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Effects of climate change and management policies on marine fisheries productivity in the north-east coast of India

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Keywords

Climate change; West Bengal; Odisha; Primary production; Hilsa; Fisheries management; Biogeochemical modelling.

Abstract

The Indian Bengal Delta and the Mahanadi delta are two important deltaic systems of the north-east coast of India that support about 1.25 million people. In this study, the change in potential marine fish production and socio-economic conditions were modelled for these two deltas under long-term changes in environmental conditions (sea surface temperature and primary production) to the end of the 21st century. Our results show that an increased temperature has a negative impact on fisheries productivity, which was projected to decrease by 5%. At the species level, Bombay duck, Indian mackerel and threadfin bream showed an increasing trend in the biomass of potential catches under a sustainable fishing scenario. However, under the business as usual and overfishing scenarios, our results suggest reduced catch for both states. On the other hand, mackerel tuna, Indian oil sardine, and hilsa fisheries showed a projected reduction in potential catch also for the sustainable fishing scenario. The socio-economic models projected an increase of up to 0.67% (involving 0.8 billion USD) in consumption by 2050 even under the best management scenario. The GDP per capita was projected to face a loss of 1.7 billion USD by 2050. The loss of low-cost fisheries would negatively impact the poorer coastal population since they strongly depend upon these fisheries as a source of protein. Nevertheless, adaptation strategies tend to have a negative correlation with poverty and food insecurity which needs to be addressed separately to make the sector-specific effort effective. This study highlights the need to have improved management plans for fisheries resources that can help to mitigate and adapt to future climate change impacts.

1. Introduction

Climate change is now identified as a global issue impacting the Earth with variable magnitude. According to the 5th assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2014a), human activity is continually affecting the Earth's energy budget by changing the concentration of radiatively important gases, aerosols, and land surface properties. The report suggests that the atmospheric concentration of greenhouse gases (i.e. CO_2, CH_4, N_2O) along with land and sea surface temperature has increased significantly during the last 200 years. Deltaic regions with prevalent household poverty are particularly vulnerable to environmental changes, climate change and natural hazards causing loss of life and property (Szabo et al. 2015; Tessler et al. 2015). With a densely populated, low-lying coastline around 7500 km long, India is one of the most vulnerable countries in the Asia-Pacific region, ranking 4th and 6th with respect to physical exposure to storms and GDP loss (IPCC, 2014b). The Indian Bengal Delta (IBD), and the Mahanadi delta (situated in the coastal states of West Bengal and Odisha respectively) are two important deltaic systems of the north-east coast of the country. According to the Food and Agriculture Organization (FAO), global human population is expected to reach more than 9 billion by the middle of the 21st century (FAO, 2018), of which India's relative share at present is 17.5% (Census, 2011). In the face of climate change, food supply to this massive population is going to be an enormous task (FAO, 2018).

Globally, fisheries and aquaculture have an important role as a source of animal protein by providing about 3.2 billion people with 20% of their average per capita animal protein intake (FAO, 2018, Hicks et al., 2019). Hence, the impact of climate change on marine fishery resources has emerged as a major global concern (Barange et al., 2018). In India over 14.5 million people depend on fisheries activities, making this sector a pillar for the country's economy and livelihood security (FAO, 2015). The average fish consumption between 2013 and 2015 in the country was 5-10 kg per year per capita (FAO, 2018). Furthermore, the exports of seafood constitute more than 70% of the total food exports from India, representing close to 3 billion USD (GoI, 2014; MPEDA, 2008). This notable importance of fisheries in the whole of India is particularly marked in the two deltaic regions: the Indian Bengal Delta (IBD) and the Mahanadi delta (situated in the coastal states of West Bengal and Odisha respectively). According to the Department of Animal Husbandry, Dairying, and Fisheries, West Bengal ranked 2nd of all Indian States with around

1.6 million tonnes of fish production in 2013-2014 (around 16.5% of all Indian fish production) (GoI, 2014). On the other hand, Odisha ranked 10th with around 0.4 million tonnes in 2013-2014 (around 4.3% of all fish production) (GoI, 2014). Furthermore, in West Bengal fish products were consumed at a rate of about 0.8-1.1 kg per capita per month, double the quantity of around 0.42-0.44 kg per capita per month in Odisha (GoI, 2014) suggesting a significant regional variation. Rural areas are highly dependent on fisheries in terms of catch (production) and income from high valued species while they depend on the production of less valued species for food. By contrast, the demand for high valued species is more in urban centers (GoI, 2014). Fisheries activities represent about 4.1% of the total Gross Domestic Product (GDP) in the IBD, West Bengal and 2.6% in Mahanadi delta (Odisha) (Cazcarro et al., 2018), which accounts for about 220 million USD and 1556 million USD respectively (PCA, 2011). According to the Census 2011 (PCA, 2011), fishing (hunting and allied activities included) involved more than 80 thousand full-time workers in the Mahanadi delta (89% of them male), and 124 thousand full-time workers in the IBD delta (78% of them male), representing about 5% of total employment in each delta. West Bengal ranked as the 4th state (out of the 29 States and 7 Union territories) with the highest number of households (879 per 1000 rural and 844 in urban environments) reporting consumption of fish and prawn (GoI, 2014).

Considering the key importance of fisheries in the socio-economy of the two deltaic regions, quantification of the future impact of climate change on the fishery resources is a major concern for scientists. Climate change is projected to reduce marine productivity (Bopp et al., 2001 and Perry et al., 2005), and also influence the distribution patterns of species depending on the predator requirements and resource availability (Durant et al, 2007). While some studies have shown that increasing temperature and nutrients influence the growth of marine algae favoring only some species (Jasper et al. 2009), the effect of climate change can have negative impacts on fish species through bottom-up processes (Stephen 2008).

In addition, some species have shown changes in distribution patterns as a response to the increase of water temperature, for example the Indian mackerel (*Rastrelliger kanagurta*) was reported to extend its northern boundaries and to descend to deeper waters in response to changes in climatic conditions (CMFRI, 2008; Vivekanandan et al., 2010). The increased catches of oil sardine (*Sardinella longiceps*) since 1990 could also be attributed to more suitable habitat conditions probably because of increased sea surface temperature (Vivekanandan et al. 2009). However, these studies look only at historical changes without considering potential future climate scenarios (Parry et al., 2007). Therefore it is key for management policies to be informed of possible changes that could occur at the ecosystem level. Five probable shared socioeconomic pathways (SSPs) were developed by IPCC to examine how global society, demographics, and economics might change over the next century in various scenarios of climate policies or climate change (O'Neill et al., 2014).

