



CONSERVATION SCIENCE IN MEXICO'S NORTHWEST

ECOSYSTEM STATUS AND TRENDS IN THE GULF OF CALIFORNIA



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CORAL REEFS

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In spite of their small size in NW Mexico, coral reefs harbors one of the highest numbers of species per area unit. The geological history of corals shows that coral community composition six million years ago (Late Miocene) was entirely distinct than the present fauna, with three abrupt shifts coupled with two periods of relative stasis in species composition; shifts occurred during 6 to 5 My, 3 to 2 My, and 1 My to actual times. Considering the multiple and severe modifications that are in course in the oceans as a consequence of global change, we suggest different scenarios regarding future frequency of coral bleaching in the southern Gulf of California, changes in species distribution, and the effects of the increasing ocean acidity by increasing carbon dioxide concentration in the atmosphere. The three independent analyses performed suggest that the status of coral communities and reefs of the Gulf of California is not optimum, and might deteriorate in the future. Higher temperature and acidification will affect coral survival and physical integrity of reefs, even if other agents such as bioerosion, predation and diseases are excluded from the picture. The models of coral potential geographic distribution evidences that the eastern coast of the Gulf may become a more hospitable place for corals than today, unfortunately models also predict that the rate of temperature increase in the area is highest, and thus the possibility of bleaching intensifies.

1. INTRODUCTION

Coral reefs are remarkably biodiverse ecosystems, which harbor hundreds of species. There are two main reasons to explain this circumstance: an elevated local productivity and structural heterogeneity. The productivity is caused by the carbon-fixing

activity of the phytoplankton, cyanophytes and other algae, but mostly because of the symbiotic relationship between the coral (an animal) and microscopic dinoflagellate cells called zooxanthellae. The coral provides housing to the algae and in turn the latter supply its host with food and an adequate chemical environment for calcium carbonate deposition. There is a surplus in the amount of energy supplied by the algae to the coral, and these compounds (carbohydrates and lipids) are expelled as mucus, which turns to particulate carbon or it is directly consumed by a myriad of other organisms resident in the coral heads (crabs, gastropods), which then are eaten by fishes or larger invertebrates, and finally ends as food for higher carnivores such as sharks, barracudas and even marine mammals. In short, the symbiotic relationship between corals and zooxanthellae are the base of the intricate food webs characteristic of reefs worldwide.

On the other hand, coral reefs are biogenic structures that modify the substrate where they grow upon. Species that build reefs are called hermatypic, a word that means “reef-builders”, and are restricted to shallow waters because the zooxanthellae need abundant light for photosynthesis. However, there are others corals that do not have algae, named azooxanthellate that live deep in the ocean and may form conspicuous structures on the sea floor, and at depths of 300 m or more.

In northwestern Mexico there is only one coral reef in Cabo Pulmo (23°N), close to the tip of the Baja California Peninsula (see Figure 1). The framework is small but nevertheless the amount of energy supports the highest fish biomass in any reef of the Gulf of California (Aburto-Oropeza *et al.* 2011). In addition, reef corals occur at five states in NW Mexico (Baja California, Baja California Sur, Sonora, Sinaloa and Nayarit) and the entire region harbor 24 species of zooxanthellate and 30 species of azooxanthellate corals. This means that 77% and 85%, respectively, of all coral species reported for the Mexican Pacific (Reyes-Bonilla *et al.* 2005) are represented in this region. The ratio of zooxanthellate: azooxanthellate is quite different among states; *e.g.* Baja California only have two zooxanthellate species and 22 azooxanthellate, while Nayarit have 20 zooxanthellate and 5 azooxanthellate (see Figure 1). However, this may be explained by the sampling effort conducted in each region, because the deep water corals require a research vessel and the Gulf of California has been the target of numerous cruises, but notwithstanding the Gulf of California is one of the richest areas for coral occurrence in Mexico.

The first reports of coral species in the region come from expeditions conducted in the XIX century by institutions from the United States (Reyes-Bonilla 2003), but in the last two decades of the XX century and the beginning of this century, most studies have been carried out by Mexican researchers.

