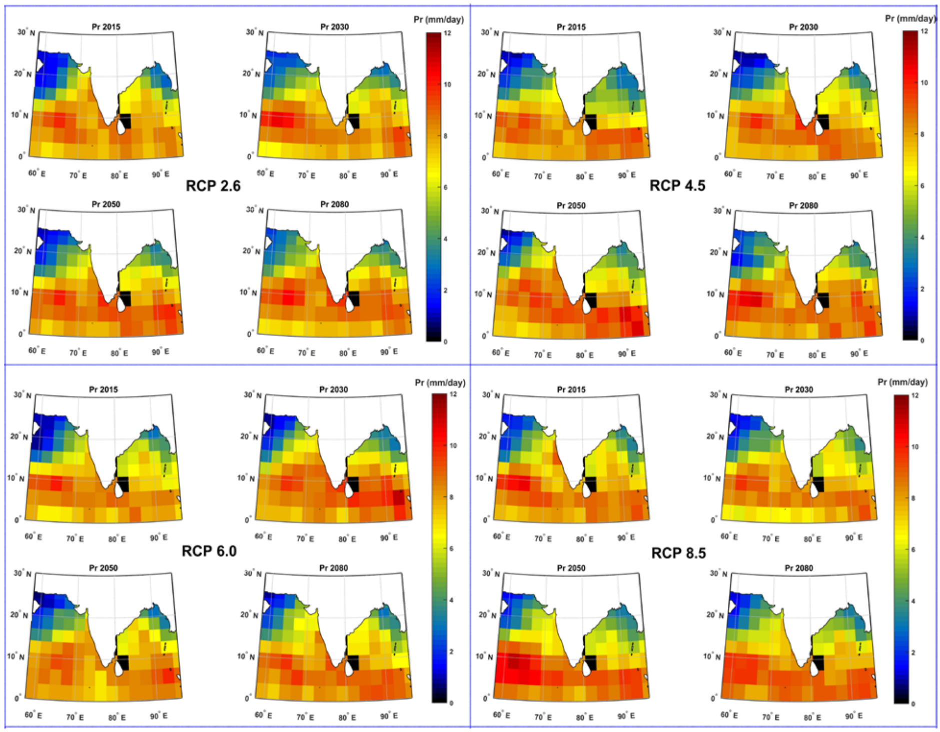


Fig. 3.4b Precipitation spatial projection for different RCP scenarios

Chlorophyll Concentration (Chl)

Fig 3.5a shows the projected change in Chl based on CMIP5 model in RCP 2.6, 4.5, 6.0 and 8.5 in 2010-2100. It shows that RCP 2.6 experiences the least variations in chlorophyll concentration in each year whereas, RCP 8.5 experiences the highest variations and chlorophyll concentration declines gradually from 2020 to 2095. Marsac (2013) pointed out that in the Western Indian Ocean, the sea surface Chl concentration showed an upward trend in the early 2000s, with a maximum in April 2006, followed by a constant decline until September 2010. Then, a slight reversal of this trend occurred until May 2011, in relation with a La Niña event. A decline with a similar rate was again observed until January 2013 and a slight rising trend occurred afterwards (Marsac 2013). The study using quality controlled blended chlorophyll data and earth system model simulations (Roxy et al. 2016) points out an alarming decrease of up to 20% in marine phytoplankton in tropical Indian Ocean region over the past six decades. Our study projects a variation of +0.013 mg/m^3 of Chl by 2080, +0.01mg/m^3 by 2050 and +0.02 mg/m^3 by 2030 compared to 2015 in RCP 2.6 whereas, it may decrease to 0.043 mg/m^3 by 2080, 0.02 mg/m^3 by 2050 and 0.015 mg/m^3 by 2030 in RCP 8.5 scenarios. Fig 3.5b shows the variations of Chl in AS and BoB in 2015, 2030, 2050 and 2080 for four RCP scenarios. NAS and NBoB shows higher values of Chl compared to other two regions. In RCP 8.5, Chl shows a significant declining trend, and among the four regions analyzed, the SAS and SBoB showed the least values.

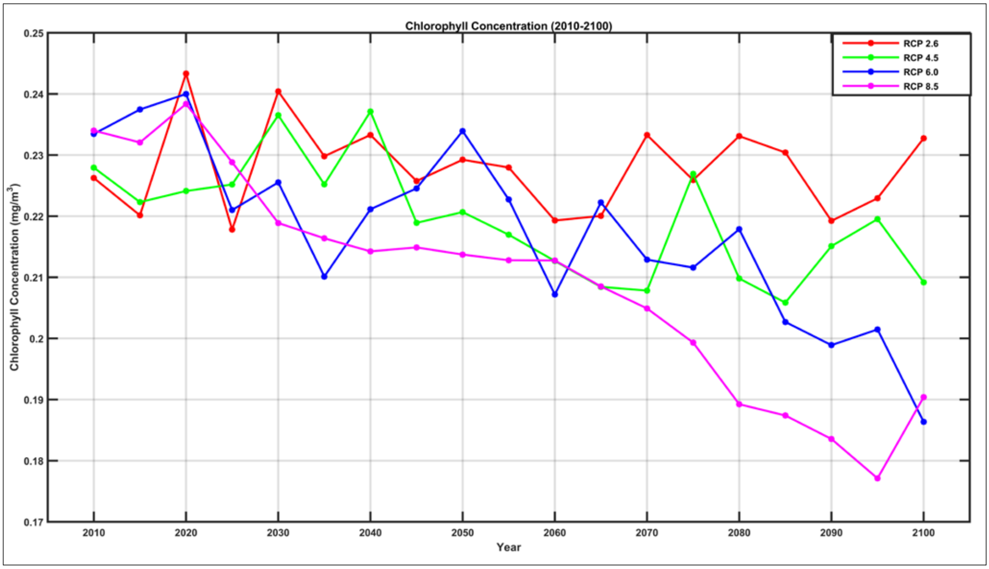


Fig.3.5a Chlorophyll concentration projection for different RCP scenarios

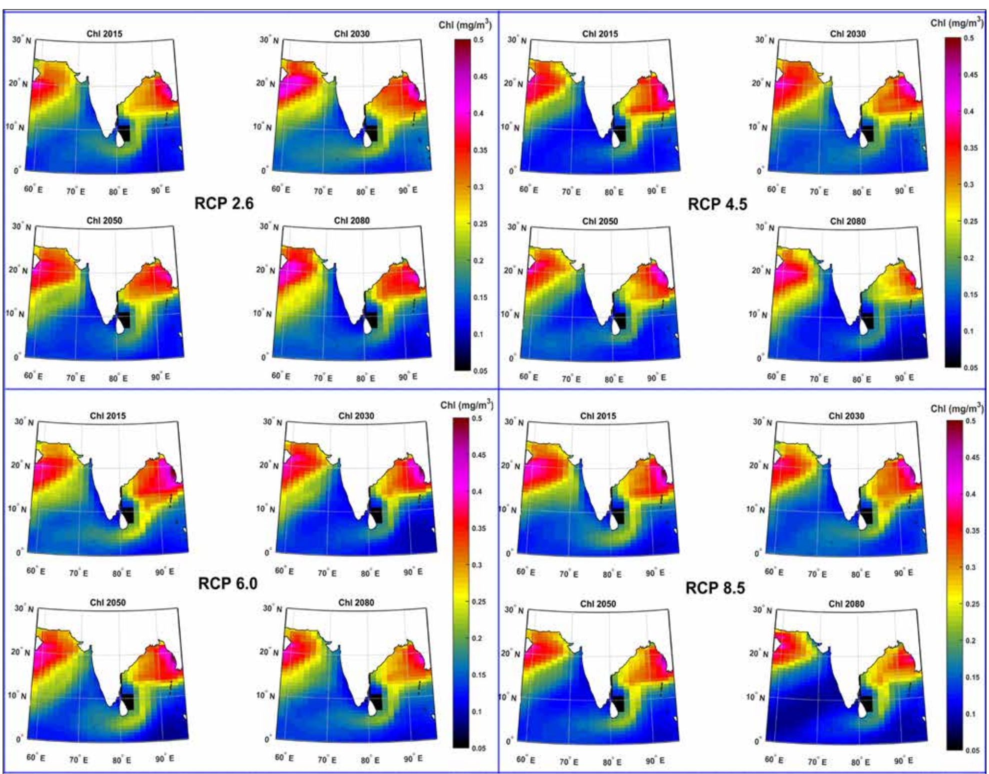


Fig. 3.5b Chlorophyll concentration spatial projection for different RCP scenarios

pH

Projections for pH are given in Fig 3.6a, which indicates that pH level shows an overall decreasing trend in 2030, 2050 and 2080 in all scenarios except RCP 2.6. IPCC projected a fall of pH in

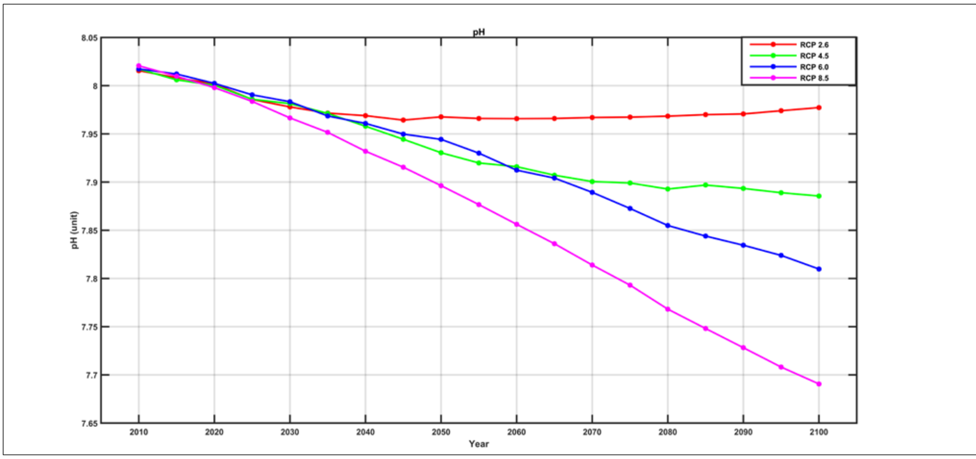


Fig. 3.6a pH level projection for different RCP scenarios

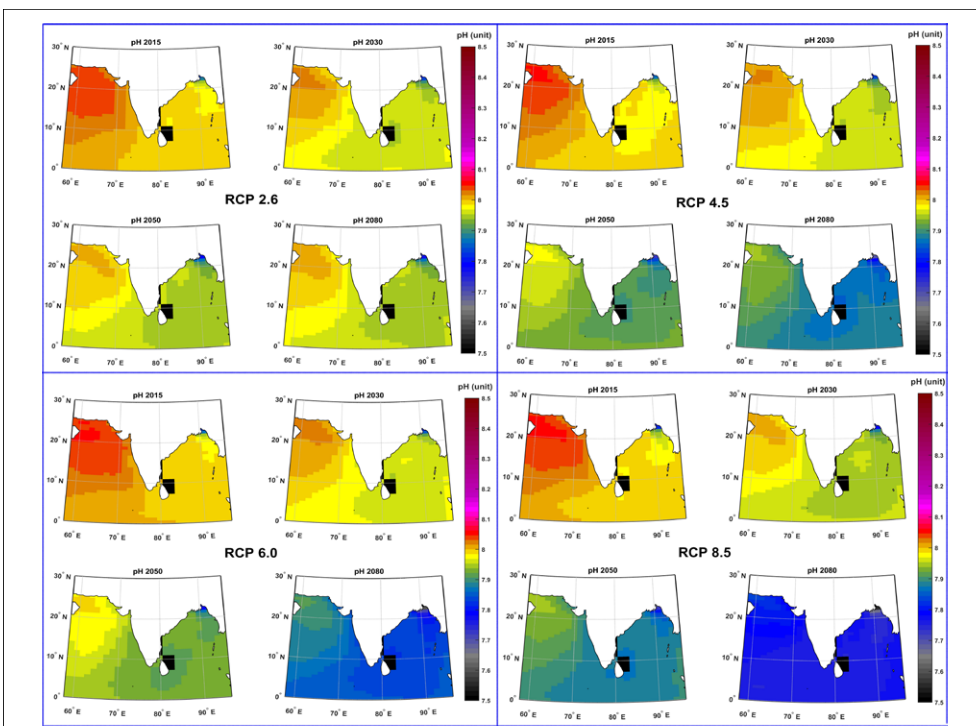


Fig. 3.6b pH level spatial projection for different RCP scenarios

open ocean of about 0.13units with RCP2.6 to a pH change of 0.42 units with RCP8.5 by 2100 relative to preindustrial times (Portner et al. 2014). In RCP 8.5, our study shows an alarming trend of decrease in pH, and it may fall to 7.77 in 2080 from 8.01 in 2015. In RCP 2.6, pH may decrease to 0.04 units by 2080, 0.041 units by 2050 and 0.03unit in 2030 compared to 2015 whereas, it falls to 0.242 units by 2080, 0.11 units by 2050 and 0.05 units by 2030 in RCP 8.5 scenario. Fig 3.6b shows the variations of pH in AS and BoB in 2015, 2030, 2050 and 2080 for four RCP scenarios which show declining trend at all the four regions, in which BoB shows high variations compared to SA. NAS shows least variations whereas SBoB shows high variations. In RCP 8.5, at NAS, pH varies from 8.1 units to 7.8 units in 2080 whereas in SBoB, it changes from 7.9–8 units to 7.7–7.8 units.

