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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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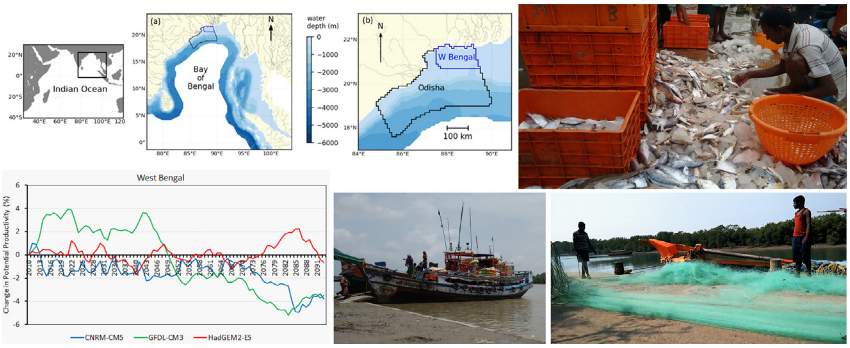
HIGHLIGHTS

- Impacts of environmental changes were modelled for two Indian deltas.
- Increased temperature caused loss of fish productivity by the end of 21st century.
- Mackerel tuna, Indian oil sardine, and hilsa fisheries projected reduced catch.
- Loss of low-cost fisheries would negatively affect the poorer coastal population.
- Improved management plans are needed to mitigate future climate change.

GRAPHICAL ABSTRACT



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ABSTRACT

The study covers two important deltaic systems of the north-east coast of India, viz. the Bengal and Mahanadi delta that support about 1.25 million people. The changes 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 (by 4 °C) 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 the 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 efforts effective. This work can be considered as the baseline model for future researchers and the policymakers to explore potential sustainable management options for the studied regions.

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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 around 7500 km long densely populated, low-lying coastline, 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 >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). 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 in the country was 5–10 kg per year per capita between 2013 and 2015 (FAO, 2018). Furthermore, the marine products constitute 19.5% of the total fresh and processed food exports from India during 2017 as reported by Goyal et al. (2017). 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 1.7 million tonnes of fish production in 2017–2018 (around 16.2% of all Indian fish production) (GoI, 2019). On the other hand, Odisha ranked 4th with around 0.68 million tonnes in 2017–2018 (around 6.4% of all fish production) (GoI, 2019). Furthermore, in West Bengal fish products were consumed at a rate of about 0.81–1.03 kg per capita per month, double the quantity of around 0.44–0.47 kg per capita per month in Odisha (GoI, 2019) suggesting a significant regional variation. Rural areas are extremely 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 mainly in urban centers (GoI, 2019). 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 >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.

Considering the key role of fisheries in the socio-economy of the two deltaic regions, quantifying of the future impact of climate change on the fishery resources is a major concern for scientists. The effects of climate change are expected to reduce marine ecosystems productivity (Bopp et al., 2001; 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, 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/t) 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 b) largely because of overfishing as reported by Dutta et al. (2012) and Das et al. (2019). Mackerel tuna (1217 USD/t) 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 (183 USD/t in 2010), Indian oil sardine (83 USD/t) and threadfin bream (989 USD/t) are non-target species forming the by-catch of the fishery. Bombay duck (179 USD/t) 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, 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).

In the face of climate change, redistribution of global marine species and reduction of marine biodiversity is going to cause reduced fisheries productivity and marine ecosystem services (IPCC, 2014b). 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). Study of marine fisheries and fish biology for economically important fish species have been already reported from West Bengal and Odisha (Kumar and Shivani, 2014; Dutta et al., 2016; Raman et al., 2017; Das et al., 2019). In addition, several studies on marine ecosystem dynamics (Das et al., 2018) and need of proper management plans to sustain the existing fish stocks have also been advocated (Dutta et al., 2012; Mohanty et al., 2017; Das et al., 2018; Das et al., 2019). Because of the importance of fish production for the survival of populations that live in deltaic regions it is essential to have long-lasting fisheries management plans that also account for possible impacts of climate change.

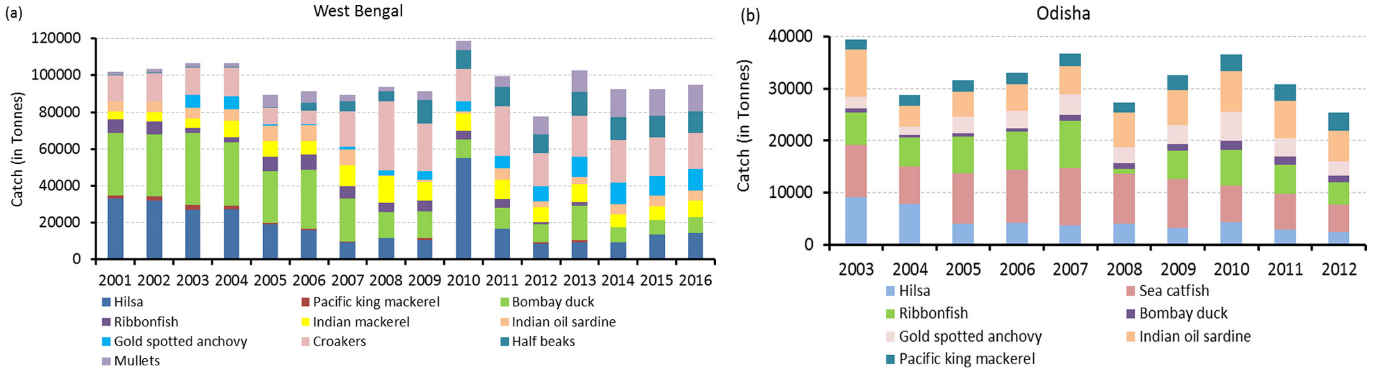

Fig. 1. Annual catch of a few selected marine fish species for West Bengal (a) and Odisha (b).

This study represents the first attempt to incorporate all the variables (biogeochemical factors, probable climatic scenarios, ecosystem model which include food web interactions, species interaction based on size-spectrum and habitat suitability, fishing scenarios and socio-economic aspects) that play a key role on the sustainability of the fishery for two important deltas of the north-east coast of India. A similar approach was applied to Bangladesh (Fernandes et al., 2016) but its application for the Indian deltas is completely new. 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. This work will provide a platform for the policymakers and future researchers to explore the probable options for sustaining the marine fish resources in this highly productive region.

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 and 108 cm s^{-1} during low and high tide respectively (De et al., 2011). This region is characterized 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 m 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 24,000 km^2 (DoES, 2016). It is a partially mixed coastal plain estuary with a semidiurnal tide (Panda et al., 2006). 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 than that of West Bengal over the last decade (Fig. 2) (DoF, 2016, and DoES, 2016). In West Bengal, around 0.38 million people are dependent on the marine fisheries sector for their livelihood (DoF, 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 and 1982 (0.028 million tonnes) and 2015–2016 (0.173 million tonnes). However, through the last 15 years (from 2002 to 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, 2016).

In Odisha, the number of people dependent on the marine fishery sector is 0.87 million (DoES, 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 t to 104,000 t, 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 to 125 mm for hilsa. Set bagnet, purse seines, longliners, dol nets, etc. are also used for targeting catfish, king mackerel, mackerel tuna, sardines, Indian mackerel (BOBP, 1990).

2.2. Climate scenarios and biogeochemical models

Future marine fish production for West Bengal and Odisha were simulated for the 21st century (up to 2100) by downscaling three of the Global Climate Models (GCMs) used in the Coupled Model Intercomparison 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 physics model POLCOMS coupled to the biogeochemical/ecosystem model ERSEM (Fig. 3 and Table 1).

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. 4); the horizontal resolution was 0.1° in latitude and longitude and the model had 40 vertical levels distributed on a hybrid z-sigma scheme. The model solves the hydrodynamic equations that describe the motion of water and the

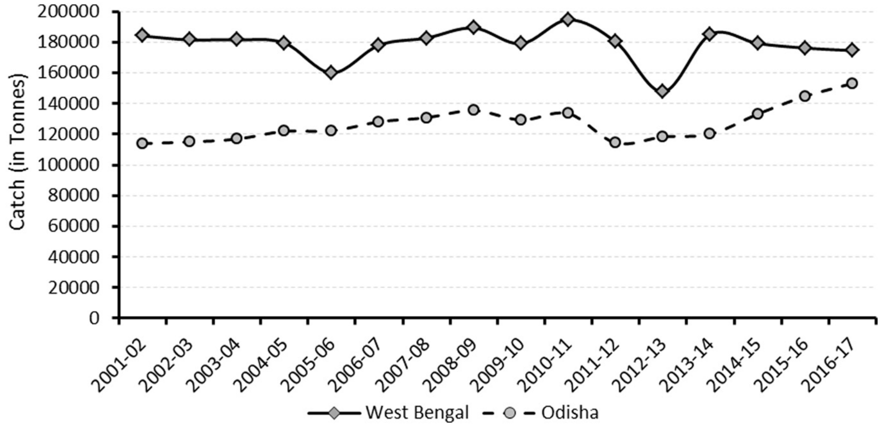

Fig. 2. Total annual marine catch trend of the two states from 2001 to 2016 indicating lower annual catch of Odisha than West Bengal.

transfer of energy and momentum. Tides are included. Physical conditions at the atmosphere and ocean boundary are inputs to the model.

