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Review

The Gulf of California: Review of ecosystem status and sustainability challenges

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Abstract

The Gulf of California is unique because of its geographical location and conformation. It hosts diverse ecosystems and important fisheries that support industry and provide livelihood to coastal settlements. It is also the site of interests and

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problems, and an intense interaction among managers, producers, and conservationists. In this report, we scrutinize the abiotic (hydrography, climate, ocean circulation, and chemistry) and biotic (phyto- and zooplankton, fish, invertebrates, marine mammals, birds, and turtles) components of the marine ecosystem, and some particular aspects of climate variability, endemisms, harmful algal blooms, oxygen minimum layer, and pollution. We also review the current conditions and conflicts around the main fisheries (shrimp, small and large pelagic fishes, squid, artisanal and sportfishing), the most important human activity in the Gulf of California. We cover some aspects of management and conservation of fisheries, especially the claimed overexploitation of fish resources and the ecosystems, and review proposals for creating networks of marine protected areas. We conclude by identifying main needs for information and research, particularly the integration of data bases, the implementation of models and paleoreconstructions, establishment of monitoring programs, and the evaluation of fishing impacts and management actions.

Keywords: Ecosystem; Fisheries; Conservation; Management; Mexico; Gulf of California

Contents

1. Introduction

The Gulf of California (Fig. 1) is the only inland sea in the Eastern Pacific, the most important fishing region in Mexico, and one of the marine systems most closely watched by the worldwide conservation sector. It has been subject of research and exploration for decades. Some isolated evaluations of the climate variations and human-

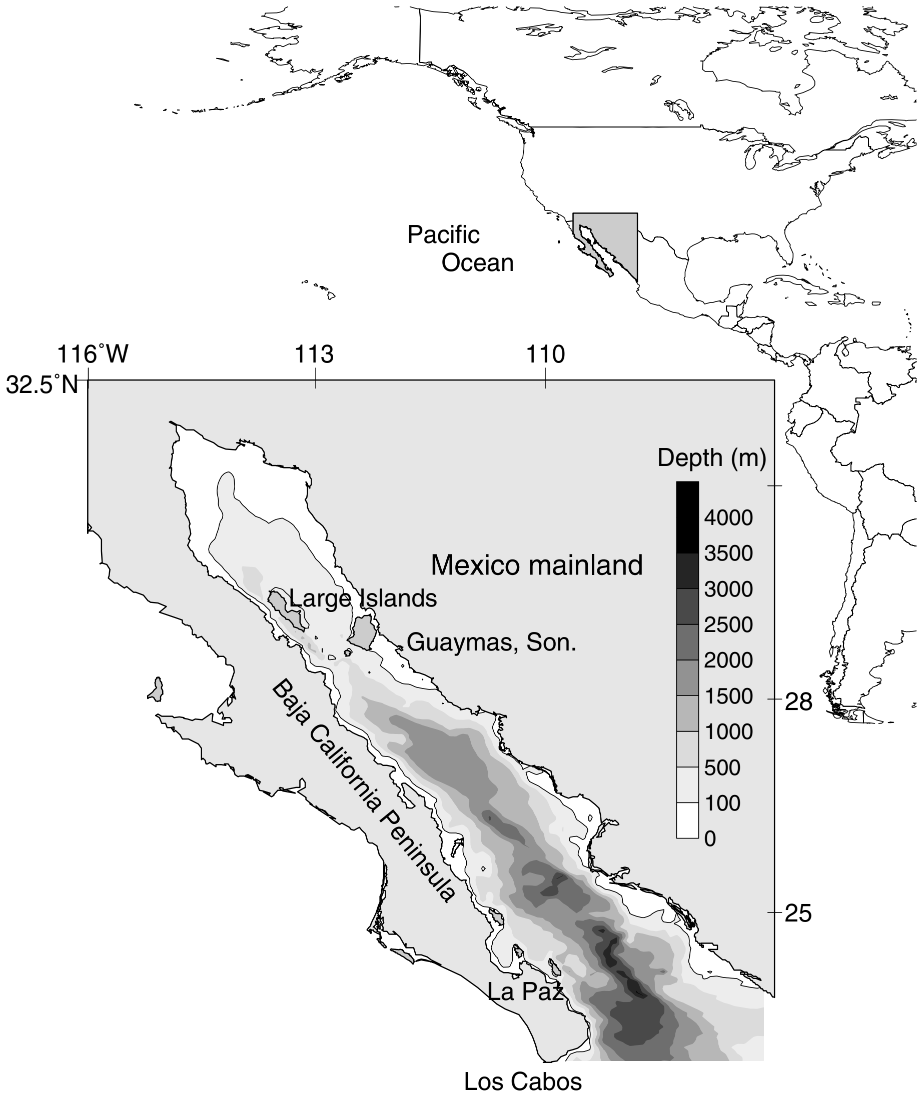

Fig. 1. Geographic location and bathymetry of the Gulf of California.

induced disturbances on the ecosystem and its components exist, but as yet no integrated ecosystem management is taking place. In this paper, we provide a review that includes the basic physical setting and variability patterns, the main inhabiting species, the most important fisheries, and the major current conservation issues.

2. Ecosystem description

Also known as the Sea of Cortés or "Mar Bermejo", the Gulf of California is a body of water that separates the Baja California Peninsula from the Mexican mainland (22–32° N and 105–107° W). It is 1130 km long and 80–209 km wide. In the northern region, where offshore mean depth is about 200 m, large amounts of sediments are maintained in suspension by strong currents that result from an extreme tidal range (up to 6.95 m at San Felipe; Gutiérrez and González, 1999). South from the shelf-like north, there is an archipelago containing sills, channels, basins, and two large islands: Angel de la Guarda and Tiburón.

South of these large islands, the Gulf of California increases in depth towards the mouth, with deep basins reaching over 3000 m. The Peninsular shore, mostly rocky, but with scattered sandy stretches and a narrow shelf, almost completely lacks drainage from rivers due to sub-desert climate conditions. The continental shore, on the contrary, is characterized by long sandy beaches, large costal lagoons and open muddy bays, a wide shelf and large supplies of freshwater that reach the coastline directly or through the lagoons.

2.1. Physical environment

Atmospheric forcing over the gulf is a strongly seasonal; weak southeasterly winds blow through the summer and stronger northwesterly ones during winter, mostly polarized along the gulf axis (Merrifield and Winant, 1989; Marinone et al., 2004). Rainfall takes place mostly during the summer (Salinas-Zavala et al., 1998), together with the northwestward transport of large amounts of water vapor (Carleton et al., 1990). Tropical storms and hurricanes take place during summer and fall, and can cause heavy rainfall and intensified water and sediment runoffs into the basin (Salinas-Zavala et al., 1992).

Ocean surface conditions are largely dominated by atmospheric forcing and ocean dynamics. Higher temperatures are found at the head and the mouth of the gulf during the summer; while lower are found in the northern half, and around the mid-gulf islands throughout the year (Argote et al., 1995; Soto-Mardones et al., 1999; Marinone and Lavin, 2003; see Fig. 2a and b).