Results are summarized in the following table.

Table 2. Predictive values of six variables in 2030, 2050 and 2080

Climatic parameters	RCP Scenario	Predictive values		
		2030	2050	2080
SST	2.6	+0.43°C	+0.60°C	+0.69°C
	8.5	+0.59°C	+1.3°C	+2.6°C
SLR	2.6	+2.64 cm	+7.27 cm	+12.7 cm
	8.5	+5.23 cm	+9.37 cm	+19.1 cm
SSS	2.6	-0.34 psu	-0.39 psu	-0.49 psu
	8.5	-0.14 psu	-0.49 psu	-0.75 psu
Pr	2.6	+0.16 mm/day	+0.26 mm/day	+0.6 mm/day
	8.5	+0.194 mm/day	+0.28 mm/day	+0.26 mm/day
Chl	2.6	+0.02 mg/m^3	+0.01 mg/m^3	+0.013 mg/m^3
	8.5	-0.015 mg/m^3	-0.02 mg/m^3	-0.043 mg/m^3
pH	2.6	-0.03 unit	-0.041 unit	-0.04 unit
	8.5	-0.05 unit	-0.11 unit	-0.242 unit

Causes and impacts of projected changes

Our study provides a quantitative evaluation of the predictive changes of oceanographic variables and their trend (in all RCP scenarios for better and worst condition analysis) for general understanding of changes and their effects in Indian Ocean. The present study shows an increasing trend in SST of 0.69°C to 2.6°C in 2080 relative to 2015 in Indian Ocean. Our results almost agree with the old scenario projection of UKMO Had CM3 model by Vivekanandan et al. (2009a). Major contributing factors that lead to the variation of SST in Indian Ocean are anthropogenic forcing, greenhouse gas effects, El Niño events, Indian Ocean dipole, monsoonal winds and La Niña events (Gnanaseelan et al. 2017; Roxy et al. 2014; Yoo et al. 2006). Similar to other regions over the global oceans, anthropogenic forcing might be a major contributor to the observed warming over the Indian Ocean too. But apart from that, modulation of ENSO skewness and associated teleconnections mechanism also impart to the decadal rising of sea surface warming. Indian Ocean SST anomalies associated with La Niña are relatively smaller in comparison with those associated with El Niño events (Roxy 2014). Apart from El Nino events, the Indian Ocean SSTs are influenced by a prominent mode of variability called the Indian Ocean Dipole (Gnanaseelan et al. 2017). The anomalies of SST over the tropical Indian Ocean are often linked to the variability of the local Indian monsoon because of the effects of latent heat and water vapour supply (Yoo et al. 2006). Weakening monsoon winds are responsible for the increasing surface warming over the Indian Ocean during the monsoon season (Gnanaseelan et al. 2017). Monthly comparison analysis of SST and Pr in 2030, 2050 and 2080 implies maximum SST rise occurs in April, May, June and July and increasing Pr in the months of May, June, July and August shows a linear relationship of SST and Pr. This is in agreement with the report of Gnanaseelan et al. (2017) that warming in the Indian ocean increases rainfall over the Indian Ocean. The difference in temperature change of BoB and AS seen in Fig. 2b indicates the increased stratification due to the high river discharge and precipitation in BoB and also increased mixing process in AS due to strong winds.

Rise in temperature as small as 1°C could have important and rapid effects on the geographical distributions and mortality of some organisms (Vivekanandan et al. 2009a) and also cause early metamorphosis of some larval stages (Chetan et al. 2012). Warming of water has potential impact on fish diversity, distribution, abundance and phenology, which in turn have effects on the ecosystem structure and function (Vivekanandan 2010). The rapid ocean warming has also resulted in increased surface stratification over the Indian Ocean. Increasingly stratified ocean waters suppress the upwelling of nutrients from the subsurface waters and reduce the marine primary production (Gnanaseelan et al. 2017). As per the latest report of FAO, marine capture production in India has decreased by -6.2% from 37,27,088 tonnes (3.73 million) in 2014 to

3,497,284 (3.497 million) tonnes in 2015 (FAO 2017) which needs to be perceived as the possible effect of SST warming due to El Nino event. Adverse effects of SST increase on coral reefs, one of the most diverse marine habitats were also evident from the extensive bleaching to an extent of 60–70% during April 2010 (Krishnan et al. 2013; Prakash et al. 2013).

Our study indicates a decreasing trend of SSS over Indian Ocean in the near (2030), middle (2050) and long term (2080). Establishing relationships between the decreasing trends of SSS in entire Indian Ocean is not reliable because in the tropical Indian Ocean, the SSS shows significant spatial distribution, featuring an east–west contrast and significant SSS variations at equatorial and southern Indian Ocean (Yan and Yuhong 2015). Yuhong and Yan, 2016 identified a salinity dipole mode in the tropical Indian Ocean, termed S-IOD, a pattern of inter-annual SSS variability in the Indian Ocean. The present study points out a variation of SSS of 0.49psu to 0.75psu in 2080 relative to 2015 in Indian Ocean and these variations are driven by various factors such as SST, Pr, evaporation, IOD, La Nina, El Nino, river discharge, monsoonal winds and coastal upwelling. SSS shows lesser values in BoB than AS, and this might have attributed due to the high river discharge and precipitation in BoB and also the higher evaporation in AS. North south gradient of surface salinity was positive in AS while it was negative in BoB (Anant et al. 2016). A major part of the variability is associated with the tropical climate modes, such as El Niño–South Oscillation (ENSO) and the IOD (Yan and Yuhong 2015) in which the impact of El Niño events on a positive IOD event was large with freshening in the equatorial Indian Ocean whereas, the impact of La Niña with negative IOD is also large with an intense freshening in the southeastern AS (Gary et al. 2011). Pr alters surface salinity stratification while the Indonesian through flow (ITF) transports fresh western Pacific water into the Indian Ocean. The equatorial jet is also an important process influencing the salinity distribution in the equatorial region, and this is particularly true during the IOD events (Yuhong and Yan, 2016). Bias in precipitation and evaporation (Ibnu et al. 2017), combination of wind driven upwelling of subsurface high salinity waters and anomalous surface circulation, higher influx of fresh water from rivers (Gary et al. 2011) and zonal advection (Anant et al. 2016) also change the ocean salinity in Indian Ocean. Increasing trend in SLR and Pr in Indian Ocean in long run may result in decreasing salinity in future.

Salinity makes an important contribution to ocean dynamics and thermodynamics in which low salinity values at the surface enhance stratification of the water column, creating a barrier layer (Gary et al. 2011). This strongly affects the ocean dynamics and air–sea interaction (Yan and Yuhong 2015) and the barrier layer which inhibits upper ocean interaction with the subsurface and make ocean surface very sensitive to the atmospheric changes (Anant et al. 2016). The salinity and barrier layer play a significant role in the seasonal variability of SST, winds and Pr over the Indian Ocean (Anant et al. 2016) which could have the potential to substantially alter the fish breeding habitats, migration of fishes, food supply and abundance of fish populations (Vivekanandan et al. 2010).

Sea level shows a gradual rise with a minimum of 12.7 cm to a maximum of 19.1 cm by 2080 relative to 2015 with peak rise in May to August indicating the direct impact of increase in SST and Pr over the same period. Increase in SST has significant effect on increasing ocean volume (Piyali and Manasa, 2015) as it influences both inter annual and decadal variability of El Nino southern oscillation and Indian ocean dipole (Unnikrishnan et al. 2015). About 90% of the heat evolved in the atmosphere due to global warming is accumulated in the oceans and this heat storage is the major factor for the mean sea-level rise (Nobuo 2013). Another possible reason for this SLR acceleration might be the melting of Himalayan glacier (Unnikrishnan et al. 2015). Wind anomalies have a strong impact on SLR near the equator. The surface Ekman mass convergence resulted due to the westerly wind anomalies and the wind driven mass redistribution and salinity effects results in mean sea level increase (Weiqing et al. 2010). The increasing trend of SLR in BoB compared to AS indicates the rise in, SST, river discharge and Pr in the NBoB compared to other regions. Coastal upwelling bears have much significance in Indian marine and coastal ecosystem.

SLR influences the nutrient level and productivity in the coastal waters (Krishnakumar and Bhat et al., 2007) and also causes exacerbated inundation and flooding of low lying coastal areas, increased coastal erosion, effects on coastal ecosystems such as salt marsh, mangroves and coral reefs, salt water intrusion into fresh water sources, changes in sediment deposition along river channels, possible occurrence of typhoons and storms, higher-order impacts on the natural environment and human society (Nobuo 2013). Mangroves, the natural barrier of coastal flooding and erosion, will be at high risk of submergence due to SLR (Piyali and Manasa, 2015) as it cannot survive in an environment with higher sea-level and salinity, because some mangrove species respire through aerial roots jetting above the sea surface (Nobuo 2013). The importance of upwelling is the higher availability of large concentrations of commercially important pelagic fishes such as oil sardine, mackerel and whitebaits. Upwelling triggers some favorable changes in the physical, chemical and biological conditions in the inshore waters which attract pelagic fishes in large numbers for feeding and spawning. During upwelling, some fish populations move into the shallow surface waters, while others move offshore, away from the center of strong upwelling to avoid cool and low oxygen zone. Apart from this, mortality and even disappearance of demersal fishes have also been reported with upwelling (Krishnakumar and Bhat 2008). Since India has a long coastline of 7,517 km, supporting millions of people for their livelihoods, the precise prediction of changes in future sea level and its impacts would be of utmost important, as rise in sea level could harm the lives and occupation of millions of people who lives in coastal regions and islands.

The summer rainfall (June-September) in the northern Indian ocean shows an increasing trend from 1979 to 2005 (Yang et al. 2013). A similar trend of increase is seen in future scenarios, in which maximum Pr is indicated from June-September in all scenarios in 2030, 2050 and 2080. No significant seasonal monsoon drift was observed in our study but shows variations in 2030, 2050 and 2080 under RCP 8.5, whereas, it shows gradual increase in RCP 2.6. As discussed earlier, Pr, SST and salinity are interrelated, the rainfall anomalies significantly influence salinity, dynamics, and temperature in the Indian Ocean, but has least effect on sea level compared to wind-driven changes (Claire et al. 2003). Indian summer monsoon is strongly correlated with the relationships between El Niño- Southern Oscillation (ENSO) and Indian Ocean climate (Yang et al. 2013). SST variability plays an important role in the ENSO-induced anomalies in the Indian monsoon region (Achuthavarier et al. 2011). The equatorial rainfall trend patterns seems to be modulated by the SST warming in the tropical Indian Ocean, which confirm the mechanism of 'warmer-get-wetter' theory (Yang et al. 2013). Summer rainfall over central Asia could be closely related to the SST anomalies in Indian Ocean (Zhao and Zhang 2016). Indian Ocean dipole leads to a similar pattern in SST called SST dipole, accompanied by a similar dipole in the precipitation anomalies, with suppressed precipitation in the east and enhanced precipitation in the western Indian Ocean (Gnanaseelan et al. 2017). Fig 5b indicates greater rainfall experiences in SAS and SBoB compared to other two regions. Larger moisture flux convergence resulting from a warming Indian Ocean can lead to the intensification of the mean rainfall (Yang et al. 2013).