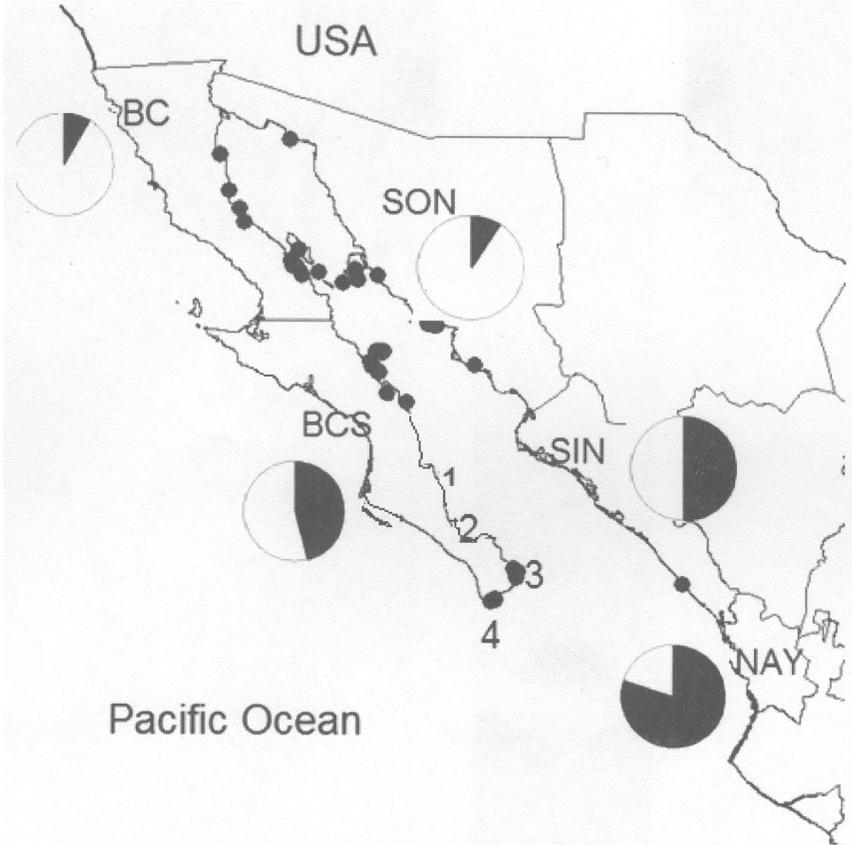


FIGURE 1. Locations of the main coral communities in the Gulf of California. Pie charts inside each state represents proportion of zooxanthellate (filled) and azooxanthellate (blank) corals.

2. CORALS OF THE PAST

Studies of stony corals in the Gulf of California have mainly focused on living species and few of these works have analyzed fossil taxa. In addition, this kind of research has been sporadic, incidental and to some extends rudimentary, and generally devoted to species description, faunal listings and reviews of the geographic affinities of the fauna (López-Pérez 2005). Recently, however, new attention has been drawn to new records of coral species (López-Pérez 2008), to the lithology, age and paleoenvironment of buildups (Johnson and Ledesma-Vázquez 1999, Mayer and Vincent 1999, Halfar *et al.* 2001, DeDiego-Forbis *et al.* 2004, Johnson *et al.*

2007), and to issues regarding scleractinian diversification in the Gulf of California (López-Pérez and Budd 2009). On this ground, here we summarize published information on fossil corals and perform a quantitative analysis of the change in species composition in the Gulf in order to highlight the relevance of the area in the development of the eastern Pacific coral fauna.

We analyzed presence/absence data collected during field expeditions to the Baja California Peninsula in June–August 2002, January 2003, June–July 2003, and January 2005. Data were arranged in time bins of one million years of duration during the last 6 million years. In addition, a relative abundance matrix was created by counting the number of specimens per species collected within each assemblage, and assigning codes for rare, common, abundant, and super-abundant, such that: 1 specimen = rare, 2–3 specimens = common, 3–9 specimens = abundant, and > 9 specimens = super abundant. Both, presence/absences and relative abundances of coral taxa among assemblages were compared using the Bray-Curtis dissimilarity index, and processed with a non-metric Multi-Dimensional Scaling (MDS). Following MDS, the relative abundance matrix was evaluated through similarity analysis (ANOSIM) to detect changes in species composition and abundance through time (Clark and Warwick 2001).

Ordination (MDS) on presence/absence data (see Figure 2) show that, for the stony coral fauna in the Gulf of California during the last six millions years, there were clear differences in community structure between time bin intervals. Several elements are worth to mention. First, coral community composition six million years ago (Late Miocene) was entirely distinct than the actual fauna, indeed, they are located at opposite ends of the graph. Second, note that there have been three abrupt shifts coupled with two periods of relative stasis in species composition; shifts occurred during 6 to 5 My, 3 to 2 My, and 1 My to actual times, particularly, species composition shifted abruptly during the last million, whereas stasis occurred between 5 to 3 My and 2 to 1 My. Finally, low similarity levels persisted from Late Miocene to Early-middle Pleistocene due to the presence of *P. panamensis* and *Pocillopora capitata* in fossil buildups during the last 5 My whereas the abrupt shifts was favored by the constant addition and extinction pulses of Caribbean derived taxa that originated in Gulf of California coral reef communities (López-Pérez and Budd 2009). It is worth to mention that except for the living *P. panamensis* and *P. capitata*, no other taxa or its descendants are known in Gulf of California or eastern Pacific reefs (Reyes-Bonilla *et al.* 2005), although related fauna (*Siderastrea*, *Favia*, *Diploria*, *Dichocoenia*, *Solenastrea*, *Eusmilia*) still persist in the Caribbean (Budd *et al.* 1994).