ERSEM, the European Regional Seas Ecosystem Model (Butenschön et al., 2016), simulates 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. The model includes all processes important for biogeochemical cycling in the marine environment, including photosynthesis, respiration, nutrient uptake, predation, cell lysis and excretion. ERSEM runs within every cell of the POLCOMS grid every 10 min. Advection of plankton, particulates and nutrients is handled by POLCOMS, and sinking under gravity is built into the model.

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,

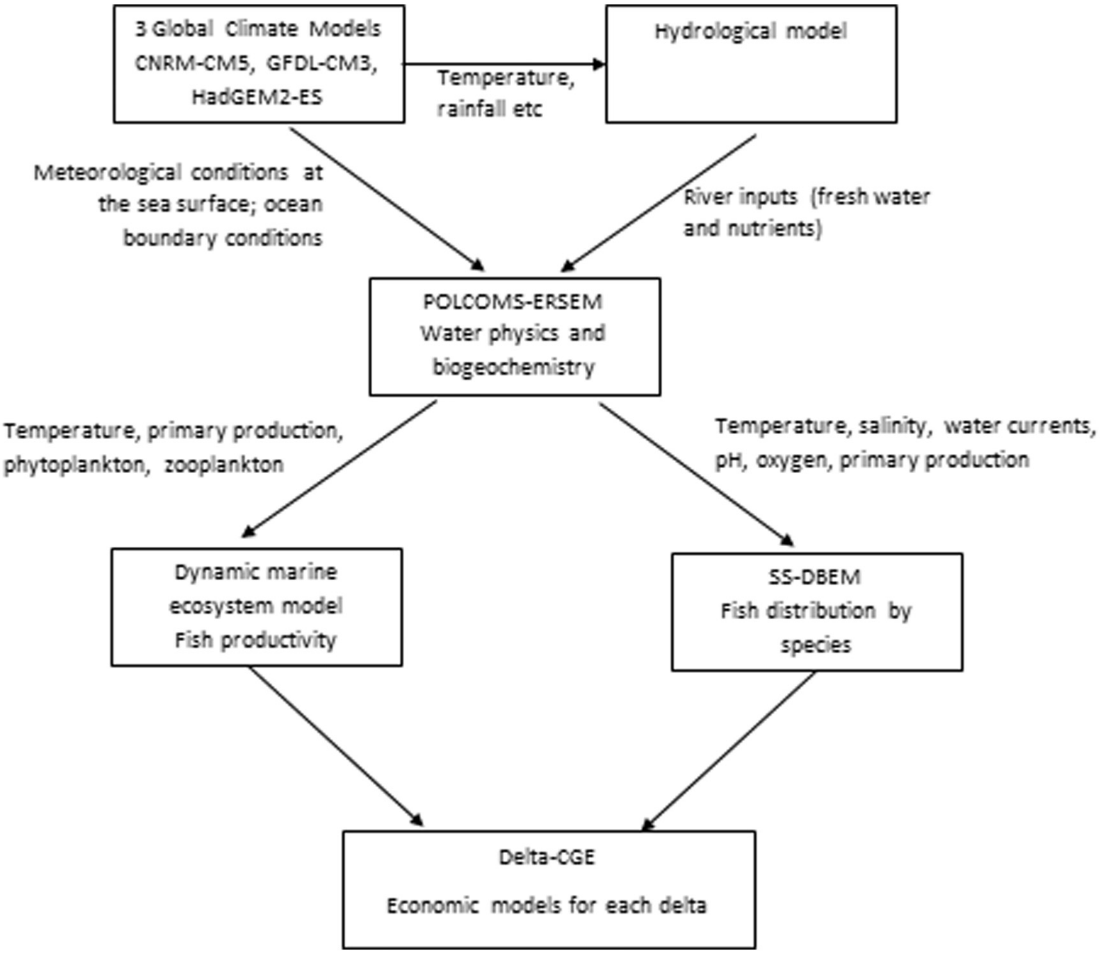

Fig. 3. Flow chart and structure of the models used in the present study to assess the impact of climate change and management policies in the fishery and socio-economy of the north-east coast of India.

Table 1
Table summarize the utility of the different models used in the present study.

Concept	Specific names (models/scenarios/pathways)	Further information
Global climate models (GCMs)	CNRM-CM5, GFDL-CM3, and HadGEM2-ES	Used as the background data for the fisheries production/productivity models.
Fisheries production/productivity models	POLCOMS-ERSEM (Holt and James, 2001; Butenschön et al., 2016)	Combination of three-dimensional baroclinic model suitable for simulating physical processes in both shelf seas and deep water areas. It includes the food web interactions which link primary production to fish production through predation. It simulates the processes and biogeochemical transfers of the lower trophic level ecosystem. Outputs are used in a dynamic marine ecosystem model.
	Dynamic Bioclimate Envelope Model (DBEM)	Used to project the distribution and abundance of the selected marine fish species.
	Size-spectrum dynamic bioclimate envelope model (SS-DBEM)	Used to simulate changes in abundance and distribution of fish species.
Fishing scenarios	Sustainable scenario (MSY); Business as usual scenario (2MSY); Overfishing scenario (3MSY)	The fisheries scenarios considered in this study were based on the ecosystem carrying capacity of the West Bengal and Odisha EEZs.
Socioeconomic pathways	Shared Socioeconomic Pathway 2 (SSP2) of the IPCC scenario framework (O'Neill et al., 2014; Riahi et al., 2017)	The scenario is the more "middle of the road".
(Socio-)economic model	Dynamic CGE model was adapted from Arto et al. (2019)	Uses fisheries production/productivity model inputs and provides socioeconomic variables outputs. It incorporates specific Social Accounting Matrices for West Bengal & Orissa, even with a focus on main deltas (Ganges-Brahmaputra-Meghna & Mahanadi).

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. 4 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 size-spectrum dynamic bioclimate envelope model (SS-DBEM) described in Fernandes et al. (2013) is used to simulate changes in abundance and distribution of fish species. The SS-DBEM projects changes in species distribution and abundance with explicit consideration of known mechanisms (Table 2) of population dynamics, dispersal (larval and adult) and ecophysiology, under changes in ocean temperature, salinity, upwelling, sea-ice extent and habitats (Cheung et al., 2011), and species interactions based on size-spectrum theory and habitat suitability (Fernandes et al., 2013). In SS-DBEM, current distributions of the studied species are first estimated based on habitat suitability (Close et al., 2006). This is done based on a global dataset of observed abundance data from Cheung et al. (2008; available at fishbase.org which redirects to maps hosted at aquamaps.com) overlaid with environmental data (temperature, salinity, oxygen and pH at sea surface for pelagic species and at sea bottom for demersal species as well as depth and distance to ice) from biogeochemical models described above. It is assumed that the carrying capacity of each species in each area is partly dependent on the inferred preference profiles which depend on the projected biogeochemical conditions (e.g. temperature, salinity, pH and currents) but limited by primary production. Simultaneously, the model considers each species' physiological preferences and tolerances to temperature, and sensitivity of key parameters determining the species' mechanisms (mortality, growth and length-weight relationship). Natural mortality rate is estimated from an empirical equation (Pauly, 1980) which considers weight, growth and temperature. The model growth algorithm (Cheung et al., 2011) is derived from the von Bertalanffy growth function (VBGF; von Bertalanffy, 1951). Therein, growth is viewed as the difference between anabolic and catabolic processes. The temporal and spatial patterns of pelagic larval dispersal (Cheung et al., 2008) are modelled by a two-dimensional

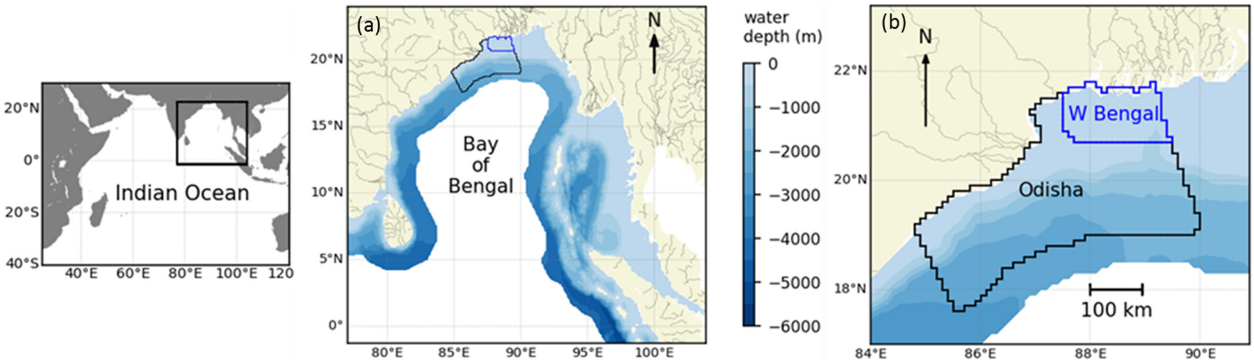

Fig. 4. (a) The Bay of Bengal, showing the modelled area in blue. (b) Part of (a) enlarged to show the Odisha and West Bengal analysis regions. The colour shading shows the bathymetry. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Table summarizing main equations and parameters to consider the species mechanisms in SS-DBEM. Further details are given in the associated references.

