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CLIMATE CHANGE: CHALLENGING THE SUSTAINABILITY OF MARINE FISHERIES AND ECOSYSTEMS

Vivekanandan, E.

Madras Research Centre of Central Marine Fisheries Research Institute, Chennai 600 028

E-mail: evivekanandan@hotmail.com

Abstract: Changes in the important oceanic climate features such as sea surface temperature, sea level, pH, and rainfall are becoming evident as a result of climate change. In this review, the influence of the primary factor, the water temperature on the biological systems is presented. Seawater temperature influences biological systems at four levels: organismal, population, community and ecosystem. At organismal level, temperature has direct influence on two vital life traits of fish, namely, food utilisation and spawning. Growth rate of fish increases with increasing temperature within the optimal temperature window. It is likely that the food utilization parameters may be operating at an elevated level in fishes at higher temperatures, demanding higher food supply to attain faster growth rate. Fishes may change their phenology of reproductive activity to adapt to elevated temperatures for spawning and larval survival. At population level, temperature and other factors related to climate change may strongly influence distribution and abundance, evidences for which are accumulating in Indian seas. As the tolerance and adaptation capacities are different between species, the species that adapt and gain from warming are increasingly becoming dominant. On the other hand, those species, which are already at the threshold limits are vulnerable and lose to adaptable ones. At community level, this is reflected as changes in species composition over the years. All these changes have the potential to alter the structure and function of ecosystems. Habitat destruction, pollution, energy production, mining, fisheries, aquaculture, and invasive species are all affecting marine ecosystems and may exacerbate the effects of climate change. Effectively reducing climate change and other human-related threats requires integrated management actions with the goal of increasing adaptive capacity of ecosystems. As a first step, robust indicators need to be developed to understand the changes at ecosystem level. With regard to fisheries, the changes pose problems on the effectiveness of fisheries management measures. Reducing fishing pressure would be a major step to increase the capacity of fish stocks to adapt to environmental changes. It is important that a concerted effort is made to address the issues related to sustainability of tropical marine fisheries and ecosystems by considering climate change as a component of a suite of anthropogenic interventions.

Key words: Global warming, fish population, community, ecosystem, adaptation

INTRODUCTION

World marine fish catches are stagnant at around 80 million tonnes for the last 20 years (FAO, 2012). On the contrary, Indian marine fisheries are showing a consistently increasing trend, with the catch almost doubling from 1.8 mt in 1990 to 3.5 mt in 2011 (CMFRI, 2011). This increase is mainly due to increase in fishing efficiency and extension of fishing effort to distant fishing grounds. It appears that the increase in catches is masking the status of fish stocks, as several stocks are reported as overfished (Srinath *et al.,* 2004). Moreover, the catches are approaching the potential yield estimate of 4.32 mt (MoA, 2011), cautioning against any further attempt to increase the catches. Overexploitation, habitat degradation and pollution have been identified as major issues challenging the sustainability of marine ecosystems and fisheries in India, and in the northern Indian Ocean as well. The root causes are high human population densities in the countries bordering northern Indian Ocean and a large proportion of dependent population on coastal resources, especially fish. Added to these issues is the ominous threat of climate change to marine fisheries and ecosystems (Vivekanandan, 2011; Vivekanandan *et al.,* 2012). Today, the global fisheries community has recognized the multiple and interlinked challenges the fisheries sector is facing.

OUR UNDERSTANDING

Fishes are projected to respond to climate in different ways. From changes in the distribution patterns of migratory fishes associated with the interannual or El Niño-scale variation in the ocean environment, climate change can be expected to affect reproduction, recruitment and growth of fish species. Climate change may also have other impacts, including cyclic changes in the production level of marine ecosystems in ways that may favour one species or group over another. The Intergovernmental Panel on Climate Change in its 4th Assessment Report (IPCC, 2007) concluded that climate change and variability is likely to modify the productivity and distribution of marine fisheries, with unpredictable consequences. In particular, the productivity of colder water species may be reduced in subtropical waters and the distribution of spawning areas and fisheries may be affected. Such species are unlikely to be able to extend their ranges further towards the poles due to the lack of suitable habitat (Sumaila *et al.,* 2011). On the other hand, the productivity of warmer water species may be enhanced in subtropical waters and distribution of more tropical species may expand poleward. Cheung *et al.* (2009) used models that linked geographic range of species with ocean conditions to predict changes in potential catch under low and high greenhouse gas emissions scenarios. They found that globally, the maximum total catch potential in the year 2055 would remain essentially unchanged from current levels under both scenarios. But catch potential changed within regions, and the magnitude of that change was greater under the high emissions scenario. In general, maximum possible catch increased at higher latitudes by 30 to 70 percent, and decreased in the tropics by about 40 percent. This change may have large implications for global food security, as more than 50% of global catches comes from the tropics (FAO, 2012).