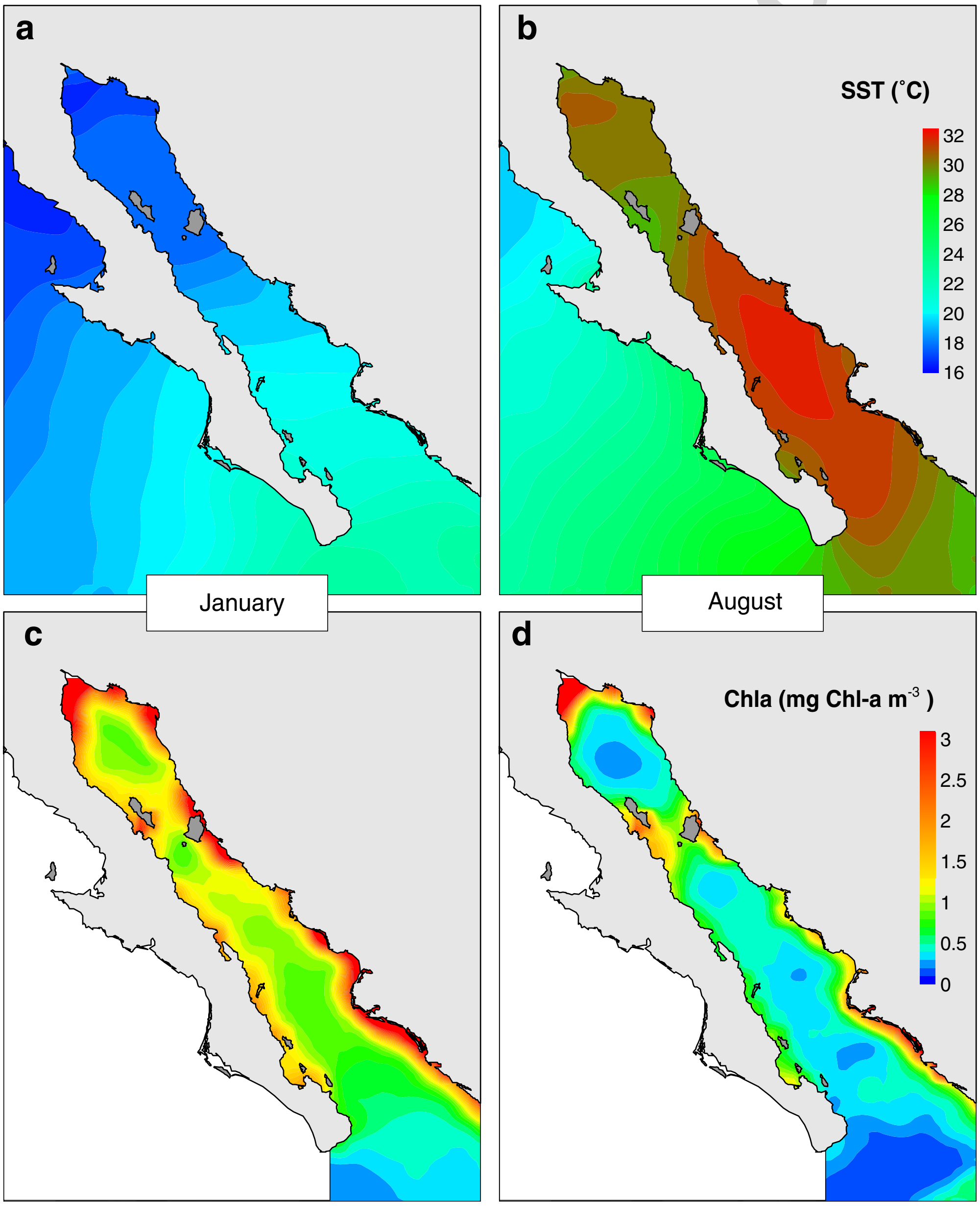

Fig. 2. Average sea surface temperature for January (a) and August (b) computed from monthly AVHRR composites for the period 1998–2004, kindly provided by the CICESE-BCS Satellite Oceanography Station <http://www.cicese.mx/lapaz/catalogo2>, and pigment concentration (c, d) derived from color SeaWiFS imagery for the 1997–2004 period <http://oceancolor.gsfc.nasa.gov/SeaWiFS/>.

Circulation is influenced by the annual and semiannual seasonal changes, and also by diurnal, semidiurnal, and fortnightly tidal cycles. Tides co-oscillate with those of the Pacific Ocean, and the semidiurnal component is near resonance, with amplitudes at the head of the gulf four times greater than those at the mouth (Marinone, 2003), and tidal currents vary accordingly. Seasonal circulation is dominated by the Pacific Ocean influence at the gulf's mouth (Castro et al., 1994; Ripa, 1997), the wind pattern (Badan-Dangon et al., 1991), and the air-sea heat exchange (Beier, 1999; Marinone, 2003). Ripa (1990, 1997) proposed that the Pacific Ocean forces the Gulf of California through an internal baroclinic Kelvin wave of annual period, which enters the gulf on the eastern coast and traverses cyclonically around the entire coastline. That hypothesis explains the seasonal circulation and the balances of temperature and salinity (Palacios-Hernández et al., 2002; Berón-Vera and Ripa, 2000, 2002).

Probably, the best-documented features of the Gulf of California circulation are the large-scale seasonally reversing gyres in the northern gulf (cyclonic from June to September, and anticyclonic from November to April), observed by means of satellite-tracked drifters by Lavín et al. (1997), from geostrophic calculations by Carrillo et al. (2002), and with current meters by Palacios-Hernández et al. (2002). There are no corresponding observations for the southern gulf, but estimates from ship drift and the distributions of temperature and salinity indicate surface outflow during winter and inflow during summer, with mass conservation requiring compensating flows at depth (Bray, 1988). Various studies document cyclonic currents of 10 cm s^{-1} at the mouth of the gulf mainly in winter, reaching depths greater than 1000 m (Roden, 1972; Collins et al., 1997; Castro, 2001).

2.2. Enrichment and primary production

Few reports, and no systematic, long time series exist for nutrients or chemistry of the Gulf of California; we believe data have been collected by researchers from different institutions over the last two decades but remain unpublished. From the available information, it is evident that nutrient enrichment is mostly due to the year-round, strong tidal mixing around the large islands, especially over the sills, and the wind-driven coastal upwelling during winter along the eastern coast. The first leads to an area of strong vertical mixing and continuous flow of cool nutrient-rich water into the euphotic layer, and a thermal refuge for temperate species during the warm part of the year or warm interannual events (Lluch-Belda et al., 1986). The second, the coastal upwelling, is similar to that along the west coast of the Baja California Peninsula, but in contrast to what happens in the open coast situation, where phytoplankton is advected offshore, enriched waters from the islands and the east coast reach the peninsular side and remain trapped inside the basin, contributing to higher primary production per unit area. Lower sea surface temperature on the west side during summer has often been interpreted as evidence of upwelling induced by the northwestward winds, but several lines of evidence (i.e. Lluch-Cota, 2000a; Mitchell et al., 2002) suggest instead that this pattern results from the mainland side of the gulf warming up faster than the peninsular side. These enrichment mechanisms are denoted by the chlorophyll concentration pattern (Fig. 2c and d).

Integrated primary production levels are normally over 1 gC m^{-2} d^{-1}. Between 1995 and 1998, a group of institutions (Centro de Investigación Científica y Educación Superior de Ensenada [CICESE], Centro Interdisciplinario de Ciencias Marinas [CICIMAR], San Diego State University [SDSU], Oregon State University [OSU]) surveyed a series of optical properties of the Gulf of California for calibrating SeaWiFS imagery. Results showed phytoplankton and derived products dominated the optical properties, except for a zone in the northwest gulf where non-living suspended material is abundant (Pegau et al., 1999; Barnard et al., 1999).

Kahru et al. (2004) obtained time series of surface chlorophyll a concentration (Csat) and phytoplankton net primary production (NPP) for 12 sub-areas inside the Gulf of California, based on satellite data from OCTS, SeaWiFS, MODIS, AVHRR and the VGPM primary productivity model. They showed variability at many scales, including an annual cycle as the dominant period in all sub-areas, except to the south of the midriff islands where the semiannual cycle dominated. The semiannual cycle was higher during the spring and fall transition periods when the general circulation is switching between cyclonic in the summer and anticyclonic in the winter. The interannual variability was dominated by the 1997–98 El Niño and the following La Niña. During the El Niño period NPP decreased by 30–40% in the southern part of the Gulf (by approximately 1 Tg C $month^{-1}$) but the changes in the central and northern parts were less evident.

It has been recently demonstrated that agricultural runoffs are also related to phytoplankton blooms in some areas of the Gulf of California, specifically offshore of the Yaqui Valley discharge (Beman et al., 2005). The temporal, spatial, and ecosystem impacts of these local blooms require further research, among other things, because of their potential linkages to climate change.

The Guaymas Trench presents volcanic features and hydrothermal vents rich in minerals, with biotic communities supported by chemosynthesis using hydrogen sulfide, rather than photosynthesis. These systems include newly-described and undescribed species (Edgcomb et al., 2002). Their biomass production, accumulation, and exportation are still the subject of exploration.

2.3. Non-exploited fauna

2.3.1. Zooplankton

Zooplankton species can become highly abundant in the Gulf of California, some even producing coloration of the water, such as the copepods *Calanus pacificus* and *Rhincalanus nasutus* and the euphausids *Nyctiphanes simplex* and *Nematoscelis difficilis*. These high abundances constitute an important source of food for fish larvae and predatory zooplankters such as the siphonophore *Muggiaea atlantica* and the chaetognaths *Sagitta enflata* and *S. minima* (Brinton et al., 1986; Esquivel-Herrera et al., 2000).

Carnivorous zooplankters have been used as indicators of hydrographic condition in the Gulf of California. Alvariño (1971, 1992) noted that the siphonophore *Lensia challengeri* is a good indicator of California Current flow into the gulf, while the siphonophore *Chelophyes contorta* and the chaetognath *Sagitta pacifica* indicate warm, Central Pacific waters, and *Sagitta decipiens* denotes recent upwelling events. Temperate zooplankters occur mainly at the northernmost region and around the large islands, where vigorous vertical mixing is reflected in the joint occurrence of *S. decipiens* and the *Sagitta minima* (Alvariño, 1965, 1992). To the south, warm water communities are easily recognized by their high diversity, especially in the southwest. The warm water siphonophores *Abylopsips eschscholtzi, Enneagonum hyalinum, Bassia bassensis, Diphyes dispar, Diphyes bojani*, and *C. contorta* are abundant in the southern gulf, along with the copepods *Candacia curta*, *Pleuromamma abdominalis*, and *Copilia* spp., the chaetognaths *Sagitta pacifica, S. regularis, S. ferox*, *Krohnitta pacifica*, and *Pterosagitta draco*, the photichthyd fish *Vinciguerria lucetia*, and the myctophids *Triphoturus mexicanus*, *Benthosema panamense*, and *Gonichthys tenuiculus*. The influence of tropical species can also be inferred from widespread parasitism: juveniles of amphipods in the siphonophores *D. bojani*, *D. dispar*, and *M. atlantica*, and trematodes and sporozoa in the chaetognaths *S. decipiens* and *S. pacifica*.

2.3.2. Non-commercial benthos

The Gulf of California hosts a unique set of habitats. Tropical mangrove forests and coral reefs are found at the southern end, while a variety of intertidal habitats occur throughout the gulf. The northern gulf benthic communities experience temperate conditions during winter and hot tropical conditions during summer. The west coast of the gulf is rocky with scattered sandy beaches and a narrow continental shelf. In contrast, the east coast has alluvial plains, except in the southernmost part, where sandy beaches, coastal lagoons, and estuaries dominate.