Mechanism	Equation	Parameters
Growth = anabolism − catabolism (Pauly, 2010; Cheung et al., 2011)	$G = HW^a - kW$ $H = g[O_2] * e^{-j1/T}$ $k = h[H^+] * e^{-j2/T}$	H = anabolism coefficient k = catabolism coefficient W = body weight a = anabolism exponent (0.5 to 0.95) W_∞ = asymptotic weight The coefficients g and h were derived from the average W1, K, and environmental temperature (T) of the species reported in the literature.
Length-weight	$W = a * L^b$	W = weight L = length
Size-spectrum production (Jennings et al., 2008; Fernandes et al., 2013)	$P = \exp(25.22 - E/kT) * W^{0.76}$	E = activation energy of metabolism k = Boltzmann's constant T = temperature in Kelvin (°C + 273)
Intrinsic population growth rate (Hilborn and Walters, 1992)	$G = r * A * (1 - (A/KC))$	r = intrinsic rate of population increase A = the relative abundance KC = population carrying capacity
Larval dispersal (Cheung et al., 2008)		D = diffusion parameter (u, v) = velocity parameters LAV = larvae recruitment
Adult movement	$Cm * h^{-1}$	Cm = centimetre h = hour
Natural mortality	$M = -0.4851 - 0.0824 * \log(W_{inf}) + 0.6757 * \log(K) + 0.4687 * \log(T)$	W_{inf} = asymptotic weight K = von Bertalanffy growth parameter T = average water temperature in the animal's range.

advection-diffusion equation (Sibert et al., 1999; Gaylord and Gaines, 2000). Adult dispersal is calculated from the dispersal or movement rate using an algorithm employed in an Eulerian spatial ecosystem simulation model (Walters et al., 1999).

The size spectrum (SS) component of the model addresses resource competition between different species co-occurring in any given cell by comparing the biomass that can be supported in the cell, as determined from primary production and the size-spectrum model, with the energy demanded by the abundance of the species predicted to inhabit this cell. This allocation is based on habitat suitability considerations and a generic group (other species) that can also compete for energy particularly if there is a surplus is available (Fernandes et al., 2013). If the energy demanded by all species in the cell exceeds the energy available, then the model allocates available energy to each species in proportion to its energy demands. If the energy demanded by all the species is lower than the energy available, the surplus energy is allocated according to the proportional energy demand of the species present. The rate at which this energy can be assimilated is limited by constraints on species' growth rates as described in Fernandes et al. (2013).

2.4. Fishing scenarios

The fisheries scenarios considered in this study were based on the ecosystem carrying capacity of the West Bengal and Odisha exclusive economic zones (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 and 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 obtained from Sea Around Us (www.seaaroundus.org) and FishBase (www.fishbase.org/) database 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 (2011), 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., 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 socio-economic 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 (Cazcarro 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 Section 2.2 (materials and methods).

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 using POLCOMS-ERSEM with input from the three selected GCMs (Fig. 5). However, the predicted increase in bottom temperatures was lower for Odisha (by 0.7 °C) than West Bengal (by 2.2 °C) (Fig. 5) because the Odisha EEZ includes much deeper water (Fig. 4) which is less influenced by surface conditions and hence takes longer to respond to the warming atmosphere. All three climatic scenarios projected an increase in sea surface temperature (SST) throughout the study period in these two regions (Table 3 and Fig. 6).

The POLCOMS-ERSEM projections of change in net primary productivity (PP) for West Bengal and Odisha showed a positive trend (Fig. 5). 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 GCMs showed a mixed impact on the change of river flow volume and nutrient load. The CNRM-CM5 model (having a small increase in precipitation

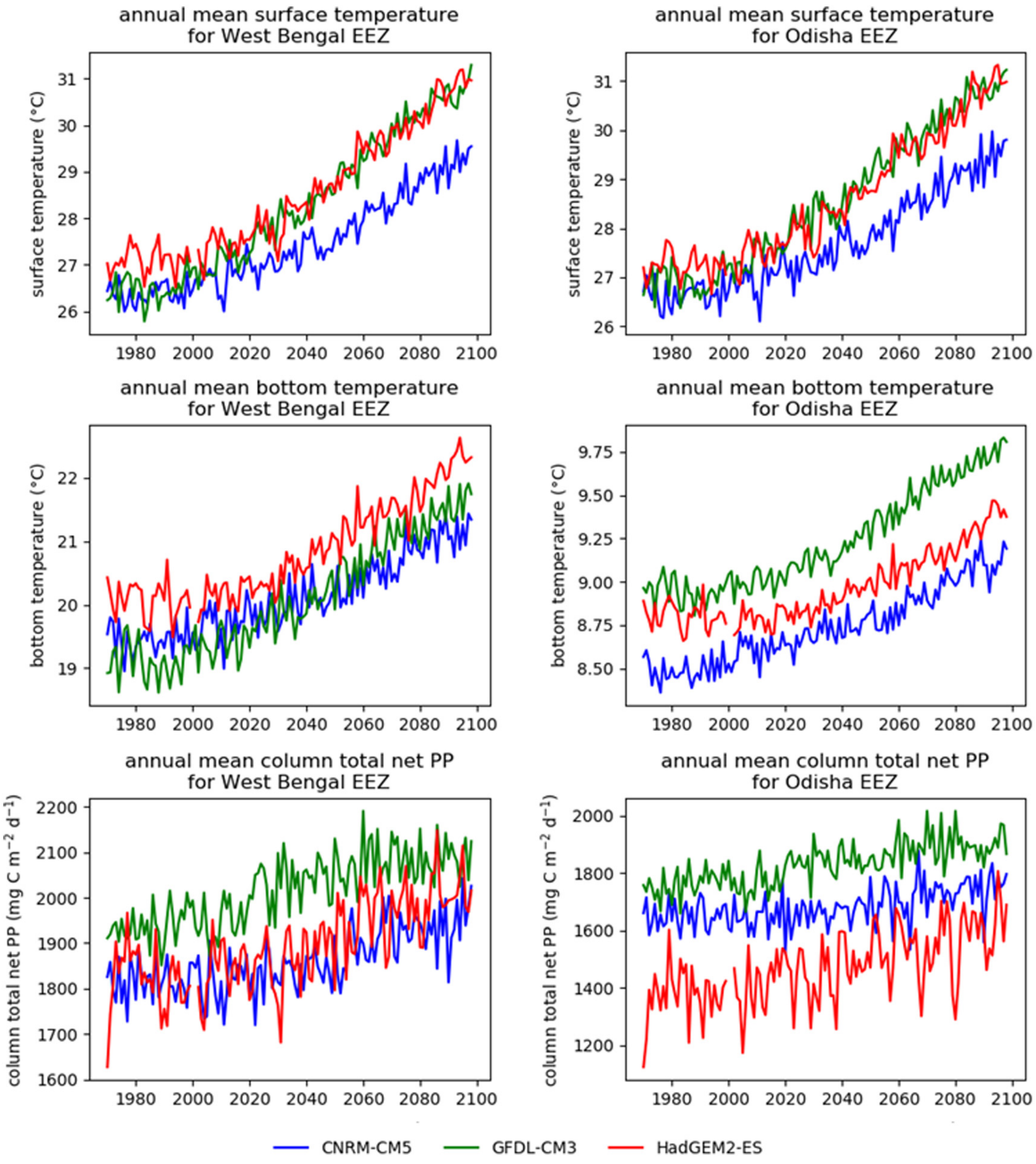

Fig. 5. Projected annual mean sea surface and bottom temperature, and mean column net primary productivity for West Bengal and Odisha. The colours show the projections made by the POLCOMS-ERSEM model using the three different GCMs as input.

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. 6). The net PP projections from this GCM 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 to 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. 7). 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 interannual 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.

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 4). 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 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 dynamic CGE model was adapted from Arto et al. (2019). The estimates from the fisheries models (with input from the three GCMs, i.e. CNRM-CM5, GFDL-CM3, and HadGEM2-ES) were used as the inputs for the CGE model. The expected changes in fish yield obtained from the SS-DBEM and dynamic marine ecosystem models have an influence in the fisheries sector. This influence is transmitted throughout the economy as reduced income for households (reduced capacity to purchase other products, etc.) and reduced role of fisheries as supplier to the domestic or foreign markets.

The change in households' 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 households' consumption by 2050 with respect to BAU (Fig. 8a). 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 assess the impacts in the economic sectors. In our study, the percentage change in the household's aggregated consumption and GDP have shown a mixed trend (Fig. 8b) ranging from a reduction of 0.4% under the CNRM-CM5 model by 2020 to a slight increase in 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.

4. Discussion

This study shows the potential impact of climate change and different forms of management options on the fish and fisheries of 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 to produce some insight into the sustainability of the fishery and food provision of the six commercially important 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 of Bangladesh EEZ by Fernandes et al. (2016). 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 to 2014 to 2065–2074; Table 3). The net PP and SST show a positive trend for

Table 3

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.