The Indian Ocean is a typical monsoon region, and the monsoon rainfall is crucial to the social and economic activities of local residents (Yang et al. 2013). The precipitation deficits affect SST by entraining more subsurface water to the surface, however, precipitation excess does not have effect on SST as the temperature difference between the mixed layer and the barrier layer is very less (Claire et al., 2003). Rainfall anomalies alter SSS stratification (Yuhong and Yan, 2016) by significantly influencing the Indian Ocean circulations and salinity, which in turn depends on the deficit and excess of rain (Claire et al. 2003). Rainfall anomalies on fish population and its availability has also been reported and it was found that periods of good rainfall have positive effect on oil sardine abundance and was also indicated that the low rainfall might be affecting the fecundity, recruitment success and food availability (Jayaprakash 2002).

Recent study on primary productivity in Indian Ocean based on earth system model output shows reduction of up to 20% in marine phytoplankton in the Indian Ocean during the past six decades (Roxy et al. 2016). In the present study, a similar decreasing trend of Chl in all RCP scenarios except RCP 2.6 was observed. In long run, it is implied that stringent climate policy implications and ambitious greenhouse gas reductions can hold the steep variations of Chl in Indian Ocean. The Indian Ocean Dipole events have great impact on chlorophyll concentration in the tropical Indian Ocean. Liu et al. (2013) pointed out the close relationships between chlorophyll and SST anomaly, chlorophyll and sea surface height anomaly in the IOD events. Declining trends in chlorophyll are driven by enhanced ocean stratification due to the rapid warming in the Indian Ocean, which suppresses nutrient mixing from subsurface layers (Roxy et al. 2016). Long run analysis indicates that Chl concentration is found to be higher in NAS and NBoB compared to SAS and SBoB. The regional structure of the blooms is intimately linked with the horizontal and vertical circulations forced by the monsoons (Levy et al. 2007). The higher chlorophyll concentration in the north-eastern AS is found during the northeast monsoon compared to those during the pre- and post-monsoon period (Sagnik and Ramesh, 2003). Water masses of different temperature and salinity partially govern the distributions of Chl (Liu et al. 2013); however, higher chlorophyll concentration is found in the coastal water compared to the open ocean (Sagnik and Ramesh, 2003). Since nutrient distributions are important for phytoplankton composition (Takahiro and Tsuneo, 2014), input of nutrients are mediated by upwelling, convection, or by horizontal advection (Levy et al. 2007) in which upwelling carries the nutrients from the deep ocean to the sea surface(Liu et al. 2013).

Long-term changes in phytoplankton biomass and community composition are important in the ecosystem–being the base of the marine food web it plays a central role in ocean biogeochemical cycles and regulates the global climate (Roxy et al. 2016; Takahiro and Tsuneo, 2014). 39% of inter-annual variability in fish landings is related to availability of chlorophyll-a during the bloom initiation month (Grinson et al. 2012). The increased phytoplankton biomass is tightly coupled to oil sardine catch (Vivekanandan2010) in which spatial and temporal variations in the intensity of chlorophyll in the coastal waters were reflected in sardine abundance (George et al. 2012). The western Indian Ocean hosts one of the largest concentration of phytoplankton blooms in summer, supporting the second largest share of the most economically valuable tuna catch (Roxy et al., 2016). Evidences are also there on the effect of phytoplankton blooms and its variability on carbon cycle (Takahiro and Tsuneo, 2014).

Our study projects a decreasing trend in pH, an indication of increasing ocean acidification from 0.04 units to 0.24 units by 2080 relative to 2015. The pH level predicted for the year 2030, in all scenario projections were less than 8.0, whereas in 2050 and 2080, it was below 7.95 and 7.9 respectively in all scenarios, except RCP 2.6. This is in agreement with the reports of Bhadury (2015) and Rashid et al.(2013). The increase of dissolved inorganic carbon (DIC) plays an important role in elevating surface water pCO_2 and decreasing pH in tropical Indian Ocean (Xue et al. 2014). The pH value of sea water and bicarbonate has a positive relationship whereas it is slightly linked with the amount of salinity (Rashid et al. 2013).

Organisms such as shell-fishes, oyster and corals are most vulnerable to ocean acidification (Rashid et al. 2013) as it affects the formation of exoskeleton of the reefs (Vivekanandan 2010). Ocean acidification affects the larval stages of calcifying marine invertebrates, which show reduction in larval size and alteration in shell integrity and these could severely affect the survival of larval life forms (Bhadury 2015). The study by Rashid et al. (2013) showed that the decrease in pH reduced the calcium carbonate of molluscs and further weakening of its shell membrane. The higher variation of pH in BoB was well correlated with the decreasing trend of salinity in BoB.

Analysis of possible changes of oceanographic variables is very important for the future assessment of impact studies and adaptation planning of marine and coastal ecosystems in Indian Ocean. In the present study, we analysed the general trend in future projections of six oceanographic variables, causes of variations and their effects on Indian marine fisheries and ecosystem from a suitable CMIP5 model for 2030, 2050 and 2080 for four RCP scenarios. Though model projections are more reliable on global scale, regional scale studies can help us to understand the possible changes of each variable in the future. Separate analysis of AS and BoB gives a clear idea of variation of each variable in 2030, 2050 and 2080 in NAS, SAS, NBoB and SBoB. As per the RCP 8.5 scenario, SST and SLR projections show a significant rising trend in 2030, 2050 and 2080 whereas, SSS, Chl concentration and pH shows a declining trend. Precipitation shows an increase in 2030, 2050 and 2080 relative to 2015 in RCP 2.6 and RCP 8.5 scenario, however, a significant rising trend was not observed, as it shows variations in each time slice. Multiple models of CMIP5 and RCP based projections have to be analyzed further in future for the Indian Ocean for 2030, 2050 and 2080 in order to assess the quality of projection, reasons for variation and effects in each oceanographic variable.

Acknowledgements: We thank the World Climate Research Programme's Working Group on Coupled Modeling, which is responsible for CMIP, and the climate model MIROC-ESM-CHEM developed by {Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology} for making available their model outputs.

Policy and institutional framework on marine fishery in India

India, being the second largest producers of fisheries and aquaculture, could not afford a back foot, in the context of climate change stressors. The studies of climate change impacts of Indian marine fisheries sector reveal several species level impacts, shift in fisheries resources, habitat alterations and ecosystem modifications that has implications on aggregating the vulnerabilities of marine fish resources, depending fishermen communities as well as the coastal infrastructure and landscape. The situation could negatively affect the national fisheries economy, livelihoods of coastal communities and marine ecosystem, which necessities formulation and implementation of adaptation strategies to negate the impact and vulnerabilities on Indian marine fisheries sector.

The national level research institutions could emerge and position itself in a lead role to provide climate resilient farming techniques and to enhance the preparedness of the coastal communities. Nation could focus on development of in-house competent aquaculture techniques and technologies than depending on costlier foreign imports. Extended steps need to be taken to make 'Aqua-Entrepreneurship' prominent as well as to train the fishermen communities over marketing of marine products to ensure better income. Research focus on climate resilient products could facilitate the bio refinery approach across the coastal states leading to significant contribution towards national bio-economy. Ensuring regional level nutrition and food safety is of prime concern and more aquatic resources and techniques could be explored for the same. Assessment and management of regional wetlands for aquaculture is a significant adaptation strategy and geospatial techniques could be employed for wetland health status. The focus on blue revolution is of high significance to enhance the fish production and scientific institutes could provide necessary region-specific aquaculture implementation techniques. Ecosystem approach integration is of essential to ensure environmental sustainability and accountability of aquaculture practices. Continuous real time monitoring system development is the area which needs to be focused for enhancing climate resilience. Effective coordinated interventions by scientific institutions, governments and coastal communities could enable the climate resilience of marine fisheries of India.

Conservation and resilient strategies to reduce the impact on vulnerable marine species and fishing community

The major vulnerabilities of marine fisheries sector identified are skeletal deformities in fishes (Zhenhua et al., 2016), changes in spawning habits (Vivekanandan et al., 2010), increased metabolic rate in farmed fish and shellfish (10% increase for 10ºC rise in temperature) (Vivekanandan et al., 2010), reduced life span and extension of boundaries of fish stocks (Vivekanandan et al., 2010), phenological changes (Vivekanandan et al., 2010), fish migration and habitat changes, uneven proportions of fish population (Zacharia et al., 2016), fish food security and livelihood related challenges (Zacharia et al., 2016), changes in direction and speed of winds (Zacharia et al., 2016), migration of fish species for reasons other than spawning, dispersal and growth (Vivekanandan et al., 2010, Zacharia et al., 2016), *Tsunami* and its recurrence effect (Vivekanandan et al., 2010), changes in phytoplankton species composition and abundance which largely affect structure and functions of marine ecosystems (Zacharia et al., 2016), fluctuations in abundance and reduction of particular variety of fish species due to reasons which are climate related (Zacharia et al., 2016), reduction and extinction of estuarine associated habitats (Zacharia et al., 2016) and many related issues.

As part of the research and various brainstorming sessions conducted, the following Adaptation strategies were developed based on the above vulnerabilities listed:

- Public awareness to enhance protection of coastal and marine ecosystems (Zacharia et al., 2016)
- Mangrove mapping, conservation and restoration (Zacharia et al., 2016)
- Habitat mapping and modelling (Zacharia et al., 2016)
- Vulnerability assessment along Indian coastal zones and conservation (Zacharia et al., 2016)
- Monitoring control and surveillance (Zacharia et al., 2016)
- Promoting aquaculture along with resilient strategies/ cage farming (Zacharia et al., 2016)
- Cultivation of halophytes (Natasha, 2015)
- Green fishing protocols for carbon footprint reduction
- Intensification of seaweed farming along Indian coastal regions
- Develop knowledge base for climate change and marine fisheries (Vivekanandan et al., 2010)
- Adopt code of conduct for responsible fisheries (Vivekanandan et al., 2010)
- Enhancing co-operation and partnerships (Vivekanandan et al., 2010)
- Evolving common platforms and sharing best practices (Vivekanandan et al., 2010)
- Protection and conservation of coral reefs, mangroves, sea grass and littoral vegetation (Zacharia et al., 2016)
- Research thrust: Address critical knowledge gaps about climate change impacts (Jena and Grinson, 2017)

Brief description on various adaptation strategies for enhancing coastal wetland eco system, establishing continuous monitoring and advisory services, integrating bio refinery approach and coastal community resilience is provided which collectively points out towards attaining an improved scenario of environmental sustainability, governmental interfaces, research interventions and community responses.

Enhancing coastal wetland ecosystem through aquaculture and geospatial monitoring

India have 5,55,557 small wetlands (<2.2ha) including coastal, estuarine and fresh water ecosystems (NWIA Project, SAC 2011). The data implies the need to align the resilience strategies with focus on region specific small wetland management and monitoring so as to enhance sustainability. Resilience of small wetlands could enhance food and nutrition security at regional

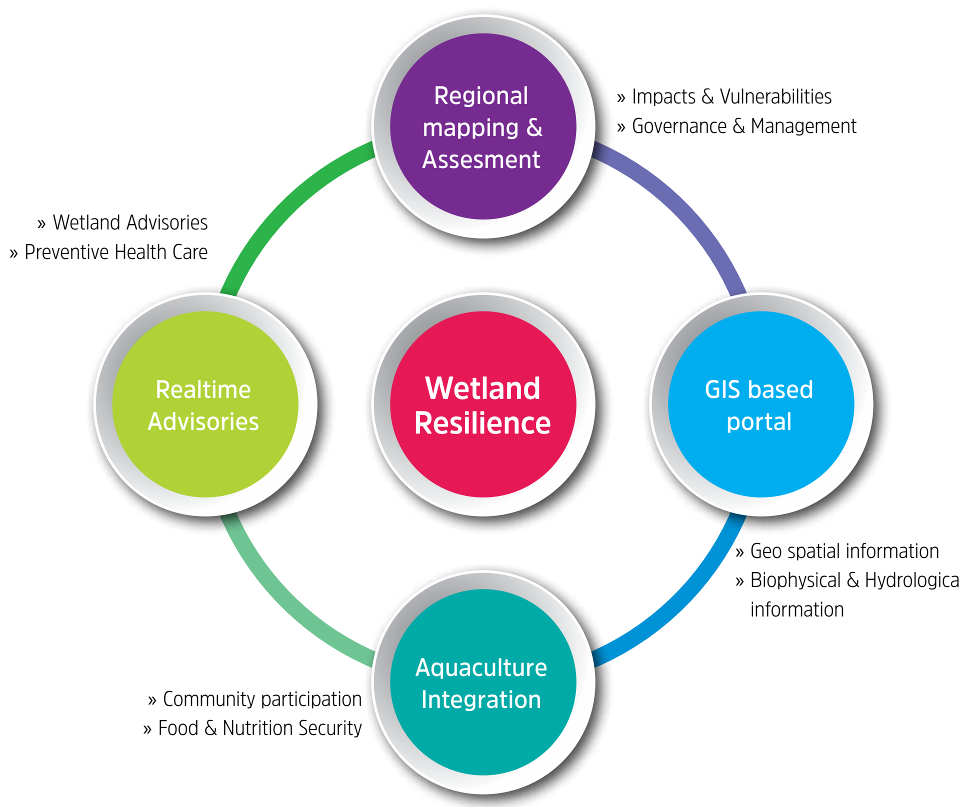


Figure 1: Resilience Framework for Coastal Wetlands

level, enhance livelihoods of dependent population, provides opportunity for development of climate resilient products; comprehensively leads to climate smart villages.