Excluding copepods and ostracods, the Gulf of California marine macrofauna includes 4853 described species. As in other tropical and subtropical ecosystems, molluscs (2195 spp.; 45% of total), arthropods (mainly crustaceans; 1051 spp.; 21.6%) and polychaete worms (717 spp.; 14.8%) are the dominant taxa; Cnidaria (253 spp.; 5.2%) and Echinodermata (262 spp.; 5.4%) are next in abundance. Among the molluscs, Gastropoda (1530 spp.; 31.6%) by far outnumber the rest (565 Bivalvia and 98 other spp.). Decapods (623 ssp.; 12.8%) and amphipods (232 spp.; 4.7%) are the most abundant crustacean groups. Some groups are poorly represented, due either to their very limited occurrence in marine ecosystems worldwide (e.g., Oligochaeta, Pogonophora, Monoplacophora), or to a lack of recognition in studies of this geographic area (e.g., Ctenophora, Mysida, Tanaidacea, Cumacea; Hendrickx et al., 2005).

To some extent, the diversity of almost every invertebrate group has been underestimated; exceptions might include such well-studied groups as the Euphausiacea and benthic Dendrobranchiata, although some new deep water or other species may be found in the area. There is a clear gradient from south to north in the biodiversity of invertebrates (3109 species in the south vs. 2251 in the north), and this gradient applies to every phylum with substantial numbers of species (Annelida, Arthopoda, Mollusca, Echinodermata, Chaetognatha). However, the numbers of known species of Cnidaria, Ctenophora, Platyhelminthes, Nemertea, Ectoprocta, and Chordata (Table 1) and of invertebrates as a group (3269 spp.) are highest in the central gulf. This might simply reflect more intensive studies in the central Gulf of California. Highest diversity of Porifera takes place in the northern gulf (46 spp. as compared to 42 and 36 in central and southern regions), but this may also be a methodological artifact, reflecting more research concentration in the north for this group.

Little can be said of phyla with very few species. The Upper Gulf of California and Colorado River Delta Biosphere Reserve, a small area extending north from San Felipe and Puerto Peñasco, contains 1049 species, or about one third of those known in the southern gulf. As expected, an analysis of macroinvertebrate biodiversity indicates that most species are found in the littoral fringe, from the intertidal to around 20 m, along the peninsular and continental coasts and around the numerous islands. On the continental shelf, biodiversity decreases with depth for all major phyla, and reaches minimum values at around 150–200 m (continental outer shelf; Hendrickx et al., 2002; Hendrickx and Brusca, 2003). The severely hypoxic upper slope environment of the continental coast, wider than that of the peninsular coast, creates a zone of low benthic biodiversity beginning around 750–800 m. Deeper fauna is not well known, although preliminary data from the southeast gulf indicate abundant and diverse fauna dominated by polychaetes, decapod crustaceans, echinoderms, and molluscs (Hendrickx, 2001).

2.3.3. Marine mammals

There is a total of 36 species of marine mammals in this inner sea (4 pinnipeds, 31 cetaceans, and one bat; Aurioles-Gamboa, 1993; Urbán et al., 1997; Brusca et al., 2004), more than the 29 species of marine mammals in Alaska, a region of recognized high diversity (Wynne, 1992). This is partly because the gulf is a feeding and breeding area for cetaceans such as blue (Gendron, 1991), humpback (Urbán et al., 2000), gray (Aurioles-Gamboa, 1993), sperm, pilot, Baird's beaked, and Bryde whales (Breese and Tershy, 1993). However, there are also several resident stocks of cetaceans and one pinniped stock, some of them isolated from the open Pacific, like the California sea lion (*Zalophus californianus*), the rorqual (*Balaenoptera physalus*) (Bérubé et al., 2002), and the vaquita *Phocoena sinus*, the latter small porpoise being considered endemic to the northern gulf (Jaramillo-Legorreta et al., 1999).

Archaelogical evidence indicates that native tribes consumed sea lions and dolphins in the Gulf of California since at least 1200 C.E., but is not clear whether they hunted or simply scavenged already dead or stranded animals (Porcasi and Fujita, 2000). Hunting marine mammals is illegal in Mexico, so that most current human

Table 1
Numbers of species of macroinvertebrates reported in the Gulf of California by phylum for the entire Gulf, the southern gulf (GCS), the central gulf (GCC), the northern gulf (GCN), and the Upper Gulf of California and Colorado River Delta Biosphera Reserve (BR)

Phylum	Total	SGC	CGC	NGC	BR	END	END%	PEL	BEN
Porifera	86	36	42	46	19	16	18.6	0	86
Cnidaria	253	112	146	114	33	47	18.5	20	209
Ctenophora	4	2	3	1	1	2	50.0	4	0
Platyhelminthes	22	5	16	12	10	9	40.9	0	22
Nemertea	17	6	7	6	2	2	11.8	0	17
Annelida	717	442	436	287	117	79	11.0	21	675
Sipuncula	11	8	10	5	4	0	0.0	0	11
Echiura	4	2	2	2	0	1	25.0	0	4
Arthropoda	1051	785	713	508	248	118	11.2	154	861
Mollusca	2193	1386	1560	1000	542	460	21.0	11	1965
Ectoprocta	169	96	146	120	10	11	6.5	0	165
Brachiopoda	5	3	0	2	2	4	80.0	0	5
Echinodermata	262	207	181	136	56	16	6.1	0	262
Chaetognatha	20	17	14	7	1	0	0.0	20	0
Chordata	38	6	13	10	3	3	8.1	21	14
	4854	3113	3293	2258	1050	766		251	4299

End = endemic; Pel = pelagic; Ben = benthic.

impacts on these species are through habitat alteration, including the potential influence of fisheries (Vidal, 1993), and pollution (Aurioles-Gamboa, 1992).

Natural variations also affect marine mammals. During the last 10 years we have witnessed three major events of massive mortalities (1995, 1997, 1999), most likely caused by HABs. Also, during abnormal conditions (ENSO years), cetaceans (Gendron, 1991) and sea lions (Aurioles-Gamboa and Le Boeuf, 1991; Samaniego, 1999) change their distribution and tend to concentrate in some areas (i.e. Canal de Ballenas and the midriff islands region; Tershy et al., 1991).

Abundance estimates are scarce, and time series exist for only some populations. The California sea lion, the only pinniped breeding in the Gulf of California, has a resident population of 13 breeding colonies accounting for between 24,000 and 31,000 individuals (Aurioles-Gamboa and Zavala, 1994; Szteren et al., 2006). Only four colonies located in the north and south Gulf, are significantly increasing but most of the sea lion rookeries in the central part, have declined in around 20% during the last 15 years (Szteren et al., 2006). An unpublished study (Aurioles-Gamboa et al. unpublished data) found remarkably similar interannual trends of sea lion pup censuses at the central area and sardine catch records over 20 years, suggesting a bottom-up food-chain control.

2.3.4. Marine birds

Information on seabird distribution and conservation needs in the Gulf of California have been integrated in three major summaries: Anderson (1983), Everett and Anderson (1991), and Velarde and Anderson (1994). Equally important are two books on the region- Wilbur (1987), and Howell and Webb (1995) and numerous recently published species accounts (Carter et al., 1995; Erickson and Howell, 2001; Massey and Palacios-Castro, 1994; Mellink, 2001; Palacios-Castro and Mellink, 2000; Pitman, 1986; Rebón-Gallardo, 2000; and others).

At least 26 species of seabirds breed in the Gulf of California (Everett and Anderson, 1991; Howell and Webb, 1995). Among these, only ground nesting seabird species on islands in the gulf and off western Baja California Peninsula have been well documented, and population estimates for subsurface nesting species such as storm petrels and murrelets are almost non-existent. Significant monitoring is limited to nine species in a few colonies: brown pelican (*Pelecanus occidentalis*), double-crested cormorant (*Phalacrocorax auritus*), blue-footed (*Sula nebouxii*) and brown boobies (*S. leucogaster*), Heermann's gull (*Larus heermmanni*), and royal (*Sterna maxima*), elegant (*S. elegans*), gull-billed (*S. nilotica*), and least terns (*S. antillarum*).

Large portions of the world populations of several species breed in the gulf, including black (*Oceanodroma melania*, 70%) and least (*O. microsoma*, 90%) storm petrels, Heermann's (90–95%) and yellow-footed (*Larus livens*, 100%) gulls, elegant tern (*S. elegans* 95%), and Craveri's murrelet (*Synthliborampus craveri*, 90%) (Anderson, 1983). All of these, plus black-vented shearwater (*Puffinus opisthomelas*), are endemic or quasi-endemic to the region (Howell and Webb, 1995). The Gulf of California also hosts the world's largest brown pelican, blue-footed booby (40%), and brown booby colonies (Anderson, 1983).

Seabirds in the gulf are of diverse faunal origin and affinity, and they exhibit highly varied patterns of dispersal, distribution, and habitat. Food abundance and habitat characteristics dictate the diversity and numbers of seabirds over large geographical areas. There are three major seabird breeding areas in the Gulf of California: the large islands, the coastal wetlands of Sinaloa, and the Isabela-Tres Marias islands. The largest concentration occurs in the first of these, where Anderson and Gress (1983) estimated between 30,000 and 40,000 breeding pairs in 12 California brown pelican colonies. The largest colony is on Isla San Lorenzo, with 15,000 pairs in a normal year. Tershy and Breese (1997) estimated 110,000 breeding pairs of blue-footed booby and 74,000 pairs of brown booby in Isla San Pedro Martir. Heermann's gull and elegant tern colonies on Isla Rasa total 240,000 and 45,000 birds, respectively (Velarde et al., 1994).