Increasing climate variability will make fisheries management, and the forecasts of fisheries production and ecosystem sustainability more challenging. Considerable progress has been made through research on the role of climate variability (such as El Niño – Southern Oscillation events) in influencing biological processes, but information on how climate change may impact fish stocks and ecosystems is scarce especially for tropical region. A better understanding of climate and its impacts on marine fisheries is critical to the management of these valuable resources for subsistence and market-based economies. Hence, there is an urgent need to improve our ability to assess the likely consequences of climate change for fisheries. The challenges to achieve this goal are many. (i) The key variables expected to drive climate change impacts on fisheries are changes in temperature, ocean currents, winds, nutrient supply, rainfall, ocean chemistry and extreme weather conditions. In India, we do not have seamless time series data on these parameters. (ii) Long-term records of abundance for most species in Indian fisheries are limited to historical commercial landings. However, these data lack spatial resolution. (iii) Fishing and other anthropogenic factors primarily and jointly influence fish abundance, and delineating climate change from this suite of attributes is difficult and may not be realistic. (iv) Most fisheries

Table 1. Changes in climate features during the period 1970-2010 and predicted changes (with mean data for the years 1970-2010 as base values) in the years 2035, 2050 and 2100 in the Indian seas

Climate features	1970-2010	2035	2050	2100
Sea surface temperature (°C)	+ 0.2[a]	+ 0.5 to 1.0[b]	+ 1.5[b]	+ 2.0 to 2.5[b]
Sea level rise (cm)	+ 8[C]	+ 10 to 15[b]	+ 20 to 40[b]	+ 50 to 70[b]
Surface aragonite saturation state (Ωarag)	+4.5[d]	4.0 to 4.5[d]	3.5 to 4.0[d]	3 to 3.5[d]
Rainfall	No significant trend[b]	8 to 10% increase[b]		

[a]International Comprehensive Ocean- Atmosphere Data Set (www.cdc.noaa.gov); [b] IPCC A2 scenario; [c]Unnikrishnan and Shankar (2007); [d]measure of ocean acidification from Fabry *et al.* (2008)

and their captured species are not amenable to experimental manipulation, and so climate change impacts cannot be readily measured as for some terrestrial or freshwater systems (Hobday *et al.,* 2008). This makes climate related trends in fish abundance difficult to detect.

Observed Climate-related Physical Changes

Changes in the important oceanic climate features such as sea surface temperature (SST), sea level, pH, and rainfall are becoming evident as a result of climate change (Table 1). Analysing the data on SST obtained from International Comprehensive Ocean – Atmosphere Data Set (ICOADS) (www.cdc.noaa.gov) and 9-km resolution monthly SST obtained from Advanced Very High Resolution Radiometers (AVHRR) satellite data (provided by the NOAA/NASA at http://podaac.jpl.nasa.gov/), it has been found that the SST increased in the Indian seas, by 0.2°C along the northwest (NW), southwest (SW) and northeast (NE) coasts, and by 0.3°C along the southeast (SE) coast during the 45 year period from 1961 to 2005. The SST showed peaks at an interval of about ten years (1969-70, 1980, 1987-88, 1997-98) during 1961-2005, and the decadal number of SST anomalous ($^+$ 1 or $^-$ 1 deviation from the 45-year mean) months increased. Off Kerala, for example, only 16% of the months were SST anomalous during 1961-1970, but 44% during 2001-2005 (Vivekanandan *et al.,* 2009a).

The current understanding is that ocean warming plays a major role in sea level rise, intensified cyclone activity and heightened storm surges. The mean global rate of sea level rise during the period 1970-2010 was nearly 8 cm, which is 10-fold higher than the average of the past several millennia. Under different emission scenarios, it is predicted that the sea level increase would be 50 to 70 cm by 2100 (Table 1).

Climate Change Impacts on Marine Fisheries

Climate change influences biological systems at four levels: organismal, population, community and ecosystem (Fig. 1). The effects of climate change on these four levels can be direct, through changing water temperatures, the length and frequency of hypoxia events, through ongoing ocean acidification trends or through shifts in hydrodynamics (such as currents and stratification) and sea level (Portner and Peck, 2010). In this review, however, the influence of only the primary factor, the water temperature on the four levels of biological systems is presented.