A resilience framework has been developed for coastal wetland management in the context of climate change and vulnerabilities of wetlands with four interconnected components. The framework addresses the challenges to develop a continuous qualitative and quantitative monitoring system for wetlands, to provide real time wetland advisory services, to improve the wetland productivity and functions, to ensure community participation and to enhance resilience of regional wetlands. Description of each component is as provided below:

Regional mapping and assessment

Panchayat level maps of small coastal wetland (<2.2ha) of coastal states could be created using remote sensing data along with construction of spatial database for better resource management and utilization. The data of small coastal wetlands marked as points are already available through the NWIA project, which could be further developed. Local self-government bodies or other concerned institutions could finance for the geospatial, biophysical and hydrological analysis of wetlands within their geographical area. Wetland assessment facilitates degraded wetlands restoration as well as management of vulnerable wetland ecosystem for improved ecosystem functions.

Aquaculture Integration

In practical sense, the local community participation for wetland restoration, management and monitoring could not be ensured based on environmental and climatic implications alone. However, integration of aquaculture is a means to ensure community/self-help group's participation as it may supplement their livelihoods as well as could enhance the regional level food and nutrition security. Climate resilient stress tolerant species suitable for aquaculture has been identified by CMFRI and similar competent scientific institutions that could be implemented as per the guidelines and technical assistance. Integrated multi trophic aquaculture (IMTA), paddy-finfish co-farming and low cost cage farming etc. has been identified as climate smart farming techniques that could be considered for the implementation in regional coastal wetlands. Besides, the mariculture residues such as seaweeds and aquatic vegetation could be utilized for development of climate resilient products such as biochar, bio-fuel as well as for fish feeds. Aquaculture practice ensures periodical water quality monitoring and thus generates continuous quantitative water quality data which aids wetland health monitoring. Thus integration of aquaculture in identified wetlands is a multi-benefit resilient component.

GIS based portal development

To have a one-stop source is of vital for the effective management and monitoring of wetlands. A national geoportal with spatial database on region wise mapped wetland data is envisaged.

Each wetland data could be integrated with associated climate data, geospatial analysis data and bio-physical data from aquaculture. The portal could ensure digitized data input that shall favour the long term scientific analysis as well. The portal could provide access to concerned scientific communities, policy makers and other stakeholders which enables the network mode assessment of possible climate related and other threats or stressors such as floods, storm water influx, agricultural runoffs, pollutant discharge, drainage pattern, catchment area status, geographical settings, slope, aquatic vegetation spread, land use, etc. on a regional basis.

Continuous wetland monitoring system

Continuous monitoring of the wetlands is of need to ensure sustainability and effective resilience. The real time qualitative monitoring of the wetlands could be done through remote sensing images whereas the geoportal could provide quantitative data of wetland. The geoportal data could be used to monitor the status of each regional wetland and water quality indexes or similar criteria could be accordingly derived for each wetlands. The qualitative and quantitative data access over coastal wetlands of the nation could result in a comprehensive monitoring system. This monitoring system could be used for preventive health care of ecosystems and could also provide real-time wetland advisories for aquaculture practices. Multi-tier monitoring system involving scientific institutes, NGOs, self-help groups isvisualized.

The implementation of the resilience framework could assess the existing scenario as well as project the future wetland impacts and vulnerabilities; accordingly adaptation strategies could be effectively planned and implemented. Continuous GHG emissions could also be monitored through this system. The framework shall enhance the ecological integrity and environmental accountability of regional coastal wetlands. The framework could be extended to other wetland categories as well for sustainable resilience of rural and urban environment.

Continuous monitoring and advisory services for Indian marine fish species

ICAR-CMFRI had developed scientific criteria for climate vulnerability assessment of Indian marine fish species, which categorizes the vulnerability of species into low, medium and high. This criterion could be followed to prioritize the species conservation and utilization. Continuous vulnerability assessment across the coastal zones (southwest, northwest, northeast, and southeast) could be carried out by research institutes and a vulnerability database for Indian marine fisheries could be evolved. A vulnerability database on important marine fisheries shall enable the policy makers to make suitable decisions.

It is evident that climate change had induced fishing pressures and over exploitation of juveniles of marine fishes, which seriously affects the spawning and growth of many commercial fisheries leading towards net loss in fisheries economy. To avoid over fishing of commercial fishes, and for conservation of juveniles as well as to maintain healthy stock of marine fishes, ICAR-CMFRI had carried out scientific studies and recommended to government for implementation of Minimum Legal Size (MLS) of capture for 58 marine species off Kerala coast. This could be used as a management tool for sustainable fisheries and each maritime state could carry out such scientific studies and species prioritization, upon which government or enforcement agencies could make decisions. The studies could be periodically updated.

Stock modeling could be used as a tool to improve the recovery of population collapses. Besides, based on impact studies modeling techniques could be applied towards predictive modeling of species distributional changes, habitat modifications, etc. Development of zone wise species level models with representation of oceanic and climatic parameter variation could enhance the adaptability planning. The shift in distributional boundaries of important commercial marine fish species had resulted in low fish catch, increased scouting time, non-target fish catch and reduced profitability. Potential fishing zone (PFZ) identification using remote sensing techniques and PFZ advisories services could help in coping with the situation. Potential fishing zone advisories and monitoring at each coastal state is an effective resilience means. Outputs of fish catch forecast models could also be integrated to the advisory services and could be effectively communicated to fisher-folks and stakeholders to enhance the adaptability. Fishing zone activities could be monitored and regulation of fleet size, mesh size, etc. could be ensured for judicious stock utilization. For sustainable exploration of Indian marine fishery resources, these scientific studies and tools could be coordinated with the Monitoring, Control and Surveillance mechanisms of Indian Exclusive Economic Zone (EEZ).

To enhance resilience, fisheries research institutes could thus focus on continuous vulnerability assessment, Minimum legal size assessments, catch forecast, predictive modeling, potential fisheries zone advisories and continuous monitoring system development; while government and concerned enforcement agencies could implement the recommendations and regulations.

Algae based climate resilient products development and biorefinery integration

The carbon sequestration abilities of seaweeds have been already established and its large scale farming along Indian coasts is a prospective climate resilient strategy. Carbon sequestration ability of seaweeds makes it as a means to combat the ocean acidification. Coastal areas are prone to extreme climate change events and intense precipitation which expedites high influx of pollutant runoffs and floods leading to marine pollution. Seaweed farming zones could act as sink for the marine pollution. Coastal populations affected by climate change could take up seaweed farming as alternate livelihood option. Seaweeds could be also converted to climate smart product 'Biochar' adding more dimensions to carbon sequestration. It is more promising to use seaweeds as feedstock for bio-fuel production, which helps in reducing the dependency on fossil fuels. Seaweed farming for energy feedstock has several advantages such as non-competent for food grains, landless cultivation, zero fertilizer dependency, etc. making it an attractive option. The bio-ethanol generated from the seaweeds could be channelized towards usage in fisheries sector, which enhances the sustainability. Algal bloom is one of the climate change associated phenomena that impacts the aquatic ecosystem either as harmful or as productive means. Solar irradiation, SST, precipitation, nutrient runoffs, etc. influences the growth of algae. The beneficial implications of growth of algal population include enhanced carbon sequestration, enrichment of food chains and net productivity improvement. Research interventions could transform the harmful effect algal bloom into beneficial outcome.

Multiple products could be developed from micro as well as macro algae (seaweed) and both could be used as a renewable energy source. National bio-fuel policy of India indicatively targets 20 % blending of bio-diesel and bio-ethanol by 2017 and the blending of 5-10 % bio-ethanol has been made mandatory since 2008. In India the ethanol demand is expected to be covered by domestic production, which implies the need for research interventions in regional bio energy feedstock and processing. In national bio-fuel policy, algae were identified as one among the source to produce bio-fuel. Augmentation of bio-fuel production strategy with bio-refinery integration could be more economically and technically feasible. The global energy prices are highly fluctuating and its weakening adds extra pressure to the economics of biomass to bio-fuel conversion technologies. It is unwise to focus on bio-fuel alone as end product and integration of algal bio refineries with multiple commercially/ industrially valuable products as outputs is the proposed sustainable strategy that could be beneficial for the overall conversion process. Currently seaweed farming is practiced by private industries for specific product needs. To enable additional large scale seaweed farming, effective research interventions with commercial products is of need. Seaweed based bio refineries need to be developed in each coastal state with integration to existing industries as well.

It could be emphatically stated that seaweed farming, bio fuel production, bio products development and bio refineries integration based on algae feedstock would be a sustainable strategy to mitigate the climate change impact as well as to improve the national economy.

Adaptation options for coastal communities

Owing to climatic impacts, low catch followed by low income is a serious issue affecting the coastal population. Income improvement for fisher folks is the challenging goal and adaptation to ICT techniques could fetch better prices for even minimal catches. The fishermen groups could be trained to deliver the fishes directly to end-consumers eliminating the middlemen and thereby ensuring better income. A multi-vendor E-Commerce platform has been launched by the ICAR-CMFRI towards the realization of the concept which could incorporate several fishermen self helps groups (SHGs) as multi-vendors and training were provided to the SHGs to familiarize with the system. The SHGs as vendors could update their daily stock and consumers could place the order through the developed E-Commerce website and the ordered fish shall be delivered by the SHGs within due time. This adaptation framework aiming better income for fishermen communities could be extended across the prioritized vulnerable coastal districts.

Several coastal areas and villages are highly prone to adverse climatic impacts. To cope-up with the adversities community level climate preparedness activities (CPAs) could be implemented by competent scientific bodies through trainings, demonstrations and participatory programs on climate change awareness, adaptation means and disaster preparedness. Climate cells could be made functional at each vulnerable coastal district, which could provide updated information as well as coordination between coastal communities and government departments for implementation of climate smart adaptation techniques and policies. Sea level rise, coastal erosion, floods and storms damages the coastal infrastructure and adaptation strategies need to be focused to deliver prompt solutions. Each coastal districts needs to be equipped with facilities and access to temporary settlement areas, food, potable water and sanitation to mitigate the negative impacts of climate change events. Integrated coastal zone management for each district with focus on climatic adaptation need to be developed which also should include mangroves and coastal forestry to act as bio-shields as well as habitat for marine species.

Adaptation to climate smart aquaculture techniques could enhance the livelihoods of fishermen communities. Fisheries research institutes are identifying climate stress tolerant fish species along with its farming guidelines, which could be used for aquaculture by fishermen. Paddy-fin fish co-farming was found to be economically beneficial and several state governments are supporting the policies. Research institutes have also developed all weather mooring low cost cages for enabling cost effective aquaculture. Besides, farmers could also adopt the Integrated Multi Trophic Aquaculture (IMTA) with seaweeds and mussels, which shall fetch them additional profits. To bring down the aquaculture cost, farmers could also rely on using seaweed based and other low cost fish feed. One of the serious climate related threat to aquaculture is that of pathogens and the microbial infection, which leads to mass mortality and drastic income loss. To negate the effect, preventive health care guidelines for aquatic animals need to be adhered. Competent research institutions could offer regular monitoring and preventive health care along with eco-system integration approach to ensure adaptability.