Archeological evidence has shown that native tribes used to hunt some seabirds species (e.g., brown pelican) for food and feathers, although their hunting capacity was limited due to low technological development. Seabird eggs have probably been collected for food at rookeries in the midriff islands since the advent of man into the region. The greatest threat to Gulf of California seabird populations comes from egg collection, developed at the turn of the 20th century, when local people become interested in harvesting eggs for local markets, and islands such as Isla Rasa were swept as often as twice a day for eggs (Anderson, 1983). Guano mining was also an important economic activity in the gulf during the late 1800s and early 1900s; seabird colonies on Islas Rasa, San Pedro Martir, and Patos were mined sporadically.

Seabirds are wide-ranging, highly visible top predators in marine food webs (Huntley et al., 1991), and therefore have potential as indicators of fish abundance (Cairns, 1987). Also, they are important in recycling nutrients such as phosphorus and nitrogen and they fertilize the ocean with their guano.

Prey for brown pelican, blue-footed and brown boobies, Heermann's gull and elegant tern includes small pelagic fish (sardine – *Sardinops caeruleus*, anchovy – *Engraulis mordax*, and mackerel – *Scomber japonicus*), for double-crested cormorant bottom fishes, for Cravieri's murrelet ichthyoplankton (e.g., juveniles of pelagic and rock fish), and for black and least storm petrels the macroplankton (e.g., euphasids). It has been estimated that an individual pelican consumes 0.5 kg of small pelagic fish per day during the non-breeding season, and that this consumption doubles during the chick-rearing period of three months.

There is ample evidence that seabirds respond manifestly to oceanographic variations such as ENSO, and to a lesser extent oceanic and atmospheric events (Sydeman et al., 2001), and thus they have been used as cost-effective indicators of environmental change and fish stocks (e.g., Anderson et al., 1980; Cairns, 1987, 1992; Sunada et al., 1981).

2.3.5. Marine turtles

Out of the seven existant marine turtle species in the World, five inhabit the Gulf of California for nesting or feeding. The leatherback (*Dermochelys coriacea*) has worldwide distribution, but it has been estimated that at least during the 1980s the Mexican population supported up to 60% of the global total (Sarti-Martinez, 2000). This species nests on Mexican shores, with its main nesting sites on the Baja California Sur coasts. From the hard-shelled Chelonidae, the olive ridley (*Lepidochelys olivacea*) concentrates around the large islands for feeding, and in the coastal lagoons and bays around the gulf States for nesting. The loggerhead turtle (*Caretta caretta*), locally known as caguama, the hawksbill or carey (*Eretmochelys imbricada*), and the green turtle (*Chelonia mydas*) feed in Gulf of California waters.

All turtles were subject of some degree of exploitation years ago, particularly the loggerhead was a highly appreciated food, and the hawksbill also for the beautiful shell used in making jewelry and other turtle shell crafts. In Mexico, sea turtle conservation efforts begun in the early 1970s, and by 1990 there was a total moratorium on all marine turtle species. Since then, many efforts have been applied for surveillance of nesting grounds and development of fishing technology to avoid incidental deaths of sea turtles in the commercial fisheries operations. Although all species remain classified as endangered, some have successfully recovered to pre-exploitation numbers (Genus Lepidochelys). Currently, the use of these species is basically related to ecotourism (Márquez et al., 1998).

2.4. Climate variability

There is strong seasonal amplitude in virtually every physical and ecological variable in the gulf area (Lluch-Cota et al., 1999). For example, when compared to nearby sites on the Baja California west coast and in the Eastern Tropical Pacific off Nayarit, Mexico, the seasonal amplitude for temperature and pigment concentration for the Central gulf is more than double (Fig. 3).

Inside the gulf, the amplitude of physical variables tends to increase from south to north. In the northern area, long term studies have documented dramatic changes in sea surface water temperatures and floral/faunal community structure from winter to summer. In short, the northern gulf is a warm-temperate environment in the winter, as shore temperature drops to lows of 8–12 °C. In the summer, nearshore temperatures rise to more than 30 °C, and the region is essentially a tropical environment. Brusca (1980), Brusca et al. (2004) and Brusca (2006) describe the seasonal changes in intertidal invertebrates and algae that result from these alternating thermal regimes. An exception to this latitudinal gradient in amplitude intensity is the midriff islands region, where the tidal mixing maintains relatively constant, conditions of cold temperature (Badan-Dangon et al., 1985), chlorophyll concentration (Kahru et al., 2004), and many other conditions (Lluch-Cota and Arias-Aréchiga, 2000).

ENSO is the most evident interannual signal. During the 1984–2004 period, for which satellite imagery is available, the strongest El Niño year (1997–1998) corresponded to the largest positive anomalies (more than 3 °C over the seasonal climatology), while the largest negative anomaly (4 °C) took place during the 1988–1989 La Niña. ENSO-related sea surface temperature anomalies tend to be stronger in the region just south

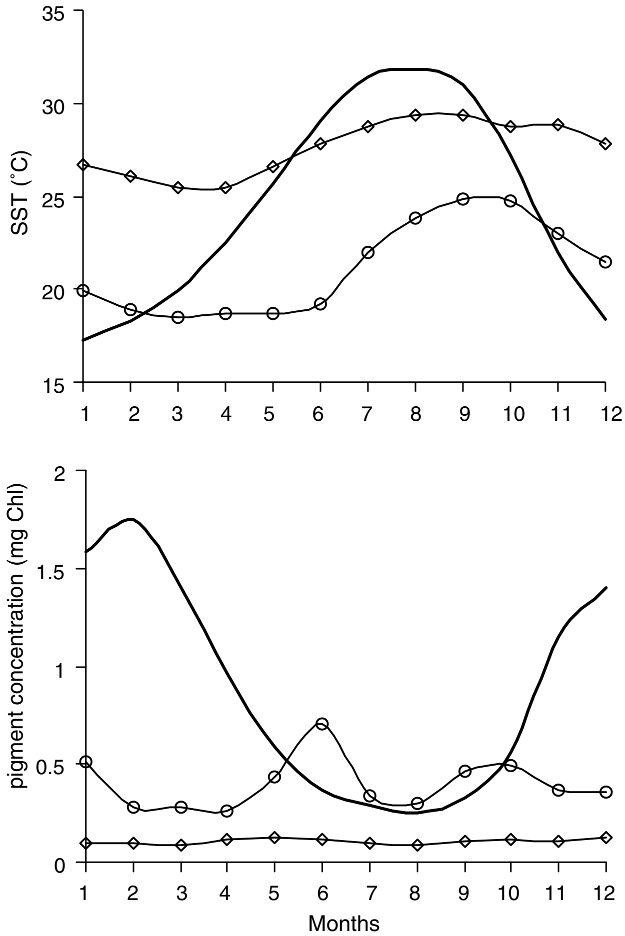

Fig. 3. Seasonal cycle of temperature and pigment concentration for the central Gulf of California (strong line), a 1° × 1° box off the Gulf of Ulloa (west coast of Baja California, centered at 25.4°N and 112.5°W; circles), and a box off Nayarit, Mexico (Tropical Pacific, centered at 20.5°N and 105.5°W; diamonds).

of the mid-gulf islands, where strong temperature fronts are found (Soto-Mardones et al., 1999; Lavín et al., 2003).

One interesting aspect of the gulf is that, despite the ENSO influence being clearly detected in physical variables, reports about the impacts on primary producers range from mentioning that ENSO does not have significant impacts (Alvarez-Borrego and Lara-Lara, 1991), and even drives increases in the phytoplankton biomass (Valdez-Holguín and Lara Lara, 1987), to color satellite imagery analyses reporting lower surface pigments, especially in the southern part, during both of the last major El Nino events, the 1982–1984 using the Coastal Zone Color Scanner (Santamaría del Angel et al., 1994; Lluch-Cota, 2000b), and those of the 1997–1998 using SeaWiFS (Kahru et al., 2004).

Herrera-Cervantes et al. (unpublished data) have recently proposed that this apparent inconsistency in the biological observations results from uneven ENSO effects throughout the gulf; a relatively strong signal at the continental side, the strongest south from the large islands, and weaker at the peninsular side (ENSO's spatial signature in the Gulf of California as shown by a 20–year, satellite-derived sea surface temperature analysis). Further research is needed to understand whether this asymmetry results from the interaction of the ENSO-related coastal Kelvin wave and the basin topography, or from a particular atmospheric configuration. As for lower frequency climate variations, it is yet unclear to what extent the gulf is affected by signals such as the Pacific Decadal Oscillation (PDO; Mantua et al., 1997), regime-scale variability (Lluch-Belda et al., 1992; Chavez et al., 2003), or long-term warming.

Clearly, identifying and documenting these variations for the entire gulf is impossible at this point, since no long-term, synoptic climate proxies exist, and the available instrumental record reaches back only into the early 1980s (Herguera-Garcia et al., 2003). However, Herguera-Garcia et al. (2003) reconstructed a >200 years sea surface temperature series based on oxygen stable isotopic composition of calcitic shells preserved in the high-resolution laminated sediments from the southeastern margin (near La Paz), and proposed that variability of winter temperature at interannual to decadal timescales is modulated by ENSO. Lluch-Cota et al. (2001, 2003) demonstrated that variability along the Eastern North Pacific is highest at the gulf's latitude, because of the mixing of the low-frequency, high-latitude PDO and the high-frequency tropical ENSO signals.

Based on one of the few relatively long time-series for the gulf, a ~40 years wind record from a coastal weather station in the eastern Central gulf (Empalme, Sonora), Lluch-Cota (2000a) computed an upwelling index and noted that since the mid-1970s there is an increasing trend of positive upwelling values during the winter, and negative during the summer. From Bakun's (1990) ideas, it was speculated that cooler winters might augment the land-ocean temperature gradient, and increase the alongshore wind velocities, and consequently the winter upwelling activity. Whether this could increase the potential of the gulf to absorb atmospheric greenhouse gases requires further investigation.