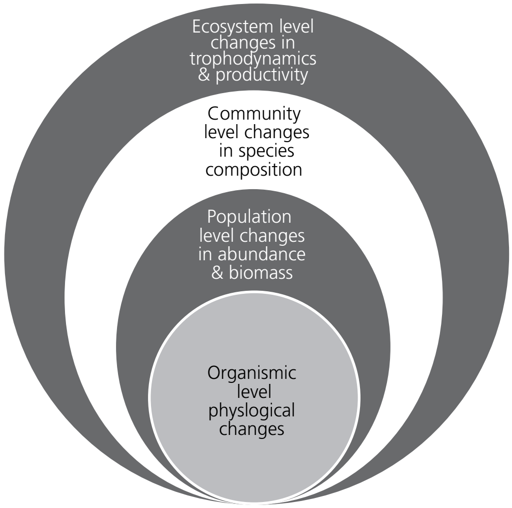

Fig. 1. Temperature-induced changes at different levels of biological organisations in marine ecosystems

IMPACT AT ORGANISMAL LEVEL

For the reason that temperature is the single most important environmental factor directly affecting molecular, biochemical and physiological processes, the increase in temperature is likely to bring about a host of changes in organismal attributes particularly in poikilotherms such as invertebrates and fishes (Strussmann *et al.,* 2010). Fishes can often perceive temperature changes of < 0.5°C (Murray, 1971). Larval fishes are usually more sensitive than adults to temperature, and are more vulnerable to climate change.

Tolerance

Portner and Peck (2010) suggested that extreme temperature limits and associated tolerance ranges within and among fish species change with latitude of the population. The range in tolerable temperatures is most narrow for fishes inhabiting high latitudes and relatively narrow for species at low latitude. In contrast, the tolerance range tends to be widest for fishes inhabiting mid-latitudes where seasonal differences in temperatures are, on average, largest. Tropical fishes inhabiting 3 to 23° N or S latitudes have the capacity to tolerate critical maximum temperature ranging from 36 to 44.5°C depending on acclimation temperature (Portner and Peck, 2010). Hence, the survival of tropical fishes may not be directly affected by increase in temperature, as the temperature is not expected to reach up to that level. However, the constraint is on life processes such as growth and reproduction. Temperature has direct influence on two vital life traits of fish, namely, food utilisation and spawning. Changes in these two traits can cause fluctuations in population biomass and recruitment.

Food Utilization

Fishes are in intimate connection with the surrounding environment, and because their body temperature usually remains within 1- 2° C of the ambient temperature, their energetic process is greatly influenced by water temperature (Graham and Harrod, 2009).

According to the second law of thermodynamics, the physiological effects of bioenergetics budget at organismal level can be expressed by the following pathway:

$$C = G + R + E + F$$

where C = food consumption, G = growth, R = respiration, E = nitrogenous excretion, and F = faecal material (Pandian and Vivekanandan, 1985, 1990). Rates of these variables are affected by a number of factors, including temperature. Balanced energy budgets provide an opportunity to gain an insight into the effects of environmental changes at the level of an individual. Sensitivity to temperature extremes rises when energy gained from C is much less than that lost via R, E and F. Above the lower threshold, when C is maximum (well-fed fishes), growth rates increase with increasing temperature until an optimal temperature is reached. With further increases in temperature, G often rapidly declines until mortality occurs. At sub-optimal high temperatures, fishes cannot consume enough food to meet increasing metabolic costs. Losses in appetite occur at the highest temperatures, rapidly leading to mortality (Portner and Peck, 2010).

Vivekanandan and Pandian (1977) demonstrated that the freshwater fish *Ophiocephalus striatus* collected from the field with water temperature of 27°C and acclimated to different temperatures in the laboratory, increased the feeding, metabolic and conversion rates to the maximum with increasing temperature up to 32°C, but decreased thereafter (Fig. 2). Considering that the annual average water temperature will be increasing from 27°C towards 32°C in future, it is likely that

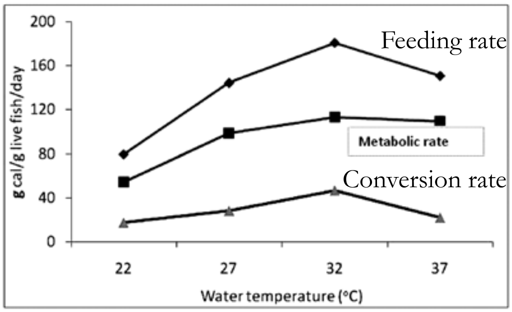

Fig. 2. Rates of food utilization parameters altered by water temperature in the freshwater fish *Ophiocephalus striatus* (modified from Vivekanandan and Pandian, 1977)

the food utilization parameters may be operating at an elevated levels in fishes, demanding higher food supply to achieve faster growth rate.

If variations in the magnitude of growth in relation to temperature are predictable, its consequences might be discernible in life history strategies or in physiological adaptations of fishes. A cursory examination of literature indicates that growth rates of teleosts inhabiting different latitudes increased from high to low latitudes, relative to temperature. Consolidating data available on 30 marine, brackishwater and freshwater fish species distributed in different latitudinal positions, Houde (1989) showed that the growth rate of fishes increased at higher ambient temperature from high to low latitudes. However, there was no significant relationship between temperature and the proportion of growth derived from ingested food (conversion efficiency, K_1). The K_1 remained at around 20% irrespective of temperature. Thus, to attain the expected growth rate, ingestion must increase with temperature. The result confirms that tropical fish or those living at high summer temperatures must ingest relatively large amounts of food to grow at average rates. The metabolic rates would also increase proportionately at elevated temperatures.