In this work, we model the changes in total marine productivity under climate change scenarios and potential changes in catches of key commercially important species in the two regions (West Bengal and Odisha), considering management scenarios as a climate change adaptation measures. The major marine fish species considered for the present study were mackerel tuna (*Euthynnus affinis*), Indian mackerel (*Rastrelliger kanagurta*), Bombay duck (*Harpodon nehereus*), Indian oil sardine (*Sardinella longiceps*), hilsa (*Tenualosa ilisha*), and threadfin bream (*Nemipterus japonicas*, *N. mesoprion*). Hilsa (487 USD/tonne) is the most important marine fish species in West Bengal as well as in Odisha, owing to its high socio-economic value (Bladon et al., 2016). During the last decade, annual catches of hilsa have shown a decreasing trend both for West Bengal and Odisha (Fig. 1a and Fig. 1b) largely because of overfishing (Dutta et al., 2012; Das et al., 2018a). Mackerel tuna (1,217 USD/tonne) is another commercially valuable fish species for these two states. A major portion of the mackerel tuna catch is exported internationally as well as to other states of India. Indian mackerel (~2.9% of the total average annual fish catch and 183 USD/ tonne in 2010), Indian oil sardine (~4.5% of the total average annual fish catch and 83 USD/ tonne) and threadfin bream (989 USD/ tonnes) are non-target species forming the by-catch of the fishery. Bombay duck (179 USD/ tonne) is mostly used in the dry fish industry and is also a favorite food item in eastern Bengal. During the last five years (from 2011 to 2015), the quantity of dried items exported from West Bengal has increased by 53% (DoF, W.B., 2016). These low-cost fish species have a significant impact on the socio-economy of the poorest coastal population of the two states, as they are highly dependent on these species (Beveridge et al., 2013; Belton and Thilsted, 2014; Thilsted et al., 2016).

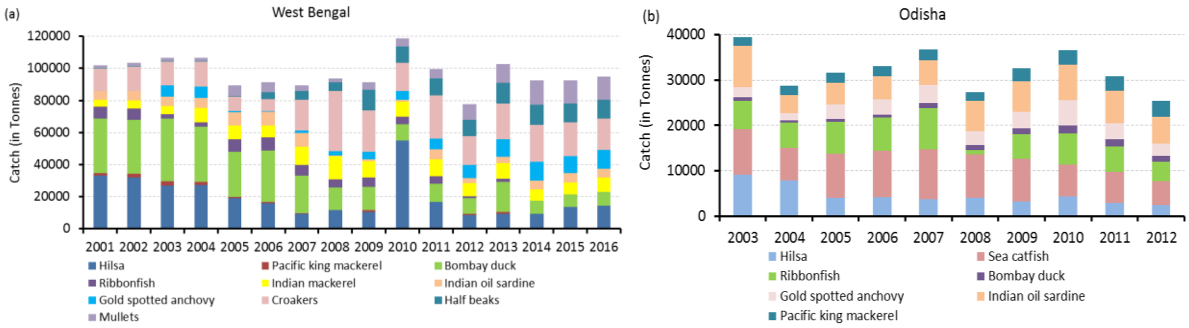

Fig. 1. Annual catch of a few selected marine fish species for West Bengal (a) and Odisha (b).

Under the current scenario of climate change, the human population will rise along with a decline in marine ecosystem productivity, consequently it is likely that the demand for marine fish is going to be higher than ever before (Delgado et al. 2003). Despite aquaculture is developing faster fish production derived from it does not seem to be enough to meet the current and future demand of the coastal population (FAO, 2018). In addition the future impact of climate change on the aquaculture sector is still unknown (Belton et al., 2014). Because of the importance of fish production for the survival of populations that live in deltaic regions it is necessary to have long-lasting fisheries management plans that also account for possible impacts of climate change. In the present study, the cumulative effect of physical, biological and ecological changes due to climate change was quantified to explore its impact on marine fish production and related socio-economy of West Bengal and Odisha by 2050.

2. Materials and Methods

2.1 Study area

The Bengal delta is the Indian part of the Ganga-Brahmaputra-Meghna (GBM) delta system which spans across five countries including India and Bangladesh. The Bengal Delta (IBD) is comprised of two maritime districts of West Bengal, i.e. North 24 Parganas and South 24 Parganas, encompassing an area of 14,054 km^{2}with a population of 18.2 million (Census, 2011). With a coastline of 158 km (1.9% of the total coastal length of India), West Bengal has a continental shelf area of 17,049 km^2 (DoF, 2016). The West Bengal deltaic coastal region (the Hugli estuary) is a well-mixed, meso-macrotidal region (tidal range 2.5-6.5 m) with current velocities ranging between 117 to 108 cm s^{-1} during low and high tide respectively (De et al., 2011). This region is characterised by very shallow waters <24 m depth even at distance of 60 km from the shoreline (Akhand et al., 2013) and is subjected to intense rainfall events of around 2000 mm with the maximum rainfall occurring during the south-west monsoon (70-80% of the total rainfall) (Mukhopadhyay et al., 2006).

The Mahanadi delta is comprised of five districts of Odisha, *viz.* Bhadrak, Kendrapara, Jagatsinghpur, Puri, and Khordha, within 5 meters elevation from the sea level, covering an area of 95,000 km^2. This area has a population of 8.03 million people (Census, 2011). The coastline of the delta stretches for 200 km (2.5% of the total coastal length of India) with a shelf area of 24000 km^2 (DoES, Odisha, 2016). It is a partially mixed coastal plain estuary with a semidiurnal tide (Panda et al., 2013). The Mahanadi River basin is a rain-fed system which undergoes large seasonal fluctuations in river runoff. Like the Hugli estuary, the maximum rainfall in the Mahanadi delta occurs during the south-west monsoon. Average annual rainfall in this region is 1572 mm, 70% of which occurs between June and October (CSE, 2003).

Though the fishing area of Odisha is larger than that of West Bengal, annual marine catches of Odisha are consistently lower over the last decade (Fig. 2) (DoF, W.B., 2016, and DoES, Odisha, 2016). In West Bengal, around 0.38 million people are dependent on the marine fisheries sector for their livelihood (DoF, W.B., 2016). Mechanization of boats was introduced in West Bengal during the 1950s but became popular only during 1970s (BOBP, 1990). With increased mechanization, the marine fish catch of West Bengal increased significantly between 1981-1982 (0.028 million tonnes) and 2015-2016 (0.173 million tonnes). However, through the last 15 years (from 2002-2003 to 2016-2017) the number of licensed boats increased by a factor of 6.8 but the annual marine fish catch did not increase much (DoF, W.B., 2016). In Odisha, the number of people dependent on the marine fishery sector is 0.87 million (DoES, Odisha, 2016). Mechanization of fishing boats increased during the 1980s and its impact on the marine fish catch of Odisha was observed from 1984 onwards. During the time span of 55 years (from 1950 to 2005), the marine catch of Odisha increased from 5080 tonnes to 104,000 tonnes, while the number of boats increased by a factor of 6.8 (Bhathal, 2014). Gillnets and set Bagnets are the major fishing gear used in Odisha and West Bengal. Along with that, trawl nets are also very popular especially for fishing in continental shelf areas. Drift gillnets and boat seines are used mainly for hilsa fishing. Mesh size ranges from 17-125 mm for hilsa. Set bagnet, purse seines, long liners, dol nets, etc. are also used targeting catfish, king mackerel, mackerel tuna, sardines, Indian mackerel (BOBP, 1990).