Recommendatons for Policy Makers

- Create increased awareness on vulnerability of coastal areas and resources among coastal communities
- Develop adaptation strategies in a co-management concept to resolve the challenges which the communities are going to face in the long-term
- Frequency of extreme events and associated climate crisis are going to be more; develop suitable adaptation strategies for such crisis based on the long-term projections
- Adopt more climate-friendly technologies or green practices
- Ensure auditing and accountability such as green audits, life cycle analysis and others so that there is accountability with respect to climate change in everything we do
- Identify how best we can utilize the impacts for the benefit of the society such as increased sea level adding more inundated brackishwater areas where coastal farming can be proposed
- Technological intervention with community interaction may be used such as the apps and models described in the text for a larger cause e.g. the case of wetland mapping, online fish sales etc.
- Ensure capacity building in different strata of the society to make them climate smart

Status of the project

Manpower

Manpower needed was selected and recruited for a period up to March 2018

Sl No	Manpower	Name	Tenure
01.	Research Associate	Dr. Rojith Girindran	01.04.2017 – 30.08.2017
		Dr. Lakshmi P.M	05.09.2017 – 31.01.2018
02.	Junior Research Fellow	Ajith S	01.04.2017 – 31.01.2018
03.	Junior Research Fellow	Akhiljith P. J	13.03.2017 – 31.01.2018
04.	Office Assistant	Lakshmipriya S	20.03.2017 – 31.01.2018
05	Technical Assistant	Alfred Dourom	01.07.2017 – 14.05.2018

Equipment

Procured workstation for modelling and related computer works.

Field study / workshop

Oceanographic sampling was done on board research vessel Silver pompano.

Designing online module for Second symposium of SAFARI was done.

Association and partial sponsorship has been done for the event 'The second symposium of SAFARI on Remote sensing for Ecosystem Analysis and Fisheries'.

Recurring expenses

Procured consumables and stationary items.

Acknowledgement

We acknowledge the financial assistance provided by UNDP-GEF-MoEF&CC for the successful completion of the project *Impact, Vulnerability and Adaptation Strategies for Marine Fisheries of India* (IVAS-MFI). We also thank the Director, ICAR-CMFRI, for his support extended towards the smooth conduct of the project at the Institute.

Annexure 1: Predictive changes, causes and impacts of oceanographic variables

Oceanographic parameters	Predictive changes in 2030, 2050 and 2080	Causes of changes	Impacts of changes
Sea Surface Temperature (SST)	Sea surface temperature in Indian Ocean will increase by 0.69°C by 2080, 0.60°C by 2050 and 0.43°C by 2030 relative to the reference year 2015 in RCP 2.6 scenario whereas respective change in RCP 8.5 scenario shows a rise of 2.6°C by 2080, 1.3°C by 2050 and 0.59°C in 2030 An increasing trend in sea surface temperature of 0.69°C to 2.6°C in 2080 relative to 2015 in Indian Ocean	Major contributing factors that lead to the variation of SST in Indian Ocean are anthropogenic forcing, greenhouse gas effects, El Niño events, Indian Ocean dipole, monsoonal winds and La Niña events (Roxy et al., 2014; Gnanaseelan et al., 2017; yoo et al., 2006) Anomalies of SST over the tropical Indian Ocean are often linked to the variability of the local Indian monsoon because of the effects of latent heat and water vapor supply (Yoo et al., 2006) Weakening monsoon winds are responsible for increasing surface warming over the Indian Ocean during the monsoon season (Gnanaseelan et al., 2017) Indian Ocean SST anomalies associated with La Niña are relatively smaller in comparison with those associated with El Niño events (Roxy, 2014)	Rapid Ocean warming resulted in increased surface stratification (Gnanaseelan et al., 2017) Corals in Andaman and Nicobar Islands suffered extensive bleaching during April 2010 to the extent of 60–70 % due to elevated sea surface temperature (Krishnan et al., 2013; Mohanty et al., 2013) Warming of sea surface, the oil sardine is able to find temperature of its preference and extending the distributional boundaries (Vivekanandan et al., 2009a) Availability of oil sardine in Kerala coast,compared to 2014, there is 17% reduction in landings in the southwest region whereas 21% increase was noted in the northeast region(CMFRI annual report 2015-16) Stratified ocean waters suppress the upwelling of nutrients from the subsurface waters and reduce the marine primary production (Gnanaseelan et al., 2017)

Oceanographic parameters	Predictive changes in 2030, 2050 and 2080	Causes of changes	Impacts of changes
Sea Level Rise (SLR)	In RCP 2.6 sea level may rise to 12.7 cm by 2080, 7.27 cm by 2050 and 2.64 cm by 2030 compared to 2015 where as it may rise of 19.1 cm by 2080, 9.37 cm by 2050 and 5.23 cm by 2030 in RCP 8.5 scenario of the same Sea level shows a gradual rise with minimum of 12.7 cm to maximum of 19.1 cm by 2080 relative to 2015 with peak rise occurs in May to Aug indicating the direct impact of increase in sea surface temperature, precipitation over May to Aug and the corresponding effects	Increase in sea surface temperature has significant effect on increasing ocean volume (Piyali and Manasa, 2015) Both inter annual and decadal variability of El Niño Southern Oscillation and Indian Ocean Dipole are expected to force considerable sea level variations in Indian ocean (Unnikrishnan et al., 2015) Increased heat storage raises the water temperature, resulting in thermal expansion of sea water. (Nobuo et al., 2013) Another possible cause for this sea level-rise acceleration may be the Himalayan glacier melt and thermal expansion of ocean (Unnikrishnan et al., 2015) Wind anomalies has a strong impact of sea level rise that near the Equator. driven mass redistribution and salinity effects increasing the basin-mean sea level (Weiqing et al., 2010)	Upwelling influence the nutrients level and productivity in the coastal waters (Krishnakumar et al. 2008) It causes exacerbated inundation and flooding of low lying coastal areas, increased coastal erosion, effects on coastal ecosystems such as salt marsh, mangroves and coral reefs, salt water intrusion into fresh water sources, changes in sediment deposition along river channels, possible occurrence of typhoons and storms, higher-order impacts on the natural environment and human society (Nobuo et al., 2013) Mangroves, the natural barrier of coastal flooding and erosion, will be at high risk of submergence due to sea level rise (Piyali and Manasa, 2015) Mangroves cannot survive in an environment with higher sea-level and salinity, because some mangrove species respire through aerial roots jetting above the sea surface (Nobuo et al., 2013) Upwelling triggers some favorable changes in the physical, chemical and biological conditions in the inshore waters which attract pelagic fishes in large numbers for feeding and spawning (Krishnakumar et al, 2008) During upwelling some fish populations move into the shallow surface waters while the others move offshore, away from the center of strong upwelling to avoid cool and low oxygen zone, mortality and even disappearance of demersal fishes also reported (Krishnakumar et al, 2008) Rise in sea level could harm the lives and occupation of millions of people who inhabit coastal regions and islands

Oceanographic parameters	Predictive changes in 2030, 2050 and 2080	Causes of changes	Impacts of changes
Sea Surface Salinity (SSS)	Sea surface salinity will decrease to 0.49 psuby 2080, 0.39 psu by 2050 and 0.34 psu in 2030 compared to 2015 in RCP 2.6 scenario where as it may fall to 0.75 psu by 2080, 0.49 psu by 2050 and 0.14 psu in 2030 in RCP 8.5 scenario of the same A variations of SSS of 0.49 psu to 0.75 psu in 2080 relative to 2015 in Indian Ocean	Salinity dipole mode in the tropical Indian Ocean, termed S-IOD, a pattern of interannual SSS variability with anomalously low-salinity in the central equatorial and high-salinity in the south eastern tropical Indian Ocean(Yuhong and Yan, 2016) These variations are driven various factors include sea surface temperature, precipitation, evaporation, Indian ocean dipole, La Nina, El Nino, river discharge, Monsoonal winds and coastal upwelling Impact of El Niño events on a positive IOD event is large with freshening in the equatorial Indian Ocean whereas the impact of La Niña with negative IOD is also large with an intense freshening in the southeastern Arabian Sea(Gary et al., 2011) Bias in precipitation and evaporation (Ibnu et al., 2017), combination of wind driven upwelling of subsurface high salinity waters and anomalous surface circulation, higher influx of fresh water from rivers (Gary et al., 2011) and zonal advection (Anant et al., 2016) may increase or decrease the ocean salinity in Indian ocean	Low salinity values at the surface enhance stratification of the water column, creating a barrier layer (Gary et al., 2011) Stratification affect the ocean dynamics and air–sea interaction (Yan et al., 2015) Barrier layer which inhibits upper ocean interaction with the subsurface and make ocean surface very sensitive to the atmospheric changes (Anant et al., 2016) The salinity and barrier layer play a significant role in the seasonal variability of SST, winds and precipitation over the Indian Ocean (Anant et al., 2016) which could have the potential to substantially alter the fish breeding habitats, migration of fishes, food supply and abundance of fish populations. (Vivekanandan et al., 2010)

Oceanographic parameters	Predictive changes in 2030, 2050 and 2080	Causes of changes	Impacts of changes
Precipitation (Pr)	RCP 8.5 scenario analysis an increase of 0.26 mm/day by 2080, 0.28 mm/day by 2050 and fall of 0.194 mm/day by 2030 compared to 2015 mean precipitation where as in RCP 2.6 scenario shows a change in rise of 0.6 mm/day by 2080, 0.26 mm/day by 2050 and 0.16 mm/ day by 2030 maximum precipitation indicated from June-Sep in all scenarios in 2030, 2050 and 2080 analysis No significant seasonal monsoon drift is observed in our study but it show variations in 2030, 2050 and 2080 in RCP 8.5 whereas it shows gradual increase in RCP 2.6	Rainfall anomalies significantly influence salinity, dynamics, and temperature in the Indian Ocean, but have narrow effect on sea level compared to wind-driven changes (Claire et al., 2003) Indian summer monsoon is strongly correlated with the relationships between El Niño-Southern Oscillation (ENSO) and Indian Ocean climate (Yang et al., 2013) SST variability plays an important role in the ENSO-induced anomalies in the Indian monsoon region (Deepthi et al., 2011) Summer rainfall over central Asia could be closely related to the SST anomalies in Indian Ocean (Zhao et al., 2016) Indian ocean dipole leads to a similar pattern in SST called SST dipole, is accompanied by a similar dipole in the precipitation anomalies, with suppressed precipitation in the east and enhanced precipitation in the western Indian Ocean (Gnanaseelan et al., 2017) Larger moisture flux convergence resulting from a warming Indian Ocean can lead to the intensification of the mean rainfall (Yang et al., 2013)	The precipitation deficits affect SST by entraining more subsurface water to the surface while the precipitation excess does not affect SST because the temperature difference between the mixed layer and the barrier layer is very little then (Claire et al., 2003) Rainfall anomalies significantly influence Indian Ocean circulation as well as salinity, make the ocean saltier when there is a deficit and fresher when there is an excess (Claire et al., 2003) it alters sea surface salinity stratification (Zhanget al., 2016) Periods of good rainfall have positive effect on oil sardine abundance, indicate that low rainfall might be affecting the fecundity, recruitment success and food availability (Jayaprakash, 2002)