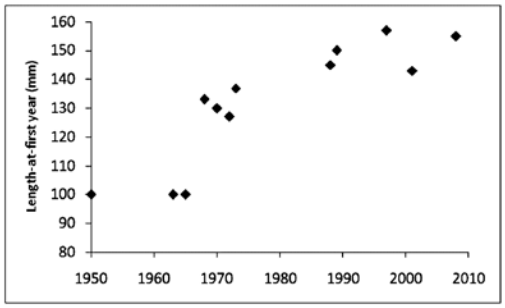

Fig. 3. Length attained by the oil sardine *Sardinella longiceps* at age 1 year along southwest coast of India; the estimated values for different years were collected from Devaraj *et al.* (1997) and CMFRI (2008, 2009)

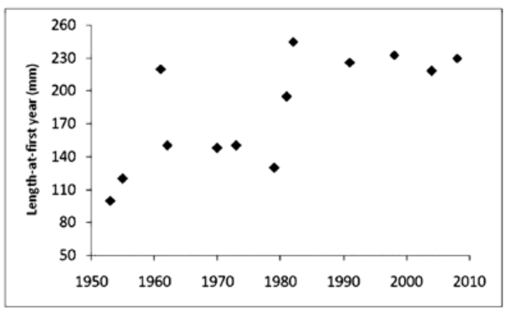

Fig. 4. Length attained by Indian mackerel *Rastrelliger kanagurta* at age 1 year along southwest coast of India; the estimated values for different years were collected from Devaraj e*t al.* (1997) and CMFRI (2008, 2009) proportionately at elevated temperatures.

For Indian fishes, energy budgets at organismal level are available for a number of freshwater species (Pandian and Vivekanandan, 1985, 1990). However, similar studies on marine species are almost non-existent. Sensitivity and difficulties in maintaining at confined laboratory conditions have hampered attempts to construct energy budgets of marine fishes at organismal level. However, there are several estimates of growth of marine fishes by collecting samples from natural populations in the Indian seas. For a few commercially important fish species such as the oil sardine *Sardinella longiceps,* Indian mackerel *Rastrelliger kanagurta* and threadfin bream *Nemipterus japonicus,* growth has been estimated from time-time by different researchers based on length frequency analysis from samples collected at landing centres. Consolidation and analysis of these publications indicate that the growth rate of all these three species has increased over long time-periods. From von Bertalanffy growth equation, it is estimated that the small pelagic *S. longiceps* attained around 100 mm during 1950-1965, but 140-155 mm during 1990-2008 at the end of first year of life along southwest coast of India (Fig. 3). Another dominant small pelagic along the southwest coast, *R. kanagurta* attained 100 to 120 mm at age 1 during 1953-1955, but more than 225 mm in the year 1980 and thereafter (Fig. 4).

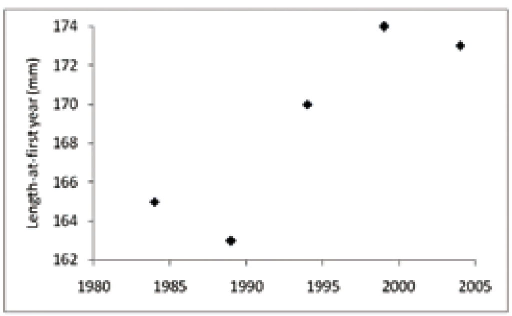

Fig. 5. Length attained by threadfin bream *Nemipterus japonicus* at age 1 year along Chennai coast; each value represents growth during five-year time periods during 1980-2004 estimated from length frequency data

Use of computer software packages such as ELEFAN and FiSAT for growth estimation using length frequency started in the mid-1980s in India. Estimates from these packages, in general, yielded higher growth values. However, a closer look of Figures 3 and 4 suggests that the higher growth estimates may not be due to use of computer packages alone. Considering the year 1985 (when software package was introduced) as a cut-off year, it could be seen that the growth rate within the pre-as well as post-software package periods increased in the case of both the species. To confirm this, an analysis was made using ELEFAN and FiSAT on the length frequency data available continuously for 25 years from 1980 to 2004 for the threadfin bream *N. japonicus* along Chennai coast. Categorising the period into 5-year time zones, growth estimate for each 5-year period showed that *N. japonicus* attained 160-165 mm at age 1 during 1980-1989, but about 175 mm during 1995-2004 (Fig. 5). These results suggest that the growth is at an enhanced level in the later years. Perhaps enhanced growth may continue until the optimum temperature limit is reached. It is not clear if increased fishing pressure would have contributed to enhanced growth in later years. In this review, a correlation with increasing seawater temperature and growth has not been attempted. A modeling approach on growth projection from predicted seawater warming under different IPCC scenarios will be rewarding. It is important that the model should incorporate the impact of fishing, on the growth performance of fish in the natural populations.