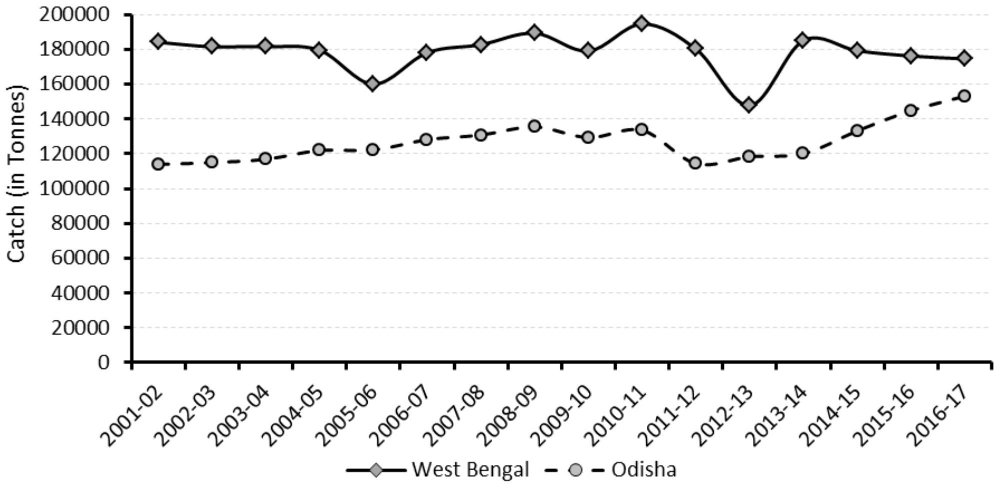

Fig. 2. Total annual marine catch trend of the two states from 2001 to 2016 indicating lower annual catch of Odisha than West Bengal.

2.2 Climate scenarios and biogeochemical models

Future marine fish production for West Bengal and Odisha were simulated by downscaling three of the Global Climate Models (GCMs) used in the Coupled Model Inter-comparison Project phase 5 (CMIP5) (Taylor et al., 2012) of the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC, 2013). The CMIP5 GCMs were dynamically downscaled to finer resolution using Regional Climate Model (RCM) simulations. The GCMs chosen for the study were CNRM-CM5 (i.e. small increase in precipitation, relatively small increase in temperature), GFDL-CM3 (i.e. moderate-large increase in precipitation, a moderate increase in temperature) and HadGEM2-ES (i.e. large increase in precipitation, a large increase in temperature). In all cases the high carbon concentration scenario Representative Concentration Pathway (RCP) 8.5 was used, to provide a strong climate signal.

Downscaling of the climate projections of the marine environment was carried out using the hydrodynamic model POLCOMS coupled to the biogeochemical/ecosystem model ERSEM. The Proudman Oceanographic Laboratory Coastal Ocean Model (POLCOMS, Holt and James, 2001), is a three-dimensional baroclinic model suitable for simulating physical processes in both shelf seas and deep water areas. It was run for the whole Bay of Bengal from the coast to 200 km out from the shelf break (Fig. 3); the horizontal resolution was 0.1° in latitude and longitude and the model had 40 vertical levels distributed on a hybrid z-sigma scheme. ERSEM, the European Regional Seas Ecosystem Model (Butenschön et al, 2016), tracks the processes and biogeochemical transfers of the lower trophic level ecosystem. It includes four functional types of phytoplankton, three of zooplankton and one group of bacteria. Carbon, nitrogen, phosphorus, silicate, and chlorophyll are tracked separately, with no assumption about stoichiometric ratios. Temperature, salinity and current speeds are provided by POLCOMS, and ERSEM runs within every cell of the POLCOMS grid every 10 minutes.

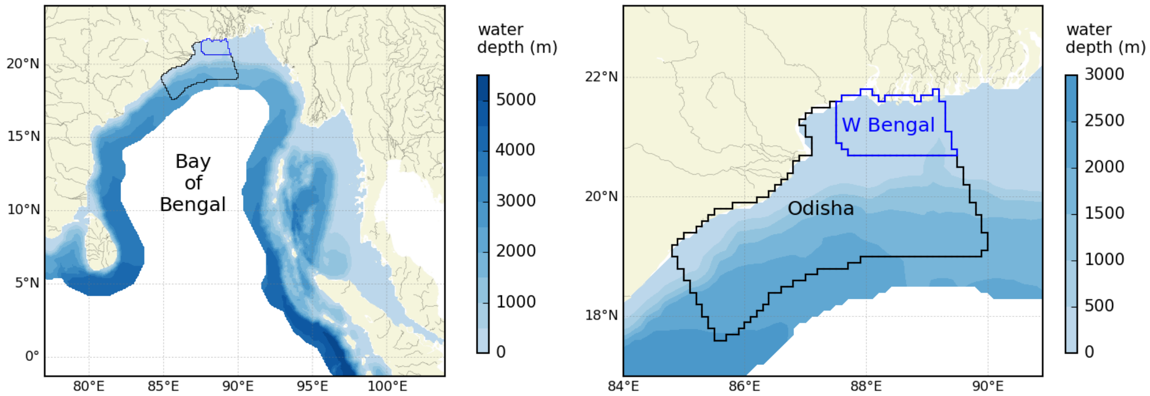

Fig. 3. (a) The Bay of Bengal, showing the modelled area in blue. (b) Part of (a) enlarged to show the Odisha and West Bengal analysis regions. The colour shading shows the bathymetry.

External forcing at the sea surface, the open ocean boundary and river mouths were derived from the three climate models listed above. Physical conditions at the atmospheric boundary were taken from regionally downscaled versions of the global models (Janes et al., 2019); physical and biogeochemical conditions at the open ocean boundary came from the global models, and freshwater run-off, nitrate, and phosphate for the GBM and Mahanadi were taken from a hydrological model run using the same regionally-downscaled climate models (Jin et al., 2018; Whitehead et al., 2018).

The coupled model produced daily and monthly outputs of temperature, salinity, current speeds, primary production, phytoplankton and zooplankton biomass pH and oxygen at 0.1° resolution. These were aggregated to 0.5° cells to give inputs for the DBEM model described in the next section and to the regions shown in Fig. 3 to give inputs for the dynamic marine ecosystem model.

2.3 Fisheries Models

Firstly, a dynamic marine ecosystem model was run using the outputs of the POLCOMS-ERSEM model. The dynamic marine ecosystem model includes the food web interactions which link primary production to fish production through predation. The model can project the climate-driven changes in potential fish production by size class, taking into account the effect of temperature on the feeding and mortality rates (Blanchard et al. 2012). This size-based method does not include the effect of species' ecology and reflects the food web properties including the energy flux and production for a particular size group (Barange et al. 2014).

Secondly, a Dynamic Bioclimate Envelope Model (DBEM) was used to project the distribution and abundance of the selected marine fish species. The DBEM includes species interactions based on size-spectrum (SS) theory and habitat suitability (SS-DBEM, Fernandes et al. 2013). The SS-DBEM, a mechanistic-statistical approach, has been applied to a large number of marine fish species globally (Cheung et al., 2008; Fernandes et al., 2013; Mullon et al., 2016) as well as at regional level (Jones et al. 2013; Fernandes et al., 2015; Fernandes et al., 2017). The distributional range for the selected fish species was first mapped in the Sea Around Us project (Close et al. 2006). Using the model-inferred environmental preference profile, the suitability of each species was defined for the environmental conditions (Cheung et al., 2008). The SS-DBEM projected the future distribution pattern, biomass and potential catch for the selected fish species by combining the ocean dynamics with mortality, growth and dispersal process (Cheung et al 2008, 2009, 2011, 2016a). Using the SS-DBEM, climate change and fishing scenarios were used to explore the potential change in total productivity of West Bengal and Odisha Exclusive Economic Zones (EEZ) for the six targeted marine fish species.