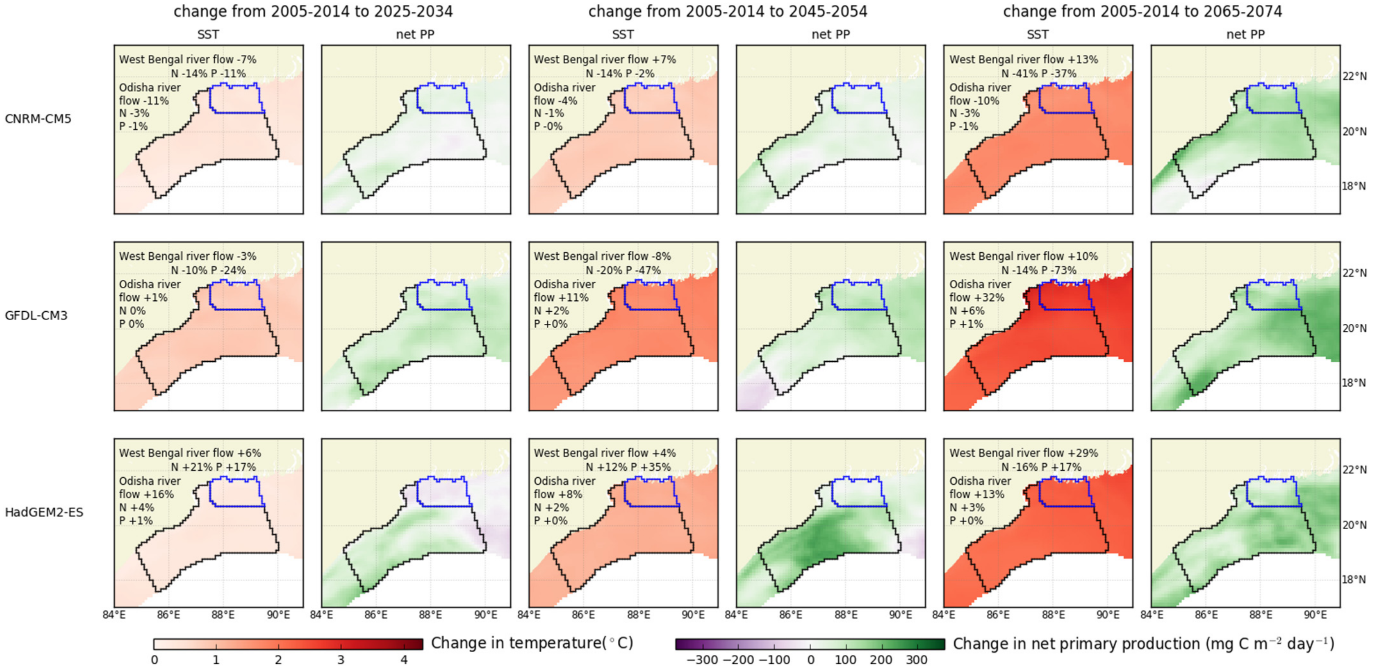

Fig. 6. Projected change in sea surface temperature (SST), net primary productivity (net PP), and river flow of the two delta regions for 2025–2034, 2045–2054 and 2065–2074 time spans compared with values for 2005–2014 as baseline data. The change in nitrate (N) and phosphate (P) river loads over the two studied regions are shown in the panels.

both the states, however, they show weak correlation with nitrate and phosphate loads. Barange et al. (2014) reported a similar work covering 67 marine national EEZs globally, including Bay of Bengal Large Marine Ecosystem (BOBLME). Globally the net PP was reported to increase by 14% at the end of 21st century. 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) showed that the northern Nay of Bengal region (the Hugli estuary off West Bengal) is phosphate-limited during post-

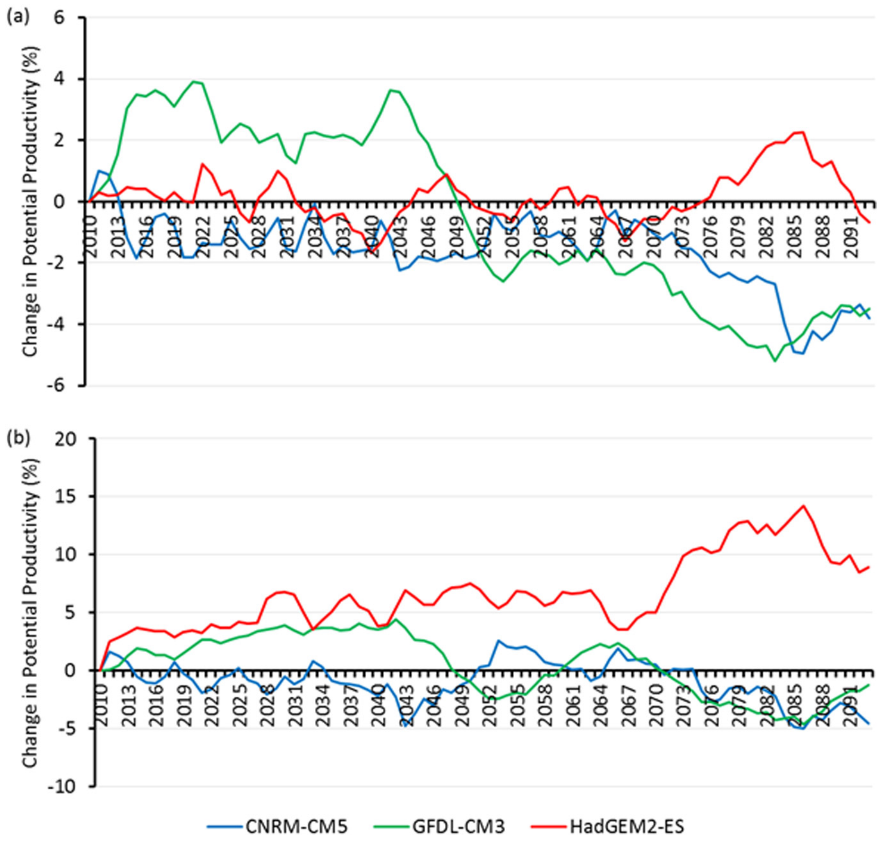

Fig. 7. Change in fisheries potential total productivity of the Bay of Bengal off West Bengal (a) and Odisha (b) under different climate scenarios during the 21st century.

Table 4
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 BAU to 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 BAU to BAU	−32 ± 25.3	−49 ± 15.6	−71.1 ± 10.8	−17.4 ± 13.2	−28.9 ± 7.4	−46.4 ± 10.1
Present BAU to 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 BAU to 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 BAU to BAU	−20 ± 12.3	−37.3 ± 7.2	−71.1 ± 13.9	−14.5 ± 27.2	−28.1 ± 20.1	58 ± 11.3
Present BAU to 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 BAU to 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 BAU to 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 BAU to 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 BAU to MSY	–	–	–	−9.4 ± 16	−24.3 ± 11.6	−35.9 ± 15.5
Present BAU to BAU	–	–	–	−1.9 ± 18.4	−16.6 ± 12.9	−27.3 ± 16.6
Present BAU to OF	–	–	–	−12.1 ± 16.4	−23.8 ± 11.4	−33.7 ± 13.6
Hilsa						
Present BAU to 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 BAU to 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 BAU to 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 BAU to 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 BAU to BAU	−7.6 ± 8.4	−9 ± 7.7	−18.5 ± 7.4	−3.8 ± 8.3	−3 ± 7.4	−3.2 ± 15.7
Present BAU to OF	−36.1 ± 5.9	−37.1 ± 5.3	−43.4 ± 5.4	−36.4 ± 5.1	−36.1 ± 5.3	−32 ± 17.6

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 (Fig. 5), 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. This is in agreement with Fernandes et al. (2016) for the Bangladesh waters.

Although the net PP increases by about 7% at the end of the 21st century, the potential change in fish production for West Bengal and Odisha is not marked. This may be attributed to an increase in sea temperature and its negative effect on fish size, leading to a reduction of fish biomass (Queirós et al., 2018). This inverse relationship has been also suggested by using simple size-spectrum models where an increase of 2 °C temperature can reduce the total fish biomass by 20% (Jennings et al., 2008; Fernandes et al., 2016).

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, 2016; DoES, 2016). During this period (from 2002 to 2016), the number of boats increased by 6.8 folds for both states, indicating high fishing pressure on the marine fish stocks. 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 period probably as a response to 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., 2019) showed that the exploitation of hilsa stock is clearly exceeding the limits of maximum sustainable yield (MSY) showed that the exploitation of hilsa stock is clearly exceeding the limits of maximum sustainable yield (MSY) in a region of West Bengal (i.e. northern Bay of Bengal, nBoB). This critical status for the hilsa population was previously observed off the Bangladesh coast (Amin et al., 2008). 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

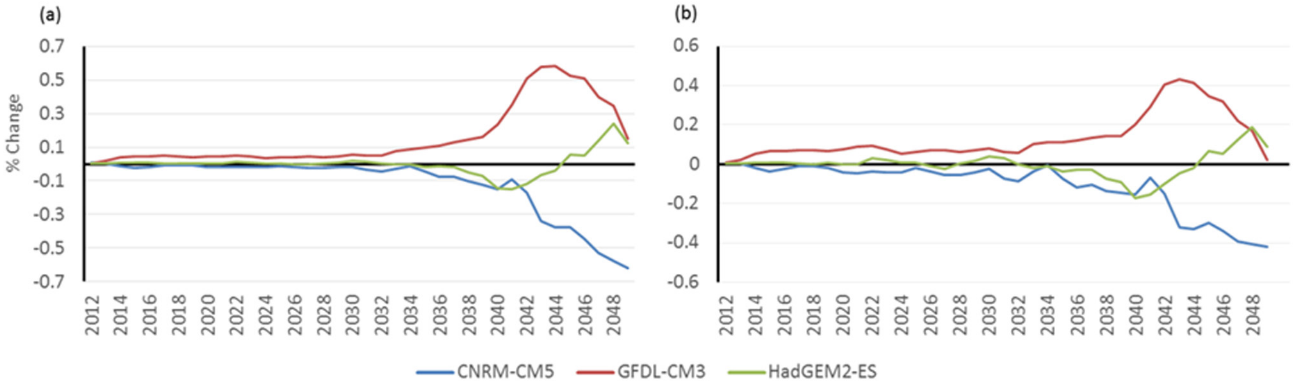

Fig. 8. Changes in yearly households' aggregated consumption (a) and GDP (b) for the IBD in West Bengal according to the Delta-CGE model, under different climate scenarios.