Because long term climate variability and climate change impacts are unclear for the gulf, strong effort is being applied today to develop alternatives, such as climate reconstructions and paleorecords (e.g., Herguera-Garcia et al., 2003), and regional scale models of the atmosphere, the ocean circulation, the terrain and sea level changes, the ecological responses and the ecosystem structures (Lluch-Cota et al., 2006).

2.5. Special issues

2.5.1. Oxygen minimum layer

Hypoxic and anoxic basins have been detected in the world oceans for many years (Richards, 1957). Dissolved oxygen concentrations are known to be lower in the Indian and Pacific Oceans, which also feature larger areas exposed to hypoxic water. The largest area of the world ocean with severe hypoxia is located in the east Pacific, roughly from southern Canada to central Chile, including most of the Gulf of California (Richards, 1957; Diaz and Rosenberg, 1995).

Parker (1964) reported a compilation of 20 years of observations of epibenthic oxygen conditions measured at or near the bottom in the gulf. The report shows a large fringe of the benthic realm with oxygen concentrations lower than 0.5 ml/l. In some areas (e.g., off the coast of Sinaloa, off the Fuerte and Mayo Rivers, off La Paz Bay), the oxygen minimum zone was estimated to be as wide as 20–30 nautical miles (nm), while in others (e.g., close to Tres Marias Islands, off Topolobampo lagoon system, off Los Cabos) the oxygen deficient fringe is narrower (<10 nm). The northern gulf is not affected by severe hypoxia along the bottom.

Hypoxic or nearly anoxic environments have also been detected in very shallow water in the southern gulf (less that 100 m depth; Hendrickx, 2001). Despite being a phenomenon affecting the distribution of fish and invertebrates (particularly penaeid shrimps), and thus of paramount importance for local fisheries, there is very little information.

Recent investigations in the southern Gulf of California have demonstrated that the oxygen minimum zone off the coast of Sinaloa, which extends roughly between depths of 150 and 750 m (Fig. 4), is totally devoid of benthic macrofauna (i.e., invertebrates and fishes). A distinct, moderately diverse fauna is found from around 800 m to 2300 m where oxygen concentration increases to 2.0–2.5 ml/l (Hendrickx, 2001). There are no data available concerning the relationship between epibenthic dissolved oxygen and the fauna that lives deeper than 2300 m in the Gulf of California.

The pelagic realm is also strongly affected by the lack of adequate levels of dissolved oxygen. In the water column, oxygen reaches severely hypoxic values (<0.5 ml/l) at about 150 m and is almost anoxic deeper. Because there has been no discrete sampling of the pelagic community of the water column as related to oxygen level, it is difficult to assess how these severe conditions affect planktonic and micronektonic species, but it is assumed that this ecological region is also devoid of large organisms.

2.5.2. Harmful algal blooms

Harmful algal blooms (HAB) can deeply impact marine ecosystems. In the Gulf of California, massive mortality of marine organisms has been associated with HABs since 1943 (Osorio-Tafall, 1943) and documented for various animal groups afterwards (sea birds, turtles, fish, and marine mammals; Sierra-Beltrán et al.,

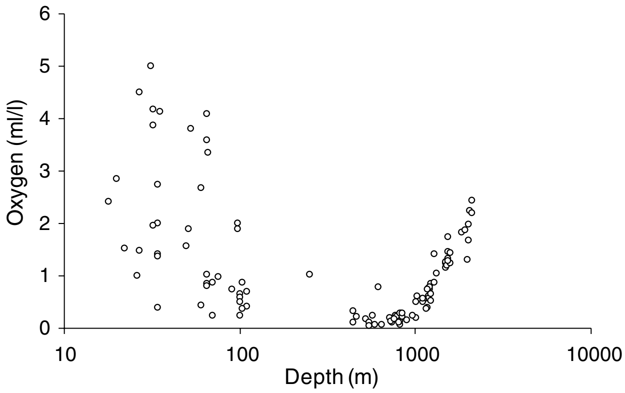

Fig. 4. Variation of epibenthic oxygen concentration with total depth off the coasts of Sinaloa. Dispersion of values measured between 10 and 100 m depth is due to sampling during different periods of the year (from Hendrickx and Brusca, 2003).

1997). Also, HABs can negatively affect spawning and recruitment of marine species (Shumway, 1990; Brusle, 1995), including pelagic fishes of commercial value, as demonstrated for other regions of the Pacific basin (Viquez and Hargraves, 1995).

During the last decade, interest in HAB ecology has increased because of its role in public and ecosystem health, and also of the apparently rapid and dramatic responses of harmful algae to environmental changes (Cortes-Altamirano and Sierra-Beltran, 2001). In the short term, the Gulf of California shows an interesting feature since, opposite to what happens in other regions, the number of HAB events decreases during El Niño years, but tends to increase after major events (Cortes-Altamirano and Sierra-Beltran, 2001). However, in the long term signals are consistent with other regions of the world.

The only long and consistent HAB time series in the gulf (22 years at Mazatlan Bay) shows that the number of toxic species and the frequency and duration of events are increasing (Cortés-Altamirano et al., 1999). Further, non-native species have recently been observed, driving strong phytoplankton community structure changes (Sierra-Beltran et al., 1998). Examples of these species include the temperate *Pseudonitzchia australis* (Cortés-Altamirano et al., 1999; Sierra-Beltran et al., 1999; Cortés-Altamirano and Núñez-Pasten, 2000), the ichthyotoxic *Cochlodinium* cf. *catenatum* (Morales-Blake et al., 2000; Gárate-Lizárraga et al., 2001), *Chatonella marina*, *Ch. ovata* and *Fibrocapsa japonica* (Barraza-Guardado et al., 2004; Cortés-Altamirano et al., 2006a). Hypotheses to explain the presence of these species include human transport (i.e., ballast water; Dickman and Zhang, 1999) and colonization by natural advection related to anomalous ocean conditions (i.e., El Niño; Hargraves and Viquez, 1981; Cortés-Altamirano et al., 2006b).

2.5.3. Endemism

The Gulf of California has one of the most diverse marine biological communities in the world, with 4852 species of invertebrates (excluding copepods and ostracods), 891 species of fish, and 222 tetrapod species. The degree of endemism varies considerably, depending on the taxon. Among the invertebrates, no zooplankton endemism has been noted, and differences between communities from the gulf and those of the surrounding ocean are related mainly to major current systems and faunistic associations. The number of known endemic non-planktonic macro-invertebrates is 766 (15.8% of the total in the Gulf), the vast majority of which are Mollusca (460 spp.), Arthropoda (118 spp.), and Polychaeta (79 spp.). The highest percentage of endemic invertebrates is found in the phylum Brachiopoda (80%), but this figure should be considered with care due to the very low number of species involved. Of the 766 endemic invertebrates, 141 (18.4%) occur throughout the gulf (records in southern, central and northern regions) while 128 species (16.7%) are known exclusively from the northern gulf.

There are 77 cases of endemic fishes, almost 10% of the total number of reported fish species for the gulf (Enriquez-Andrade et al., 2005), 52 of them reef fishes. The most famous endemic fish in the Gulf of California is the totoaba (*Totoaba macdonaldi*), a fish under heavy exploitation several decades ago. The fishery began around 1920, and reached a historical maximum of 2300 ton in 1942. Since then, landings decreased systematically until 1954, when catch was about 230 ton. Between 1954 and 1960 yields moderately rebuilt to

1200 ton, just to plummet again to 59 ton in 1975. This collapse has been related to overfishing, habitat loss, and more recently to climate change (Lercari-Bernier and Chavez, unpublished data). The particular extent to which these variables are responsible for this situation cannot be deduced from the available historical information; meanwhile the endemic totoaba is considered as critically endangered.

Large portions of the world populations of several marine bird species breed in the gulf, including black (*Oceanodroma melania*, 70%) and least (*O. microsoma*, 90%) storm petrels, Heermann's (90–95%) and yellow-footed (*Larus livens*, 100%) gulls, elegant tern (*S. elegans* 95%), and Craveri's murrelet (*Synthliborampus craveri*, 90%; Anderson, 1983). All of these species, plus black-vented shearwater (*Puffinus opisthomelas*), are endemic or quasi-endemic to the region (Howell and Webb, 1995).

The Gulf of California has an outstanding diversity of marine mammals; 36 species (four pinnipeds, 31 cetaceans and one bat; Aurioles-Gamboa, 1993; Urbán et al., 1997; Brusca et al., 2004), and hosts one of the most emblematic marine mammals worldwide: the vaquita (*Phocoena sinus*), an endangered endemic small porpoise whose decline in abundance has been estimated at 17.7% per year between 1986 and 1993 (Barlow et al., 1997). The federal government declared a moratorium in 1975 through the Secretary of Fisheries, and created the Technical Committee for the Protection of the Totoaba and the Vaquita ("Comité Técnico para la Preservación de la Totoaba y la Vaquita"), with the purpose of evaluating, studying, and monitoring their populations. Other conservation-oriented measures for both species have been undertaken since then. In 1991, all marine mammals occurring in Mexican waters were fully protected by the federal government; during 1993, the upper GC and the Colorado River's Delta was officially declared a Biosphere Marine Reserve; and in 2001 this reserve was extended *ex profeso* according to the vaquita's observed geographical distribution.

