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Vulnerability to climate change of marine and coastal fisheries in México

A. MARTÍNEZ ARROYO
Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, Circuite exterior,
Ciudad Universitaria, México D. F. 04510, México
Corresponding author; e-mail: amparo@atmosfera.unam.mx

S. MANZANILLA NAIM
Centro de Investigaciones Biológicas del Noroeste, Mar Bermejo 195, Playa Palo de Santa Rita,
La Paz 23090, Baja California Sur, México

J. ZAVALA HIDALGO
Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México, Circuito exterior,
Ciudad Universitaria, México D. F. 04510, México

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RESUMEN

Se estudia la vulnerabilidad al cambio climático de la pesca en México con base en la revisión de los impactos de las variables físicas a los ecosistemas y ambientes que sostienen a las principales pesquerías, considerando los problemas ecológicos y socioeconómicos que actualmente impiden su sustentabilidad. Se analizan ambientes marinos de los que dependen la mayor parte de las especies importantes para la pesca en México en alguna etapa de su ciclo de vida y que son susceptibles de ser afectados por variables climáticas. Los ambientes marinos que se discuten son arrecifes, pastos marinos, lagunas, humedales, corrientes marinas, frentes y surgencias. Con base en los escenarios climáticos generados por tres modelos de circulación general: ECHAM5/MPI, HADGEM1 y GFDL CM 2.0; y los escenarios de emisiones A1B, A2 y B2 para los años 2030 y 2050, se examinan los impactos del cambio climático en los ecosistemas y la afectación que tendría en la pesca, ejemplificando con 16 pesquerías que constituyen más del 70% del volumen y el valor comercial de la pesca nacional. Entre los impactos que afectarían la producción pesquera en México y frente a los cuales hay que dirigir la construcción de estrategias de adaptación y mitigación, destacan el incremento en la temperatura superficial del mar, el aumento en el nivel del mar y la disminución de los caudales de los ríos por cambios en los patrones de precipitación.

ABSTRACT

The vulnerability of fisheries to climate change in México is explored on the basis of an overview of the possible impacts of physical variables of ecosystems and habitats which sustain these fisheries, taking in consideration the socioeconomic and ecological problems which hinder their sustainability. Marine environments were analyzed in view of their importance in sustaining the populations of the main commercial species during some stage of their life cycle, and which are susceptible to be affected by climatic variables. We addressed coral reefs, sea grasses, coastal lagoons, wetlands, sea currents, frontal systems and upwelling, based on the climatic scenarios generated by three general circulation models –ECHAM5/MPI, HADGEM1 and GFDL CM 2.0– as well as the scenarios of emissions A1B, A2 and B2 for the years 2030 and 2050. Impact of climate change in ecosystems and its effects on fisheries were examined, specifically with 16 of the main fisheries which constitute more than 70% of the volume and commercial value of national fisheries. The impacts, around which we have to structure adaptation and mitigation strategies, are: increase in sea surface temperature, sea level rise, and the change of precipitation patterns which will affect the volume of river flow.

Keywords: ecosystems, vulnerability, fishing, scenarios, models.

1. Introduction

The diverse products of the fishing activity in continental shelves and inland waters continues to be an important food source, with a great potential for the needs of the world's population today. In addition to the problems caused by overexploitation, pollution, ecosystem deterioration, and the stagnation of the major commercial fisheries, we must consider the mostly unknown potential impacts of climate change over this sector.

Fishing is an activity determined and affected by the local ecological and socioeconomic conditions. At industrial and small scales, fishing depends almost equally on the state of the natural populations as well as on socioeconomic and cultural conditions. Ecological conditions include from the phenology of each particular species to the functionality of the ecosystems, whereas socioeconomic conditions include a wide range of variables that may consider the fishing gear used, the social organization of this activity, and the processing, distribution and consumption of fishing products.

Marine and coastal ecosystems change due to the combined effects of natural conditions and human activities. At the same time, the changes produced on these ecosystems have an impact on human populations and the way in which these respond to these impacts may exacerbate or reduce their natural and social effects (Pikitch *et al.*, 2004). Hence, knowing the physical and anthropogenic factors that work as stressors at an ecosystem level, it is crucial to understand the natural and social vulnerability of fishing as an economic activity (Perry and Barange, 2009).

Fisheries show different tendencies in response to changes in the environmental conditions within ecosystems, because there is a differential effect on the population depending if the organisms are in larval or reproductive stages, or if they are migrating or foraging. Exploration of the impacts of climate change on the sector has to consider not only the direct effect of physical variables over target organisms, but also their ecological interactions. This paper presents a general diagnosis of marine and coastal fishing in México, discussing its vulnerability in the present and future based on the potential effects of climate change on the ecosystems that sustain the activity. The analysis of the possible impacts of climate change on the main fisheries is based on scenarios projected to 2030 and 2050, providing preliminary elements for the construction of adaptation and vulnerability reduction strategies.

Climate, ecosystems and fishing

Most of the global fishing yield is affected by regional climate variability that impacts oceanographic variables at a temporal and spatial scale (Trenberth and Hurrel, 1994; GLOBEC Intl., 1995; Barkun and Broad, 2002). The reported changes on key physical factors during events like El Niño and decadal oscillations in the Atlantic and the Pacific, have allowed a glimpse to the long term effects that global climate change will potentially have.

Climate change influences fisheries through the modification of habitat characteristics, affecting the organisms to the extent that the physical, chemical and biological conditions that influence their productivity, development, nourishment, reproduction and distribution are altered. Subtle changes in key environmental variables like temperature, salinity, wind velocity and direction, currents, upwelling intensity, as well as the ones that affect predator populations, can drastically modify the abundance, distribution, and availability of fish populations.

Some of the oceanic processes that influence fish and invertebrate aggregations, and which are affected by climate variability are those which concentrate nutrients (upwelling and mix), promote aggregations of populations and food (fronts, convergences), and those which enhance retention of organisms (reefs, sea grass, wetlands, lagoons). These processes are fundamental for a favorable breeding habitat (Bakun, 1990), and therefore, any alterations to these, will be reflected on the fisheries they support.

