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# Status of Eastern Brazilian coral reefs in time of climate changes

ZELINDA M. A. N. LEÃO, RUY K. P. KIKUCHI, MARÍLIA D. M. OLIVEIRA & VIVIAN VASCONCELLOS

*Universidade Federal da Bahia, Centro de Pesquisa em Geofísica e Geologia, Instituto de Geociências. Rua Barão de Jeremoabo s/n, Campus Universitário de Ondina, Salvador 40170-115, Bahia, Brasil. E-mails: zelinda@ufba.br; kikuchi@ufba.br; mariliad@ufba.br; vivianvasconcellos@hotmail.com*

**Abstract.** Brazilian reefs comprise the largest and the richest reefs of the Southwestern Atlantic Ocean. Indicators of reef vitality reveal that reefs located less than 5 km from the coastline, the inshore reefs, are in poorer conditions than those located more than 5 km off the coast, the offshore reefs. The inshore reefs are the most impacted by the effects of eutrophic waters associated with sewage pollution, high sedimentation rates and water turbidity, and the most exposed to the effects of bleaching and infectious diseases. From 1998 to 2005, long-term sea water thermal anomaly events, equal or higher than 1ºC, were responsible for more than 30% of bleached corals in the inshore reefs. In the offshore reefs of the Abrolhos area, bleaching was milder, but the reefs are strongly threatened by the incidence of diseases that have escalated in prevalence from negligible to alarmingly high levels in recent years. Although bleaching and coral disease have not yet caused mass mortality in the Brazilian reefs, these natural disturbances associated with the effects of global climate changes and human-induced activities, could lead the reefs to higher levels of degradation.

**Keywords:** Coral bleaching, Sea surface temperature anomaly, Abrolhos

**Resumo. Estado dos recifes de coral da costa leste Brasileira em tempo de mudanças climáticas.** Os recifes de coral do Brasil são os maiores e mais ricos recifes do oceano Atlântico Sul-Ocidental. Indicadores da vitalidade dos corais revelaram que os recifes localizados menos de 5 km da linha de costa, os recifes costeiros, apresentam condições inferiores aos recifes de alto mar, que estão afastados mais de 5 km do continente. Os recifes costeiros além de estarem severamente impactados pelos efeitos da eutrofização das águas, associada à poluição de esgotos domésticos, altas taxas de sedimentação e turbidez, estão ameaçados pela ocorrência de eventos de branqueamento e doenças dos corais. De 1998 a 2005 eventos de longa duração das anomalias térmicas da água do mar de 1ºC ou mais, foram responsáveis por mais de 30% do branqueamento nos recifes costeiros. Nos recifes de alto mar da área de Abrolhos, apesar dos eventos de branqueamento terem sido mais suaves, os recifes estão ameaçados pela incidência de doenças cuja prevalência alcançou níveis alarmantes nos últimos anos. Embora os eventos de branqueamento e a ocorrência de doenças não tenham provocado, ainda, mortalidade em massa dos corais, estes distúrbios associados aos efeitos dos fenômenos climáticos globais e de ações induzidas pela atividade humana constituirão uma grave ameaça que poderá levar os recifes a níveis elevados de degradação.

**Palavras-chave:** Branqueamento de coral, anomalia térmica da água superficial do mar, Abrolhos

## Introduction

In the coastal zone of Eastern Brazil, coral reefs are one of the most prominent marine ecosystems, comprising the largest and richest area of reefs in all of the southwestern Atlantic Ocean. Studies during the last two decades have shown that these coral reefs are experiencing increasing degradation due to a combination of large-scale natural threats (*e.g.* sea level oscillations and ENSO events), and of more local scale anthropogenic stressors, such as accelerated coastal development, reef eutrophication, marine pollution, tourism pressure, over-exploitation of reef resources, overfishing and destructive fisheries and, more recently, the introduction of non-indigenous invasive species (De Paula & Creed 2004, Leão & Kikuchi 2005, Leão *et al.* 2008). At the global scale, there are many cases in which these threats have already caused a reef phase shift away from corals (Riegl *et al.* 2009).