2.4 Fishing scenarios

The fisheries scenarios considered in this study were based on the ecosystem carrying capacity of the West Bengal and Odisha EEZs. The scenarios aimed to provide trends of fish catch potential by size class at the species level. The fishing pressure in relation to maximum sustainable yield (MSY) was considered while constructing the scenarios. MSY is defined as the highest average theoretical equilibrium catch that can be continuously taken from a stock under average environmental conditions (Hilborn & Walters, 1992). Based on a simple logistic population growth function and under equilibrium conditions, MSY can be defined as:

$MSY = B_\infty * intR /4$

where intR is the intrinsic rate of population increase and B_∞ is the biomass at carrying capacity (Schaefer, 1954; Sparre and Venema, 1992). In our application, the intR values are calculated based on natural mortality (Pauly 1980; Cheung et al., 2008). This is an approximation and not as reliable as estimates of biomass using survey-based methods (McAllister et al. 2001; Pauly et al., 2013). However, these estimates have proven to be significantly correlated with those from aggregated stock assessments (Froese et al., 2012; Fernandes et al., 2013).

Fishing mortality (Fm) scenarios were defined by comparing Fm estimates from the literature with the modelled fishing mortality associated with MSY. Three fishing scenarios were considered for this present study (Kebede et al., 2018);

i) Sustainable scenario (MSY): Fishing mortality consistent with the respective F_{MSY} (sustainable fishing mortality rate) which would cause maximum production without affecting the population dynamics and species recruitment.

ii) Business as usual scenario (2MSY): Fishing mortality was set considering the recent mortality rates for the selected fish species.

iii) Overfishing scenario (3MSY): This scenario depicts a situation where regulatory management is not constraining the fishing practice.

2.5 Economic Model

A dynamic Computable General Equilibrium (CGE) model was adapted to translate physical outputs from the fisheries modelling into economic values. The economics of the two study areas were presented using the Delta-CGE model of the IBD and the Delta-CGE of the Mahanadi (Arto et al., 2019, Cazcarro et al., 2018). In the base year, the models replicated the flows of money, goods, and services between the different agents in the economies of the deltas and their relationship with the rest of the country; these were obtained from a Social Accounting Matrix which constituted the core data of the model (Arto et al., 2018, 2019). In this study, the Delta-CGE models were used to simulate how the economy of the deltas might react to the impacts of climate change under different scenarios. More specifically, the Delta-CGE models translated the outputs from the fisheries models into some key socioeconomic indicators such as employment, prices, production, income or consumption. In the present simulation, the changes in the aggregate private consumption (i.e. the sum of the consumption of all goods and services by all households) was used as a proxy of the changes in economic welfare.

A set of scenarios characterizing the future socio-economic conditions of the deltas until 2050 were constructed as also done in the fisheries sector. The baseline scenario used in the present study was based on the Shared Socioeconomic Pathway number 2 (SSP2) of the IPCC scenario framework (O’Neill et al., 2014; Riahi et al., 2017) and adapted to the particularities of the case study areas (Arto et al., 2018). This baseline scenario defined the future trends of different variables such as population, labor force, Gross Domestic Product (GDP), economic structure, etc. and assumed that there were no changes in fisheries yields. The economic impact was simulated using the changes in potential productivity, the baseline socio-economic scenario and the climatic scenarios already described in the introduction.

3. Results

3.1 Climate scenarios and biogeochemical models

Projections of change in bottom and surface temperature for the Bay of Bengal off the West Bengal and Odisha coast showed a steady increasing trend from 1970 to 2098. The sea surface temperatures were projected to increase by 3-4°C for both West Bengal and Odisha at the end of the 21st century (Fig. 4). However, the predicted increase in bottom temperatures was lower for Odisha (by 0.7°C) than West Bengal (by 2.2°C) (Fig. 4) because the Odisha EEZ includes much deeper water which is less influenced by surface conditions (Fig. 3). All three climatic scenarios predicted an increase in sea surface temperature (SST) throughout the study period in these two regions (Table 1 and Fig. 5).

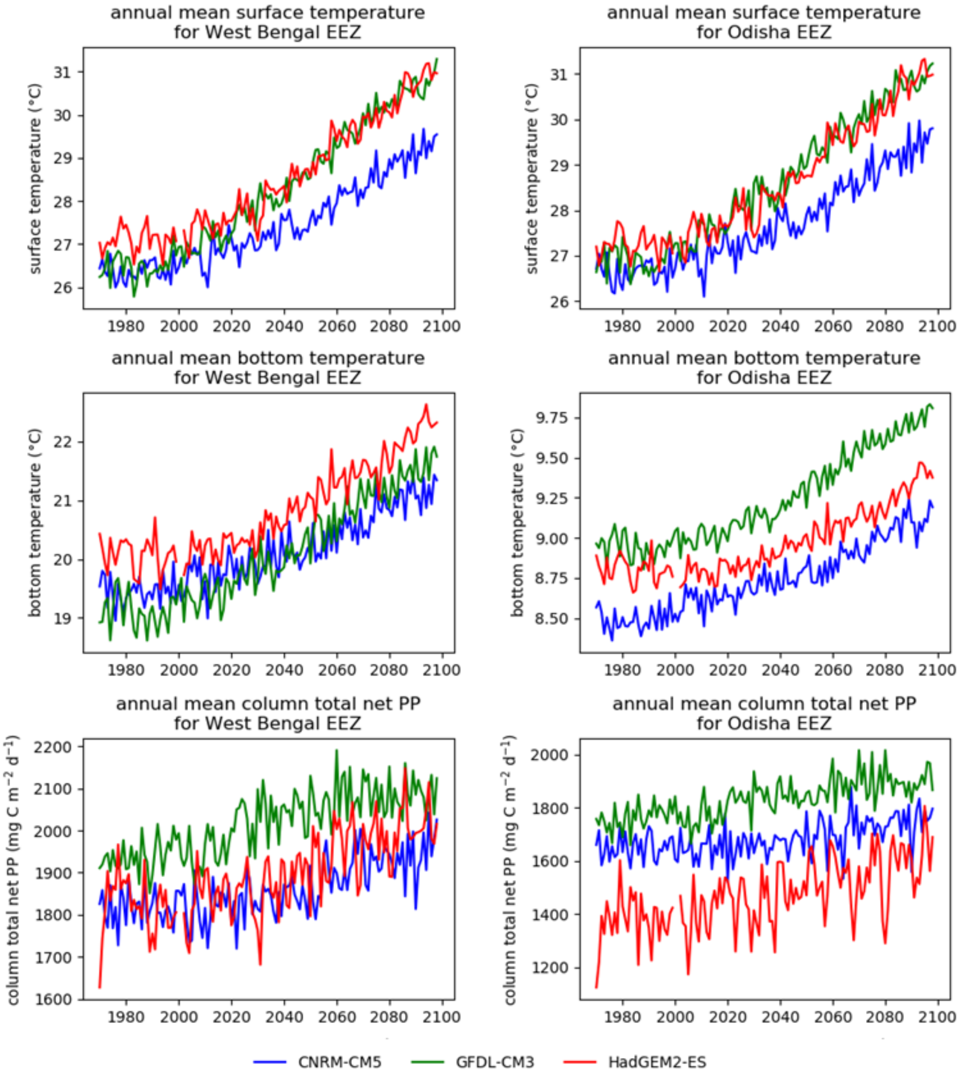

Fig. 4. Projected annual mean sea surface and bottom temperature, and mean column net primary productivity for West Bengal and Odisha.