Climate change has a direct impact over marine systems altering ecosystems and bringing about changes in distribution ranges of species, as well as in their migration and recruitment patterns. In a greater scale, this leads to changes in the traditional fishing sites. Among the most relevant physical impacts of climatic change on marine and coastal ecosystems on which the main fisheries in México and the world depend, are: 1) increase in sea surface temperature; 2) sea level rise; 3) increased incidence of intense hurricanes; 4) changes in precipitation patterns and runoff; 5) changes in sea surface currents; 6) increase CO_2 concentration; and 7) habitat compression due to falls in the oxygen concentration, or a decrease in nutrient availability in the ocean's top layer (Easterling *et al.*, 2007; Nicholls *et al.*, 2007).

There are different approaches to analyze the effects of climate on fisheries which consider the physical, biological and human components (Kinnell and Perry, 2002; Edwards and Richardson, 2004; Perry *et al.*, 2005). One of these is the study of the phenology of target species and populations; another incorporates the natural and anthropogenic forcing over the complete ecosystem. Ecosystem management is the current tendancy in fisheries management, rather than focusing on the target species (Pikitch *et al.*, 2004).

The IPCC's Fourth Assessment Report (IPCC, 2007) highlights that the impacts of climate change will affect a wide range of species and will be notorious at the level of ecosystem functionality. Additionally, the effect of climate variability is strengthened by the negative impact that human development has already had over these ecosystems, increasing damage directly or indirectly, as well as decreasing their resilience. In this paper, we analyzed the country's marine and coastal areas which represent environments or habitats with on-going fisheries that could be susceptible to climate change; we present these potential impacts at a national scale. These ecosystems and habitats include: coral reefs, sea grasses, rocky bottoms, coastal lagoons, estuaries, wetlands, upwelling areas and large areas with surface currents, frontal systems and gyres.

2. Methodology

We analyzed the environmental variables that most influence the different types of commercial fish and invertebrate species, as well as some socioeconomic variables involved. We present a preliminary diagnosis of the current state of the main national fisheries, grouped according to the ecosystem on which they are mostly dependent, considering the potential effects of climate change on these ecosystems. Based on this information, we used three general circulation models ECHAM5/MPI, HADGEM1 and GFDL CM 2.0, and the emission scenarios A1B, A2 and B2 for the years 2030 and 2050 (Conde *et al.*, 2009). These scenarios allowed the further analysis of the possible impacts on the environments of reference on the regional and national fisheries.

For the selection of the coastal and marine environments analyzed in this paper, we considered the fact that 97% of fishing activity in México takes place in these environments, and that over 60 types of the fisheries registered on the national fishing statistics are associated, in important stages of their life cycle, to one or more of these habitats: 1) coral reefs, sea grass praries and rocky bottoms; 2) coastal lagoons, estuaries and wetlands; 3) upwelling zones; and 4) sea currents, fronts and gyres.

3. Study area

The study area includes all the Mexican marine and coastal zones with fishing activity. México has more than 11 000 km^2 of coastline; more than 70% of it is on the Pacific Ocean and the rest is in the Gulf of México and the Caribbean Sea. The Mexican marine territory, including the exclusive economic zone (almost 3 million km^2), is 1.5 times larger than its continental territory. According to the Longhurst (1998) classification, Mexican seas present three out of four marine biomes: coastal, trade-winds and westerlies.

Coral reefs. In México, there are three important locations for coral reefs: in the Pacific coast (that includes the Baja California region, the Islas Marías and the Revillagigedo islands), the Veracruz and Campeche coasts in the Gulf of México, and the east coast of the Yucatán Peninsula (from Contoy Island to Xcalak, including the Banco Chinchorro atoll) (Fig. 1). It is estimated that the area of coral reef ecosystems in the country's warm waters is over 780 thousand m^2, which represents almost 0.63% of the total world´s reefs (Spalding *et al.*, 2001).

Estuaries. Most estuaries in México are characterized by the wetlands they sustain, mainly mangrove forests. According to CONABIO (2008), the estimated mangrove cover area in México is 655 667 hectares, and mangrove ecosystems are present in the 17 coastal states in the country (Fig. 1). The state of Campeche is the one that has the largest mangrove surface of the country (29.9%), followed by Yucatán, Sinaloa and Nayarit (12.2, 10.8 and 10.2%, respectively).

Upwelling zones. These are productive coastal zones where cold subsurface waters, rich in nutrients emerge. In the Pacific coast, during winter and spring, and in non-ENSO years, upwelling is generated when the thermocline is shallower. Wind patterns promote this process along the western coast of the Baja California Peninsula and in the Gulf of California (during summer in the western coast and during autumn-winter in the eastern coast); seasonal upwelling occurs in the coasts of Jalisco, Colima and Michoacán (Fig. 1). In the Gulf of México including Tabasco, Veracruz and Tamaulipas upwelling occurs in the summer (Fig. 1). In the Gulf of Tehuantepec, vertical mixing and upwelling is associated to the *Tehuano* winds, and in the coast of Yucatán, they are associated to the Yucatán Current as well as other dynamic processes which are not well understood yet. Upwelling, frontal systems and convergences also occur in the confluence of the California Current and the North Equatorial Current (Bulgakov and Martínez-Zatarain, 2006).