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 effective fishery management plans in our study areas.

The results from the SS-DBEM model combined with environmental changes and management scenarios indicated that the future 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 4) as also observed by Fernandes et al. (2016) in Bangladeshi waters. Cisneros-Mata et al. (2019) studied the impacts of climate change on 25 commercially exploited fish species in the Mexican fisheries and projected reduced potential productivity for most of the selected fish species. In the present study, the 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 of the 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 4.

Findings of the present study are consistent with the observations reported by Anh et al. (2015) over the structural changes in the food web induced by environmental changes and fishing activity. Barange et al. (2014) projected a change in percentage contribution in the net PP by different size class of phytoplankton by 2050. Contribution of flagellates in the net PP was predicted to increase by a global average of 10.2%. Smaller phytoplankton were expected to support longer food chain with reduced transfer efficiency in the context of global warming (Morán et al., 2010; Bode et al., 2011). These changes in phytoplankton species composition along with physico-chemical changes in the marine ecosystems were predicted to affect the ecological functions and sustainable harvests from the oceanic resources (Denman et al., 2011; Doney et al., 2011). Das et al. (2018) studied the food web structure and functioning of nBoB (West Bengal coast) and documented the interdependency of the predator and prey species within the ecosystem. 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*), lizardfish (*Saurida tumbil*), and cephalopods. Bombay duck is ranked among the top predators of the nBoB ecosystem off West Bengal (Das et al., 2018). With a trophic level (TL) of 3.71, Bombay duck has diverse prey options in the nBoB ecosystem, such as ribbon fish, croakers (*Otolithes cuvieri*), hilsa (*Tenualosa ilisha*), anchovy (*Coilia dussumieri*), sardines (*Sardinella fimbriata*), penaeid prawns and cephalopods (Das et al., 2018). 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. (2016) 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 and livelihood. 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 (>300 thousand tonnes) followed by Bombay duck (>100 thousand tonnes) and Indian mackerel (>60 thousand tonnes) (Hornby et al., 2015; Zeller and Pauly, 2015; O'Meara et al., 2011). 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 et al., 2007) and are most vulnerable to climate change. Our results clearly show that the impact of climate change on the coastal populations of West Bengal and Odisha could be drastic. In fact, the household consumptions and the GDP for the studied region was predicted to face a loss of 0.8 billion USD and 1.7 billion USD respectively by 2050. The economic dependency of the coastal population on the fish and fishery products along with higher vulnerability to climate change may enforce switching to alternative livelihood (Perry et al., 2011). Formulating policies to achieve the sustainable development goals (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 the context of climate change and the 17 SDGs mentioned in the United Nations' 2030 Agenda for sustainable development (UN General Assembly, 2015), the present study becomes important, for it addressed a few SDGs, related to food security (Goal 2), economic growth (Goal 8), climate action (Goal 13) and particularly Goal 14: conserve and sustainably use the oceans, seas and marine resources. The mitigation-oriented nationally determined contributions (NDCs) proposed by nations in the framework of the Paris Agreement (Vázquez-Rowe, 2020) barely covers the greenhouse gas (GHG) emissions from the fishing industry, protection of fishing grounds, fishing infrastructure, and small coastal fishing communities from increasing sea level due to ocean melting (Rogers et al., 2019). According to Sachs et al. (2019), globally India ranked 115th among 162 countries with a score of 61.1 and major interventions are needed in 13 out of 17 SDGs. NITI Aayog, a policy “think-tank” of Government of India, introduced a single measurable index to quantify the achievement of the country towards its commitment to the SDGs (NITI Aayog, 2018). According to this index, West Bengal and Odisha ranked 17th and 14th among the 36 states and union territories with the SGD index of 57 and 59 respectively. Owing the key role of fishery and reduced decadal catches for some economically important marine fish species in both states, several amendments have been made in the existing fishing regulation acts over the last decade. For West Bengal, most of these changes concerned the improvement of hilsa fishery in the state (The Kolkata Gazette, 2013, No. 718 Fish/C-I/9R-3/20 12), while for Odisha, conservation of the sea turtle congregation sites were the area of focus (available at: http://www.fardodisha.gov.in/sites/default/files/pdfs/OMFRA-Rules.pdf). Studies covering the overexploitation of marine fish stocks especially hilsa (Das et al., 2019; Ghosh et al., 2015) unanimously advocated the need for proper management plans to sustain this stock. Since, most of the studied marine fish species belong to a common shared stock, coordinated formulation and implementation of the fishing regulation is needed from the neighboring states as well as countries. The present study reinforce the above idea by projecting the differences in the future stock status for the two states under different management scenarios, hence providing relevant information for decision-making.

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 (in terms of size or power or both) 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 levels and sectors of government, civil society, community organization, and academia need to interact to formulate and implement different pathways and policies (Bavinck et al., 2013; 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 reduce the impacts of climate change on poor communities (Winder Rossi 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 were 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 that 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 to 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 sustainably manage the 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. Along with that, 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.

CRediT authorship contribution statement

Isha Das: Data curation, Writing - original draft. **Valentina Lauria:** Data curation, Writing - review & editing. **Susan Kay:** Data curation, Formal analysis, Visualization, Writing - review & editing. **Ignacio Cazcarro:** Data curation, Formal analysis, Writing - review & editing. **Iñaki Arto:** Data curation, Writing - review & editing. **Jose A. Fernandes:** Data curation, Visualization, Formal analysis, Writing - review & editing. **Sugata Hazra:** Visualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Ahirwal, S.K., Jaiswar, A.K., Chakraborty, S.K., 2018. Diet composition of oil sardine, Sardinellalongiceps (Valenciennes, 1847) from Mumbai waters of Maharashtra, India. IJMS 47 (9), 1880–1887. http://nopr.niscair.res.in/handle/123456789/44908.

Akhand, A., Chanda, A., Dutta, S., Manna, S., Hazra, S., Mitra, D., Rao, K.H., Dadhwal, V.K., 2013. Characterizing air-sea CO2 exchange dynamics during winter in the coastal water off the Hugli-Matla estuarine system in the northern Bay of Bengal, India. J. Oceanogr. 69 (6), 687–697. https://doi.org/10.1007/s10872-013-0199-z.

Amin, S.M.N., Rahman, M.A., Haldar, G.C., Mazid, M.A., Milton, D.A., 2008. Catch per unit effort, exploitation level and production of hilsa shad in Bangladesh waters. Asian Fisheries Science 21 (2), 175–187. https://www.researchgate.net/profile/S_M_Nurul_Amin/publication/261993446.

Anh, P.V., Everaert, G., Goethals, P., Vinh, C.T., De Laender, F., 2015. Production and food web efficiency decrease as fishing activity increases in a coastal ecosystem. Estuar. Coast. Shelf Sci. 165, 226–236. https://doi.org/10.1016/j.ecss.2015.05.019.

Arto, I., García-Muros, X., Cazcarro, I., González, M., Markandya, A., 2019. The socioeconomic future of deltas in a changing environment. Sci. Total Environ. 648, 1284–1296. https://doi.org/10.1016/j.scitotenv.2018.08.139.

Barange, M., Merino, G., Blanchard, J.L., Scholtens, J., Harle, J., Allison, E.H., Jennings, S., 2014. Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nat. Clim. Chang. 4, 211–216. https://doi.org/10.1038/NCLIMATE2119.

Impacts of climate change on fisheries and aquaculture - synthesis of current knowledge, adaptation and mitigation options. In: Barange, M., Bahri, T., Beveridge, M., Cochrane, K., Funge-Smith, S., Poulain, F. (Eds.), Fisheries and Aquaculture Technical Paper. No. 627. FAO, Rome (ISBN 978-92-5-130607-9).

Bavinck, M., Chuenpagdee, R., Jentoft, S., Kooiman, J., eds. 2013. Governability in fisheries and aquaculture: theory and applications. Dordrecht, Netherlands, Springer Science. 382 pp. ISBN 978-94-007-6107-0.

Belton, B., Thilsted, S.H., 2014. Fisheries in transition: food and nutrition security implications for the global South. Glob. Food Sec. 3, 59–66. https://doi.org/10.1016/j.gfs.2013.10.001.

Belton, B., van Asseldonk, I.J.M., Thilsted, S.H., 2014. Faltering fisheries and ascendant aquaculture: implications for food and nutrition security in Bangladesh. Food Policy 44, 77–87. https://doi.org/10.1016/j.foodpol.2013.11.003.

Béné, C., Macfadyen, G., Allison, E.H., 2007. Increasing the contribution of small-scale fisheries to poverty alleviation and food security. FAO Fisheries Technical Paper No. 481. FAO, Rome 125 p. http://www.fao.org/docrep/009/a0237e/A0237E00.htm.

Beveridge, M.C., Thilsted, S.H., Phillips, M.J., Metian, M., Troell, M., Hall, S.J., 2013. Meeting the food and nutrition needs of the poor: the role of fish and the opportunities and challenges emerging from the rise of aquaculture. J. Fish Biol. 83 (4), 1067–1084. https://doi.org/10.1111/jfb.12187.