The projections of change in net primary productivity (PP) for West Bengal and Odisha showed a positive trend (Fig. 4). The average annual net PP of Odisha was lower (1657±75 mgC/m^2/d) compared to West Bengal (1921±71 mgC/m^2/d). Three different climatic models showed a mixed impact on the change of river flow volume and nutrient load. The CNRM-CM5 model (having a small increase in precipitation and a relatively small increase in temperature) gave an increase in West Bengal river flow volume by 13% at the end of the 21st century for West Bengal, though the nitrate (N) and phosphate (P) loads showed a significant decrease (Fig. 5). The net PP projections from this model did not show much change until mid-century (2045-2054) for both states, however, an increase of about 7% was obtained at the end of the century. The river flow volume for Odisha reduced by 10% (from 2005-2014 to 2065-2074), likewise, the N and P loads also reduced by 3% and 1% respectively (as per CNRM-CM5 model outputs). The GFDL-CM3 model (moderate to a larger increase in precipitation and a moderate increase in temperature) projected 10% and 32% increase in river flow of West Bengal and Odisha respectively. The N and P load projections for West Bengal showed a reduction by 14% and 73% respectively, however, for Odisha, it increased by 6% and 1% respectively. The HadGEM2-ES model (large increase in precipitation and temperature), showed increased river flow and N-P loads for both regions, though levels of nitrate in West Bengal decreased after mid-century .

3.2 Fishing scenarios

The size spectrum model outputs projected the impact of the chosen climatic models on the fish productivity of the two states (Fig. 6). Both the CNRM-CM5 and GFDL-CM3 models projected a minor reduction of marine fish production potential for West Bengal (5%) and Odisha (4%). The potential marine fish production for West Bengal did not change much under the HadGEM2-ES model, though irregular inter-annual fluctuations were observed. However, a larger increase in potential marine fish production (9.3%) was projected for Odisha by this model at the end of the 21st century.

Table 1

Differences in the physico-chemical parameters of three climatic scenarios during different time spans of the 21st century used in the physico-biogeochemical models

	Area	Climate Scenario	2005-2014	2025-2034	2045-2054	2065-2074	2025-2034	2045-2054	2065-2074
							(change from 2005-2014)*		
SST (°C)	West Bengal	CNRM-CM5	26.7	27.1	27.5	28.3	0.4	0.8	1.6
Net PP (mgC/m2/d)		CNRM-CM5	1806.1	1840.0	1836.0	1938.2	1.9	1.7	7.3
SST (°C)	Odisha	CNRM-CM5	26.9	27.3	27.7	28.6	0.4	0.9	1.7
Net PP (mgC/m2/d)		CNRM-CM5	1641.7	1665.1	1682.9	1746.1	1.4	2.5	6.4
SST (°C)	West Bengal	GFDL-CM3	27.1	27.9	28.8	29.8	0.8	1.7	2.7
Net PP (mgC/m2/d)		GFDL-CM3	1940.0	2024.2	2047.4	2087.9	4.3	5.5	7.6
SST (°C)	Odisha	GFDL-CM3	27.5	28.3	29.1	29.9	0.8	1.6	2.4
Net PP (mgC/m2/d)		GFDL-CM3	1759.9	1843.9	1829.0	1895.4	4.8	3.9	7.7
SST (°C)	West Bengal	HadGEM2-ES	27.5	27.8	28.7	29.8	0.3	1.2	2.3
Net PP (mgC/m2/d)		HadGEM2-ES	1857.5	1846.1	1919.2	1971.9	-0.6	3.3	6.2
SST (°C)	Odisha	HadGEM2-ES	27.6	28.0	28.8	29.7	0.3	1.2	2.1
Net PP (mgC/m2/d)		HadGEM2-ES	1371.0	1432.8	1520.6	1497.6	4.5	10.9	9.2

SST= Sea surface temperature; Net PP= Net primary productivity.

Change in SST and Net PP in °C and % respectively.