Reproduction

Temperature is one of the main environmental factors influencing the reproductive system in fishes. Even small changes in temperature can affect gonadal development and function (Bromage *et al.,* 2001; Pankhurst and Porter, 2003). Simulations show that a 1°C drop in water temperature during vitellogenesis delays spawning in the Atlantic cod *Gadus morhua* by 8 to 10 days (Kjesbu, 1994). Elevated temperatures beyond optimum range inhibit ovarian oestrogen production.

In addition to direct effects on embryonic duration and egg survival, temperature also influences length-at-first maturity, fecundity, size at hatching, developmental rate, larval duration and survival. A companion effect of marine climate change is ocean acidification, which may pose a significant threat through its capacity to alter larval behaviour and impair sensory capabilities. This, in turn, impacts population replenishment and connectivity patterns of marine fishes.

In climate change research, understanding how ambient temperature changes influence the timing of life history events such as spawning is a key area. Phenology, the study of annually recurring life cycle events such as spawning, can provide particularly sensitive indicators of climate change (Hughes, 2000). Studies on the phenological changes in fish in relation to global warming are increasing (Vander Kraak and Pankhurst, 1997; Munday *et al.,* 2008). There are indications that shifts in timing of these recurrent events can have strong influence on population parameters, such as annual recruitment and survival (Visser and Both, 2005; Genner *et al.,* 2010). Thus, if we are to understand how projected climatic change may influence ecological diversity and ecosystem processes, there is need for a better understanding of both the direct and indirect effects of temperature changes on phenology of natural systems.

Most research evaluating climate impacts on fish phenology has focused on reproduction and early life history stages (Pankhurst and Munday, 2011), and timing of spawning and migration (Jonsson and Jonsson, 2009). Warmer waters have been associated with delayed spawning migration in flounder *(Platichthys flesus)* in the English Channel (Sims *et al.,* 2004), early spawning of Pacific herring *(Clupea harengus pallasi)* off British Columbia (Ware and Tanasichuk, 1989) and early appearance of planktonic larvae of several fish species within the southern North Sea (Greve *et al.* 2005). Warren *et al.* (2012) found that elevated summer mean of maximum daily air temperature by 1°C delayed the spawning of the brook trout *Salvelinus fontinalis* by one week. These publications, which are mostly on temperate fish, show that information on marine phenological changes is important for understanding population dynamics of marine organisms.

However, relatively little attention has been paid to evaluate climate impacts on spawning, recruitment and fishery of tropical marine fish. Tropical fish have protracted spawning, abundant and extended recruitment, and almost year-round fishery (Mohanraj *et al.,* 2002). Moreover, tropical fish are exposed to higher, but narrow intra-seasonal temperature range (Vivekanandan, 2011). The effects of changing temperature conditions are particularly important to tropical fish, which are already exposed to higher ambient temperatures, and are likely to be very close to threshold level. Analysing the data on the number of female spawners collected every month off Chennai (southeast coast of India) from 1981 to 2004, Vivekanandan and Rajagopalan (2009) showed, for the first time in the Indian seas, that the percent occurrence of spawners of the two species of threadfin breams, *N. japonicus* and *N. mesoprion* decreased during the warm months of April-September, but increased in the relatively cooler months of October-March. Data collected from ICOADS show that the annual average SST off Chennai increased from 29.0° C (1980-1984) to 29.5° C (2000-2004) during April-September and from 27.5° C (1980-1984) to 28.0° C (2000-2004) during October-March. Vivekanandan and Rajagopalan (2009) concluded that SST between 27.5 and 28.0°C may be the optimum and when the SST exceeds 28.0°C, the fish are adapted to shift the spawning activity to seasons when the temperature is around the preferred optima. Thus fishes may change their distribution or the phenology of reproductive activity to adapt to elevated temperatures for spawning and larval survival, but there is hardly any evidence to suggest that such a strategy could be successful for recruitment into the fishery.

IMPACT AT POPULATION LEVEL

Climate change may strongly influence distribution and abundance of fish populations (Wood and McDonald, 1997). The most significant impact of temperature at population level is the change in fish distribution pattern. A rise in temperature as small as 1°C could have important and rapid effects on the geographical distributions (Perry *et al.,* 2005). Temperature and ocean currents affect the dispersal of fish larvae. This is one of the commonly reported response of fish populations to climate change. Range limits may increase or decrease depending on thermal tolerances (Munday *et al.,* 2008). Many tropical marine fishes have large latitudinal ranges that extend across temperature gradients of 3-4°C.