Bhathal, B., 2014. Government-Led Development of India's Marine Fisheries since 1950: Catch and Effort Trends, and Bioeconomic Models for Exploring Alternative Policies. Doctoral dissertation. University of British Columbia https://doi.org/10.14288/1.0103394.

Bladon, A.J., Katherine, M.S., Essam, Y.M., Milner-Gulland, E.J., 2016. Payments for ecosystem services in developing world fisheries. Fish Fish. 17, 839–859. https://doi.org/10.1111/faf.12095.

Blanchard, J.L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J.I., Holt, J., Dulvy, N.K., Barange, M., 2012. Potential consequences of climate change for primary production and fish production in large marine ecosystems. Philos. Trans. R. Soc. B 367, 2979–2989. https://doi.org/10.1098/rstb.2012.0231.

BOBLME, 2010. Status of Hilsa (Tenualosailisha) Management in the bay of Bengal. Bay of Bengal Large Marine Ecosystem Project. BOBLME-2010-Ecology-01. 67. http://aquaticcommons.org/18651/1/BOBLME-2010-Ecology-01.pdf.

BOBP, 1990. Marine Small-Scale Fisheries of West Bengal: An Introduction. Bay of Bengal Programme for Fisheries Development, Madras, India. BOBP/INF/11. http://www.fao.org/3/a-ae489e.pdf.

Bode, A., Hare, J. A., Li, W. K. W., Mora ´n, X. A. G., and Valde ´s, L. 2011. Chlorophyll and primary production in the North Atlantic. In ICES Status Report on Climate Change in the North Atlantic, pp. 77–102. Ed. by P. C. Reid, and L. Valde ´s. ICES Cooperative Research Report, 310. 262 pp.

Bopp, L., Monfray, P., Aumont, O., Dufresne, J.L., Le Treut, H., Madec, G., Terray, L., Orr, J.C., 2001. Potential impact of climate change on marine export production. Glob. Biogeochem. Cycles 15 (1), 81–99. https://doi.org/10.1029/1999GB001256.

Bopp, L., Resplandy, L., Orr, J.C., Doney, S.C., Dunne, J.P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Seferian, R., Tjiputra, J., 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences 10, 6225–6245. https://doi.org/10.5194/bg-10-6225-2013.

Butenschön, M., Clark, J., Aldridge, J.N., Allen, J.I., Artioli, Y., Blackford, J., Bruggeman, J., Cazenave, P., Ciavatta, S., Kay, S., Lessin, G., van Leeuwen, S., van der Molen, J., de Mora, L., Polimene, L., Sailley, S., Stephens, N., Torres, R., 2016. ERSEM 15.06: a generic model for marine biogeochemistry and the ecosystem dynamics of the lower trophic levels. Geosci. Model Dev. 9, 1293–1339. https://doi.org/10.5194/gmd-9-1293-2016.

Cazcarro, I., Arto, I., Hazra, S., Bhattacharya, R., Osei-Wusu Adjei, P., Ofori-Danson, P., et al., 2018. Biophysical and socioeconomic state and links of deltaic areas vulnerable to climate change: Volta (Ghana), Mahanadi (India) and Ganges-Brahmaputra-Meghna (India and Bangladesh). Sustain 10. https://doi.org/10.3390/su10030893.

Census, India, 2011. http://censusindia.gov.in/2011-prov-results/data_files/india/Final_PPT_2011_chapter3.pdf Accessed on: 06.05.2019 (India).

Cheung, W.W.L., Lam, V.W.Y., Pauly, D., 2008. Modelling present and climate-shifted distribution of marine fishes and invertebrates. Fisheries Centre Research Report 16 (3). University of British Columbia, Vancouver https://www.researchgate.net/publication/269576107.

Cheung, W.W.L., Dunne, J., Sarmiento, J.L., Pauly, D., 2011. Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES J. Mar. Sci. 68, 1008–1018. https://doi.org/10.1093/icesjms/fsr012.

Cisneros-Mata, M.A., Mangin, T., Bone, J., Rodriguez, L., Smith, S.L., Gaines, S.D., 2019. Fisheries governance in the face of climate change: assessment of policy reform implications for Mexican fisheries. PLoS One 14 (10). https://doi.org/10.1371/journal.pone.0222317.

Close, C., Cheung, W.W.L., Hodgson, S., Lam, V.W.Y., Watson, R., Pauly, D., 2006. Distribution ranges of commercial fishes and invertebrates. In: Palomares, M.L.D., Stergiou, K.I., Pauly, D. (Eds.), Fishes in Databases and Ecosystems. Fisheries Centre Research Reports. 14 (4). Fisheries Centre, University of British Columbia, Vancouver , pp. 27–37. http://citeseerx.ist.psu.edu/viewdoc/download;jsessionid=0F45C3DF8493B86D31D53E875721215C?doi=10.1.1.298.6052&rep=rep1&type=pdf.

CMFRI, 2008. Research Highlights 2007–2008, Central Marine Fisheries Research Institute. Cochin, India 36 p. http://eprints.cmfri.org.in/6342/1/Annual_report_2007-2008.pdf.

CSE, 2003. Climate Change and Odisha, Factsheet, Global Environmental Negotiations. Available at. http://www.cseindia.org/programme/geg/pdf/Odisha.pdf.

Das, I., Hazra, S., Das, S., Giri, S., Chanda, A., Maity, S., Ghosh, S., 2018. Trophic-level modelling of the coastal waters of the northern Bay of Bengal, West Bengal, India. Fish. Sci. 84 (6), 995–1008. https://doi.org/10.1007/s12562-018-1246-x.

Das, I., Hazra, S., Das, S., Giri, S., Maity, S., Ghosh, S., 2019. Present status of the sustainable fishing limits for Hilsa Shad in the northern Bay of Bengal, India. Proceedings of the National Academy of Sciences, India Section B: Biological Sciences, 1–8 https://doi.org/10.1007/s40011-018-0963-3.

Das, S., Giri, S., Das, I., Chanda, A., Ghosh, A., Mukhopadhyay, A., Akhand, A., Choudhury, S.B., Dadhwal, V.K., Maity, S., Kumar, T.S., 2017. Nutrient dynamics of northern Bay of Bengal (nBoB)—emphasizing the role of tides. Reg. Stud. Mar. Sci. 10, 116–134. https://doi.org/10.1016/j.rsma.2017.01.006.

De, T.K., De, M., Das, S., et al., 2011. Phytoplankton abundance in relation to cultural eutrophication at the land-ocean boundary of Sunderbans, NE coast of Bay of Bengal, India. J. Environ. Stud. Sci. 1 (3), 169–180. https://doi.org/10.1007/s13412-011-0022-3.

Denman, K., Christian, J.R., Steiner, N., Pörtner, H.O., Nojiri, Y., 2011. Potential impacts of future ocean acidification on marine ecosystems and fisheries: current knowledge and recommendations for future research. ICES J. Mar. Sci. 68 (6), 1019–1029. https://doi.org/10.1093/icesjms/fsr074.

DoES, 2016. Odisha at a glance, 2016. Directorate of Economics and Statistics. Govt. of Odisha. http://www.desOdisha.nic.in/pdf/odisha_at_glance_2016.pdf Assessed on 28 September 2018.

DoF, 2016. Handbook of fisheries statistics 2015- 2016. Department of Fisheries. Directorate of Fisheries. Govt. of West Bengal. https://www.wbfisheries.in/files/Statistical%20handbook15-16.pdf.

Doney, S.C., Ruckelshaus, M., Duffy, J.E., Barry, J.P., Chan, F., English, C.A., Galindo, H.M., Grebmeier, J.M., Hollowed, A.B., Knowlton, N., Polovina, J., 2011. Climate change impacts on marine ecosystems. Annual Reviews in Marine Science 4, 1–27. https://doi.org/10.1146/annurev-marine-041911-111611.

Durant, J.M., Hjermann, D.Ø., Ottersen, G., Stenseth, N.C., 2007. Climate and the match or mismatch between predator requirements and resource availability. Clim. Res. 33 (3), 271–283. https://doi.org/10.3354/cr033271.

Dutta, S., Maity, S., Chanda, A., Hazra, S., 2012. Population structure, mortality rate and exploitation rate of Hilsa Shad (Tenualosailisha) in West Bengal Coast of Northern Bay of Bengal, India. World Journal of Fish and Marine Sciences 4 (1), 54–59. https://doi.org/10.5829/idosi.wjfms.2012.04.01.6196.

Dutta, S., Maity, S., Bhattacharyya, S.B., Sundaray, J.K., Hazra, S., 2014. Diet composition and intensity of feeding of Tenualosailisha (Hamilton, 1822) occurring in the northern Bay of Bengal, India. Proceedings of the Zoological Society. 67. Springer, India, pp. 33–37. https://doi.org/10.1007/s12595-013-0066-3.

Dutta, S., Chakraborty, K., Hazra, S., 2016, June. The status of the marine fisheries of West Bengal coast of the northern Bay of Bengal and its management options: a review. Proceedings of the Zoological Society 69 (1), 1–8 Springer India. https://doi.org/10.1007/s12595-015-0138-7.

FAO, 2015. Food and Agriculture Organization of the United Nations, 2015. National Aquaculture Sector Overview – India. http://www.fao.org/fishery/countrysector/naso_india/en#tcN70019 Assessed on 30 September, 2018.

FAO, 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the Sustainable Development Goals. Rome. Licence: CC BY-NC-SA 3.0 IGO. http://eprints.cmfri.org.in/8998/1/India_report_full.pdf.