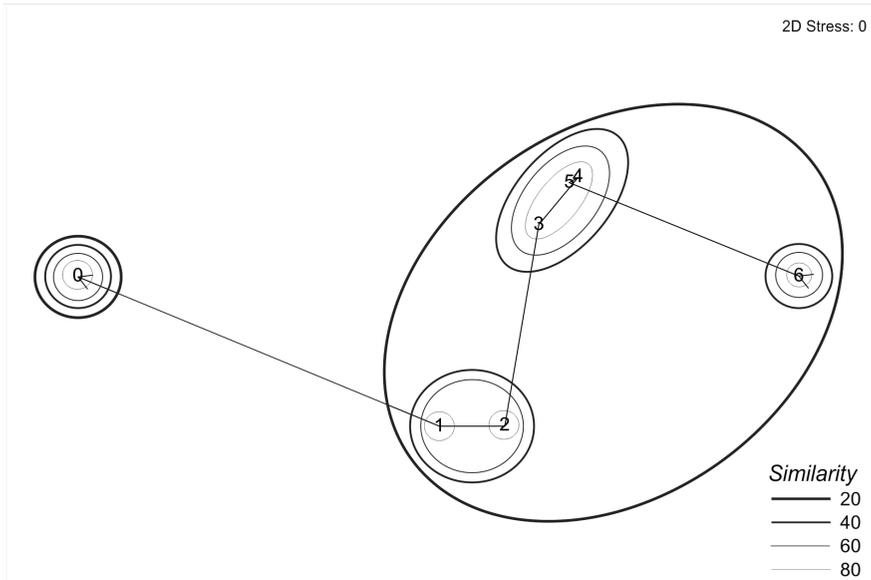


FIGURE 2. Qualitative change of coral reef communities during the last six million years in the Gulf of California, Mexico. Dissimilarities among time bin intervals (one million years of duration; 6 = Oldest, 0 = Recent) were generated with a Bray-Curtis index from a presence/absence matrix. Distance map produced by multidimensional scaling. Similarity contours = 20, 40, 60, 80 %; overlay trajectory = arrows.

Two elements converge in the abrupt shift that favored the current composition of Gulf and eastern Pacific coral fauna: the extinction pulses that drove the local extirpation of Caribbean related fauna between 3–1 My (López-Pérez and Budd 2009), and the immigration of species into the Gulf from the Indo-Pacific (Dana 1975). As demonstrated by López-Pérez and Budd (2009), both pre-turnover (Caribbean related) and post-turnover (Indo-Pacific) taxa does not coincide in space or time, therefore ruling out the role of biological interactions or ecological replacement as the leading role on species extinction; on the contrary, Indo-Pacific species invade the Gulf at a steady but sporadic rate after the arrival of *Pavona clavus* during lower to Middle Pleistocene near the mouth of the Gulf (López-Pérez 2008).

Two further figures depict species relative abundance changes in Gulf coral communities from Middle Pleistocene to the Recent (see Figure 3). *Porites panamensis* flourished and constructed relatively large and monospecific reefs from Punta Chivato to Isla Cerralvo in Pleistocene times (Johnson *et al.* 2007) and became the most widespread species in living eastern Pacific coral communities and reefs