Considering fish catch as a surrogate of distribution, Vivekanandan *et al.* (2009b) found that the oil sardine *S. longiceps* has extended its northern and eastern boundaries of distribution along the Indian coast. Oil sardine fishery did not exist before the year 1976 in the northern latitudes and along the east coast as the resource was not available. With warming of sea surface, the oil sardine is able to find temperature to its preference especially in the northern latitudes and eastern longitudes, thereby extending the distributional boundaries and establishing fisheries in larger coastal areas. Vivekanandan (2011) reported similar trend for the distribution of the Indian mackerel R. Kanagurta. However, if the SST in the southern latitudes increases beyond the physiological optimum of the fish, it is possible that the population may be driven away from the southern latitudes, which will reduce the catches along the southwest and southeast coasts in the future.

Warming ocean waters causes fish species to shift to deeper waters in the water column. The Indian mackerel, *R. kanagurta,* in addition to extension of its northern boundary, has been found to descend to deeper waters in the last two decades along the Indian coasts. This fish normally occupies surface and subsurface waters. As the subsurface waters are also warming up, it appears that the mackerel, being a tropical fish, has extended its vertical depth of occurrence to deeper waters.

The more mobile species should be able to adjust their ranges over time, but less mobile and sedentary species may not (Perry *et al.,* 2005). Tropical fish species with more rapid turnover of generations may show the most rapid demographic responses to temperature changes. Fishes in warmer waters have a smaller maximum body size and smaller size at first maturity (Daufresne *et al.,* 2009). Fishes with smaller body that live in warmer environments are likely to suffer higher natural mortality rates. These are important factors that determine population dynamics and productivity. However, as the longevity of these fishes is short, the generation turnover is fast and thereby, the resilience potential is relatively better compared to their temperate counterparts. Depending on the species, the area occupied by mobile species may expand, shrink or be relocated with changes in oceanic conditions.

The population-level changes may have impacts on the nature and value of commercial fisheries. These changes may influence fishing operations and may also create new fishing opportunities. For instance, the newly emerging oil sardine resource along the northwest coast of India has given an opportunity to establish a new fishery by increasing operation of small-meshed gillnets, and a bottom trawl fishery for Indian mackerel. phenological changes pose problems on the effectiveness of fisheries management measures. For instance, the main objective of seasonal closure of mechanised fishing for 45 to 60 days along the Indian coast is to protect the spawners during spawning season. As the peak spawning season of major fish groups is changing, the period and duration of fishing closure may have to be reviewed from time-to-time. In some cases, changes in distribution and availability of straddling stocks may lead to changes in sharing of stocks between countries. For instance, in the Bay of Bengal region, seven countries, namely Sri Lanka, India, Bangladesh, Myanmar, Thailand, Malaysia and Indonesia (north coast of Sumatra) are located contiguously, with overlapping Exclusive Economic Zone (EEZ). Gulf of Mannar ecosystem is shared by India and Sri Lanka; Sunderbans by India and Bangladesh; eastern Andaman Sea by India (Andaman & Nicobar Islands), Thailand, Malaysia and Indonesia; and Malacca Strait by Indonesia, Malaysia and Thailand. Due to the proximity of EEZs, the fish stock distribution overlaps to a great extent. As the ecosystem structure and functions have a large amount of generalities between these countries, a few hundred species/stocks are common to any 2 or 3 contiguous countries. Many of the fisheries resources are transboundary and straddling in nature and harvested by fishermen of more than one country. As there are no agreed regional measures to sustain the shared fish stocks, and also no mechanism to share information regarding changes in the distribution of shared

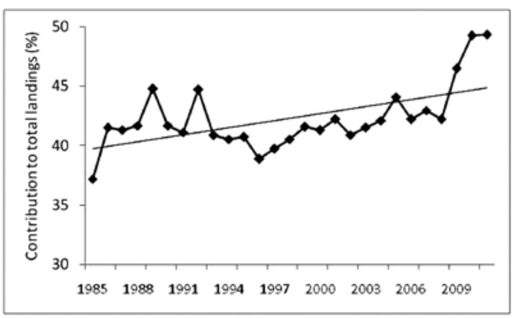

Fig. 6. Contribution of small pelagics to the total landings along southeast coast of India; the straight line indicates the trend

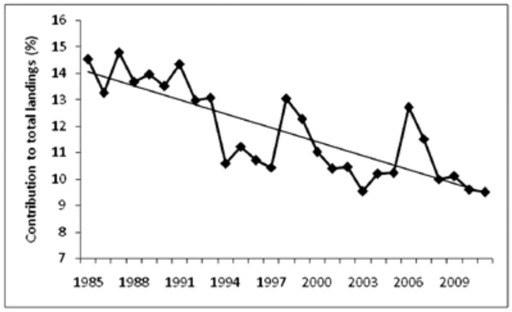

Fig. 7. Contribution of large pelagics to the total landings along southeast coast of India; the straight line indicates the trend

stocks and their levels of exploitation, it is becoming important that these countries jointly evolve a mechanism to sustain the fish stocks by taking into consideration the climate change-related distribution perturbations.