Oceanographic parameters	Predictive changes in 2030, 2050 and 2080	Causes of changes	Impacts of changes
Chlorophyll Concentration (Chl)	A variation of +0.013 mg/m^3 of Chl by 2080, +0.01 mg/m^3 by 2050 and +0.02 mg/m^3 by 2030 compared to 2015 in RCP 2.6 whereas it may be decreased to 0.043 mg/m^3 by 2080, 0.02 mg/m^3 by 2050 and 0.015 mg/m^3 by 2030 in RCP 8.5 scenarios of the same Significant declining trend of chlorophyll concentration is followed in our study in all RCP scenarios except RCP 2.6	The Indian Ocean Dipole events have great impact on chlorophyll concentration in the tropical Indian Ocean, (Liu et al., 2013) Declining trends in chlorophyll are driven by enhanced ocean stratification due to the rapid warming in the Indian Ocean, which suppresses nutrient mixing from subsurface layers (Roxy et al., 2016) Chl concentration is found to be higher in the north-eastern Arabian Sea compared to those in the southern Bay of Bengal, is attributed to the shallow depth of the shelf in the Arabian Sea (Sagnik and Ramesh, 2003) The regional structure of the blooms is intimately linked with the horizontal and vertical circulations forced by the monsoons (Levy et al., 2007) The higher chlorophyll concentration in the north-eastern Arabian Sea is found during the northeast monsoon compared to those during the pre- and post-monsoon period (Sagnik and Ramesh, 2003) Water masses of different temperature and salinity partially govern the distributions of chlorophyll concentration (Liu et al., 2013) Higher chlorophyll concentration is found in the coastal water compared to the open ocean (Sagnik and Ramesh, 2003) As nutrient distributions are important for phytoplankton composition (Takahiro et al., 2014) input of nutrients are mediated by upwelling, convection, or by horizontal advection (Levy et al., 2007)	Long-term changes in phytoplankton biomass and community composition are important in the ecosystem, being the base of the marine food web, it plays a central role in ocean biogeochemical cycles and regulates the global climate (Takahiro et al., 2014; Roxy et al., 2016) 39% of inter-annual variability in fish landings is related to availability of chlorophyll-a during the bloom initiation month (Grinson et al., 2012) The increased phytoplankton biomass is tightly coupled to the oil sardine catch (Vivekanandan, 2010) Spatial and temporal variations in the intensity of chlorophyll in the coastal waters were reflected in the sardine abundance (Grinson et al., 2012) The western Indian Ocean hosts one of the largest concentration of phytoplankton blooms in summer, supporting the second largest share of the most economically valuable tuna catch (Roxy et al., 2016)

Oceanographic parameters	Predictive changes in 2030, 2050 and 2080	Causes of changes	Impacts of changes
pH	In RCP 2.6 pH may decreases to 0.04 units by 2080, 0.041 units by 2050 and 0.03 unit in 2030 whereas pH falls to 0.242 units by 2080, 0.11 units by 2050 and 0.05 unit by 2030 in RCP 8.5 scenario An indication of increasing ocean acidification from 0.04 unit to 0.24 unit by 2080 relative to 2015 pH level will be less than 8.0 in 2030 in all scenario projection whereas below 7.95 in 2050, below 7.9 in 2080 in all scenarios except RCP 2.6, which shows a stable projection of pH in 2030, 2050 and 2080	The dissolved inorganic carbon (DIC) increase played the most important role in elevating surface water pCO2 and decreasing pH in tropical Indian ocean (Xue et al., 2014) The pH value of the sea water and bicarbonate has a positive relationship where as it is slightly linked with the amount of salinity (Rashid et al., 2013)	Organisms such as shell, oyster and coral are the most vulnerable to ocean acidification (Rashid et al., 2013) Increasing acidity of seawater would affect formation of exoskeleton of the reefs, given their central importance in the marine ecosystem; the loss of coral reefs is likely to have several ramifications (Vivekanandan, 2010) Ocean acidification affects the larval stages of calcifying marine invertebrates, which shows reduction in larval size and alteration in shell integrity, these could severely affect the survival of larval life forms(Bhadury, 2015) Decrease in pH reduced the calcium carbonate of the Molluscs that the shell membranes of the Molluscs are going to be weaker (Rashid et al., 2013)

Annexure 2: Oceanographic parameters: Vulnerability and Adaptation strategy

Parameters	Vulnerabilities	Adaptation Strategy
Sea Surface Temperature (SST)	Skeletal deformities in fishes (Zhenhua et al., 2016) Changes in spawning (Vivekanandan et al., 2010) Increased metabolic rate(10% increase for 10C rise in temperature) (Vivekanandan et al., 2010) Reduced life span and extension of their boundaries (Vivekanandan et al., 2010) Phenological changes (Vivekanandan et al., 2010) Affect fish migration and habitats, uneven proportions of fish populations (Zacharia et al., 2016) Fish food security and livelihoods (Zacharia et al., 2016) Affect direction and speed of winds (Zacharia et al., 2016)	Public awareness to enhance protection of coastal and marine ecosystems(Zacharia et al., 2016) Mangrove mapping, conservation and restoration (Zacharia et al., 2016) Habitat mapping and modellng (Zacharia et al., 2016) Vulnerability assessment along Indian coastal zones and conservation (Zacharia et al., 2016) Monitoring control and surveillance (Zacharia et al., 2016). Promoting aquaculture along with resilient strategies/ cage farming (Zacharia et al., 2016) Cultivation of halophytes (Natasha, 2015) Green fishing protocols for carbon footprint reduction See weed farming along Indian coast Develop knowledge base for climate change and marine fisheries (Vivekanandan et al., 2010) Adopt code of conduct for responsible fisheries (Vivekanandan et al., 2010) Enhancing co-operation and partnerships(Vivekanandan et al., 2010) Evolving common platforms and sharing best practices (Vivekanandan et al., 2010) Protection and conservation of coral reefs, mangroves, sea grass and littoral vegetation (Zacharia et al., 2016) Research thrust: Address critical knowledge gaps about climate change impacts(Jena and Grinson, 2017)
Rain fall	Migration of fish species for spawning, dispersal and growth(Vivekanandan et al., 2010) Sea level rise(Zacharia et al., 2016) Tsunami like recurrence affect coastal population(Vivekanandan et al., 2010)	
Chlorophyll Concentration	Changes in Phytoplankton species composition and abundance largely affect structure and functions of marine ecosystems (Zacharia et al., 2016) Abundance and reduction of particular variety of fish species (Zacharia et al., 2016)	
Sea Level Rise	Reduction and extinction of estuarine associated habitats (Zacharia et al., 2016) The availability and landings of large fishes may be reduced (Zacharia et al., 2016)	
Wind patterns	Drive ocean currents and mix surface waters with deeper nutrient rich waters (Natasha, 2015) Affect the abundance and variety of phytoplankton (Natasha, 2015)	
PH	Ocean acidification (Zacharia et al., 2016) Corals are more vulnerable to change in PH of sea water (Jena and Grinson, 2017) Coral bleaching expelling of Zooxanthellae from corals (Zacharia et al., 2016) Phenology and fecundity (Adriaan et al., 2009)	

References

Adriaan D. Rijnsdorp, Myron A. Peck, Georg H. Engelhard, Christian Mollmann, and John K. Pinnegar (2009) Resolving the effect of climate change on fish populations, Oxford Journals, p.1570-1583.

Akhiljith, P. J., Liya, V. B., Rojith, G., Zacharia, P. U., Grinson, G., Ajith, S., Lakshmi, P. M., Sajna, V. H. and Sathianandan, T. V., 2019. Climatic Projections of Indian Ocean During 2030, 2050, 2080 with Implications on Fisheries Sector. Journal of Coastal Research, 86(sp1), pp.198-208.

Anant Parekh, Jasti S. Chowdary, Ojha Sayantani, T. S. Fousiya (2016). Tropical Indian Ocean surface salinity bias in Climate Forecasting System coupled models and the role of upper ocean processes, ClimDyn, DOI 10.1007/s00382-015-2709-8, p. 2403–2422.

Anne B Hollowed, Manuel Barange, Richard J. Beamish, Keith Brander, Kevern Cochrane, Kenneth Drinkwater, Michael G. G. Foreman, Jonathan A. Hare, Jason Holt, Shin-ichi Ito, Suam Kim, Jacquelynne R. King, HaraldLoeng, Brian R. MacKenzie, Franz J. Mueter, Thomas A. Okey, Myron A. Peck, Vladimir I. Radchenko, Jake C. Rice, Michael J. Schirripa, Akihiko Yatsu, and Yasuhiro Yamanaka (2013). Projected impacts of climate change on marine fish and fisheries, ICES Journal of Marine Sciences, 70 (5), p. 1023-1037.

Arthur, R., Coral bleaching and mortality in three Indian reef regions during an El Nino southern oscillation event. Current Science, 2000, 79, 1723-1729.

Ateweberhan, M., McClanahan, T. R., Graham, N. A. J. and Sheppard, C. R. C., Episodic heterogeneous decline and recovery of coral cover in the Indian Ocean. Coral Reefs, 2011, 30, 739-752.

Azmi, S., Agarwadkar, Y., Bhattacharya, M., Apte, M. and Inamdar, A., Indicator Based Ecological Health Analysis Using Chlorophyll and Sea Surface Temperature Along with Fish Catch Data off Mumbai Coast. Turkish Journal of Fisheries and Aquatic Sciences, 2015, 15(4), 923-930.

Badjeck, M. C., Allison, E. H., Halls, A. S. and Dulvy, N. K., Impacts of climate variability and change on fishery-based livelihoods. Marine policy, 2010, 34(3),. 375-383.

Bakun, A. (1990). Global Climate Change and Intensification of Coastal Ocean Upwelling: Science, New Series, Vol. 247, No. 4939, pp. 198-201.

Beaugrand, G., Reid, P. C., Ibáñez, F., Lindley, J. A. and Edwards, M. (2002). Reorganisation of North Atlantic marine copepod biodiversity and climate. Science, 296: 1692–1694.

Bellerby, R. G. J., Schulz, K. G., Riebesell, U., Neill, C., Nondal, G., Johannessen, T. and Brown, K. R., 2007. Marine ecosystem community carbon and nutrient uptake stoichiometry under varying ocean acidification during the PeECE III experiment.

Brierley, A. S. and Kingsford, M. J., Impacts of climate change on marine organisms and ecosystems. Current biology, 2009, 19, R602-R614.

Bruno, J. F., Selig, E. R. and Casey, K. S. (2007). Thermal stress and coral cover as drivers of coral disease outbreaks. PLOS Biol., 5 (6), 1-8.

Butler M. J. A., M. G. Mouchot., V. Barale and C. LeBlanc. (1988). The application of remote sensing technology to marine fisheries: an introductory manual. FAO Fisheries Technical Paper 295, Food and Agricultural Organization of the United Nations. Rome. 165 pp.

Chaturvedi, R.K., Joshi, J., Jayaraman, M., Bala, G. and Ravindranath, N.H., 2012. Multi-model climate change projections for India under representative concentration pathways. Current Science, pp.791-802.

Chetan A. Gaonkar, Samiksha S. V., Grinson George, Aboobacker V. M, Vethamony. P, Arga Chandrashekar Anil (2012). Numerical simulations of barnacle larval dispersion coupled with field observations on larval abundance, settlement and recruitment in a tropical monsoon influenced coastal marine environment, Journal of Marine Systems. p. 218–231

Chowdhury, M. T. H., Sukhan, Z. P. and Hannan, M. A. (2010).Climate change and its impact on fisheries resource in Bangladesh. Proceedings of the International Conference on Environmental Aspects of Bangladesh (ICEAB10), The University of Kitakyushu, Japan, p. 95-98.

Claire Perigaud, Julian P. McCreary Jr., Kate Q. Zhang (2003). Impact of interannual rainfall anomalies on Indian Ocean salinity and temperature variability, journal of Geophysical Research, doi:10.1029/2003JC001857, Vol. 108, no. C10, 3335.

Claire Perigaud, Julian P. McCreary Jr.,(2003), Influence of interannual rainfall anomalies on sea level variations in the tropical Indian Ocean, journal of Geophysical Research., doi:10.1029/2003JC001857108(C10), 3335.

Climate Change 2014 Synthesis Report (2015). Intergovernmental Panel on Climate Change (IPCC) Summery for policy makers.

CMFRI, 2006. LAKFISH Integrated perspective plan for fisheries development of Lakshadweep.

CMFRI, Kochi (2016) CMFRI Annual Report 2015-2016. Technical Report. CMFRI, Kochi.

Dam Roy, S., Krishnan, P., Grinson George, Kaliyamoorthy, M. and Goutham Bharathi, M. P., 2009. Mangroves of Andaman and Nicobar islands. CARI, Port Blair.

Daniel K. Gibson-Reinemer, Brian S. Ickes, and John H. Chick. (2017). Development and assessment of a new method for combining catch per unit effort data from different fish sampling gears: multigear mean standardization (MGMS): Canadian Journal of Fisheries and Aquatic Science, 74: 8–14.

Deepthi Achuthavarier, Krishnamurthy. V, Ben P. Kirtman, Bohua Huang (2011), Role of Indian Ocean in the ENSO-Indian summer monsoon teleconnection in the NCEP Climate Forecast System, COLA Technical Report 309.