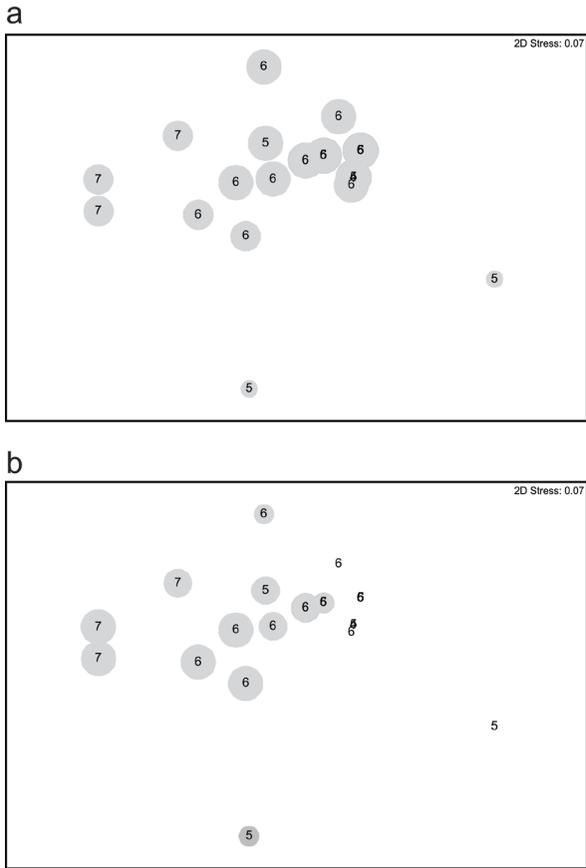


FIGURE 3. Quantitative change of coral reef communities from Middle Pleistocene to Recent in the Gulf of California, Mexico. Dissimilarities among assemblages were generated with a Bray-Curtis index from an abundance matrix. Distance map produced by multidimensional scaling. 5 = Middle Pleistocene; 6 = Late Pleistocene; 7 = Recent. Bubbles = species relative abundance. (a) Overlay *Porites panamensis* relative abundance. (b) Overlay *Pocillopora capitata* relative abundance.

(Reyes-Bonilla *et al.* 2005). Figures 3a/3b illustrate the shift from *P. panamensis* to *Pocillopora* spp. dominated communities in the Gulf; in particular, it is remarkable how *P. capitata* has increased its abundance from Middle Pleistocene to the Recent (see Figure 3b), while *P. panamensis* has remained stable during the same time interval (see Figure 3a) becoming a relatively minor element in the living south and central coral communities as demonstrated by Reyes-Bonilla and López-Pérez (2009). On this ground, it can be safely claimed that rather than being caused by the lower contribution of *P. panamensis* to living reefs, community change was due to

the increase of *P. capitata*; therefore the relative abundance of *Porites* and *Pocillopora* in the Gulf, can be explained by a dilution effect instead of the competitive displacement of *P. panamensis* by *P. capitata* from Gulf communities.

So far, we have reviewed the past and current situation of the coral communities and reefs of the Gulf, and the last section will address its potential future. It is understandable that due to the multiple and severe modifications that are in course in the oceans as a consequence of global change, it is of the foremost importance to make use of updated information to suggest feasible scenarios about how coral communities will behave, and from there to examine if their distribution, abundance and status might be modified by the new set of conditions. In the following pages we deal with three topics related to the rising sea surface temperatures: future frequency of coral bleaching in the southern Gulf of California, changes in species distribution, and the effects of the increasing ocean acidity by increasing carbon dioxide concentration in the atmosphere.

3. CORAL BLEACHING

This phenomenon represents the loss of the relationship between the zooxanthellae (symbiont dinoflagellates) and their coral hosts, and has become one of the main worries for the health of coral reefs worldwide as its consequences are plenty, impact the entire ecosystem, and is practically impossible to control as it can affect entire oceans (Baker *et al.* 2008). Bleaching tends to occur when conditions are atypical, including several cumulative weeks with high ocean temperature, high irradiance and low wind stress (Hoegh-Guldberg *et al.* 2007). However, many studies have indicated that the current rate of sea temperature increase will lead to a situation when the loss of algae will happen much more frequently and eventually become chronic (yearly), as the temperature surpass a given limit. This marker is known as the “temperature threshold” (Goreau and Hayes 1994, Podestá and Glynn 1997), and represents an increase of 1°C above the long term average temperature of the warmest month (*e.g.*, if August is the warmest month in a given site and its average is 28.5°C, then the local bleaching threshold is 29.5°C). In this section we will present the bleaching thresholds of the main reef areas of the Gulf, located on the southeastern tip of the Baja California Peninsula, and use a simple and conservative statistical model to assess when coral bleaching will become chronic and occur at least one month every year.

To determine the current bleaching threshold, quadrats of 1° x 1° latitude and longitude were selected to encompass four key areas for coral development in the Gulf: Los Cabos region (south and east limits at 22°N, 109°W), Cabo Pulmo (23°N,

TABLE 1. Bleaching threshold, annual rate of increase and year when bleaching will become chronic at selected sites in the Gulf of California.

Site and latitude	Bleaching threshold (°C; calculated from 1984–2008)	Slope (annual rate of increase)	Year when bleaching will become chronic
Los Cabos (22.5°N)	29.81	0.0114 + 0.0032	After 2050
Cabo Pulmo (23.5°N)	30.27	0.0089 + 0.0031	After 2050
La Paz (24.5°N)	30.03	0.0005 + 0.0033	2046
Loreto (25.5°N)	29.78	0.0178 + 0.0033	2034

109°W), La Paz (24°N, 110°W) and Loreto (25°N, 111°W). At each quadrat we analyzed monthly data of sea surface temperature from the Reynolds SST analysis (www.nhc.noaa.gov/aboutsst.shtml) considering the time span of 1984 to 2007 (N=288), as suggested by Sheppard (2003) and Eakin *et al.* (2008); further, we calculated the bleaching threshold on the basis of the average temperature of August, which in all cases was the warmest month. The next step was to perform individual linear regressions for each quadrat, using the year as independent variable and the temperature of each month as dependent; this way we obtained the monthly rate of increase directly from the slope of the twelve lines. Finally, we extrapolated the regression lines to calculate the expected temperature for each month from 2008 to 2050, and performed a general analysis of year versus average temperature (N=24) to estimate the general trend of temperature change at each quadrat. The linear approach was considered conservative since most global change models advise that the trend of ocean warming is faster than monotonic (Donner *et al.* 2009), and thus our predictions can be placed on the safe side.