In Eastern Brazil, several parameters of reef vitality, among them the living stone coral cover, the density of reef building coral species and of coral recruits, and the abundance of macroalgae, indicate that, overall, the reefs located closer to the mainland are in poorer condition than those that are more than 5 km from the coastline (Kikuchi *et al.* 2010). A lowering of sea-level that occurred after 5,000 years BP, along that part of the Brazilian coast, placed the inshore reefs closer to the coastline and mobilized the western continent-derived siliciclastic sediment toward the eastern reef systems. This event exposes them to increased runoff and sedimentation and intense solar radiation, as well as threats induced by human activities (Leão & Kikuchi 2005).

Bleached corals have been seen in Eastern Brazil since the summer of 1982/1983 (Z.M.A.N.L. pers. observation), but the first published records of coral bleaching date from the summer of 1993/1994, after the occurrence of a worldwide El-Niño event (Castro & Pires 1999, 2001). Since then, there are records of bleached corals coincident with every occurrence of sea water temperature anomaly along this part of the Brazilian coast (Leão *et al.* 2008). There seems to be a strong linkage between coral bleaching and periods of elevated sea surface temperatures along the coast of Brazil. On the other hand, coral diseases have flourished worldwide since the 1980s (Harvell *et al.* 1999, 2002, Rosenberg & Loya 2004), but only recently has the incidence of coral diseases in the Brazilian reefs increased (Francini-Filho *et al.* 2008). Both coral bleaching and diseases seem to be intensified by warming of the sea surface temperature, and they are affecting mostly the inshore reefs.

This work presents a synthesis of the status of the coral reefs from Eastern Brazil based on data collected during the last decade. It was examined a variety of environmental factors in an effort to distinguish the dominant attributes on the intensity of bleaching. The combination of these studies increase the chances of making predictions concerning the effects of the expected temperature increase on reef organisms, and to set regional priorities for research and conservation of the reefs in the face of global climate changes.

## Materials and Methods

**Study area:** The Eastern Brazilian reefs are spread along about 800 km of the coastline of the state of Bahia, between 12º and 18º S (Fig. 1). This part of the Brazilian coast has a tropical climate, with rainfall ranging from 1300 mm $y^{-1}$ in its northernmost part to a maximum of 2000 mm $y^{-1}$ in the southern region. Average air temperatures range from 23 ºC in the winter to 28 ºC in the summer. The most significant wave front directions are from the NE, E, SE and SSE. NE and E wind-induced waves have periods of 5 sec and heights of 1.0 m, and SE and SSE wind-induced waves have periods of 6.5 sec and 1.5 m heights (Bittencourt *et al.* 2005). Spring tides vary from 1.7 m in the southernmost region to 3.0 m at the extreme north. The temperature of the surface water varies from around 24 ºC (winter) to 28 ºC (summer).

**Study reefs:** The studied reefs comprise two groups: inshore and offshore. The inshore reefs are adjacent to the coast or a few kilometers from the shoreline (< 5 km). They include fringing reefs and shallow bank reefs, both in depths from 5 m to 10 m in the fore-reef zone and are not longer than 1 km. The offshore reefs consist of reef structures of variable dimensions, from a few meters up to 20 km, and are located more than 5 km off the coastline, at various depths. They include coral knolls, patch and bank reefs, and isolated coral pinnacles. Besides these, there are also oceanic shelf edge reefs that occur at the border of the continental shelf, with widths up to 3 km and a relief of about 30 m at depths of 50 m. These reefs must have started to grow earlier in the Holocene, at lower sea level stands, and are now veneered with a deeper water community (Kikuchi & Leão 1998).

**Reef-building fauna:** Brazilian reefs were built by a low diversity coral fauna rich in endemic species (Laborel 1970). Twenty three species of stony corals and five species of hydrocorals are registered along the Brazilian coast, and eighteen corals and four hydrocorals occur on the Eastern Brazilian reefs (Table 1). From these, six species are endemic of the Western South Atlantic waters, some have affinities with Caribbean coral forms and some are remnants of a more resistant relict fauna dating back the Tertiary time, which was probably preserved during Pleistocene sea level low stands in a refuge provided by the sea-mountains off the Abrolhos Bank (Leão *et al.* 2003). These archaic species are the most common forms in all studied reefs. They are the three species of the genus *Mussismilia*: *M. braziliensis* Verrill 1868, *M. hispida*