Diaz A. J and Rosenberg. R. (2008). Spreading dead zones and consequences for marine ecosystems. Science. 15; 321 (5891):926-9.

Doney, S. C., 2006. Plankton in a warmer world. Nature, 444(7120), pp.695-696.

Emori S, Taylor K, Hewitson B, Zermoglio F, Juckes M, Lautenschlager M, Stockhause M(2016). CMIP5 data provided at the IPCC Data Distribution Centre. Fact Sheet of the Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA) of the Intergovernmental Panel on Climate Change (IPCC), p.8.

FAO, 2017. FAO Global Capture Production database updated to 2015–Summary information.

Francis Marsac (2013). Outline of climate and oceanographic conditions in the Indian Ocean: an update to August 2013, IOTC–2013–WPTT15–09,p.2-5.

Fu, F. X., Warner, M. E., Zhang, Y., Feng, Y. and Hutchins, D. A., 2007. Effects of Increased temperature and CO2 on photosynthesis, growth, and elemental ratios in marine Synechococcus and Prochlorococcus (cyanobacteria) 1. Journal of Phycology, 43(3), pp.485-496.

Gary Grunseich, Bulusu Subrahmanyam, V. S. N. Murty, Benjamin S. Giese (2011). Sea surface salinity variability during the Indian Ocean Dipole and ENSO events in the tropical Indian Ocean, journal of Geophysical Research, Vol. 116, C11013, doi:10.1029/2011JC007456.

Gitay, H., Suárez, A., Watson, R. T. and Dokken, D. J., Climate change and biodiversity. IPCC Technical Paper V, 2002.

Gnanaseelan.C, M. K. Roxy, Aditi Deshpande (2017). Variability and Trends of Sea Surface Temperature and Circulation in the Indian Ocean, Springer Geology, DOI 10.1007/978-981-10-2531-0_10, p. 165-179.

Goddard, L. and Graham, N. E., 1999. Importance of the Indian Ocean for simulating rainfall anomalies over eastern and southern Africa. Journal of Geophysical Research: Atmospheres, 104(D16), pp.19099-19116.

Grinson George, Bharathiamma Meenakumari, Mini Raman, Srinivasa Kumar, Ponnumony Vethamony, Madavana Thomas Babu, Xivanand Verlecar (2012), Remotely sensed chlorophyll: a putative tropic link for explaining variability in Indian oil sardine stocks, Jourmalof Coastal Research., vol.28, p.105-113.

Guhathakurta, P., Rajeevan, M., Sikka, D. R. and Tyagi, A., 2015. Observed changes in southwest monsoon rainfall over India during 1901–2011. International Journal of Climatology, 35(8), pp.1881-1898.

Guinotte, J. M. and Fabry, V. J., Ocean acidification and its potential effects on marine ecosystems. Annals of the New York Academy of Sciences, 2008, 1134(1), 320-342.

Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M.M., Teeters, E.J., Griffis, R.B., Alexander, M.A., Scott, J.D., Alade, L., Bell, R.J. and Chute, A.S., 2016. A vulnerability assessment of fish and invertebrates to climate change on the Northeast US Continental Shelf. PloS one, 11(2), p.e0146756.

Harvell C. D., K. Kim,J. M. Burkholder, R. R. Colwell, P. R. Epstein, D. J. Grimes, E. E. Hofmann, E. K. Lipp, A. D. M. E. Osterhaus, R. M. Overstreet, J. W. Porter, G. W. Smith,G. R. Vasta. (1999). Emerging Marine Diseases—Climate Links and Anthropogenic Factors. Faculty Publications from the Harold W. Manter Laboratory of Parasitology. 580.

Hazra, S., Ghosh, T., Das Gupta, R. and Sen, G., Sea level and associated changes in the Sundarbans. Science and Culture, 2002, 68(9/12), 309-321.

Hoegh-Guldberg, O., 1999. Climate change, coral bleaching and the future of the world's coral reefs. Marine and freshwater research, 50(8), pp.839-866.

Hoegh-Guldberg, O., R. Cai, E. S. Poloczanska, P. G. Brewer, S. Sundby, K. Hilmi, V. J. Fabry, and S. Jung, 2014: The Ocean. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Barros, V. R., C. B. Field, D. J. Dokken, M. D. Mastrandrea, K. J. Mach, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. Mac Cracken, P. R. Mastrandrea, and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1655-1731.

Hossain, M. S., Chowdhury, S. R., Sharifuzzaman, S. M. and Sarker, S. (2015). Vulnerability of the Bay of Bengal to Ocean Acidification. IUCN, International Union for Conservation of Nature, Bangladesh Country Office, Dhaka, Bangladesh, Pp. 55.

Hoyer, M. V., Frazer, T. K., Notestein, S. K. and Canfield, Jr, D. E., 2002. Nutrient, chlorophyll, and water clarity relationships in Florida's nearshore coastal waters with comparisons to freshwater lakes. Canadian Journal of Fisheries and Aquatic Sciences, 59(6), pp.1024-1031.

Hu, K., Huang, G. and Huang, R., 2011. The impact of tropical Indian Ocean variability on summer surface air temperature in China. Journal of climate, 24(20), pp.5365-5377.

Hutchins, D. A., Mulholland, M. R. and Fu, F., 2009. Nutrient cycles and marine microbes in a CO_2-enriched ocean. Oceanography, 22(4), pp.128-145. .

Ibnu Fathrio, Atsuyoshi Manda, Satoshi Iizuka, Yasu-Masa Kodama, Sachinobu Ishida (2017). Evaluation of CMIP5 models on sea surface salinity in the Indian Ocean, IOP Conf. Series: Earth and Environmental Science54, 012039.

International CLIVAR project (2006). Understanding the role of the Indian Ocean in climate system- Implementation plan for sustained observations, No.100.

IPCC expert meeting report (2007). Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies. p.2-34.

IPCC, 2013: Summary for Policymakers. In: Climate Change (2013): The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014: Climate Change (2014): Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Inter-governmental Panel on Climate Change [Core Writing Team, R. K. Pachauri and L. A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Jayaprakash A. A (2002). Long term trends in rainfall, sea level and solar periodicity: A case study for forecast of Malabar sole and oil sardine fishery, J. mar. biol. Ass. India,p. 163 – 175.

Jena J K, Grinson George (2017). Climate and Climate Variability: Impact on Fisheries in Food and Nutritional Security,XIII Agricultural Science Congress,p.1-6.

Kizhakudan, S.J., 2014. Correlation between changes in sea surface temperature and fish catch along Tamil Nadu coast of India-an indication of impact of climate change on fisheries?.

Krishnakumar P. K, Bhat G. S (2008). Seasonal and interannual variations of oceanographic conditions off Mangalore coast (Karnataka, India) in the Malabar upwelling system during 1995–2004 and their influences on the pelagic fishery, Fish. Oceanography. 17:1, p.45–60.

Krishnan, P., George, G., Immanuel, T., Bitopan-Malakar, M. and Anand, A. (2013), Studies on the recovery of bleached corals in Andaman: Fishes as indicators of reef health. In Ecology and Conservation of Tropical Marine Faunal Communities, 2013, 395-407.

Krishnan.P, Grinson George, Titus Immanuel, MalakarBitopan-Malakar, Anand.A (2013). Studies on the Recovery of Bleached Corals in Andaman: Fishes as Indicator of Reef Health, Springer-Verlag Berlin Heidelberg, p. 395-407.

Kumar, V., Jain, S. K. and Singh, Y., (2010). Analysis of long-term rainfall trends in India. Hydrological Sciences Journal–Journal des Sciences Hydrologiques, 55(4), pp.484-496.

Kumari. S, Zacharia. P. U, Kripa.V, Sreenath. K. R, George Grinson (2015). Distribution pattern and community structure of zoanthids (Zoantharia) along the coast of Saurashtra, Gujarat, India. Journal of the Marine Biological Association of the United Kingdom, pp.1-8.

Lehodey, P., Alheit, J., Barange, M., Baumgartner, T., Beaugrand, G., Drinkwater, K., Fromentin, J. M., Hare, S. R., Ottersen, G., Perry, R.I. and Roy, C., 2006. Climate variability, fish, and fisheries. Journal of Climate, 19(20), pp.5009-5030.

Levy. M, Shankar. D, Andre. J. M, Shenoi. S. S. C, Durand.F, De Boyer Montegut. C (2007). Basin-wide seasonal evolution of the Indian Ocean's 3 phytoplankton blooms, journal of Geophysical Research Vol. 112,doi:10.1029/2007JC004090.

Liu Lin, Feng Lin, Yu Weidong, Wang Huiwu, Liu Yanliang, Sun Shuangwen (2013), The Distribution and Variability of Simulated Chlorophyll Concentration over the Tropical Indian Ocean from Five CMIP5 Models, J. Ocean Univ. China (Oceanic and Coastal Sea Research), p.253-259.

Lu Dong, Tianjunzhou (2014). The Indian Ocean sea surface temperature warming simulated by CMIP5 models during the twentieth century: competing forcing roles of GHGs and anthropogenic aerosols, Journal of Climate, volume 27, 3348-3361.

Malin L. Pinsky and Michael Fogarty. (2012). Lagged social-ecological responses to climate and range shifts in fisheries. Climatic Change, 115:883–891

Martin Edwards and Anthony J. Richardson. (2004). Impact of climate change on marine pelagic phenology and trophic mismatch. Nature, 430,881–884

Mathew Koll Roxy, Aditi Modi, Raghu Murtugudde, Vinu Valsala, Swapna Panickal, S. Prasanna Kumar, M. Ravichandran, Marcello Vichi, Marina Lévy (2016). A reduction in marine primary productivity driven by rapid warming over thetropical Indian Ocean,Geophys. Res. Lett., vol.43(2),p. 826-833

Mathew Koll Roxy, KapoorRitika, Pascal Terray, Sebastien Masson (2014). The Curious Case of Indian Ocean Warming, Journal of Climate, vol 27, p.08501-8509

Miranda C. Jones,William W. L. Cheung (2015) Multi-model ensemble projections of climate change effects on global marine biodiversity, ICES Journal of Marine Science, p.741–752.

Natasha Kuldeep (2015) Impact, adaptation and vulnerability of marine fisheries to climate change : a case study of Kerala. International Journal of Economic and Business Review, vol-3 issue-2, p.2.

Nobuo MIMURA (2013). Sea-level rise caused by climate change and its implications for society, Proceedings of Japanese Academy., Ser. B 89, p. 281-301.

Nye, J. A., Link, J. S., Hare, J. A. and Overholtz, W. J., Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf. Marine Ecology Progress Series, 2009, 393, 111-129.

Osovitz, C. J. and Hofmann, G. E., 2007. Marine macrophysiology: studying physiological variation across large spatial scales in marine systems. Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology, 147(4), pp.821-827.

Ottersen, G., Planque, B., Belgrano, A., Post, E., Reid, P. C. and Stenseth, N. C. 2001, Ecological effects of the North Atlantic oscillation. Oecologia, , 128(1), 1-14.

Perry, A. L., Low, P. J., Ellis, J. R. and Reynolds, J. D., Climate change and distribution shifts in marine fishes. Science, (2005), 308, 1912-1915.

Piyali Chowdhury, Manasa Ranjan Behera (2015). A study on regional sea level variation along the Indian coast, 8 th International Conference on Asian and Pacific Coasts (APAC), p. 1078 – 1084.

Plisnier, P., Serneels, S., and Lambin, E. (2000). Impact of ENSO on east African ecosystems: a multivariate analysis based on climate and remote sensing data. Global Ecology and Biogeography, 9, 481–497.

Pörtner, H. 2001, Climate change and temperature-dependent biogeography: oxygen limitation of thermal tolerance in animals. The science of nature, 88, 137-146.

Pörtner, H. O. (2010). Oxygen and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. Journal of Experimental Biology, 213: 881–893.

Pörtner, H.-O., D. M. Karl, P. W. Boyd, W. W. L. Cheung, S. E. Lluch-Cota, Y. Nojiri, D. N. Schmidt, and P. O. Zavialov, (2014): Ocean systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C. B., V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, and L. L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411-484.