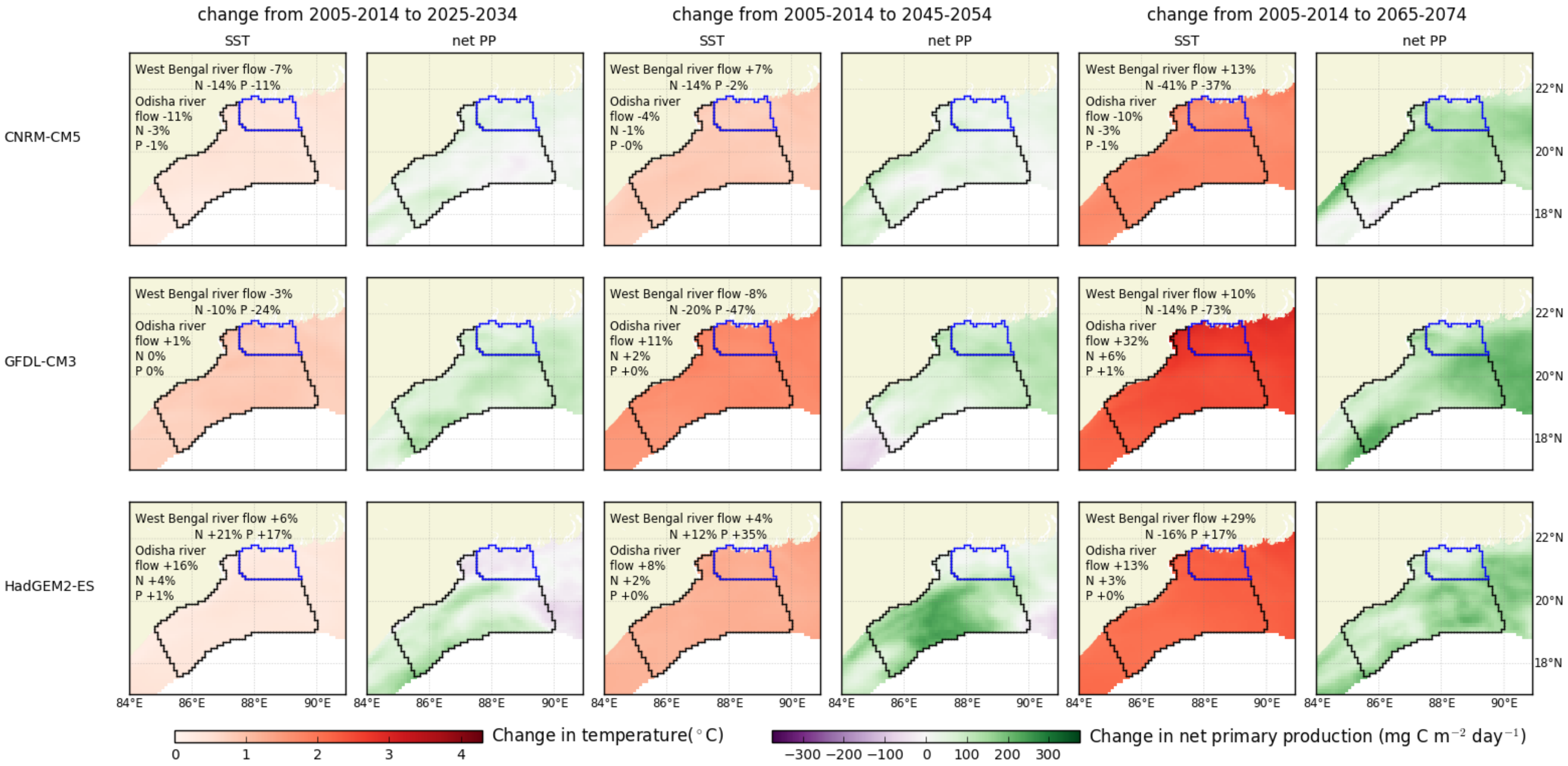

Fig. 5. Projected change in sea surface temperature (SST), net primary productivity (net PP), and river flow of the two delta regions for 2025-2034, 2045-2054 and 2065-2074 time spans compared with values for 2005-2014 as baseline data. The change in nitrate (N) and phosphate (P) river loads over the two studied regions are shown in the panels.

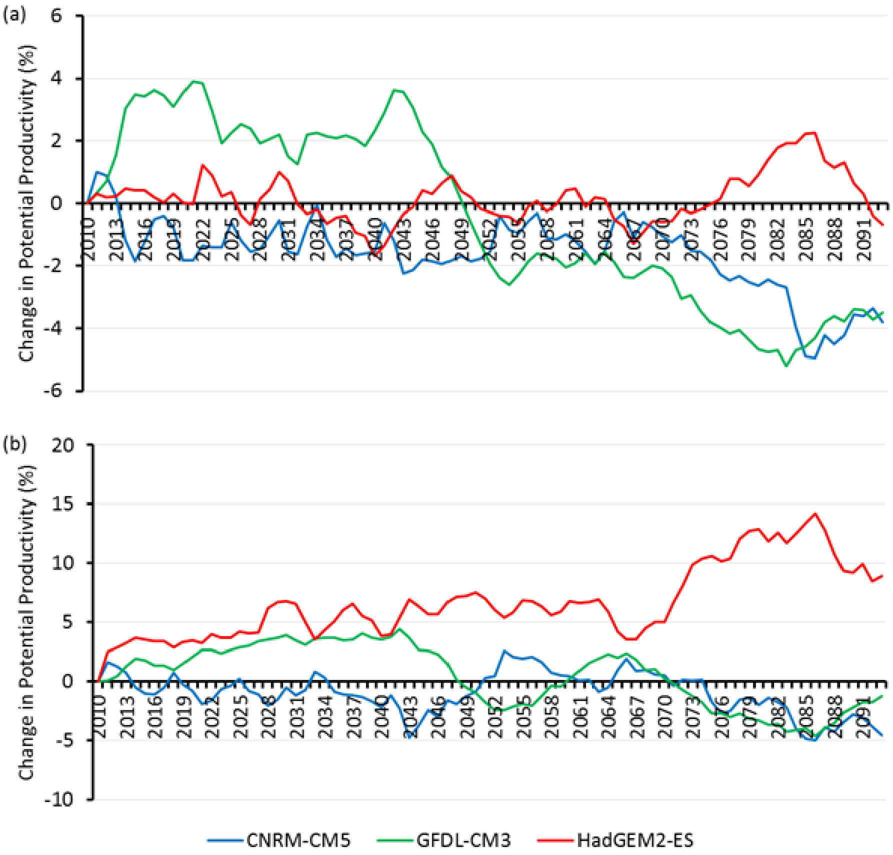

Fig. 6. Change in fisheries potential total productivity of the Bay of Bengal off West Bengal (a) and Odisha (b) under different climate scenarios during the 21st century.

Though the size-spectrum models produce good results with limited data demands, these models do not provide a projection of the potential catch for a specific fish species, because the model does not account for the specific interactions between an individual fish species and its surrounding environmental factors. Hence, to understand the impact of different fishing scenarios at species level the SS-DBEM model was run for mackerel tuna, Indian mackerel, Bombay duck, Indian oil sardine, hilsa, and threadfin bream (Table 2). The comparisons were performed with respect to the year 2010 since both the state fisheries started overexploiting the marine fish resources during that time in their respective EEZs. Indian mackerel, Bombay duck, and threadfin bream showed an increase in respective percent change in potential catches throughout the simulations when sustainable

Table 2

Decadal change in potential production of the selected fish species in the two states according to different fishing scenarios using the 2011-2020 BAU as the base scenario (present scenario)

Fishing Scenarios	West Bengal			Odisha		
	2020s-2010s Δ Catch (%)	2030s-2010s Δ Catch (%)	2040s-2010s Δ Catch (%)	2020s-2010s Δ Catch (%)	2030s-2010s Δ Catch (%)	2040s-2010s Δ Catch (%)
Mackerel Tuna						
Present BAUto MSY	-23.5±27.1	-47.1±16.7	-70.7±10.4	-25.7±11.6	-37±6.9	-53.1±8.4
Present BAUto BAU	-32±25.3	-49±15.6	-71.1±10.8	-17.4±13.2	-28.9±7.4	-46.4±10.1
Present BAUto OF	-47.2±19	-62±12.1	-76.4±9.3	-24.9±12.5	-35.2±7.1	-51.1±9.7
Indian Mackerel						
Present BAUto MSY	40.4±23.1	4.9±17.4	-31.2±13.2	151.3±71.6	111.4±38.5	43.9±24.7
Present BAUto BAU	-20±12.3	-37.3±7.2	-71.1±13.9	-14.5±27.2	-28.1±20.1	58±11.3
Present BAUto OF	-33.8±5.9	-66.3±5.1	-72.1±1.7	-95±4.4	-97.5±2.5	-98.9±1.3
Bombay Duck						
Present BAUto MSY	35.6±5.6	28.3±4.6	19.3±4.7	36.5±5.4	29±3.9	20.9±4.2
Present BAUto BAU	-0.8±4.1	-5.1±3	-10.6±3.5	-1.5±4.1	-6.8±2.9	-11.4±3.5
Present BAUto OF	-36.2±2.6	-39±2.1	-42.2±2.1	-40.2±3.1	-42.7±2.2	-47.7±1.6
Indian Oil Sardine						
Present BAUto MSY	-	-	-	-9.4±16	-24.3±11.6	-35.9±15.5
Present BAUto BAU	-	-	-	-1.9±18.4	-16.6±12.9	-27.3±16.6
Present BAUto OF	-	-	-	-12.1±16.4	-23.8±11.4	-33.7±13.6
Hilsa						
Present BAUto MSY	-24.0±25.4	-30.1±11.0	-51.4±18.6	-2.2±31.9	-3.6±15.8	-33.3±23.6
Present BAUto BAU	-26.9±22.6	-28.1±8.8	-50.3±20.5	-23.2±24.6	-21.6±12.7	-44.5±20.0
Present BAUto OF	-39.0±17.1	-35.5±8.1	-56.7±18.8	-58.0±14.2	-57.3±9.6	-65.6±10.4
Threadfin Bream						
Present BAUto MSY	9.1±9	7.3±8.1	-4.2±8.2	26.4±10.8	26.8±9.7	22.4±14.1
Present BAUto BAU	-7.6±8.4	-9±7.7	-18.5±7.4	-3.8±8.3	-3±7.4	-3.2±15.7
Present BAUto OF	-36.1±5.9	-37.1±5.3	-43.4±5.4	-36.4±5.1	-36.1±5.3	-32±17.6

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fishing measures were applied to the fishery (present BAU to future MSY). However, moving towards the overfishing scenario (present BAU to future BAU and future OF) where no such fishing regulations were applied, all these fisheries projected reduced catch for both the states. Mackerel tuna, Indian oil sardine, and hilsa showed reduced catch potential throughout all the fishing scenarios.