Verrill 1868 and *M. hartti* Verrill 1868 and the species *Favia leptophylla* Verrill 1868. The other two endemic species are *F. gravida* Verrill 1868 and *Siderastrea stellata* Verrill 1868, both related to the Caribbean coral fauna. The species *M. braziliensis* and *F. leptophylla* are the Brazilian corals that show the greatest geographical confinement, because they are, so far registered, only found along the coast of the state of Bahia. The species *S. stellata* and *F. gravida* have a broader distribution along the coast of Brazil, and are the most common corals in the shallow intertidal pools of reef tops. Along the whole coast of Brazil, the reefs of Abrolhos in its eastern region, have the largest number of coral species (eighteen), but this number reduces northward the state of Bahia (see Table 1) (Laborel 1969, 1970, Belém *et al.* 1982, Leão 1982, Araujo 1984, Nolasco 1987, Castro 1994, Leão *et al.* 2003, Neves *et al.* 2006, 2008, Amaral *et al.* 2008, Kikuchi *et al.* 2010).

**Field procedures:** the status of coral reefs was assessed through visual census using band transects. In most reefs it was applied the methodology of the AGRRA protocol (*Atlantic and Gulf Rapid Reef Assessment* http://www.agrra.org, Ginsburg *et al.* 1998, last updated in 2007), except for the reefs from Todos os Santos Bay, where the video transect method was applied. Reef assessments began in 1998, when three shallow reef sites from the North Coast of the state of Bahia were surveyed using belt transects positioned parallel to the coastline. Starting in 1999, the reefs were assessed using the AGRRA method that was designed for assessing and comparing reef status in the Atlantic Ocean, including reefs in the Gulf of Mexico. In the AGRRA protocol, the assessment of reef status is performed along six 10 m long transects, where the line intercept method is applied for coral cover. Colony diameter, dead surfaces, bleaching and diseases are analyzed in a belt 1 m wide along the line transects, and five quadrats (25 cm X 25 cm) per transects are used to estimate the relative abundance of algal types: macro, turf ($\leq$ 1 cm high), and crustose corallines, the average canopy height of macroalgae, and the density of coral recruits (colonies $\leq$ 2 cm).

The video-transect technique consists of two distinct phases: a) field data acquisition, when images taken along a belt-transect are recorded by a video-camera, and b) the identification of organisms on the screen of a computer, from the images acquired in the field. Studies using this technique were carried out in several reef areas around the world, and are described in Aronson *et al.* (1994), Carleton & Done (1995), Aronson & Swanson (1997).