Fernandes, J.A., 2018. Climate change impacts, vulnerabilities and adaptations: Southern Asian fisheries in the Arabian Sea, Bay of Bengal and East Indian Ocean. In: Barange, M., Bahri, T., Beveridge, M., Cochrane, K., Funge-Smith, S., Poulain, F. (Eds.), Projected Changes in Global and National Potential Marine Fisheries Catch under Climate Change Scenarios in the Twenty-First Century. FAO Fisheries and Aquaculture Technical Paper , p. 629. https://www.researchgate.net/publication/326850316.

Fernandes, J.A., Cheung, W.W., Jennings, S., Butenschön, M., Mora, L., Frölicher, T.L., Barange, M., Grant, A., 2013. Modelling the effects of climate change on the distribution and production of marine fishes: accounting for trophic interactions in a dynamic bioclimate envelope model. Glob. Chang. Biol. 19, 2596–2607. https://doi.org/10.1111/gcb.12231.

Fernandes, J.A., Kay, S., Hossain, M.A., Ahmed, M., Cheung, W.W., Lazar, A.N., Barange, M., 2016. Projecting marine fish production and catch potential in Bangladesh in the 21st century under long-term environmental change and management scenarios. ICES J. Mar. Sci. 73 (5), 1357–1369. https://www.researchgate.net/publication/283420581.

Froese, R., Zeller, D., Kleisner, K., Pauly, D., 2012. What catch data can tell us about the status of global fisheries. Mar. Biol. 159, 1283–1292. https://link.springer.com/content/pdf/10.1007%2Fs00227-012-1909-6.pdf.

Gaylord, B., Gaines, S.D., 2000. Temperature or transport? Range limits in marine species mediated solely by flow. Am. Nat. 155 (6), 769–789. https://doi.org/10.1086/303357.

Ghosh, S., Muktha, M., Rao, M.H., Behera, P.R., 2015. Assessment of stock status of the exploited fishery resources in northern Bay of Bengal using landed catch data. Indian Journal of Fisheries 62 (4), 23–30. https://www.researchgate.net/profile/Pralaya_Behera/publication/289196671.

GoI, 2019. Handbook on Fisheries Statistics. Department of Animal Husbandry, Dairying and Fisheries. Available at. http://dof.gov.in/sites/default/filess/Handbook%20on%20FS%202018.pdf.

Goyal, T.M., Mukherjee, A., Kapoor, A., 2017. India's exports of food products: food safety related issues and way forward. Working Paper No. 345. Indian Council for Research on International Economic Relations (ICRIER) Available at. https://icrier.org/pdf/Working_Paper_345.pdf.

Harrod, C., Ramírez, A., Valbo-Jørgensen, J., Funge-Smith, S., 2018. How climate change impacts inland fisheries. In: Barange, M., Bahri, T., Beveridge, M., Cochrane, K., Funge-Smith, S., Poulain, F. (Eds.), Projected Changes in Global and National Potential Marine Fisheries Catch under Climate Change Scenarios in the Twenty-First Century. FAO Fisheries and Aquaculture Technical Paper , p. 629. https://www.researchgate.net/publication/326274448.

Hilborn, R., Walters, C.J., 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Chapman and Hall, New York https://doi.org/10.1007/BF00042883.

Holt, J.T., James, I.D., 2001. An s coordinate density evolving model of the northwest European continental shelf 1, model description and density structure. J. Geophys. Res. 106, 14015–14,034. https://doi.org/10.1029/2000JC000304.

Hornby, C., Bhathal, B., Pauly, D., Zeller, D., 2015. Reconstruction of India's marine fish catch from 1950-2010. Fisheries Centre, The University of British Columbia Working Paper #2015 - 77.

Hossain, M.S., Hein, L., Rip, F.I., Dearing, J.A., 2013. Integrating ecosystem services and climate change responses in coastal wetlands development plans for Bangladesh. Mitig. Adapt. Strateg. Glob. Chang. 20, 241–261. http://eprints.cmfri.org.in/8435/1/Global_Climate_Change_Vivekanandan_89-92.pdf.

IPCC, 2013. In: Stocker, T.F., et al. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. https://doi.org/10.1017/CBO9781107415324 1535 pp.

IPCC, 2014a. In: Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland 151 pp. https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf.

IPCC, 2014b. Climate change 2014: impacts, adaptation, and vulnerability. Part B: regional aspects. In: Barros, V.R., Field, C.B., Dokken, D.J., Mastrandrea, M.D., Mach, K.J., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 688. https://doi.org/10.1017/CBO9781107415386.

IPCC, 2014c. Annex II: Glossary. In: Mach, K.J., Planton, S., von Stechow, C. (Eds.), In Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report on the Intergovernmental Panel on Climate Change. Core writing team, R.K. Pachauri and L.A. Meyer, eds. Geneva, Intergovernmental Panel on Climate Change , pp. 117–130. https://www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_Glossary.pdf.

Janes, T., McGrath, F., Macadam, I., Jones, R., 2019. High-resolution climate projections for South Asia to inform climate impacts and adaptation studies in the Ganges-Brahmaputra-Meghna and Mahanadi deltas. Sci. Total Environ. 650, 1499–1520. https://doi.org/10.1016/j.scitotenv.2018.08.376.

Jasper, B., Kizhakudan, J.K., Vivekanandan, E., Mohamad Kasim, H., 2009. Effect of temperature and nutrients on growth of marine algae. In: Vivekanandan, E., et al. (Eds.), Marine Ecosystems Challenges and Opportunities, Book of Abstracts. Marine Biological Association of India, February, pp. 9–12.

Jennings, S., Me ́lin, F., Blanchard, J. L., Forster, R. M., Dulvy, N. K., and Wilson, R. W. 2008. Global-scale predictions of community and ecosystem properties from simple ecological theory.Proc. R. Soc. London, Ser. B, 275: 1375–1383. doi:https://doi.org/10.1098/rspb.2008.0192.

Jin, L., Whitehead, P.G., Rodda, H., Macadam, I., Sarkar, S., 2018. Simulating climate change and socio-economic change impacts on flows and water quality in the Mahanadi River system, India. Sci. Total Environ. 637–638, 907–917. https://doi.org/10.1016/j.scitotenv.2018.04.349.

Kalikoski, D.C., Jentoft, S., Charles, A., Herrera, D.S., Cook, K., Béné, C., Allison, E.H., 2018. Understanding the impacts of climate change for fisheries and aquaculture: applying a poverty lens. In: Barange, M., Bahri, T., Beveridge, M., Cochrane, K., Funge-Smith, S., Poulain, F. (Eds.), Projected Changes in Global and National Potential Marine Fisheries Catch under Climate Change Scenarios in the Twenty-First Century. FAO Fisheries and Aquaculture Technical Paper, p. 629 (ISBN 978-92-5-130607-9).

Kebede, A.S., Nicholls, R.J., Allan, A., Arto, I., Cazcarro, I., Fernandes, J.A., Hill, C.T., Hutton, C.W., Kay, S., Lázár, A.N., Macadam, I., 2018. Applying the global RCP–SSP–SPA scenario framework at sub-national scale: a multi-scale and participatory scenario approach. Sci. Total Environ. 635, 659–672. https://doi.org/10.1016/j.scitotenv.2018.03.368.

Kooiman, J., Bavinck, M., Jentoft, S., Pullin, R., 2005. Fish for Life – Interactive Governance for Fisheries. Amsterdam University Press, Amsterdam 432 pp. http://www.jstor.org/stable/j.ctt46mzgb.

Kumar, S.T., Shivani, P., 2014. Marine fisheries; its current status, sustainable management and socio-economic status of the marine fishers of Odisha, through Indian Marine Policy: a case study. Research Journal of Animal, Veterinary and Fishery Sciences 2 (7), 10–19 (ISSN 2320 – 6535).

Laane, R.W.P.M., Brockmann, U., Liere, L.V., Bovelander, R., 2005. Immission targets for nutrients (N and P) in catchments and coastal zones: a North Sea assessment. Estuar. Coast. Shelf Sci. 62 (3), 495–505. https://doi.org/10.1016/j.ecss.2004.09.013.

McAllister, M.K., Pikitch, E.K., Babcock, E.A., 2001. Using demographic methods to construct Bayesian priors for the intrinsic rate of increase in the Schaefer model and implications for stock rebuilding. Can. J. Fish. Aquat. Sci. 58, 1871–1890. https://doi.org/10.1139/f01-114.

Miller, D.D., Ota, Y., Sumaila, U.R., Cisneros-Montemayor, A.M., Cheung, W.W., 2018. Adaptation strategies to climate change in marine systems. Glob. Chang. Biol. 24 (1), e1–e14. https://doi.org/10.1111/gcb.13829.

Mohanty, B., Vivekanandan, E., Mohanty, S., Mahanty, A., Trivedi, R., Tripathy, M., Sahu, J., 2017. The impact of climate change on marine and inland fisheries and aquaculture in India. Climate Change Impacts on Fisheries and Aquaculture: a Global Analysis 2, 569–601. https://doi.org/10.1002/9781119154051.ch17.

Morán, X.A.G., López-Urrutia, A., Calvo-Díaz, A., Li, W.K.W., 2010. Increasing importance of small phytoplankton in a warmer ocean. Glob. Change Biol. 16 (3), 1137–1144. https://doi.org/10.1111/j.1365-2486.2009.01960.x.