Although there are no prior population assessment data suitable for comparisons to the last estimate made in 1999, the current situation indicates that the vaquita numbers 567 individuals, with a 95% confidence interval from 177 to 1073 (Jaramillo-Legorreta et al., 1999), and the mortality due to incidental catch for this species stands between 7% and 15% per year. Presently, the vaquita is regarded as critically endangered by the Mexican government. Further information concerning future population trends will require quantitative and reliable data. No strict endemism exists for other marine mammal groups, such as sea lions, even though resident populations have little or no contact with those of the open Pacific (Aurioles-Gamboa and Zavala, 1994).

The 922 islands within the gulf host some 90 endemic species of plants and animals (more than 10% of the total number of species), including 60 endemic reptiles. Currently the Gulf of California islands are regarded as reserve zones and refuges for wildlife and migratory birds.

2.5.4. Pollution and habitat degradation

The Gulf of California may roughly be divided into three zones, depending on the degree of pollution and habitat modification: the western and eastern coasts, and the northern area. The western coast of the gulf has important tourist appeal, and some infrastructure has been built. However, population density is relatively low, and except for La Paz Bay and Los Cabos areas (Ortiz-Lozano et al., 2005), the coast is nearly pristine. In contrast, a sizeable portion of the eastern coast of the gulf is subject to pollution from industrial and human wastes, aquaculture residues, and agricultural run-offs. For instance, preliminary findings indicate that some coastal lagoons in Sinaloa show high concentrations of zinc and lead (Orduña-Rojas and Longoria-Espinoza, 2006), and Ortiz-Lozano et al. (2005) have reported that Guaymas Bay shows extreme levels of contamination.

Aquacultural activities are relatively recent, but are rapidly developing along the eastern gulf shore. Currently, there are more than 900 companies (chiefly based upon shrimp) distributed mostly on the continental side, most of them established within the last 15 years. Regarding the ecosystem impacts of aquaculture, experience from other countries indicates intensive aquaculture can negatively affect the coastal topography, biological communities, and environmental conditions, such as increases in the incidence of diseases and HAB events (Alonso-Rodriguez et al., 2000). It appears that the more vicious ecological effects can be noted in abandoned shrimp farms, particularly as soil salinization, acidification and erosion increases (González-Ocampo et al., 2006).

Intensive agriculture systems are mainly found in Sonora and Sinaloa, providing 40% of the national agriculture production (Enriquez-Andrade et al., 2005). Particularly in the Yaqui Valley, fertilizer application rates are extremely high (250 kg N ha^{-1}) and these materials are quickly washed-out by surface water runoff from irrigation. Beman et al. (2005) related the irrigation activity and run off intensity to meso-scale phytoplankton blooms, as revealed by satellite imagery. Further, they suggested that up to 22% of the annual Chlorophyll variability in the Gulf of California is related to the nitrogen run-off from the Yaqui Valley. Even if these results may be controversial, their potential role in environmental and climate projections deserve further investigation.

The Upper Gulf of California is a natural refuge for thousands of species, including commercial, endemic, and some endangered forms. Pesticides (DDE, DDT and DDD) have been found in organisms from the Mexicali Valley's irrigation channels and from the delta wetlands (García-Hernández et al., 2001). The DDE: DDT ratio was lower than 50, which is thought to indicate recent exposure to the parent compound (García-Hernández, 2001). However, the most noticeable human activity to impact this area has been the construction of more than 20 dams along the Colorado River since the 1930s, reducing the flow of fresh water to basically zero, except for unusually high precipitation years. The Colorado River used to supply freshwater, silt, and nutrients to a complex of wetlands that provided feeding and nesting grounds for birds, and spawning and nursery habitat for fishes and crustaceans (Glen et al., 1996). Clearly, the reduction in the river's flow has totally transformed the region, from an estuarine system into an anti-estuary (Lavín and Sánchez, 1999; Brusca et al., 2004), thus reducing the critical habitats for many species (Aragón-Noriega and Calderón-Aguilera, 2000).

The population density in the Gulf of California region is still relatively low, but rapidly increasing. Projections based on current growth rate, almost twice the national one, indicate that the population will reach 10.4 million by the end of this decade. Pollution-related problems will tend to increase, and permanent monitoring, prevention and restoration actions are a must.

3. Fisheries

Fishing is the most important human activity in the Gulf of California, with a strong cultural component, social relevance and a wide spectrum of problems. Different fisheries take place in the region, from highly industrialized pelagic to coastal artisanal, each with particular catch and variability levels, conditions and number of fishers, economic and social impact, magnitude of conflicts and management challenges.

3.1. Shrimp

Shrimp (brown, *Farfantepenaeus californiensis*; white, *Litopenaeus vannamei*; and blue, *Litopenaeus stylirostris*) in the Gulf of California is the most important fishery in Mexico in terms of income and employment. It represents nearly 40% of the total national fish production value, with revenues of over US$132 million per season, and generating over 30,000 direct and indirect jobs. Today, two fleets depend on this resource, one operating small boats (pangas) in coastal lagoons and shallow waters, and another, fully industrialized, comprised of trawling boats working over the continental shelf. The shrimp fishery began in 1921 and became industrialized by the late 1930s (López-Martínez et al., 2001). The gulf also hosts 90% of the shrimp farming industry, developed mostly during the last 15 years and currently producing around 40% of the national shrimp tonnage. It represents a serious competitor for fisheries and an important market component influencing price and demand.

The shrimp fishery is also the most controversial and problematic one in the country; strong debate exists regarding the level of exploitation and the present and potential effects on the ecosystem, mainly because the very high levels of effort and overcapitalization of the industry (detected since the early 1970s; Lluch-Belda, 1974), and also because the trawling gear that has been operated intensively for the last 60 years is recognized as one of the most ecologically aggressive (Jones, 1992). On the other hand, this fishery still represents the main source of income for many coastal communities around the gulf, and has been tightly associated with Gulf of California regional development for several decades.

Currently, knowledgeable authors, based on informal observations, conclude that intensive trawling over the past 60 years in the northern region has had negative effects on the epifauna and infauna, as well as caused sediment re-suspension due to constant disturbance of the benthos, consequently altering the ecology (Brusca et al., 2004). During recent years, strong pressure has mounted against trawl fishing for shrimp to prevent ecosystem deterioration, particularly from ''catch-and-discard'' practices. Unfortunately, no quantitative formal study has evaluated the real impact of these fishing activities, the social and economic consequences of closing them, or the potential development of economic alternatives. Other authors believe that, if fisheries themselves are regarded as an indicator of ecosystem health, the nearly sustained levels of landings in the shrimp fishery, together with the mostly constant of by-catch to shrimp ratios (by biomass), over several decades can be considered as indicative of, at least, a still rather productive ecosystem. This approach has not taken into account, though, the loss of biodiversity or the changes in community composition.

Certainly, much research is urgently needed to assess, on a more confident basis, the real effects of trawling on benthic ecosystems of the gulf. Fortunately, different agencies and foundations (including the David and Lucile Packard Foundation, The World Wildlife Fund (WWF), and the ''Secreataría de Medio Ambiente y Recursos Naturales'' (SEMARNAT)), have recently opened calls, or are devoting people, to investigate these themes; we believe these efforts will provide the urgently needed technical base for a near-future evaluation of the situation.

During the 2004–2006 period, the environmental agenda of the Mexican government, in agreement with the shrimp industrial fisheries chamber, included an unprecedented program of shrimp fleet voluntary retirement. In a first phase the government is investing more than 23.2 million US Dollars to withdraw 250 ships and the associated fishing permits, and the second phase will further reduce effort levels until the fishery shows economic and ecological health. The program also considers that the ships remaining in operation will closely follow responsible practices and a yet to be defined sustainable fishery policy, including setting quotas, fishing exclusion zones and changes in the fishing gear. Attached to this program are two other relevant initiatives: an ambitious fishery operation monitoring program through onboard observers and satellite-based ship tracking, and an investment program on fishing technology, that will help to control the size of catch, to incorporate turtle and fish excluders and to increase efficiency. The next few years will see the results of these programs.

3.2. Small pelagic fishes

In terms of volume, the small pelagic fishery is by far the most important in the country, contributing with up to 40% of total national marine catch in some years (SePesca, 1990). Although this is a multispecies fishery, the prime species is the Pacific sardine (*Sardinops caeruleus*) because of its larger proportion in the catch and higher preference by the fleet, and consequently most of the total variability has resulted from changes in this species (Nevárez-Martínez, 1990).

The fishery developed mainly during the 1970s and reached its highest production season in 1988–89 (Fig. 5b). Since then, the average catch of the Pacific sardine has remained above 50% of the historic maximum. At the beginning of the 1990s, however, a dramatic collapse occurred to less than 3% of the historic maximum in two years, then a fast recovery with catch reaching 97% of historic maximum in three seasons, decreased again during El Niño 1997/1998, and since then gradually increased to an almost historic maximum. During years of poor sardine abundance, its low catches are compensated to some degree by increases of other small pelagic fishes such as the tropical thread herring *Opisthonema libertate* (Lluch-Belda et al., 1986) and the anchovy *Engraulis mordax* (Cisneros-Mata et al., 1991). For this reason, the reduction industry is not as strongly affected as the canning industry, where there is a clear preference for the Pacific sardine.