Prakash Chandra Mohanty, Ranganalli Somashekharappa Mahendra, Hrusikesh Bisoyi, Srinivasa Kumar Tummula, George Grinson, Shailesh Nayak, Bijaya Kumar Sahu (2013). Assessment of the coral bleaching during 2005 to decipher the thermal stress in the coral environs of the Andaman Islands using Remote Sensing, European Journal of Remote Sensing, 46: p.417-430.

Pratchett, M.S., Caballes, C.F., Wilmes, J.C., Matthews, S., Mellin, C., Sweatman, H., Nadler, L.E., Brodie, J., Thompson, C.A., Hoey, J. and Bos, A.R., 2017. Thirty years of research on crown-of-thorns starfish (1986–2016): scientific advances and emerging opportunities. Diversity, 9(4), p.41.

Pravat Jena, Sarita Azad, Madhavan Nair Rajeevan (2016). CMIP5 Projected Changes in the Annual Cycle of Indian Monsoon Rainfall, Climate, 4.14.

Bhadury, P (2015). Effects of ocean acidification on marine invertebrates -a review, Indian journal of Geo-Marine Sciences, vol. 44 p.454-464.

Qasim, S. Z. (1973). An appraisal of the studies on maturation and spawning in marine teleosts from the Indian waters. Indian Journal of Fisheries, 20, 166 -181.

Rajiv Kumar Chaturvedi, Jaideep Joshi, Mathangi Jayaraman, G. Bala, N. H. Ravindranath (2012). Multi-model climate change projections for India under representative concentration pathways, Current Science, vol-103, no- 7, p.3-12.

Rao P. and Vivekanandan, E. 2008, Impact of climate change on Indian marine fisheries. Bay of Bengal News, 2008, 33.

Rao, G. S. (2011), Climate Change and Marine Fisheries Management,.

Rashid T, Hoque S, Akter F (2013) Ocean Acidification in the Bay of Bengal, scientificreport,.2: 699 doi:10.4172/scientific reports. 699.

Reid, P. C., de Fatima Borges, M. and Svendsen, E. 2001, A regime shift in the North Sea circa 1988 linked to changes in the North Sea horse mackerel fishery. Fisheries Research, 2001, 50(1), 163-171.

Reid, P. C., Johns, D. G., Edwards, M., Starr, M., Poulin, M. and Snoeijs, P. (2007). A biological consequence of reducing Arctic sea ice cover: arrival of the Pacific diatom Neodenticula taseminae in the North Atlantic for the first time in 800,000 years. Global Change Biology, 13: 1910-1921.

Riebesell, U., Schulz, K. G., Bellerby, R. G.J., Botros, M., Fritsche, P., Meyerhöfer, M., Neill, C., Nondal, G., Oschlies, A., Wohlers, J. and Zöllner, E., 2007. Enhanced biological carbon consumption in a high CO 2 ocean. Nature, 450(7169), pp.545-548.

Roxy, M. K., Modi, A., Murtugudde, R., Valsala, V., Panickal, S., Prasanna Kumar, S., Ravichandran, M., Vichi, M. and Lévy, M., (2016). A reduction in marine primary productivity driven by rapid warming over the tropical Indian Ocean. Geophysical Research Letters, 43(2), pp.826-833.

Sagnik Dey, Ramesh P. Singh (2003). Comparison of chlorophyll distributions in the northeastern Arabian Sea and southern Bay of Bengal using IRS-P4 Ocean Color Monitor data, Remote Sensing of Environment 85. p. 424–428.

Secretariat of the Convention on Biological Diversity (2014). An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity (Eds: S. Hennige, J. M. Roberts & P. Williamson). Montreal, Technical Series No. 75, 99 pages.

Shah, M., Chaturvedi, N. and Pandya, H., (2017). Climate change and biological productivity: Indian Ocean. Indian Journal of Marine Geosciences, 46, 480-484.

Sharad K. Jain, Vijay Kumar (2012) Trend analysis of rainfall and temperature data for India, Current Science, vol-102, no-1, p.2-13.

Shelley McGuire, FAO, IFAD, and WFP. The State of Food Insecurity in the World 2015: Meeting the 2015 International Hunger Targets: Taking Stock of Uneven Progress. Rome: FAO, 2015, Advances in Nutrition, Volume 6, Issue 5, September 2015, Pages 623–624.

Shyam, S. S. and Manjusha, U., Climate change impacts: Implications on marine resources and resource users, 2015.

Singh R P, Chaturvedi P (2010). Comparison of chlorophyll concentration in Bay of Bengal and Arabian Sea using IRS-P4 OCM and MODIS Aqua, Indian Journal of Marine Sciences, 39(3), pp334-340.

Solanki, H. U., Dwivedi, R. M., Nayak, S., Gulati, D. K., John, M. E. and Somvanshi, V. S. (2003). Potential Fishing Zones (PFZ) Forecast Using Satellite Data Derived Biological and Physical Processes; Journal of the Indian Society of Remote Sensing 31 2. 10.1007/BF03030773.

Suárez, J., W. Ritter, C. Gay & J. Torres (2004):"ENSO-Tuna Relations in the Eastern Pacific Ocean and its Prediction as a Non-Linear Dynamic System". Atmosfera, pp.245-258.

Supraba, V., Dineshbabu, A. P., Thomas, S., Rohit, P., Rajesh, K. M. and Zacharia, P. U. (2016), Shift in diet composition of Indian mackerel Rastrelliger kanagurta-an analysis in relation to climate change. Indian Journal of Fisheries, 2016, 63(2), 42-46.

Takahiro Iida, Tsuneo Odate (2014). Seasonal variability of phytoplankton biomass and composition in the major water masses of the Indian Ocean sector of the Southern Ocean, Polar Science 8, p. 283-297.

Tsukamoto, K., Kawamura, T., Takeuchi, T., Beard Jr, T. D. and Kaiser, M. J. (2008), Effects of Climate Change on Marine Ecosystems. Fisheries for Global Welfare and Environment, 2008, 307.

Unnikrishnan A. S, Nidheesh A. G, Lengaigne. M (2015), Sea-level-rise trends off the Indian coasts during the last two decades, Current Science Vol. 108, no. 970 5

Unnikrishnan A. S., K. Rupa Kumar, Sharon E. Fernandes, G. S. Michael and S. K. Patwardhan Current Science Vol. 90, No. 3 (10 February 2006), pp. 362-368

Unnikrishnan, A. S. and Shankar, D., 2007. Are sea-level-rise trends along the coasts of the north Indian Ocean consistent with global estimates?. Global and Planetary Change, 57(3-4), pp.301-307.

Vinay, A., Ramasubramanian, V., Krishnan, M., Kumar, N.R. and Ayoob, A.E., 2017. Economic analysis of tuna pole and line fisheries in Lakshadweep. Indian Journal of Geo-Marine Sciences. 46. 947-957

Vivekanandan E, Jeyabaskaran R (2010). Impact and adaptation options for Indian marine fisheries to climate change, Scientific Publishers, p.3-12.

Vivekanandan, E (2010) Impact of Climate Change in the Indian Marine Fisheries and the Potential Adaptation Options. In: Coastal Fishery Resources of India–Conservation and sustainable utilisation. Society of Fisheries Technologists, pp. 169-185.

Vivekanandan, E, Srinath, M and Kuriakose, Somy. (2005). Fishing the Marine Food Web along the Indian Coast. Fisheries Research. 72. 241-252.

Vivekanandan, E., Hussain Ali, M. and Rajagopalan, M. (2009), Vulnerability of corals to seawater warming, 2009.

Vivekanandan, E., Impact of Climate Change in the Indian Marine Fisheries and the Potential Adaptation Options, 2010.

Vivekanandan, E., Rajagoparan, M., Pillai, N. G. K. (2009a). Recent trends in sea surface temperature and its impact on oil sardine, Central Marine Fisheries Research Institute,Kochi,p.1-3.

Walther, G. R., Post, E., Convey, P. and Menzel, A. (2002), Ecological responses to recent climate change. Nature. 2002, 416, 389.

Warren, R, Price, J, Fischlin A, de la Nava Santos, S, Midgley G, Increasing impacts of climate change upon ecosystems with increasing global mean temperature rise. Climatic Change, 2011, 106, 141-177.

Wayne G. P (2013). The beginner's guide to Representative Concentration Pathways, Skeptical science, version 1.0,p.1-24

Weiqing Han, Gerald A. Meehl, Balaji Rajagopalan, John T. Fasullo, Aixue Hu, Jialin Lin, William G. Large, Jih-wang Wang, Xiao-Wei Quan, Laurie L. Trenary, Alan Wallcraft, Toshiaki Shinoda6 and Stephen Yeager (2010), Patterns of Indian Ocean sea-level change in a warming climate, Nature geoscience, Vol. 3

Xue L, Yu.W, Wang.H, Jiang.L. Q, Feng. L, Gao. L, Li.K, Li. Z, Wei. Q, Ning. C (2014). Temporal changes in surface partial pressure of carbon dioxide and carbonate saturation state in the eastern equatorial Indian Ocean during the 1962–2012 period, Biogeosciences, 11, p. 6293-6305.

Yan DU, Yuhong Zhang (2015). Satellite and Argo Observed Surface Salinity Variations in the Tropical Indian Ocean and Their Association with the Indian Ocean Dipole Mode, JOURNAL OF CLIMATE, vol 28. p.695-713.

Yang Yali, Du Yan, Zhang Yuhong, Cheng Xuhu (2013). Recent Changes of Northern Indian Ocean Summer Rainfall Based on CMIP5 Multi-Model, J. Ocean Univ. China (Oceanic and Coastal Sea Research), p.201-208.

Yoo, S. H., S. Yang, C.-H. Ho (2006), Variability of the Indian Ocean sea surface temperature and its impacts on Asian-Australian monsoon climate, J. Geophys. Res., 111, D03108, doi: 10.1029/ 2005JD006001.

Yuhong Zhang,Yan Du Tangdong Qu (2016). A sea surface salinity dipole mode in the tropical Indian Ocean, ClimDyn, DOI 10.1007/s00382-016-2984-z, p,1-13.

Zacharia P. U, A. Gopalakrishnan, K. K. Vijayan, M. Muralidhar, Grinson George (2016). Climate change impact on coastal fisheries and aquaculture in the SAARC region: Country paper – India, p.1-21.

Zacharia P. U, A. P. Dineshbabu, Sujitha Thomas, Shoba Joe Kizhakudan, E. Vivekanandan S. Lakshmi Pillai, M. Sivadas, Shubhadeep Ghosh, U. Ganga, K. M. Rajesh, Rekha J. Nair T. M. Najmudeen, Mohammed Koya, Anulekshmi Chellappan, Gyanranjan Dash Indira Divipala, K. V. Akhilesh, M. Muktha, Swathipriyanka Sen Dash (2016). Relative Vulnerability Assessment of Indian Marine Fishes to Climate Change: Using Impact and Adaptation Strategies, Central Marine Fisheries Research Institute, Cochin, India, CMFRI Special Publication No.125 : 10-42.

Zacharia P. U. and Jayabalan N. (2010). Age and growth of Lactarius lactarius (Bloch & Schneider, 1801) from Karnataka, south-west coast of India. Indian Journal of Fisheries., 57 (4): 31-38.

Zhao. Y, Zhang. H (2016). Impacts of SST Warming in tropical Indian Ocean on CMIP5 model-projected summer rainfall changes over Central Asia, ClimDyn, doi:10.1007/s00382-015-2765-0, 46: p.3223–3238.

Zhenhua Ma, Nan Zhang, Jian G. Qin, Mingjun Fu and Shigui Jiang (2016) Water temperature induces jaw deformity and bone morphogenetic proteins (BMPs) gene expression in golden pompano Trachinotus ovatus larvae, Springer Plus,p.1-12.

0972-2351

Impact, Vulnerability and Adaptation Strategies for **Marine Fisheries of India**

This publication is the report of the work carried out under the project **Impact, Vulnerability and Adaptation Strategies for Marine Fisheries of India** awarded to ICAR-CMFRI by the Ministry of Environment, Forest and Climate Change of the Government of India in December 2016. The UNFCC with the support of UNDP-GEF has undertaken Initial National Communication (INC) & Second National Communication (SNC) and this report is towards preparation of India's third national communication (TNC). The report contains information on improved climate change projections, impact assessment in the marine fisheries sector of India using the latest scientific models and methods, development of vulnerability profiles at decentralized level, assessment of adaptation options and development of strategy for mainstreaming adaptation.

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