Oceanic anomalies. These anomalies include: frontal systems, thermocline depth, boundary currents, hypoxic zones, convergences and eddies (Cushing, 1969). Pelagic fish distribution is related to the strong thermal anomaly associated to frontal systems. Fronts are long areas along

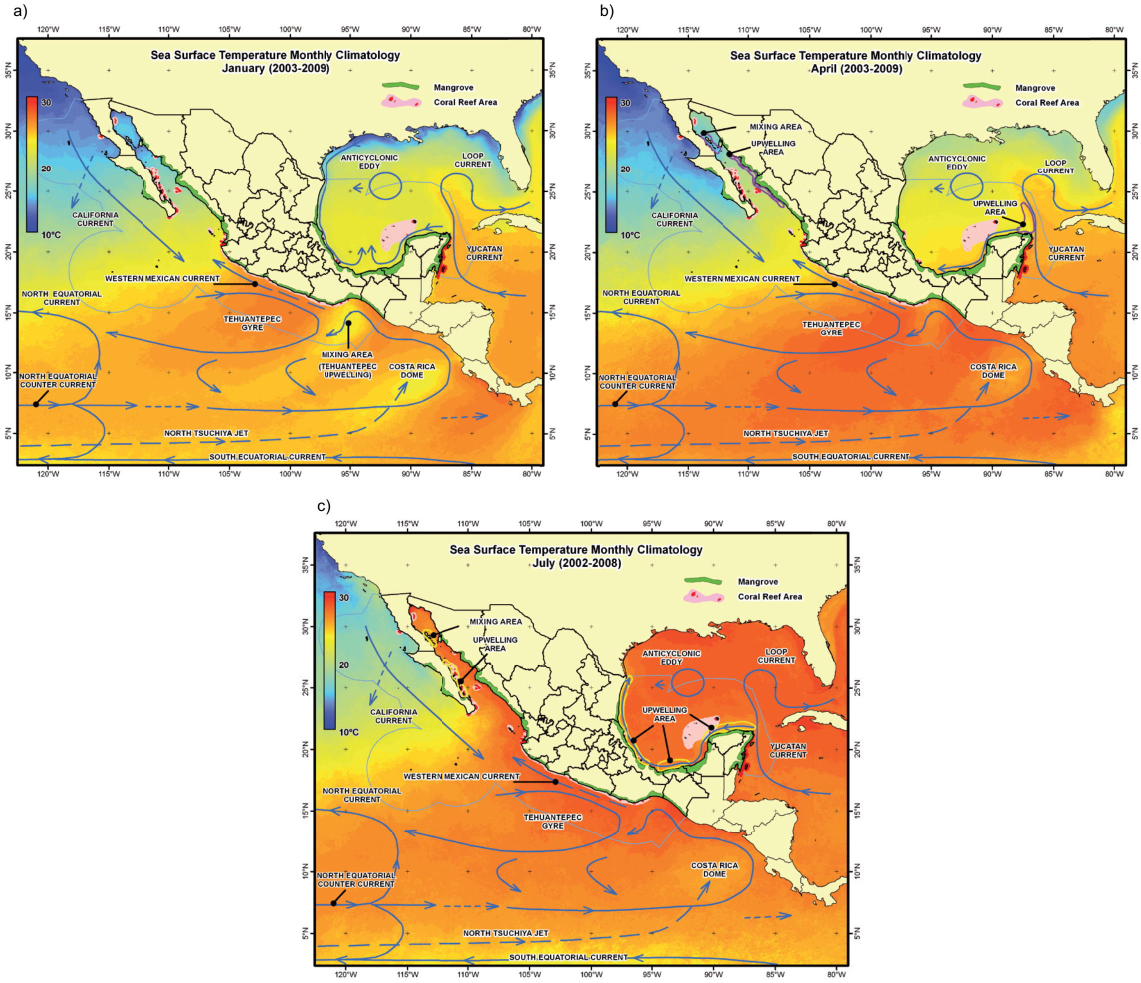

Fig. 1. Sea surface temperature, surface currents, upwelling zones (yellow lines), mangrove zones (green shading), coral reefs (pink with red shading) and vertical mix zones for a) January, b) April and c) July.

which there are horizontal gradients of temperature, salinity, density and velocity. Frontal systems like the ones in the borders of boundary currents, like the California Current, are oceanographically important because they outline a boundary between the different water masses: the warmer water mass of the California Current and the colder one associated to the upwelling. Fronts are also convergence zones where nutrients, floating objects, organisms and plankton accumulate.

4. Results

4.1 Fishing in México

México holds the fourth place in the continent in catch volume, with almost 1.5 million tons of annual catch and a 0.7% contribution to the gross domestic product. Even when traditional fisheries are overexploited or at their exploitation limit, fishing is assumed to be an activity with great potential growth due to the possibility of diversifying the number and type of species caught. The importance of this sector is notably regional: two thirds of the fishing production is concentrated in four northwestern states of México, where the main fisheries are small pelagic fish (sardines and anchovies) and shrimp. On the other hand, major pelagic fish, like tuna and shark, are mostly captured in the Gulf of Tehuantepec, whereas octopus, oysters and shrimp in the Gulf of México (INP, 1999-2000). Sardine, shrimp and tuna constitute 55.5% of the total landed volume.

According to the Annual Fishing Statistics 2005, the total landed catch volume was 1366 513 tons, from which 1081 162 tons correspond to the Pacific coast (79%), 253 275 tons to the Gulf of México and the Caribbean Sea (18.5%) and 2.5% to inland freshwater bodies (SAGARPA, 2005).

The anthropogenic environmental impact on the coast and continental shelf –where close to 89% of the fishing in México is caught– added to the overexploitation and the use of inadequate fishing gear, are all greatly responsible for the marine and continental fishing problems today. Moreover, the change in periodicity and increase in intensity of natural phenomena such as hurricanes have provoked a loss of critical habitat, especially in coastal ecosystems. Fishing is an activity with development potential if target species are diversified, a change of consumer habits is ensued and processing of the product is improved by adequate management.

4.2. Fisheries classification according to habitat and critical environmental conditions

4.2.1 Coral reefs, sea grass, rocky substrate

In México, the main fisheries associated to coral reef ecosystems and rocky substrates, which are affected by the impacts of climate change are, among others: 1) red snapper (Lutjanidae family); 2) groupers or cabrillas (Serranidae family); 3) spiny lobster (*Panulirus genus*); 4) queen conch (*Strombus gigas genus*); 5) red sea urchin (*Strongylocentrotus franciscanus*); and 6) octopus (*Octopus maya*).