Our results indicate that the slope of temperature increase in the 25 years analyzed differs noticeably among sites, as in Loreto and Los Cabos is two to three times higher than in La Paz and Cabo Pulmo (see Table 1). This is a clear indication that warming is not homogeneous in the study region nor has a latitudinal array, but instead is driven by local conditions; for example, in the case of La Paz the rate is slower probably as a consequence of the spring wind-induced upwelling that occur west of San José Island. The bleaching threshold is not constant either, being highest at Cabo Pulmo and lowest at Loreto, with a difference of almost 0.5°C between these areas (see Table 1). These finding points out that at Cabo Pulmo corals are possibly more tolerant to sea water temperature increases, and that may be one of the reasons why they survived the last two intense bleachings in 1997 and 2008, and

minor events in 1987, 2007 and 2009 (Reyes-Bonilla 2003, LaJeunesse *et al.* 2007, Reyes-Bonilla and López-Pérez 2009, Reyes-Bonilla unpublished data).

Considering the rate of increase and the bleaching threshold from the linear regression, we predict that the two southernmost reef areas of the Gulf of California may not experience chronic bleaching in the following four decades, while by 2034 the problem may develop yearly (during August and September) at Loreto and after 2046 in La Paz (see Table 1). By 2050, Loreto corals may experience loss of zooxanthellae from July to September, while at La Paz the bleaching will be present only in September, because by that time we predict that this will be the warmest month of the year, instead of August.

Our model and the actual temperature trends (see Figure 4) support the idea that the central part of the Gulf will be in more thermal stress than the south, probably as the latter is more influenced by the California Current during winter and early spring (Kessler 2006). However, as the current temperature in these areas is not adequate for reef corals, we might suggest that global warming can bring conditions that will actually improve the situation, at least temporarily, for reef corals in the eastern Gulf of California. We fear that with so high warming rate, the threshold of adequate conditions may be surpassed and corals might experience chronic bleaching soon, a condition that will avoid reef development in that region of the Gulf. All these observations are important as several authors (Glynn 2001, Reyes-Bonilla *et al.* 2002, Precht and Aronson 2004) have suggested that the relatively colder waters of the Gulf would provide shelter to corals during global warming; unfortunately, that may not be the case in the entire region.

4. CORAL POTENTIAL DISTRIBUTION

The second analysis consisted in the application of niche models to determine possible changes in coral species distribution and consequently richness, along the Gulf. This subject is important as the continuous increase in sea temperature occurred in the last 25 years, has favored the colonization of the Gulf by several coral species such as *Leptoseris papyracea* (first found in 1997; Leyte-Morales *et al.* 2001) *Psammocora superficialis* (found in 1997; Reyes-Bonilla 2003) and *Pavona varians* (found in 2003; Reyes-Bonilla *et al.* 2005) and, at the same time, it has affected the health of an endemic coral, *Porites sverdrupi*, which has reduced its northern distribution range about 250 km, currently from Los Cabos (22°N) to San José Island (25°N; Reyes-Bonilla and López-Pérez 2009). The most recent distribution shifts was observed in 2009; the previous *Pocillopora verrucosa* northern geographic limit was Loreto