3.3 Economic Model

The change in housholds' aggregate consumption is commonly used as a proxy of the impact of different scenarios on welfare. For the West Bengal delta, following the results of the CNRM-CM5 model, the results of the simulations with the Delta-CGE model show a 0.67% reduction in housholds' consumption by 2050 with respect to BAU (Fig. 7a). Though this might seem to be a small change, in 2011 the aggregate consumption was 26 billion USD and is projected to be 123 billion USD in 2050. Hence, for the CNRM-CM5 model, the 0.67% would mean a reduction in consumption of 0.8 billion USD in 2050. Moreover, according to the model projections, this reduction in consumption would occur even with the best management scenario.

The change in the GDP is also a common approximation to the economic impacts of changes. In this case we observe that the effects in terms of GDP are lower than in terms of aggregate consumption (Fig. 7b), ranging from a reduction of 0.4% under the CNRM-CM5 model in 2050 to a slight increase under HadGEM2-ES model (+0.1%). Despite these apparent low and erratic changes, the CNRM-CM5 modelling involves a loss of 1.7 billion USD in 2050, as indicated by the -0.4% change of the GDP.

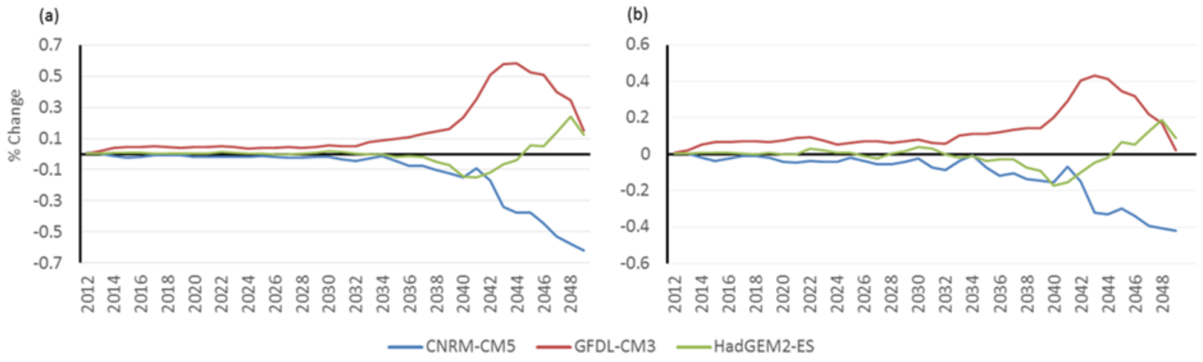

Fig. 7. Changes in yearly housholds' aggregated consumption (a) and GDP (b) for the IBD in West Bengal according to the Delta-CGE model, under different climate scenarios.

4. Discussion

This study shows the potential impact of climate change and different forms of management on fish and fisheries catches for West Bengal and Odisha up to the mid-21st century, combining projections of regional climate models, associated river runoff statistics, nutrient loading volumes, and ecological models. The impact of different fishing scenarios and the global environmental change were modelled in this study producing some insight into the sustainability of the fishery and food provision of the six selected marine fish species up to 2050.

Our results show that sea surface temperature increases by 4°C towards the end of the 21st century, which is consistent with both the global study by Bopp et al. (2013) and the regional study by Fernandes et al. (2015) of the Bangladesh EEZ. Similarly our models project an increase in the net PP for the two studied regions (West Bengal and Odisha) at the end of the 21st century (from 2005-2014 to 2065-2074; Table 1). The net PP and SST show a positive trend for both the states, however, they showed weak correlation with nitrate and phosphate loads. Estuaries and nearshore coastal waters are transition regions which experience high volume freshwater inflow, dissolved nutrients and organic matters from the rivers of surrounding areas, resulting in high productivity (Laane et al., 2005). However, Das et al. (2017) studied the nutrient dynamics of northern Bay of Bengal (nBoB) of West Bengal and reported this region as phosphate-limited during post-monsoon and light-limited for the rest of the year resulting in lower primary production. All the three models used in the present work show an increase of net PP for West Bengal and Odisha (Figure 4), indicating that the increase of primary production in the studied regions is more influenced by temperature and other meteorological conditions rather than river nutrient loading.

Although the net PP increases by about 7% at the end of the 21st century, the change in potential fish production for West Bengal and Odisha is not marked. This may be attributed to an increase in sea temperature and its indirect effect on fish size decreasing, leading, as a consequence, to reduced overall fish biomass (Queiros et al., 2018). Studies using simple size-spectrum models have shown that an increase of 2°C temperature can reduce total fish biomass by 20% (Jennings et al., 2008; Fernandes et al., 2015).

According to fisheries statistics reports, catches for West Bengal decreased by 2% between 2000 and 2016; while for Odisha, with a larger potential fishing area within the

EEZ, the catches increased by 26% (DoF, W.B., 2016; DoES, Odisha, 2016). During the same period, the number of boats increased by 6.8 fold from 2002 to 2016, indicating high fishing pressure on the marine fish stocks of both states. Among the six fish species selected for our study, the catches of hilsa, Bombay duck and Indian oil sardine showed a decreasing trend over this time period probably as an effect of overfishing. The BOBLME report (BOBLME, 2010) on the status of hilsa management in the Bay of Bengal suggests that the hilsa stock in the Indian waters is overexploited and recommend the need for age structure study and stock assessment to protect this species. In addition, a more recent study (Das et al. 2018a) reported over-exploitation of the hilsa stock, with catches exceeding the maximum sustainable yield (MSY) limits in the nBoB region of West Bengal. A similar observation for the hilsa population was reported by Amin et al. (2008) off the Bangladesh coast. Both these studies advocated the need for a reduction in the number of fishing fleets operating in the respective regions to sustain the hilsa fishery. Ghosh et al. (2015) studied the stock status of the exploited fishery resources of nBoB and reported that 56.1% of the stocks are fully-exploited while 36.8% of the stocks are over-exploited. This alarming state of these stocks in addition to our results highlight the need to implement long-lasting fishery management plans in our study areas.