Mukhopadhyay, S.K., Biswas, H., De, T.K., Jana, T.K., 2006. Fluxes of nutrients from the tropical river Hooghly at the land–ocean boundary of Sundarbans, NE coast of bay of Bengal, India. J. Mar. Syst. 6, 9–21. https://doi.org/10.1016/j.jmarsys.2006.03.004.

Nicholls, R.J., Hutton, C.W., Lazar, A.N., Rahman, M., Salehin, M., Ghosh, T., 2013. Understanding climate change and livelihoods in coastal Bangladesh. Hydrolink 2, 40. https://www.researchgate.net/publication/313395749.

NITI Aayog, 2018. SDG India Index. Baseline Report, 2018. https://www.niti.gov.in/writereaddata/files/SDX_Index_India_21.12.2018.pdf Accessed on: May, 2019 (India).

O'Meara, D., Harper, S., Perera, N., Zeller, D., 2011. Reconstruction of Sri Lanka's fisheries catches: 1950-2008. In: Harper, S., Zeller, D. (Eds.), Fisheries Catch Reconstruction. Islands, Part II. Fisheries Centre Research Reports, No. 4. 19. University of British, Columbia, Vancouver, pp. 85–96.

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., et al., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Chang. 122, 387–400. https://doi.org/10.1007/s10584-013-0905-2.

Panda, U.C., Sundaray, S.K., Rath, P., Nayak, B.B., Bhatta, D., 2006. Application of factor and cluster analysis for characterization of river and estuarine water system— a case study, Mahanadi River (India). J. Hydrol. 331 (3–4), 434–445. https://doi.org/10.1016/j.jhydrol.2006.05.029.

Parry, M., Parry, M.L., Canziani, O., Palutikof, J., Van der Linden, P., Hanson, C., 2007. Climate Change 2007- Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC. 4. Cambridge University Press. https://www.ipcc.ch/site/assets/uploads/2018/03/ar4-wg2-intro.pdf.

Pauly, D., 1980. On the interrelationships between natural mortality, growth parameters and mean environmental temperature in 175 fish stocks. ICES J. Mar. Sci. 39, 175–192. https://doi.org/10.1093/icesjms/39.2.175.

Pauly, D., 2010. Gasping fish and panting squids: oxygen, temperature and the growth of water-breathing animals. Excellence in Ecology 22, 216.

Pauly, D., Hilborn, R., Branch, T.A., 2013. Fisheries: does catch reflect abundance? Nature 494, 303–306. https://www.nature.com/articles/494303a.

PCA, 2011. Primary Census Abstract. Census of India. Census of West Bengal. Census of Odisha. Directorate of Census Operations, Government of India, New Delhi http://censusindia.gov.in/pca/.

Perry, A.L., Low, P.J., Ellis, J.R., Reynolds, J.D., 2005. Climate change and distribution shifts in marine fishes. Science 308 (5730), 1912–1915. https://science.sciencemag.org/content/sci/308/5730/1912.full.pdf.

Perry, R.I., Ommer, R.E., Barange, M., Jentoft, S., Neis, B., Sumaila, U.R., 2011. Marine social–ecological responses to environmental change and the impacts of globalization. Fish Fish. 12 (4), 427–450. https://doi.org/10.1111/j.1467-2979.2010.00402.x.

Queirós, A.M., Fernandes, J., Genevier, L., Lynam, C.P., 2018. Climate change alters fish community size-structure, requiring adaptive policy targets. Fish Fish. 19 (4), 613–621. https://doi.org/10.1111/faf.12278.

Raman, R.K., Sathianandan, T.V., Sharma, A.P., Mohanty, B.P., 2017. Modelling and forecasting marine fish production in Odisha using seasonal ARIMA model. National Academy Science Letters 40 (6), 393–397. https://doi.org/10.1007/s40009-017-0581-2.

Riahi, K., Van Vuuren, D.P., Kriegler, E., Edmonds, J., O'neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., 2017. The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Chang. 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Rogers, L.A., Griffin, R., Young, T., Fuller, E., Martin, K.S., Pinsky, M.L., 2019. Shifting habitats expose fishing communities to risk under climate change. Nat. Clim. Chang. 9 (7), 512–516. https://doi.org/10.1038/s41558-019-0503-z.

Sachs, J., Schmidt-Traub, G., Kroll, C., Lafortune, G., Fuller, G., 2019. Sustainable Development Report 2019. Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), New York.

Schaefer, M., 1954. Some aspects of the dynamics of populations important to the management of the commercial marine fisheries. Bull I-ATTC 1, 27–56. http://aquaticcommons.org/3530/1/Vol._1_no._2.pdf.

Sibert, J.R., Hampton, J., Fournier, D.A., Bills, P.J., 1999. An advection–diffusion–reaction model for the estimation of fish movement parameters from tagging data, with application to skipjack tuna (*Katsuwonus pelamis*). Can. J. Fish. Aquat. Sci. 56 (6), 925–938. https://doi.org/10.1139/f99-017.

Sparre, P., Venema, S.C., 1992. Introduction to tropical fish stock assessment. Part 1. Manual. FAO Fisheries Technical Paper 306. FAO, Rome https://iwlearn.net/resolveuid/bae3ae95-2b5c-4969-ae69-cc627d4a5c89.

Stephen, R., 2008. Zooplankton reflecting global warming. Winter School on Impact of Climate Change on Indian Marine Fisheries Held at CMFRI Cochin 18.1. 2008 to 7.2. 2008. http://eprints.cmfri.org.in/5392/1/41.pdf.

Szabo, S., Renaud, F., HossainMd, S., Sebesvari, Z., Matthews, Z., Foufoula-Georgiou, E., Nicholls, R.J., 2015. Sustainable development goals offer new opportunities for tropical delta regions. Environ. Sci. Policy Sustain. Dev. 57 (4), 16–23. https://doi.org/10.1080/00139157.2015.1048142.

Taylor, K., Stouffer, R., Meehl, G., 2012. An overview of CMIP5 and the experiment design. Bull. Amer. Meteor. Soc 93 (4), 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1.

Tessler, Z.D., Vörösmarty, C.J., Grossberg, M., Gladkova, I., Aizenman, H., Syvitski, J.P.M., Foufoula-Georgiou, E., 2015. Profiling risk and sustainability in coastal deltas of the world. Science 349 (6248), 638–643. https://science.sciencemag.org/content/sci/349/6248/638.full.pdf.

Thilsted, S.H., Thorne-Lyman, A., Webb, P., Bogard, J.R., Subasinghe, R., Phillips, M.J., Allison, E.H., 2016. Sustaining healthy diets: the role of capture fisheries and aquaculture for improving nutrition in the post-2015 era. Food Policy 61, 126–131. https://doi.org/10.1016/j.foodpol.2016.02.005.

Toufique, K.A., Belton, B., 2014. Is aquaculture pro-poor? Empirical evidence of impacts on fish consumption in Bangladesh. World Dev. 64, 609–620. https://doi.org/10.1016/j.worlddev.2014.06.035.

UN General Assembly, 2015. Transforming our World: The 2030 Agenda for Sustainable Development. A/RES/70/1. https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf.

Vázquez-Rowe, I., 2020. A fine kettle of fish: the fishing industry and environmental impacts. Curr. Opin. Environ. Sci. Heal. 13, 1–5. https://doi.org/10.1016/j.coesh.2019.08.004.

Vivekanandan, E., 2010. Impact of Climate Change in the Indian Marine Fisheries and the Potential Adaptation Options. FAO Accessed on 22/07/2016 at. http://eprints.cmfri.org.in/8754/1/E_Vivekanandan.pdf.

Vivekanandan, E., Rajagopalan, M., Pillai, N.G.K., 2009. Recent trends in sea surface temperature and its impact on oil sardine. In: Aggarwal, P.K. (Ed.), Impact, Adaptation and Vulnerability of Indian Agriculture to Climate Change. Indian Council of Agricultural Research, New Delhi http://eprints.cmfri.org.in/8435/1/Global_Climate_Change_Vivekanandan_89-92.pdf.

Von Bertalanffy, L., 1951. General system theory; a new approach to unity of science. 1. Problems of general system theory. Hum. Biol. 23 (4), 302.

Walters, C., Pauly, D., Christensen, V., 1999. Ecospace: prediction of mesoscale spatial patterns in trophic relationships of exploited ecosystems, with emphasis on the impacts of marine protected areas. Ecosystems 2 (6), 539–554. https://doi.org/10.1007/s100219900101.

Whitehead, P.G., Jin, L., Macadam, I., Janes, T., Sarkar, S., Rodda, H.J.E., Sinha, R., Nicholls, R.J., 2018. Modelling impacts of climate change and socio-economic change on the Ganga, Brahmaputra, Meghna, Hooghly and Mahanadi river systems in India and Bangladesh. Sci. Total Environ. 636, 1362–1372. https://doi.org/10.1016/j.scitotenv.2018.04.362.

Winder Rossi, N., Spano, F., Sabates-Wheeler, R., Kohnstamm, S., 2017. Socialprotection and Resilience. Supporting Livelihoods in Protracted Crises, Fragile and Humanitarian Context. FAO Position Paper. FAO. Institute for Development Studies, Rome http://www.fao.org/3/a-i7606e.pdf.

Zeller, D. and Pauly, D., 2015. Reconstructing marine fisheries catch data. *Catch reconstruction: concepts, methods and data sources*. *Online Publication*. *Sea Around Us* (www.seaaroundus.org). *University of British Columbia*.