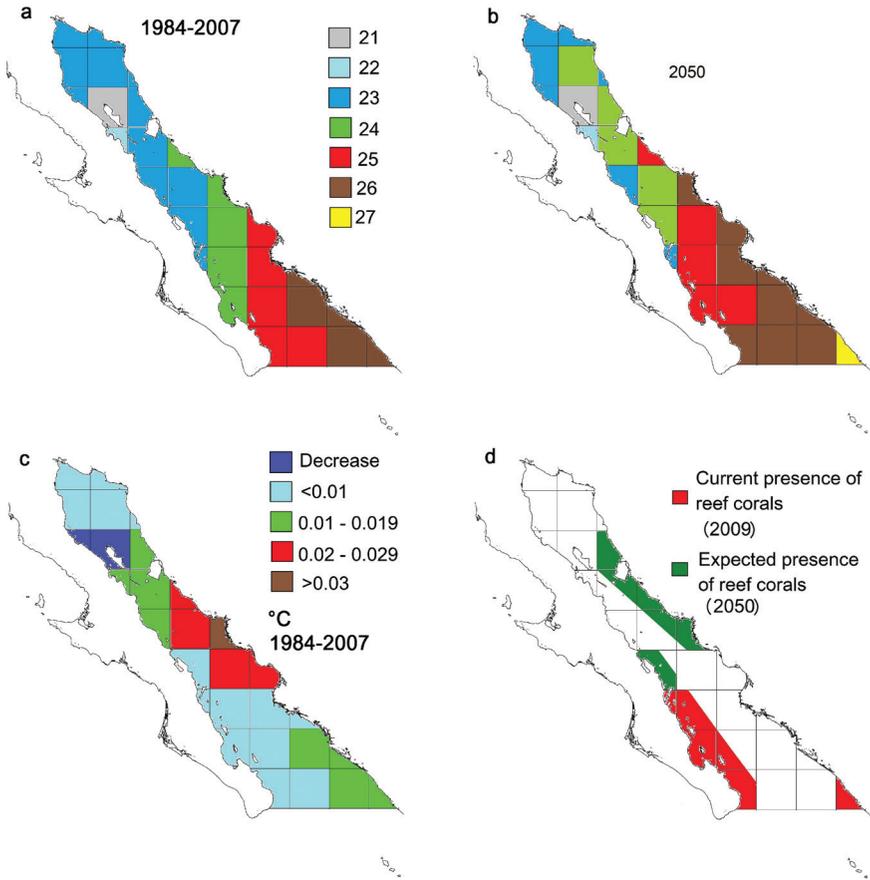


FIGURE 4. (a) Average sea surface temperature of the Gulf of California (1984-2007); (b) Expected temperature by 2050; (c) Rate of temperature increase (linear model; yr⁻¹) from 1984-2007; (d) General result of the MAXENT model for reef corals of the Gulf.

(25°N), but currently it is found at Concepción Bay (26.5°N), while *P. damicornis* has moved about 100 km north, from Agua Verde Bay to northern Loreto Bay.

To model the potential distribution range for the each of the 19 hermatypic coral species that inhabit the Gulf, we used over 1,500 georeferenced records from the area published by Reyes-Bonilla *et al.* (2005). The information was processed using MAXENT (maximum entropy modelling; Tittensor *et al.* 2009) along with 22 environmental variables obtained for all 29 squares of 1° x 1° lat-long area that cover the Gulf down to the parallel 22°N. The environmental variables considered were the

surface maximum, minimum and average values of chlorophylla (SEAWIFS and MODIS-AQUA satellites, monthly data from 1997-2008; <http://las.pfeg.noaa.gov/oceanWatch/oceanwatch.php#>, and <http://reason.gsfc.nasa.gov/OPS/Giovanni/ocean.aqua.shtml>), salinity and nutrient concentration (nitrate, phosphate and silicate; monthly data from the World Ocean Atlas 2005, average 1955-2004; www.nodc.noaa.gov/OC5/SELECT/woaselect/woaselect.html), and alkalinity (calculated from salinity and temperature following the algorithm of Lee *et al.* 2006), plus a dummy variable indicating the type of substrate (hard or soft; from the general classification presented by Moreno-Casasola *et al.* 1998). Further, we substitute the historical temperature data with that predicted with our linear models for 2030 and 2050 for each 1° x 1° quadrat, and re-run the models. Finally, we determine that a given area is acceptable for reef coral occurrence if the expected number of species is higher than 6, the current number at Loreto (Reyes-Bonilla 2003).

Results indicated that most of the western Gulf of California has fair oceanographic conditions for coral development as nutrient concentration is not so high and rocky bottoms are dominant in that region. However, the limiting factor is temperature, as most species prefer relatively warm waters because they have colonized the eastern Pacific from the west (Reyes-Bonilla 2003); in fact, the key factor is lowest yearly temperature, as most species are not able to survive if winter temperature is lower than 18°C. The maps of potential distribution (not shown) point out that from 2007 to 2030 there will be few range shifts, as only two species will move from 23°N to 24°N, on the coast of the Baja California Peninsula (*Pavona varians* and *P. duerdeni*), but by 2050 seven out of 19 species (37% of the total) will move northward; that said, today species turnover rate is slow but four decades from now rise to over 30% at latitudes 27°N and 30°N. It is important to notice that the analysis identified that the increase in richness at 27°N will be caused by colonization of the eastern coast of the Gulf by *Pavona gigantea* and *Pocillopora verrucosa*. Finally, the only species that reduces its distribution range was *Porites sverdrupi*, which according to his potential distribution map will be restricted to waters north of 26°N in the Gulf.