The results from the SS-DBEM model combined with environmental changes and management scenarios indicated that the management plans taken up in the coming decade are crucial for achieving sustainable fisheries. Projections indicated that the potential catches of mackerel tuna, Indian oil sardine, and hilsa will be drastically reduced for both states despite the application of management strategies (Table 2). Potential production of hilsa was projected to decrease by around 50% at the end of the 2050s for both West Bengal and Odisha. Mackerel tuna also showed a reduction by 72% and 50% for West Bengal and Odisha respectively, irrespective of the level of exploitation. This marked reduction in potential production would have a critical impact on the local economy associated with these fisheries. Fishermen will be negatively impacted and will need to shift into other livelihood options (Hossain et al., 2013; Nicholls et al., 2013). Being a highly prized fish due to its extraordinary market demand and unique taste, reduced availability of hilsa would impact the common people of the two states as well as the entire country (Bladon et al., 2016). Most of the mackerel tuna catch is exported to foreign countries while Indian oil sardine has significant market demand in the southern states of India. On the other hand, Indian mackerel, Bombay duck, and threadfin bream population showed increased production under the sustainable management scenario (MSY). Their production reduced significantly under the business as usual (BAU) and overfishing (OF) scenarios as shown in Table 2.

As well as the direct effect of changes in environmental conditions, changes in the structure of the food web due to fishing activity, as also observed by Anh et al. (2015), are consistent with our findings. Hilsa and Indian oil sardine are primarily herbivorous species which feed on plankton, crustaceans, detritus, and algae (Dutta et al., 2014; Ahirwal et al., 2018). Hilsa is a preferred food for a range of predators such as Bombay duck (*Harpodon nehereus*), ribbon fish (*Trichiurus lepturus*), wolf herring (*Chirocentrus dorab*), sharks, tuna, seer fish (*Scomberomorus guttatus*), catfish (*Arius arius*), lizard fish (*Saurida tumbil*), and cephalopods. Bombay duck is ranked among the top predators of the nBoB ecosystem off West Bengal (Das et al., 2018b). With a trophic level (TL) of 3.71, Bombay duck has diverse prey options in the nBoB ecosystem, such as ribbon fish, croakers (*Otolithescuvieri*), hilsa (*Tenualosailisha*), anchovy (*Coiliadussumieri*), sardines (*Sardinella fimbriata*), penaeid prawns and cephalopods (Das et al., 2018b). Likewise, threadfin bream (TL 3.35) also has a diverse range of prey, and having a range of alternative food options might make the Bombay duck and threadfin bream populations more resilient to changes in trophic interaction patterns. Whereas, being a preferred food for many of the upper TL fish species in the Bay of Bengal, hilsa production is more sensitive to the fluctuations of predator abundance and changes in the marine food chain. Fernandes et al. (2015) reported similar findings from the Bangladesh EEZ. According to that study, the potential catch of hilsa was projected to reduce by around 25% and 95% by the end of 2060 under MSY and overfishing scenarios respectively.

Both the states, West Bengal and Odisha, are dependent on fisheries not only in terms of catches and exports, but also for nutrition: a significant amount of fish is consumed within the states. Having some species already at the level of overexploitation (e.g. hilsa), the challenge for these areas is enormous, since even under the best management, the total productivity of the system could decrease. The decreasing catch, in particular for low-cost species such as Indian mackerel and Indian oil sardine would adversely affect the coastal communities, because these species make up most of the consumption and catch in these regions. In the whole Indian mainland EEZ, the highest catch is recorded for Indian oil sardine (more than 300 thousand tonnes) followed by Bombay duck (more than 100 thousand tonnes) and Indian mackerel (more than 60 thousand tonnes) (Hornby et al., 2015; Zeller and Pauly, 2015; Meara et al., 2011; Zeller and Pauly, 2014). Loss of low-cost fisheries tends to affect the low-income coastal population more strongly since they are more dependent on these species for protein intake (Beveridge et al., 2013; Belton and Thilsted, 2014; Thilsted et al., 2016). Hence, a decrease in the catch potential of the relatively low-priced species may notably affect the consumption and livelihoods of the studied regions.

According to Harrod et al. (2018), small-scale fishers and aquaculture farmers are particularly vulnerable to climate change. Globally, the price of indigenous small fish species from capture fisheries systems which are nutrient-rich and mostly consumed by the poor has shown a sharply rising trend (Belton et al., 2014; Toufique and Belton, 2014). Since 90% of the coastal fishermen are engaged in small-scale fishing, fish processing, and marketing, they form the proportion of the population with most prevalent poverty (Béné, Macfadyen, and Allison, 2007) and are most vulnerable to climate change. Formulating policies to achieve the SDGs for these populations is a complex task for the policymakers as greater obstacles are often faced while building adaptive capacity in poorer communities and in poor countries (IPCC, 2014c). In our study regions population growth, irrigation needs, heavy metal and waste pollution, habitat modification and destruction, illegal fishing, lack of adequate infrastructure and skills further impede the ability of poorer people to adapt (Fernandes, 2018). Reducing the capacity of the boats would probably help to recover the over-exploited marine fish stocks to a sustainable state, but that would need further attention based not only on capacity but also on projected future trends from climate and biogeochemical models (Fernandes, 2018). Furthermore, climate change adaptation in the fisheries and aquaculture sector is a governance challenge, where different level and sectors of government, civil society, community organization, and academia need to interact to formulate and implement different pathways and policies (Bavinck et al., 2011; Kooiman et al., 2005; Kalikoski et al. 2018). Several adaptive strategies are available to improve small-scale fisheries and fish farmers (Miller et al., 2018). Risk-informed and shock-responsive social protection schemes are key to reducing the impacts of climate change on poor communities (Winder et al., 2017). The national framework for emergency response and disaster risk reduction can act as a key instrument to uplift the economic condition of the fishers and fish farmers when implemented properly at each level of the institutional hierarchy. Insurance schemes can provide social safety for those in extreme poverty by increasing their resilience and robustness. The coastal communities need to be empowered organizationally and with knowledge (Kalikoski et al. 2018). Cooperation and coordination of all climate-related policies and actions are required to build a collective resilience in the coastal population.

5. Conclusions

Impacts of climate change and management options on the potential marine fish production was studied for West Bengal and Odisha for the 21st century. Coastal population of both the states are dependent on fisheries as a source of livelihood and nutrition. Combined study of the regional climate models, river runoff statistics, nutrient loading, and ecological models provided an insight into the sustainability of the regional marine fishery and food provision of six selected fish species. The study showed that the net primary productivity in the Indian Bengal delta and Mahanadi delta was more influenced by temperature rather than nutrient load. Projections indicated, increased sea surface temperature in this deltaic region masked the positive impact of net primary productivity on the future fish productions. Reduced potential production would have critical impact on the local economy. Owing the extraordinary market demand and unique taste of hilsa, its reduced availability would impact the local fishermen and common people of the two states as well as the entire country. Overall, the adverse impact of climate change on marine fisheries would mostly affect the low-income coastal population of both the states since fishery products are one of the major livelihood options for these population.

Non-inclusion of several specific adaptive measures and other regulatory factors (as mentioned earlier) which might have a key role for sustaining the fishery in the future even in the face of climate change is the major limitation of the model we used. Despite this limitation, the results presented this work can be considered as an initial step towards achieving the information needed to manage a sustainable fishery in West Bengal and Odisha. It is evident from the present study that climate change is working as an additional pressure on the already overexploited fisheries resources of the present study area. In order to mitigate and adapt to the changing climatic conditions, the fishery resources should be managed and regulated appropriately to achieve sustainability. Along with that, the generation of alternative livelihood options for the coastal population is also required. Hence, integrated models as used in the present work should be further studied with innovative management options formulated for the practical field use.

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