Ecological requirements of fisheries species related to coral reefs

Reef fish, such as snappers and groupers, aggregate in high concentrations to spawn in a specific location and season depending on the lunar calendar (Domeier and Colin, 1997). Fishing takes advantage of these concentrations and targets reproductive adults, which results in a collapse of the fishery since there is site fidelity during spawning every year (Colin, 1996; Luckhurst, 1998). Grouper fishery represents the fishery with most value in southeastern México, but it is also vulnerable because of the current mismanagement.

The cabrillas, along with groupers, are among the most representative species in the Serranidae family. In México they are abundant in the Pacific and most of the capture takes place in the Baja California and Sonoran coasts. They are also abundant in the Gulf of México, from Tampico to Tuxpan (Cifuentes *et al.*, 1997).

México holds the seventh place in spiny lobster production worldwide and the seventeenth in catch volume of different lobster species. The spiny lobster of the Caribbean represents 23% of the national catch and is located in the states of Yucatán and Quintana Roo, the rest corresponds to different species in the Pacific. This crustacean resource is in the fourth place (after shrimp, prawn and freshwater crab) among crustaceans that generate significant income to the country (SEMARNAP, 1998). The Caribbean spiny lobsters (*Panulirus argus* Latreille, 1804) live in tropical and subtropical waters of the Atlantic, Caribbean Sea and Gulf of México. Reproduction takes place from April to October when the temperature is over 23 ºC. This resource has been overexploited in the continental shelf of the Mexican Caribbean and there is an outstanding recommendation to fully stop capture so that fishery can recover; however this measure has never been implemented.

The most important gasteropod fishery in México is the Caribbean queen conch (*Strombus gigas*). It takes place in the Caribbean coast, north of the Yucatán Peninsula, and in Campeche. It represents an important commercial resource, which is showing a decline due to its mismanagement and systematic violation of current regulations and closed seasons.

México is the world's fifth producer of red urchin (*Strongylocentrotus franciscanus*) by means of an artisan fishery with high export prices, especially to the Asian market. From the four species that can be found in Baja California only two are commercially exploited. This species is density-dependent and very vulnerable to environmental changes and overexploitation (INP, 1999-2000).

The octopus (*Octopus maya*) is an endemic-benthic species that lives in continental shelf of the Yucatán Peninsula, and inhabits sea grass prairies and is associated to coral formations. Ninety eight percent of octopus fishery at national scale comes from Yucatán, Campeche and Quintana Roo, with industrial and artisanal fleets participating in it (SEMARNAP, 1998). Due to its commercial value it is one of the top five national fisheries, and it occupies the twelfth place in catch volume. Apparently, hurricanes have a positive effect in octopus recruitment (INP, 1999-2000).

Ecosystem vulnerability to climate change and variability

Close to 35% of coral reefs in México are at risk (Spalding *et al.*, 2001). It has been suggested that fishing and tourism are the anthropogenic activities with the greatest impact on shallow and deep coral reefs. There is evidence that 62% of fish species, related directly or indirectly to coral reefs, are decreasing in abundance when there is a 10% decrease in coral reef cover (Wilson *et al.*, 2006). Any factor that promotes the loss of the reef cover will also provoke a decrease in the abundance of fish and invertebrate species related to it, thus undoubtedly affecting fisheries that depend on these systems (Lum Kong, 2002).

Coral reefs depend on specific environmental conditions such as a temperature interval (23 to 29 ºC) needed for an optimal growth. There is enough evidence to state that a high percentage of coral death or its disease is associated with incremental temperature events (Crabbe *et al.*, 2008). The vulnerability factors directly linked to global climate change for coral reefs and sea grasses are: increase in sea surface temperature, sea level rise, and marine acidification due to a rise in atmospheric CO_2. On the other hand, as a consequence of the higher intensity of hurricanes foreseen in climate change scenarios, the turbidity would increase causing mortality of coral reefs (Short and Neckles, 1999).

4.2.2. Estuaries, coastal lagoons and wetlands

Ninty percent of artisanal fishing in México depend on estuaries and coastal wetlands. In tropical estuaries, interaction of abiotic factors –such as tides, turbidity, salinity and habitat structure– determine the distribution and abundance of the catch (Rueda, 2001). More than 80% of commercial species in México are related to estuaries, coastal lagoons and wetlands in some development stage of their life cycle. Examples of these are: 1) shrimp, with eight species in the Pacific, six in the Gulf of México and the Caribbean; 2) mullets (Mugilidae) are multispecies and commonly associated to Lebrancha fishery; 3) oyster (*Crassostrea virginica,* mainly); and 4) croakers (Scianidae) with more than 30 species.

Ecological requirements of fishery species associated to estuaries

Shrimp is a multispecies fishery which has the first place in terms of economical value in the country. Nearly 80% of the catch is from the Pacific and the rest is from the Gulf of México. It is also constituted by species at their different stages of development. Juveniles are caught in coastal lagoons, and adults in coastal and marine zones. There are two highly productive regions in the Pacific: the Gulf of California and Gulf of Tehuantepec. Some of the species reproduce in the marine environment and, although they are eurythermal and euryhaline; their optimal growth is in temperature intervals of 24 to 28 ºC and salinity levels between 23 and 36 ups. Water temperature is an important trigger for reproduction, since it favors recruitment and growth (Madrid-Vera *et al.*, 2002).

Aside from an optimal temperature for each species, an important factor is the food availability (Aragón-Noriega, 2007). The spawning habitat has to be favorable as far as refuge and food are concerned. Larvae are transported by tides and follow salinity gradients in order to penetrate in estuaries (García and Le Reste, 1982).

The rise in temperature, and consequently the decrease in dissolved oxygen (hypoxia), cause changes in the distribution of all species of shrimp and croakers, due to the metabolic demands that it imposes. These changes have effects over all kinds of commercial fishing, as well as in the species' trophic interactions (Craig and Crowder, 2005). The croaker in the Gulf of México is affected by the great seasonal hypoxic zones resulting on a habitat loss that also affects the brown shrimp. Croakers from the family Sciaenidae are tropical species that inhabit estuaries and sandy bottoms. Artisanal fishing greatly depend on these species, at their coastal migrations and reproductive aggregations.