Figure 4d highlight the areas for development of reef corals by 2050. As observed, the rise in temperature will remarkably increase the potential habitat for reef corals by 2050, and is expected than northern Sinaloa and southern Sonora (27° to 29°N) may soon have elements of this ecosystem. The addition of these species may represent a boost in species richness in those areas as corals provide new resources and also facilitate the entrance of western Pacific species (crabs, fishes, gastropods) that are not present in the eastern Gulf of California nowadays.

5. OCEAN ACIDIFICATION

Ocean acidification has been called “the other CO₂ problem” because at the same time that carbon dioxide increases atmospheric temperature, it also acidifies the ocean water as a consequence of hydrogen ions liberated by the carbonate system (Doney *et al.* 2009). The situation was first noticed in the 1990s (Kleypas *et al.* 1999) and has caused serious concern as acidification is not only damaging shallow water reefs but also can affect deep water scleractinian species (Guinotte *et al.* 2006, Hoegh-Guldberg *et al.* 2007). It is predicted that lower pH values will reduce calcification rate for both the marine benthos and plankton, and can be especially damaging for larvae and juveniles (Fabry *et al.* 2008, Munday *et al.* 2008). In the specific case of reefs, the problems are plentiful, including depleted recruitment of corals and other invertebrates, lower tolerance to predators, and especially a more fragile reef framework (Baker *et al.* 2008).

To analyze the current and future status of omega aragonite in the southwestern Gulf of California, we followed the method described by Manzello *et al.* (2008) on the same 1° x 1° lat-long quadrats. We used average monthly salinity, phosphate and silicate concentration at depths from surface to -50 m (data from the World Ocean Atlas 2005, average 1955-2004; www.nodc.noaa.gov/OC5/SELECT/woaselect/woaselect.html); monthly temperature for 2008 from a combination of the WOA atlas and the MODIS-AQUA satellite data; monthly atmospheric carbon dioxide concentration from air flask samples taken at La Paz in 2008 (Scripps Institution of Oceanography CO₂ program; http://scrippsco2.ucsd.edu/data/flask_co2_and_isotopic/monthly_co2/monthly_bcs.csv); calculated alkalinity following Lee *et al.* (2006) algorithm, and included all cited parameters in the program CO₂SYS. In addition, to forecast the possible carbonate saturation state from 2010 to 2050, we calculated yearly average of nutrients and salinity and considered them as constant as there is no useful method to estimate future values (Donner *et al.* 2009). Then we used the expected value of sea surface temperature from linear extrapolations described earlier, calculated alkalinity with Lee *et al.* (2006) procedure, and calculated the anticipated carbon dioxide concentration according to the power model of the Mauna Loa Observatory (http://scrippsco2.ucsd.edu/data/in_situ_co2/monthly_mlo.csv) in order to calculate the possible omega aragonite value with CO₂SYS. Finally, to evaluate the status of Gulf coral communities and reefs we took as landmark the figure of 3.28 + 0.09, considered by Kleypas *et al.* (1999) as the lowest limit for coral reef formation.

As shown in Figure 5, aragonite conditions were very different among reefs, even when they are geographically nearby (between Loreto and Los Cabos the distance

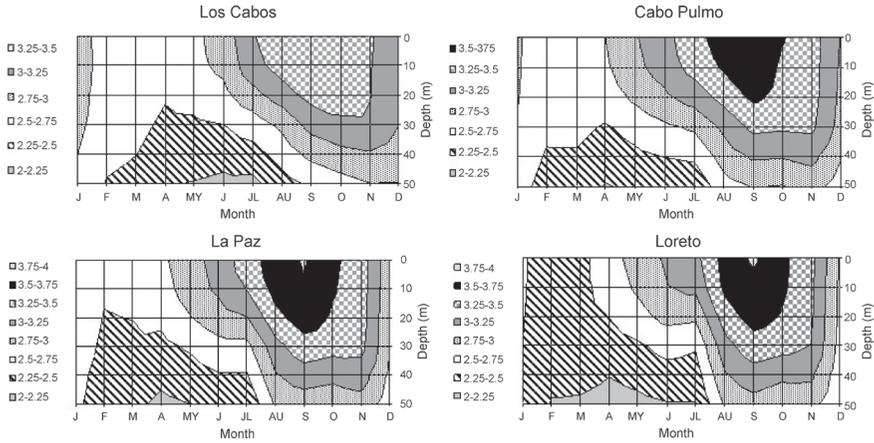


FIGURE 5 Bathymetric distribution of omega aragonite in four rocky and coral reefs of the Gulf of California.

is less than 300 km). The southernmost region, Los Cabos, bordering the Pacific Ocean, is characterized by low omega values (range of 2.18 to 3.49), and the best seasons for coral calcification is summer and fall (from late July to November), when Ω surpasses 3.25. Analyzing the depth levels it can be seen that below 30 m the conditions do not allow for a healthy development of coral reefs, and at -20 m only September and October are adequate. On the other hand, from Cabo Pulmo to Loreto the conditions are much better, but still far away from the ideal condition. From mid June to mid November the calcification index was over 3.25, and peaks in September when it reached 3.66 in Cabo Pulmo and over 3.77 in La Paz and Loreto. This value is similar to the lowest monthly average in the Caribbean Ocean during 2009 (http://coralreefwatch.noaa.gov/satellite/oa/saturationState_GCR.html). Finally, the possibility to construct reefs exists in waters deeper than -30 m, and very good in summer months down to 20 m depth.