These large fluctuations are similar in intensity to those of other areas of the World, but it is still unclear whether the dominant frequency is in the 40–60 year band, as in the eastern boundary current systems (Chavez et al., 2003) or not, and whether it is in phase or not with the California Current sardine (Lluch-Cota, 2000b). Contrary to what happens in the California Current system, the gulf represents the tropical (warmer) distribution limit of the northeast Pacific sardine (Lluch-Cota, 2000b); while warm periods appear to be beneficial for the California Current sardine (Lluch-Belda et al., 1989, 1992), its has been observed that high temperatures associated with ENSO diminish or even suspend the annual southward migration of the sardine within the gulf, thus reducing catches (Lluch-Belda et al., 1986; Huato-Soberanis and Lluch-Belda, 1987) and affecting reproduction (Lluch-Cota, 2000b).

One interesting, still unsolved, issue relevant for management is whether the Gulf of California sardine should be considered a separate stock from that of the western Baja California Peninsula. Even though California sardines are harvested in the gulf, they have been considered implicitly separated by assumed isolation

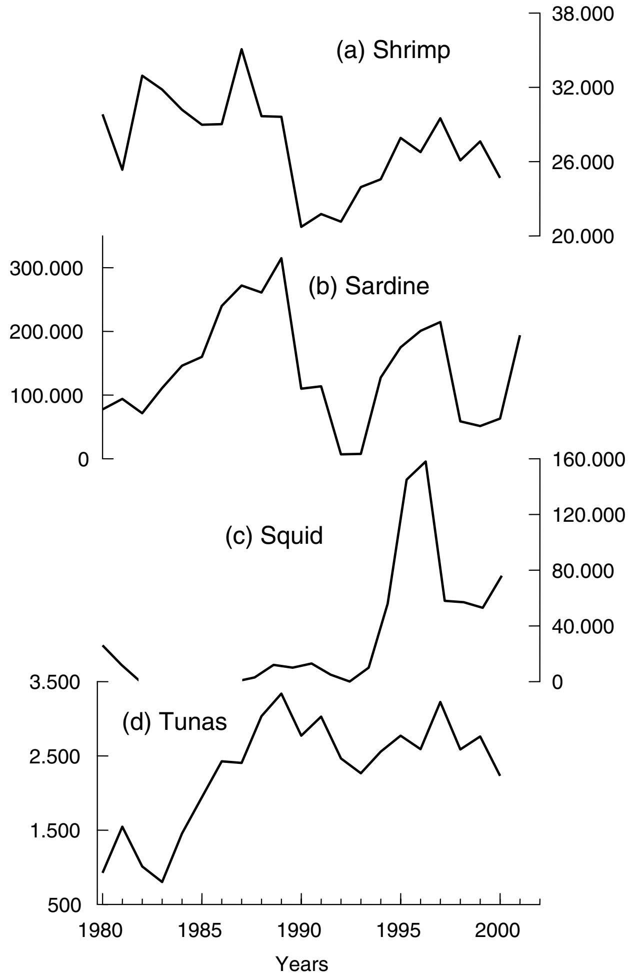

Fig. 5. Catch series (tons) for the four main fisheries in the Gulf of California.

from the west coast populations (Schwartzlose et al., 1999). The same is true for mackerel (*Scomber japonicus*) and northern anchovy (*Engraulis mordax*) population, among others. However, recent investigations indicate substantial interchange of both water masses and organisms between the west coast of the Peninsula and the Gulf of California (Collins et al., 1997; Rodriguez-Sanchez et al., 2001; Lluch-Belda et al., 2003).

3.3. Squid

The Gulf of California giant squid (*Dosidicus gigas*) fishery is also important, although the industry is relatively new. Catches for squid began in the gulf in the early 1970s, mostly supported by small boats at a local scale. By 1980, with the advent of larger boats, the annual catch reached more than 22,000 ton. In 1982, the fishery collapsed and the squid virtually disappeared for almost a decade. It reappeared since 1989, and by 1993 the fishery resumed operations. Catch rapidly increased to 140,000 ton in 1997 (Fig. 5c). During the 1997–1998 fishing season, an extraordinary relocation of the fishing grounds took place. Ehrhardt et al. (1986) stated that, during February and March of normal years, the squid migrates towards the central gulf where it remains concentrated for at least the spring season. During 1997–98, however, landing records from Guaymas and Santa Rosalía, the most important fishing harbors inside the gulf, indicated almost no catch in those months, while high concentrations of animals were detected off the west coast of the peninsula.

During the last few years, squid became one of the most important fisheries in the country, and probably the most dramatic case of fishery fluctuation in the Gulf of California. Causes of this variability are unknown, and hypotheses range from hydrographic (pers. comm. C. Salinas-Zavala, Centro de Investigaciones Biológicas del Noroeste, Mexico), and biological processes (migratory responses of mainly small pelagic populations to prey availability, reproductive success and recruitment; Klett-Traulsen, 1981; Ehrhardt et al., 1982, 1986), to economy (change in catch effort due to market demand; pers. comm. Salvador Lizarraga-Saucedo, Secretaría de Desarrollo Económico y Productividad, Gobierno del Estado de Sonora).

3.4. Large pelagic fishes

A large pelagic fish industry is targeting mainly tuna (yellowfin *Thunnus albacares*, and skipjack *Katsuwonus pelamis*), billfish (striped marlin *Tetrapturus audax*, blue marlin *Makaira nigricans*, black marlin *Makaira indica*, sailfish *Istiophorus platypterus*, and swordfish *Xiphias gladius*), dorado *Coryphaena hippurus*, and around 40 species of sharks including *Mustelus*, *Carcharhinus*, *Alopias*, *Sphyrna* and *Squatina*. Tuna feed (Galván-Magaña, 1999) and spawn (González-Ramírez, 1988; Granados-Alcantar, 2002) in the mouth of the Gulf of California year-round, but are more concentrated during January to April and June to October (Ortega-García, 1998). This fishery is less variable than those for either the small pelagics or for squid, but still some interannual variations have been observed (Fig. 5d). Torres-Orozco et al. (2005) identified a positive relation between the ENSO and the abundance of yellowfin tuna in the region, with time lags of 3 and 12–14 months, apparently associated to northward movement and enhanced recruitment, respectively.

3.5. Artisanal fisheries

Many human settlements depend on coastal, small–scale, artisanal fisheries, exploiting numerous species of bony fish, elasmobranches, molluscs, and crustaceans. Coastal fisheries in this region comprise some 70 species, for an annual catch of nearly 200,000 ton (Enriquez-Andrade et al., 2005). However, because official catch statistics refer to a relatively small number of groups (DOF, 2004), formal fisheries assessment is extremely difficult. Ramírez-Rodríguez and Hernández-Herrera (2000) grouped the species recorded on the east coast of Baja California Sur, and found that species composition of the catch varied greatly between areas within the gulf.

The artisanal fishermen use gillnets, hooks and lines and traps. There were 56,174 fishers, using 23,304 pangas registered in 2001. Together with the associated marketing network, this represents an important regional socioeconomic component, not properly analyzed yet (Cudney-Bueno and Turk-Boyer, 1998). With a few exceptions, natural shellfish resources in the intertidal and circalitoral fringes (0–10 m depth; e.g., oysters, Pen shells, clams, spiny lobsters) are now overexploited or have been heavily exploited in the recent past, and stocks have been seriously depleted. Non-anthropogenic events such as El Niño and La Niña affect the abundance and distribution of coastal artisanal fish resources, but because there are strong differences between components of the fishery, locations, and community structures, no generalization can as yet be made.

3.6. Sport fishing

Another important fishing sector in the Gulf of California is organized around recreational fisheries. The region is considered a natural port for international traffic routes and tourism development. Tourism alone attracts more than 4.8 million visitors per year and generates almost US$2 billion in revenue (Aburto-Oropeza and López-Sagástegui, 2006). The Mexican Government and the "Fondo Nacional de Fomento al Turismo" (FONATUR) have recently announced plans to proceed with a project called "Megaproyecto Mar de Cortés" formerly "Escalera Náutica", or Nautical Ladder, in the Gulf of California, a massive project that includes future operation of 27 ports. Of these, four are currently operative, 11 already exist but need upgrading and expansion, and 14 will be new (<http://www.fonatur.gob.mx> consulted on December 1st, 2006).

Currently, the largest concentration of sport fishing effort is located at the southern end of the Baja California Peninsula, with a mean annual catch rate of 0.6 fish per fishing trip (Ortega-García et al., 2003). In this area, striped marlin (*Tetrapturus audax*) is present during winter and spring, and blue marlin (*Makaira nigricans*) and sailfish (*Istiophorus platypterus*) during summer and autumn. The catch has been estimated at 17,000 individuals per year for marlin and sailfish, plus some 54,000 smaller fish like tuna and dolphin fish (Klett-Traulsen et al., 1996). The supporting tourist infrastructure creates employment in many fields. Estimates of total direct income related to sport fishing in the Los Cabos area, including fishing trips, licenses, lodging, and food, are on the order of 53 million dollars a year, with an indirect impact at least twice that (Ditton et al., 1996).

4. Management and conservation

Given the plural nature of the conflicts related to the natural resources in the Gulf of California region, and given its ecological uniqueness and beauty, it has been the focus of important conservation initiatives for more than a decade. One of the claims has been that fish and shellfish resources in the Gulf of California are overexploited, particularly in the northern part, due to the increase of fishing vessels and fishing gear types, from small pangas, handlines with multiple hooks and spearguns to gill nets, trawls and longlines. Unfortunately, because proper historical data are lacking, and because the region has been subject to strong environmental disturbances, such as the damming of the Colorado River, it is hard to separate fishing from other impacts on abundance and distribution of the gulf species. Even more difficulty is imposed by the alternative hypothesis that the current state of some stocks resulted from environmental changes with fishing acting as an additive effect. This means that, at least in the northern area, controlling effort (selectivity of fishing gears and intensity of fishing pressure) might not ensure the recovery of populations.