An important artisanal, multispecies fishery is for mullets and it is also strongly influenced by environmental changes. They are demersal species, mostly inhabiting brackish waters, although some are freshwater species. Juvenile recruitment is produced in shallow estuaries and coincides with the rise of temperature to more than 20 ºC as well as with low salinity associated to rainfall. In some lagoons, striped mullet fishery (*Mugil curema*) is the most important after shrimp. Positive correlation coefficients between climate variables and *M. cephalus* and *M. curema* catches are shown when analyzing water temperature, photoperiod and precipitation (Ibáñez and Gutiérrez-Benítez, 2004).

Oyster is the most important fishery in the Gulf of México. It represents 90% of national production and is concentrated in coastal lagoons especially in Tabasco and Veracruz. Like other lagoon species it is highly dependent of the mangrove ecosystems and because of its economic value it is one of the top 10 fisheries nationwide.

There are many species which cannot be classified as belonging to only one of these environments because the stages of their life cycles depend on several of them, as in the case of jack mackerel (Carangidae). This family of 140 fish species consists of fast predators associated to reefs and open sea. It is one of the most important tropical fish families of commercial interest. Estuaries are their breeding and recruitment grounds at their juvenile stage, later they migrate to pelagic waters. It is more abundant in the Gulf of México and in the Caribbean than in the Pacific, and regarding its economic value it is one of the top 15 fisheries of the country.

Ecosystem vulnerability to climate change and variability

The vulnerability of most of estuaries and mangrove ecosystems is a consequence of changes in land use, pollution, salinity changes and sea level rise. Freshwater water input, mostly determined by the amount of rain in watersheds, is also influenced by human activities such as deviation of flow and deforestation. These activities influence sediment deposition and eutrophication processes, thus impacting nursery habitat quality of a number of marine species.

4.2.3 Upwelling

Important commercial species associated to this process are: 1) sardines (six species); 2) anchovies and 3) squid (*Dosidicus gigas*). Sardine and anchovy distribution responds to a combination of biotic and abiotic factors. Their populations expand and contract obeying unknown environmental signals. In terms of catch volume, these small pelagic species constitute the first fishery nationwide, with more than 40% of the total landed weight in México. It is a multispecies fishery, in which 70% of the annual catch constituted by six species, change proportions presumably due to climatic stimuli, such as the presence of El Niño (INP, 1999-2000).

There is evidence of an existing relationship between the heating of the Eastern Pacific system and the increased production of sardine. The high abundance of sardine larvae is also associated with the presence of eddies in the California Current (Bakun, 1990) which are an important recruitment source. Any change in the boundary current flow of the continental shelf will affect the spawning habitat of these species (Bakun and Broad, 2002). This region of the Mexican Pacific is where the most productive seasonal upwelling has been reported. The impacts, mitigation or modification of the upwelling environments will have effects over the capture of both sardines and anchovy (Lluch-Cota *et al.*, 1998).

The squid is a fishing resource integrated by several species. Most are incidentally captured and only the giant squid has been developed as fishery, with increasing importance as an export product. It is distributed in the eastern Pacific from the northern Mexican border to Chile, captured from surface waters to more than 400 m depth, with the highest concentration in upwelling zones. It presents several spawning peaks but the most important ones are related to changes in oceanographic conditions (INP, 1999-2000).

Ecosystem vulnerability to climatic change and variability

Any event, either if it has an annual scale as ENSO, or long term, such as the surface temperature rise due to global climate change, which may mitigate the emergence of deep-productive cold waters, will have direct negative effects in fishing production. The descent of zooplankton biomass during the last 50 years has had a negative effect over the fishery, even if it began to recover by 1999. The intensity of the fishing effort and its relation with periodic fluctuations on fish populations, have not been well understood yet, and these are some of the vulnerability factors. Squid fishing frequently takes place in spawning areas and this consequently decreases recruitment.

4.2.4 Oceanographic anomalies

Important commercial species associated with these environments are: 1) tuna (skipjack, yellowfin, bluefin, albacore); 2) billfish; 3) sharks; 4) sierras and mackerel.

The distribution, migration, aggregations and foraging of the major pelagic species or Scombridae (tuna, mackerels and sierras) respond to surface temperature and to the location of oceanic anomalies (frontal systems, convergences, vortices, thermocline, mixed layer).

Tuna is México's second most important fishery, for its catch volume as well as for its economic value. It is distributed in the Pacific as well as in the Gulf of México and in the Caribbean. Under the name of tuna, there are several types of fish included, mainly of the *Thunus* and *Kastuwonus* genera. Other species included in this pelagic fishery are the mackerel (Scomber), sierras (*Scomberomorus*) and wahoo (*Acanthocybium*); all of them belong to the family Scombridae (Cifuentes *et al.*, 1997).

The yellowfin tuna is concentrated in thermal fronts, though inter-annual temperature variations suggest that foraging factors also influence their distribution. The highest abundance of yellowfin tuna can be found between the isotherms of 20 and 30 ºC. Some tuna like the albacore are concentrated in thermal anomaly zones (Andrade, 2003). The skipjack can be found in zones with temperatures ranging from 20 to 29 ºC. On the other hand, bluefin tuna is one of the endothermic fish capable of maintaining an internal temperature ranging from 24º to 35 ºC, while it swims in waters with temperatures between 6 and 30 ºC.

Foraging ability under the thermocline in the coastal banks indicates that temperature may not be a limiting factor for their vertical or horizontal distribution (Prince and Goodyear, 2006). However, one of the limiting factors is hypoxia or a low dissolved oxygen concentration.

The sailfish, swordfish, and the marlin are part of the fish group called billfish. They constitute a multispecies fishery of highly migratory species which are preferred primarily as sport fish. They are distributed in tropical and subtropical seas, reason why they are very susceptible to environmental changes, each one with different environmental requirements. They follow their migration routes mainly with surface currents. On the other hand, shark fishery includes more than twenty species, generally from a pelagic habitat. The Gulf of Tehuantepec is an important zone for this fishery.