There are two references addressing the omega aragonite value in the southern Gulf of California. Kleypas *et al.* (1999) calculated that surface value in the mid 1990s was from 3.34 to 3.49, much higher than that calculated for 2008 (see Figure 3), from $3.00 + 0.14$ in Loreto, to $3.12 + 0.11$ in Cabo Pulmo, while Manzello *et al.* (2008) show that the Gulf has a mean omega of around 2.9, a little lower than the calculated here. Dismissing the small differences in estimated values, the key point here is that the main coral communities and reefs of the Gulf are currently under the threshold for reef formation, as it occurs in other areas like the Galápagos Islands, subtropical

Japan and southern Australia, which periodically are under the influence of upwelling (Kleypas *et al.* 1999). It is expected that moving northward in the Gulf, where acidity and primary productivity are higher by effect of the colder water (more catch of atmospheric CO₂) and continuous tide and wind disruption of the thermocline (Álvarez-Borrego 2007), the situation is even worse.

If conditions nowadays are difficult for reef corals in the Gulf, the future seems bleaker. Most studies show that ocean acidity will be higher in the future as a consequence of increasing carbon dioxide concentrations (Hoegh-Guldberg *et al.* 2007); concurrently, we showed that coral calcification in the Gulf will become rougher during the following decades. As indicated by Manzello *et al.* (2008) for the Galápagos Islands, Panamá and Costa Rica, more acid ocean water represents brittle coral skeletons and a heightened effect of chemical and biological erosion. If this is the case, even with no increase in frequency and strength of tropical hurricanes and cyclones, the physical stability of reef areas in the Gulf will be compromised, and thus their function and ecosystem services will be severely affected, with unknown but deleterious consequences for the human communities in northwestern México.

6. FINAL REMARKS

The three independent analyses performed point out toward a conclusion: the status of coral communities and reefs of the Gulf of California is not optimum, and might deteriorate in the future. Higher temperature and acidification will affect coral survival and physical integrity of reefs, even if other agents such as bioerosion, predation and diseases are excluded from the picture. The models of coral potential geographic distribution evidences that the eastern coast of the Gulf may become a more hospitable place for corals than today, unfortunately models also predict that the rate of temperature increase in the area is highest, and thus the possibility of bleaching intensifies. Reef corals are very long-living animals with extended generation times, and for that reason local adaptation is usually quite slow (Sheppard *et al.* 2009); nevertheless, dramatic mortality events may accelerate it (Donner *et al.* 2005) or in the specific case of bleaching, the exchange of clade types is a potential option to do so (Baker *et al.* 2008). We expect that the low effective population size of coral populations north of 25°N may boost the speed of evolutionary change for the current fauna, and that Indo Pacific colonizing species will also do well under future conditions. That way, reef coral environments will survive throughout the century; however, if this is not the case, we may be on the verge of the loss of a rare but nevertheless important marine ecosystem in the Gulf of California.

ACKNOWLEDGMENTS

Project SEMARNAT-CONACYT 108302 to HRB and 023390 to LECA. Pedro González (UABCS), Leonardo Vázquez (UNAM) discussed many of the ideas presented in the final part of the chapter.

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Exploring Mexico's northwest, the Baja California Peninsula, its surrounding oceans, its islands, its rugged mountains, and rich seamounds, one feels diminished by the vastness and the greatness of the landscape while consumed by a sense of curiosity and awe. In a great natural paradox, we see the region's harsh arid nature molded by water through deep time, and we feel that its unique lifeforms have been linked to this desert and sea for thousands of years, as they are now.

These landscapes of fantasy and adventure, this territory of surprising, often bizarre growth-forms and of immense natural beauty, has inspired a wide array of research for over two centuries and continues to inspire the search for a deeper knowledge on the functioning, trends, and conservation status of these ecosystems in both land and ocean.

This book offers a compilation of research efforts aimed at understanding this extraordinary region and preserving its complex richness. It is a synthesis of work done by some exceptional researchers, mostly from Mexico, who indefatigably explore, record, and analyze these deserts and these seas to understand their ecological processes and the role of humans in their ever-changing dynamics.

Elisabet V. Wehncke



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ISBN 978-1-4951-2222-4
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