The American Fisheries Society's official list of marine fish at risk of extinction includes six species of large groupers and snappers, four of which are endemic to the Gulf of California. Even when no clear evidence of over harvesting exists, the sensitivity of these species, because of late maturity, the formation of localized spawning aggregations (Musick et al., 2000) and their regional endemism, is sufficient to support protective actions.

For these and almost all natural marine populations subject to exploitation in national waters, each year the Federal Government makes a thorough assessment, and derives management actions that may include limitations to fishing effort and fishing mortality, minimum size/age limits, mesh limitations, time and space closures, etc. A brief stock-by-stock summary of all these management actions can be found in the updated version of the "Carta Nacional Pesquera" and all quantitative assessment details are in a document called "Sustentabilidad y Pesca Responsable: Evaluación y Manejo", both available at the INP–SAGARPA website <http://www.inp.sagarpa.gob.mx>.

It is much harder to state the current status of overexploitation of the Gulf of California as an entire ecosystem, or even regions within it. In fact, even when the institutions recognize the need of an ecosystem-based approach to management, still no equivalent of the "Carta Nacional Pesquera" exists at ecosystem level. However, some actions and proposals are pointing to that direction, particularly considering: (a) the implementation of Marine Protected Areas and (b) the design of ecosystem health proxies.

4.1. Marine Protected Areas

One of the first management actions was implemented by the Mexican Government in 1993, when the Colorado River Delta and the Upper GC were declared a Biosphere Reserve (recognized by UNESCO in 1995). There are two additional marine parks in this region: the Cabo Pulmo National Marine Park and The Loreto National Marine Park, and two Natural Resources Protection Areas. In the state of Nayarit, outside the basin circumscribed by the gulf but within its range of influence, there are two more protected areas: the Biosphere Reserve of Islas Marías and the National Park of Isla Isabel (<http://whc.unesco.org/>, consulted November 15, 2005). A general overview of management policies for the Gulf of California is summarized by the Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT; <http://www.semarnat.gob.mx>, consulted December 1, 2006).

Some of the conservation initiatives were proposed by non-governmental organizations (NGO), and some of them have been successfully implemented by the local, regional and Federal governments. The "Comisión Nacional para el Conocimiento y Uso de la Bodiversidad" (CONABIO), The Nature Conservancy (TNC), World Wide Fund for Nature (WWF), and the "Coalición para la sustentabilidad del Golfo de California" are some of the institutions and NGO's that have actively participated in these proposals, recently reviewed by Aburto-Oropeza and López-Sagástegui (2006). The common ground for all these efforts is the establishment of a network of Marine Protected Areas along the coastline of the gulf. Such initiatives have undoubtedly seeded among residents and official institutions a considerable public consciousness concerning the health of the Gulf of California. However, as recognized in many of the models, there is still a great deal of technical information (physical, ecological, sociological and economic) that needs to be incorporated.

4.2. Ecosystem overfishing

Building observation-based proxies of ecosystem health is still a developing topic worldwide and, particularly for the gulf, extremely difficult because ecological historical information is insufficient, no official records of commercial catch exist specifically for the gulf, and its environments and fisheries are diverse. One promising tool is ecosystem modeling; today there are already several trophic models of ecosystem function in selected environments of the gulf (Table 2), and some have already been used to explore management scenarios and potential fishing impacts. For example, Lercari-Bernier (2006) recently evaluated management scenarios for the northern gulf and found that compatibility between conservation and fishing can be reached through fleet control strategies.

It has been suggested that historical changes in mean trophic level (MTL) of catch, along with the diminution of the total landings, could indicate fishing impact. The Fisheries in Balance Index (FIB) is aimed at describing how fisheries exploit the trophic levels within an ecosystem (Pauly et al., 1998). In contrast to many other regions of the world, MTL has increased in the Gulf of California during recent years, and FIB index has been stable during the last five decades (Fig. 6). In the 1950s, the fisheries targeted shrimp almost exclusively, after which species of higher trophic level progressively became targets. The FIB index shows no change due to exploitation of sardines, a massive resource with trophic level close to that of shrimp. Today, shrimp is still one of the most important catches, together with small pelagic fish, while higher trophic level species such as sea basses, groupers, and sharks, contribute far less.

Sala et al. (2004) stated that coastal food webs have been ‘‘fished down’’ in the Gulf, based on interviews with fishers, fisheries statistics (not specifically for the gulf), and field surveys. According to these authors, a decline in fish stocks has been accompanied by a marked shift in the composition of the coastal fishery and a decrease in the maximum individual length of fish caught. In contrast, based on annual catches of the last five decades, estimates of the MTL of catches for trophic levels higher than 3.25 has remained almost constant (a

Table 2
Documented ecosystem models within the Gulf of California

Ecosystem	Environment	Approach	Reference
Northern	Benthic	Compatibility between fishing activities and conservation	Morales-Zarate et al. (2004)
Central	Pelagic	Commercial pelagic species (squid and sardine)	Hernández and Cisneros-Mata (unpublished)
Central	Benthic	Shrimp fishery bycatch and species of commercial interest (shrimp, sardine and small scale fish species)	Arreguín-Sanchez et al. (2002)
Concepcion Bay	General	Ecosystem structure and invertebrate species of commercial interest	Gorostieta-Monjaraz (2001)
Huizache–Caimanero Lagoon system	Benthic	Shrimp and species of secondary interest	Zetina-Rejon et al. (2003)
La Paz Bay	General	Small-Scale fishery	Pérez-España (unpublished)
South Baja California	Pelagic	Pelagic species of commercial interest and sport fishery species	Torres-Alfaro and Villalobos-Bañuelos (unpublished)

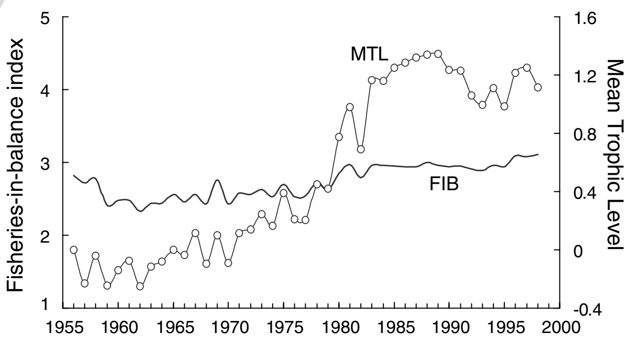

Fig. 6. Historical trends of the mean trophic level of the catch (MTL), and the Fisheries in Balance Index (FIB) in the Gulf of California.

decrease of only 0.09% per year), which does not support the fishing down process, at least at a critical level (Arreguín-Sánchez, unpublished data). Clearly these proxies must be combined with other sources of information before formally proposing ecosystem overfishing. For example, understanding the structure of the catches and documentation of the history of the fisheries are sometimes needed to explain changes in mean trophic level properly. Also, it is essential to consider natural and human- induced disturbances, such as the damming of the Colorado River. We believe the present review might prove valuable for this purpose.

5. Summary

The Gulf of California is a unique system because of its geographical location and conformation; it is complex, productive, and variable. It hosts diverse ecosystems and important fisheries that support industry and provide livelihood to coastal settlements. It also holds an ample variety of interests and problems, and an intense interaction of producers, managers, and conservationists. To properly use and preserve this Large Marine Ecosystem, scientific and technical knowledge is needed. In this section, we list what we believe are the most urgent research actions:

1. An effort to integrate a data base on field records of nutrients, primary and secondary productivity, and plankton composition and dynamics (published and not published). This integration would help us describe and model the lower trophic levels and bottom-up control dynamics in the Gulf of California.
2. Climate variability in the gulf is different from that of surrounding areas. To properly understand and describe it we need to extend the current research on the topic, incorporate regional-scale physical and ecological models and integrate climate reconstructions and paleorecords. Reconstruction of past environments seems to be particularly important for the northern area, where habitat and carrying capacity dramatically changed after the damming of the Colorado River. This unidirectional change must be considered for any attempt at ecosystem restoration or management.
3. Permanent monitoring is needed to properly keep track of ecosystem health (pollutants, biodiversity, HAB events, invasion by exotic species, etc.) throughout the coastal areas, but particularly in those districts with intense human activity. Specific and urgent tasks along this line must help define scales (temporal, spatial, and ecosystem) of impacts caused by local phytoplankton blooms derived from agricultural runoff. Monitoring will also contribute to building an effective inventory of current conditions (fauna, flora, circulation) in the locations where the Nautical Ladder and other large-scale projects may produce changes, in order to properly evaluate and mitigate environmental impacts.
4. We need formal evaluation of fishing impacts on the ecosystem at different locations in the gulf, especially regarding trawling on soft bottoms, bycatch, and mortality of important or icon species. Also, we need a critical test of the potentially positive impacts of shrimp fleet reduction, the use of fish and turtle excluders and other technological improvements in fishing gear.
5. While there have been proposals to establish marine protected areas around the gulf, including a network along the coastline, such actions need to be based on ample scientific knowledge, including interacting variables from physical, ecological, socioeconomic and cultural aspects.
6. The degree of isolation of the gulf ecosystems and biological populations should be further investigated to build proper grounds on which to construct scenarios of future conditions, particularly those likely resulting from global climate change.

Of course, there are many other knowledge needs and interesting topics for research, and it is possible that their relative importance and relevance might change dramatically in the near future. For example, the exploration of the volcanic and hydrothermal vents, and the oxygen minimum layer and its relation to biota distribution.

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