Ecosystem vulnerability to climatic change and variability

Major pelagic fish populations are at their maximum exploitation yield or are already overexploited (FAO, 1997), which makes them more vulnerable. The levels of dissolved oxygen in some areas of the Pacific and of the Gulf of México have reached sufficiently low levels as to inhibit the vertical movement of some species to lower depths (Bakun *et al.*, 1999), making them more vulnerable to fishing exploitation. The changes of temperature and currents, for example, during the ENSO events, seem to have significant effects on the migration and distribution of different pelagic fish populations.

Table I has a summary of the main characteristics of these environments and their fisheries.

4.3 Climate change scenarios for 2030 and 2050

Temperature

Considering the scenarios B1, A1B and A2 obtained with the IPCC's multimodel average for periods 2020-2029 and 2090-2099 in relation to the 1980-1999 average, it was estimated that there will be a rise of the sea surface temperature in all tropical seas and, in the Mexican marine territory in particular for all the scenarios. However, we have to highlight that this temperature increase is less than the one

Table I. Vulnerability factors for Mexican fisheries in different marine and coastal environments (continued).

Environment	Main fisheries	% national volume	% total value	Actual vulnerability	Vulnerability to CC
Coral reefs, sea grasses rocky substrates				Overfishing, pollution, uncontrolled tourism	Increase of temperature and acidification, extreme events (hurricanes)
	Snappers and red snapper	0.76	2.1	Fishing in spawning and juvenile areas	
	Groupers and cabrillas	1.09	1.64	Incidental fishing of juveniles in shrimping nets	
	Spiny lobster	0.17	1.62	Overfishing	
	Queen conch	0.71	0.3	Illegal fishing	
	Urchin	0.13	0.28	In development, size is temperature-dependent	
	Octopus	0.73	1.68	Inadequate fishing gears, overexploited endemic species	
	Subtotal	3.59	7.62		
Lagoons, estuaries, wet lands				Pollution, physical destruction, overfishing	Precipitation patterns, run-off, freshwater input. Rise of sea level, hurricanes
	Shrimp (8 species from the Pacific, 6 from Gulf of México and the Caribbean)	10.85	46.59	Different in each species, overexploitation, fishing of juveniles	
	Mullets (Mugilidae) and lebrancha	0.65	0.47	Disturbed spawning areas, capture of small sized	
	Oyster (*Crassostrea virginica*)	3.16	1.54	Pollution, inadequate fishing gears, illegal fishing	

Table I. Vulnerability factors for Mexican fisheries in different marine and coastal environments (continued).

Environment	Main fisheries	% national volume	% total value	Actual vulnerability	Vulnerability to CC
	Croakers (Scianidae) more than 30 species.	0.37	0.45	Overexploitation target species, waste of associated species	
	Mackerels (Carangidae) multispecies	0.79	0.51	Lack of follow-up by target and associated species	
	Subtotal	15.82	49.56		
Upwellings				ENSO and La Niña impacts, excess of fishing effort	Wind patterns, temperature, precipitation
	Sardines (six species)	35.77	1.89	Populations fluctuation, zooplancton reduction	
	Anchovies	1.17	0.17	Linked to sardine fishery as an alternative	
	Squid	3.67	0.67	Reduction due to El Niño	
	Subtotal	40.61	2.73		
Marine currents, frontal systems				Hypoxia, excess of fishing effort	Changes in speed and direction of currents, wind patterns, hypoxia, rise of temperature
	Tuna (skipjack, yellowfin, bluefin, albacore)	10.62	10.28	Disturbance of recruitment, waste of incidental fishing	
	Billfish (seven species)	not quantified	not quantified	Lack of control and follow-up	
	Sharks (more than 20 especies)	1.85	2.03	Inadequate fishing gears, species in risk, vulnerable associated species	

Table I. Vulnerability factors for Mexican fisheries in different marine and coastal environments.

Environment	Main fisheries	% national volume	% total value	Actual vulnerability	Vulnerability to CC
	Sierra (Scombridae) and Mackerel	0.91	1.06	Opportunistic fishing, overfishing of small sized	
	Subtotal	13.38	13.37		
	Total	73.4	73.28		

expected for the terrestrial territory. For the period from 2020-2029, an increase is projected ranging from 0.5 to 1.0 ºC according to the average for 1980-1999 in scenarios B1, A1B y A2.

In these scenarios the spatial distribution of temperature increase is not homogeneous but the equatorial zone and the zone near the Mexican coast of the Pacific Ocean have a higher temperature increase than the rest of the Tropical Pacific. This pattern is similar to the one observed when El Niño phenomena is present, which suggests that the average anomalies caused by climate change in the Mexican Pacific may be similar to the ones observed during this event.

In the variety of models of the IPCC we can observe a temperature increase in the hot water pool of the Eastern Tropical Pacific. This pattern is very interesting and causes preoccupation because it suggests a temperature rise in a region, which is currently high already. This pattern, in case of being analogous to the one observed during El Niño events, aside of being associated to high temperatures, could also be associated to a positive anomaly in the sea level and a deeper mixed layer that inhibits vertical mixing and upwelling. If this pattern occurs, a negative effect on the productivity of the Pacific is expected, with the inhibition of thermal fronts, mixing and the upwelling in the Gulf of Tehuantepec; also vertical mixing in the Gulf of California, particularly in the midriff islands. The season on which this kind of anomaly appears is important because its impact is higher in the summer, when winds are weaker and temperature higher.

Outputs of the models HADGEM1, GFDLCM 2.0 and ECHAM5 MPI were analyzed for years 2030 and 2050, for scenarios A1B, A2 and B2 (Conde *et al.*, 2008). In general, the estimates of these models show that the land masses of the United States and the Northern México will have a higher temperature rise (average latitudes) than the surrounding ocean. These models forecast, for these scenarios, that the oceanic temperature will increase reaching 1.5 ºC over the temperature observed the last century. However, there are differences in temperature changes depending on the season of the year and the region itself.