IMPACT AT COMMUNITY LEVEL

The changes at organismal and population levels are reflected at community level. As the tolerance and adaptation capacities are different between species, the species that adapt and gain from warming are increasingly becoming dominant. On other hand, those species, which are already at the threshold limits are vulnerable and lose to adaptable ones. This is reflected as changes in species composition over the years. Sumaila *et al.* (2011) have enumerated the publications from different geographic locations between the years 1982 and 2006 on the observed biological and ecological changes that are considered to be related to climate change, and may have direct implications for marine fisheries. Of the 66 publications considered by them (which do not include publications from northern Indian Ocean), the maximum number of publications (21) is on changes in community structure, indicated by changing species composition caused by shifts in species distribution. Along the Indian coast too, changes in species composition are observed in the last three decades. For instance, the catch contribution of small pelagics, which includes oil sardine and Indian mackerel, has increased from about 40% during 1985-1989 to about 46% during 2007-2011 along the southeast coast of India (Fig. 6). On the other hand, the contribution of large pelagics has decreased from about 14% to 10% during the corresponding period (Fig. 7). Along the southeast coast of India, extension of distribution and increasing abundance of oil sardine and Indian mackerel have altered the community composition, which is suggested to be the result of combination of fishing and climate change effects (Vivekanandan and Krishnakumar, 2010). Recently, Mohamed *et al.* (personal communication) reported regime shifts along the southwest coast of India with the emergence of pufferfish as a result of decline in population of large predators. These examples emphasise that differential physiological effects of temperature on individual species are key to understanding and projecting climate-induced changes in species interactions and, furthermore, in community composition (Portner and Farrell, 2008)

Although the possible role of increasing water temperature in determining community composition and abundance has been emphasised by several publications (for example, Portner and Peck, 2010), extremes in salinity levels, along with relatively low primary productivity will also act synergistically to have substantial effects on the structure and assembly of communities of a given region (Feary *et al.,* 2010).

Changes in community level will alter fishing opportunities. For instance, increasing small pelagic abundance will encourage operation of ringseines and gillnets with small mesh size, and also small coastal fisheries engaging boats with outboard motor. There will be losses too. Emergence of pufferfish is perceived as an economic disadvantage to the fishermen as they often complain about damage to the net caused by the powerful teeth of the fish. Jellyfish emergence is also considered a liability as commercially important fishes are stated to avoid the areas and seasons of jellyfish abundance (James *et al.,* 1985).

IMPACT AT ECOSYSTEM LEVEL

Rising atmospheric CO_2 and associated shifts in oceanic parameters, especially changing seawater temperature, currents, stratification, nutrient input, dissolved oxygen concentration and ocean acidification jointly exert immense concurrent biological effects in marine ecosystems (Fig. 8). Oceanic uptake of anthropogenic (CO_2) is altering the seawater chemistry of the world's oceans with consequences for marine biota. Elevated partial pressure of CO_2 (pCO) is causing calcium carbonate saturation in many regions, with pronounced acidity and hypoxic zones (Fabry *et al.,* 2008). The cumulative biological effects that are evident now are, as mentioned in the previous sections of the paper, effects on survival, distribution, growth, phenology and species composition. The ability of marine animals, most importantly pteropod molluscs, foraminifera, and some benthic invertebrates which have to produce calcareous skeletal structures is directly affected by acidity and hypoxia.

Changes are occurring for several other components of the ecosystem as well. For instance, monospecies static culture of phytoplankton at various temperatures indicated that cell density and biomass were directly proportional to temperature elevations from 24°C up to 32°C, beyond which cell death occurs (CMFRI, 2009). Significantly, the decay of phytoplankton in the culture cycle occurred much earlier at higher temperatures than at lower temperatures. Moreover, the dominance ranking of different species of microalgae differed within the temperature range (24 - 32°C). These important findings show temperature-related changes in the abundance and species dominance of phytoplankton, indicating the potential changes at the base of the food web in the marine ecosystems.