For the Gulf of México, in scenarios A1B, A2 and B2 for the year 2030, the model HADGEM1 forecasts a temperature rise between 0 and 1.0 ºC; the GFDL CM 2.0 estimates a similar rise for the Mexican region of the Gulf of México and a slightly higher increase in the American region of the Gulf. In January, it is striking that this model forecasts, for the three scenarios, a temperature decrease of less than 1.0 ºC. The MPIECHAM5 model shows a rise of 1ºC for the whole Gulf, highlighting a slightly higher rise in the northern zone in November, being a little bit more intense in the B2 scenario.

In Mexican Pacific, all models for all scenarios, forecast a temperature increase from 0.5 to 1.5 ºC for 2030. The most important differences are located in the California Current, where models forecast the highest temperature rises for several months, without coinciding in the period of the year. For example, the GFDL CM 2.0 forecasts a rise lower than 1.0 ºC, while the other two forecast rises in temperature in the order of 1.5 ºC.

The same patterns are maintained for 2050 but with a higher temperature increase, in the order of 0.5 to 1.0 ºC more than in the 2030 scenarios. Therefore, in 2030 temperature increases in general from 0.5 to 1.5 ºC, while in 2050 it does from 1.0 to 2.0 ºC. For this year the differences between scenarios are larger, being A2 the one which forecasts the highest temperature increase.

These rises in temperature will probably cause higher stratification, which will reduce vertical mixing and upwelling; it will also probably be associated to changes in the depth of the mixed layer, which in case of increasing will also weaken the upwelling and the zones of oceanographic anomalies (fronts, current interaction zones and eddies) that favor the recruitment and fertilization of surface waters.

Precipitation

Precipitation changes affect oceanic conditions, mainly because of the variability of salinity gradients in estuarine zones, rivers and lagoons caused by the changes in the freshwater input. Possible changes in the river plumes, which transport nutrients, sediments and organic matter, and pollutants, also affect the coastal zone. The impact of changes in the sedimentation patterns affects the erosion of the coastal line and the formation or removal of barrier islands, which are present along most Mexican coasts, and frequently delimit coastal lagoons.

Precipitation in México and its natural variability are distributed differentially in the different regions of the country and seasons or the year. The complex rainfall patterns have been reflected in the IPCC's forecast models of precipitation change, showing México as one of the zones in the entire planet with the highest variance between the different models.

The models here discussed, i.e. MPIECHAM 5 and GFDL CM 2.0 forecast a very important decrease in spring precipitation for year 2030; in the MPIECHAM 5's case, this decrease extends until July, while for the same month, model GFDL CM 2.0 forecasts a precipitation increase in Chihuahua and Coahuila, but an important decrease in Sonora. On the other hand, model HADGEM1 also forecasts a precipitation decrease in spring, though it is lower than the other two models and with a rise in Sonora and Chihuahua. With this last model, precipitations at the beginning of summer are slightly lower than in the present and slightly higher at the end of summer, rising near autumn.

The patterns described on the paragraphs above are similar for scenarios A1B, A2 and B2, and are maintained for 2050 forecasts. However, in zones where the lower (higher) precipitation is forecasted for 2030, the changes (decreases or increases) are intensified even more in 2050. There are some important differences between estimates for both periods; particularly model HADGEM1 shows that in Yucatán Peninsula precipitation during 2050's summer and autumn decreases. A strong fall in precipitation is also evident during autumn in Baja California, Sinaloa and Chihuahua, while an important rise is estimated in the center and south of the country. Although there are no rivers in Yucatán Peninsula, it is estimated that a fall in precipitation may affect groundwater replenishment.

Sea level

Global data indicates that sea level has increased at an average rate of 1.8 ± 0.5 mm per year between 1961 and 2003. This data also show that from 1993 to 2003 the rate of increase was of 3.1 ± 0.7 mm per year, though there is not enough information to know whether this last period's increase was due to decadal scale natural oscillations, that have been previously observed, or if it can be attributed to climate change.

IPCC's forecasts indicate that sea level will continue to rise, which could cause changes in coastal morphology which must be studied separately since coastal zone changes are the result of the influence of many processes, sea level rise being one of them. Sedimentation process is one of the most important and particularly what refers to its input and removal balance, sediment transport and extreme events.

It is known that in the Mexican Pacific coast there is great tectonic activity with fast movements associated to earthquakes and low-frequency earthquakes. In the coast of the Gulf of México there is significantly less tectonic activity than in the Pacific, but there are elements that suggest there could be subsidence in the crust.

5. Discussion

Possible climate change effects on marine and coastal environments

México's main fisheries are multispecies, this being the reason why sometimes global statistics mask impacts of climatic events when changes in the proportion of species are presented in the catch. Intense or industrial fisheries use a larger fleet, while hundreds of minor species are caught by small scale or artisanal fishing, which merit radically different management strategies. The study of the vulnerability of the fishing activity by climate change, and possible adaptation mechanisms require the consideration of natural factors, as well as technological, social, economic and cultural aspects. An ecosystemic and mesoscale analysis, with multi-disciplinary and multi-sectorial focus allows a more comprehensive analysis of the activity and its alternatives, as well as the involvement of the sectors affected by decisions and public policies.

Reefs, sea grass and rocky bottoms

Increase in global temperature can affect the Mexican reef systems. It should be noted that some models estimate a decrease in temperature in the Gulf of México; but this will be more important in winter than in summer, when temperatures are higher.

According to the models, in the state of Quintana Roo coral reefs are expected to be subjected to stress due to high temperatures. For those in the Gulf of México, it is important to follow and study the evolution of the summer upwelling which contributes with cold waters and may decrease the impact of high temperatures.

The excess of suspended sediments is a threat for reefs and sea grasses in the Gulf of México since they are in the zone of influence of several rivers which have been increasing their sediment load due to deforestation and change in the land use patterns.

Healthy reef communities will have certain resilience to the sea level rise, but damaged, weakened ones are at risk of not surviving.

Coastal lagoons, estuaries and wetlands

The increase in sea level seems to be one of the most important threats derived from climate change because this phenomenon, together with the modification of sediment input, as a result of damming and decrease in river output, is causing erosion of the coast in several areas of the country and this situation is worsening. This problem may greatly affect a number of coastal lagoons along the coast, eroding barrier islands that separate them partially or totally from the sea. This can modify salinity within the lagoons and their estuarine conditions, with consequent habitat modification.