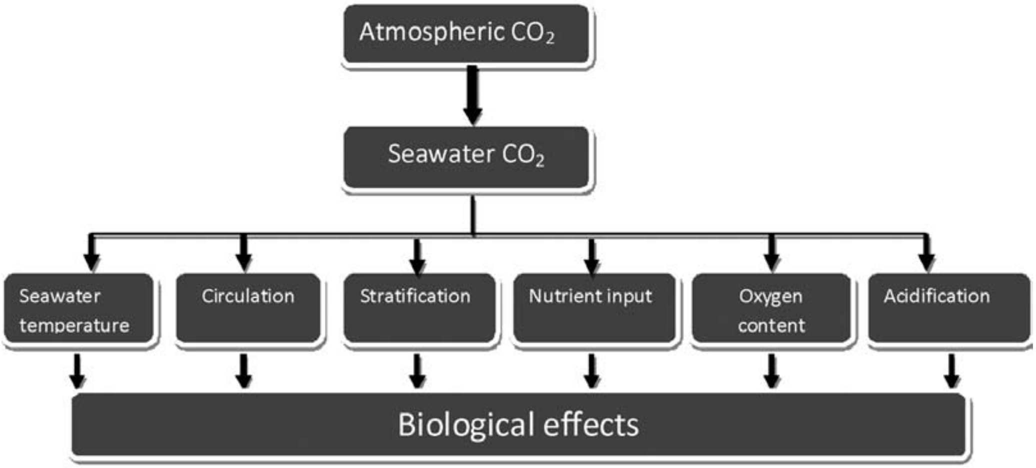

Fig. 8. Rising atmospheric CO_2 and associated shifts in oceanic parameters and concurrent biological effects in marine ecosystems

Important ecosystem components such as the coral reefs are sensitive and vulnerable to elevated seawater temperature and acidification. Indian coral reefs have experienced 29 widespread bleaching events since 1989. To understand how reefs will respond to increasing thermal stress in the coming years, Vivekanandan *et al.* (2009c) used UKMO HadCM3 model SRES A2 experiment output for the Indian corals. To understand the effect of elevated temperatures, they used the large scale (50 km) SST coral bleaching hotspot anomaly image provided by the United States National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Service (NOAA/NESDIS), and made a forecast on potential bleaching conditions. On a simple first inspection of this SRES A2 scenario, they found that corals will be soon exposed to regular summer temperatures that will exceed the thermal thresholds observed over the last 20 years. For example, if the summer temperatures exceed 31.5° C for even a few weeks, then bleaching will eventuate. If, as suggested by this scenario, these temperatures reach almost every summer from 2025 onwards, then annual bleaching will become almost a certainty from 2030 in all the coral regions of the Indian seas. By 2050, catastrophic exposure is the most likely outcome. Given the implication that reefs will not be able to sustain catastrophic events more than three times a decade, reef building corals are likely to disappear as dominant organisms on coral reefs between 2020 and 2040 and the reefs are likely to become remnant between 2030 and 2040 in the Lakshadweep region and between 2050 and 2060 in the Andaman and Nicobar regions.

All these changes have the potential to alter the structure and function of ecosystems. Importantly, the impacts of climate change on marine ecosystems do not occur in isolation of other human activity (Levin *et al.,* 2010). Habitat destruction, pollution, energy production, mining, fisheries, aquaculture, and invasive species are all affecting marine ecosystems and may exacerbate the effects of climate change. Indeed, multiple stressors in marine ecosystems have the potential to act in concert with climate change and cause significant degradation to coastal ecology.

Effectively reducing climate-related threats requires integrated management actions with the goal of increasing adaptive capacity of ecosystems. As a first step, robust indicators need to be developed. Indicators are quantitative measurements that provide insight into the state of the ecosystems. More than one hundred ecosystem indicators have been identified as important features of ecosystem health, such as diversity, resilience, primary or secondary productivity, energy recycling, and mean trophic level (Samhouri, 2009). Identifying reliable and monitorable parameters for such difficult-to-measure ecosystem attributes is important to generate an ecologically meaningful indicator set. It is important that the identified indicators have high social and economic values (*i.e.,* those important to the public) (Levin *et al.,* 2010).

With regard to fisheries, reducing fishing pressure would be a major step to increase the capacity of fish stocks to adapt to environmental changes. Hence solving the problem of overfishing is fundamental to reduce the impact of climate change (Brander, 2007). The ability of fishers and fishing enterprises to adapt depends on a number of factors, including the mobility of fishing fleet (Sumaila *et al.,* 2011). Fleets of distant-water fishing nations, which have access arrangements with several island states may be able to adapt to the change (Mcilgorm, 2010). In contrast, domestic fleets, as in India, have less ability to adjust to the change because they are usually confined to their own EEZ. In India, several demographic, infrastructure facilities and social and economic responses are the major attributes that influence the adaptive capacity of fishers.

CONCLUSION

Climate change is expected to affect fish stocks, marine ecosystems and fisheries. In tropical fisheries and ecosystems, gains and losses may accrue due to climate change. However, there are large knowledge gaps that prevent a comprehensive understanding of the impacts of climate change on marine fisheries and ecosystems. It is important that a concerted effort is made to address the issues related to sustainability of tropical marine fisheries and ecosystems by considering climate change as a component of a suite of anthropogenic interventions.

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