Many existing lagoons will be incorporated by the sea and the estuarine zones will move upstream. These regions must be identified, prepared and reserved so the ecosystems can develop when the lagoon systems move. The problem reaches the complex sphere of land ownership and land use, which is the reason why actions should be taken as soon as possible to reduce the impact and to adapt to new situations.

In the face of a possible annual precipitation decrease, the management of dams will be fundamental to maintain the minimum requirements necessary for the survival of estuarine and lagoon ecosystems.

Upwelling

Coastal upwelling can be affected by the change in the wind component parallel to the coast, the deepening of the mixed layer or the increase in stratification. The change in wind patterns associated to climate change is one of the most debated and uncertain topics. In general terms, it would be expected that the decrease in thermal gradients between tropical and polar latitudes will decrease wind intensity, which cannot be extrapolated at a regional scale. Another process which has to be taken into consideration is that local winds largely depend on the local thermal gradients between the ocean and the continent. Our models forecast in this case that the temperature increase in the continent will be higher than in the ocean, which would cause an increase in wind intensity and therefore possibly favoring upwelling. This process should be studied carefully for each area with a coastal upwelling individually. Depth of the mixed layer is also very much related to winds at basin scale and to stratification.

Currents and anomalies

Surface currents and eddies largely depend on large scale and local winds. In the Gulf of México the Lazo Current and the eddies that derive from it are not expected to be affected by climate change unless the intensity of the Yucatán Current has a significant decrease, which could occur if the formation of North Atlantic deep water is substantially modified. In the Mexican continental shelf of the Gulf of México the currents are generated by local winds. These currents are associated to upwelling during the summer (Zavala-Hidalgo *et al.*, 2006). In the Gulf of California, circulation is the result of a combined effect of remote forcing associated to the dynamics of the Equatorial Pacific and to local winds. Also, in case that frequency or intensity of ENSO is modified, the Gulf of California could be affected.

In the Gulf of Tehuantepec, the formation of eddies and mixing associated to the *Tehuano* winds could vary if there are changes in the southern penetration of the average-latitude high pressure systems during autumn-winter, similar to what happens during El Niño (La Niña) event when there is higher (lower) penetration of these systems to the south (Romero-Centeno *et al.*, 2003). This region can also be affected if the high pressure system of the North Atlantic has higher or lower intensity and penetration to the west.

An average sea surface temperature rise of only 1.4 ºC would result in a decrease in zooplankton biomass in some areas where there is seasonal upwelling. The increased warming of the surface stratum decreases nutrient richness, thus reducing the productive waters emerging from beneath the thermocline (NMFS, 2001).

The Northeastern Tropical Pacific is characterized by a thermocline rise near the coast. In coastal regions of the Costa Rica Dome, as well as in the Gulf of Tehuantepec, the depth of the thermocline presents minimum values, mainly during winter. In particular, the influence and relationship of productive regions with shallow thermocline has been demonstrated, and they are potentially high-productive areas due to the fertilization of surface waters. The results of billfish habitat use and other major pelagic fish can be explained by the shallow thermocline in the Pacific, more than in the Atlantic.

The effects of climate change on nutrient concentration processes such as fronts, eddies, mixed layer and others, will be seen as a change in the depth, geographic displacement and extension of these oceanic anomalies. Each case will be different because of the unique factor combinations that characterize them (Bakun, 1990).

6. Conclusions

Changes in the physical variables, forecasted by the climate change scenarios, will be added to the already existing impacts of pollution, species overexploitation and habitat destruction that have resulted from decades of human activities in the four environments where the main fisheries in México take place.

Fisheries that depend on coral reefs will be the most threatened by the impact of increased temperature and the frequency and intensity of hurricanes. The estuarine species with less tolerance to salinity changes will also be affected by changes in discharge from land as well as by sea level rise. Upwelling can decrease in some zones, as a result of the changes in thermal stratification and wind patterns. On the other hand, winds could intensify in some regions favoring upwelling, in which case the associated fisheries could present geographic displacement. The impacts on a fishery that depends on currents, fronts and eddies are more difficult to forecast at greater scale; they depend on regional oceanographic processes and on the migratory responses of different species.

However, the magnitude of climate change impacts over fisheries will depend more, in general terms, on the management and adaptation responses that the fishing sector starts to develop, from the small scale to industrial fisheries. This includes the strategic planning of the use of fishing gear, diversification of target species, alternation of the fishing areas, commercial use of incidental catch, identification of species with ecological and economic advantages for aquiculture, as well as the modification of the public's consumer habits.

Necessary actions needed for a long term strategy

Implementing, coordinating and/or strengthening permanent monitoring networks of oceanographic, environmental and biological variables is needed to allow the measurement of deviations to the general patterns in the coastal and marine environments. This measure must be implemented by federal institutions, national and state research institutions, in conjunction with greater monitoring systems at an international level.

It is necessary to monitor the health of ecosystems, identifying key commercial species which may be indicators of these impacts, as well as analyzing their populations considering the redefinition of fishery management, at the levels of target species and total catch. These actions should fall on federal and state institutions, and in the fishing, scientific and private sectors.

At an ecosystem level, a precautionary approach focus implies the reduction of the vulnerability of commercial species, the restoration and protection of environments and ecosystems that are key for populations or commercial value, as well as the implementation of diverse management parameters that propitiate current sustainability as well as the gradual adaptation to climate change. These actions, besides requiring the support of the federal and state institutions, are directly incumbent with local fishing communities and social networks related to fishing effort, product distribution and product processing, as well as new technology development.

This comprehensive overview at a regional scale or mesoscale based on the key ecosystems is presented as an alternative for the design and monitoring of environmental vulnerability-reduction measures and of adaptation to climate change in México's fisheries. These measures should take into consideration the fisheries' multispecies characteristics and their different biological and socioeconomic stressors associated to physical impacts on the natural environment.

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