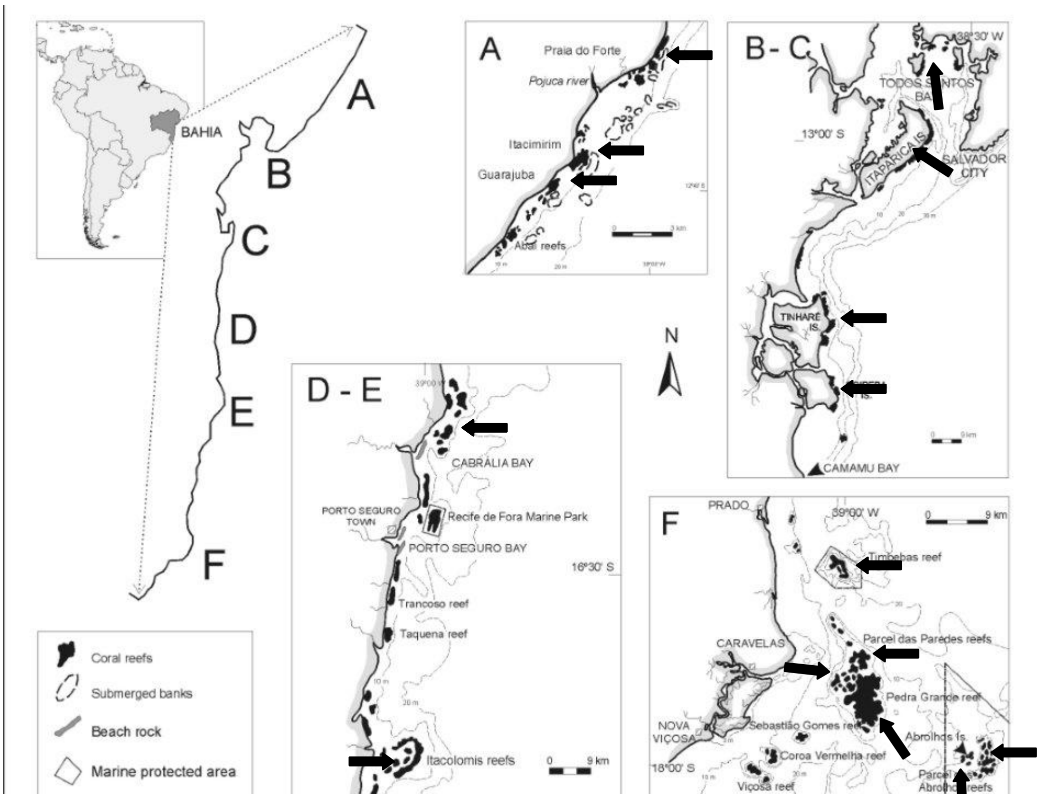


**Figure 1.** Location of reefs along the coast of Eastern Brazil. A - North Coast; B - C- Todos os Santos Bay and Tinharé and Boipeba islands; D - E- Cabrália and Itacolomis reefs; F – Abrolhos. Black arrows indicate studied reef sites.

In Brazil, the videography technique was introduced in 2003 (Dutra *et al.* 2006) with the purpose of assessing the status of coral reefs within Todos os Santos Bay, which was re-evaluated late in 2007 (Cruz 2008). The purpose of using this technique in the reefs of Todos os Santos Bay was its previous successful performance in water with low visibility, due to the short distance between the video camera and the surface of the reefs. This condition of low visibility is common in the bay waters.

**The assessed reef areas:** Six areas along the coast of the state of Bahia were assessed: North Coast, Todos os Santos Bay, Tinharé and Boipeba islands, Cabrália, Itacolomis reefs and Abrolhos (see Fig. 1). Information of location, depth of reefs, date of survey, the values of sea surface temperature anomalies during survey, the measured parameters and the applied methods are shown in Table II. The reefs of the North Coast were assessed before the development of the AGRRA protocol. They were surveyed using 3 x 1 m wide belt transects 20 m long completing a total area of 60 $m^2$ in each reef site (Leão *et al.* 1997, Kikuchi & Leão 1998, Kikuchi 2000, Leão & Kikuchi 2005). The methodology of the AGRRA protocol was applied in the reefs of Tinharé and Boipeba islands, Cabrália, Itacolomis and Abrolhos. The Tinharé/Boipeba, Cabrália and Itacolomis reefs were surveyed only once or two times, but in the Abrolhos area reefs were surveyed four times. In all these reefs the surveyed area summed 60 $m^2$ in each site (Kikuchi *et al.* 2003 a, b, Kikuchi *et al.* 2010). Most surveys were performed between the months of March and April after the occurrence of sea water thermal anomalies (Leão *et al.* 2008).

The reefs of Todos os Santos Bay were assessed twice (2003 and 2007), applying the methodology of the video transects. In 2003, eight groups of reefs in the inner region of the bay were investigated (Dutra *et al.* 2006), and in 2007 (Cruz 2008, Cruz *et al.* 2009) twenty-three reef sites were assessed, being eight located at the entrance of the bay and fifteen in the interior of the bay; eight of them were the same reefs investigated by Dutra *et al.* (2006).

Two *in situ* investigations were carried out in order to evaluate the behavior of coral bleaching in fixed colonies of specific coral species. The first was performed in 2006, in corals located at the entrance of Todos os Santos Bay, where thirty colonies of the coral *Montastrea cavernosa* and of *Siderastrea* spp were surveyed for a year to determine their rate of growth and investigate the occurrence of bleaching (Chaves 2007). The other one was performed in the Abrolhos area during the summer and winter seasons of the years 2006, 2007 and 2008, in fixed colonies of the coral *Montastrea cavernosa*, located on the tops and lateral walls of 14 reef sites, to evaluate the percent of bleaching and its progression rate during the period of investigation (Meirelles 2009).

Surveys for coral diseases were carried out yearly from 2001 to 2007 on twenty-eight sites distributed along the Abrolhos area, during summer periods (January to April) when northeastern winds prevail, water visibility is from 5 to 10 m, and sea surface temperatures are relatively higher (~25-28 $^{o}$C). The disease progression rates was estimated for one site (Portinho Norte, within the Abrolhos Archipelago) between April 14 and July 4, 2006, and the disease prevalence was determined at two sites (Pedra de Leste, within Parcel das Paredes reefs, and one site in Timbebas reef) between January and March 2007 (Francini-Filho *et al.* 2008, 2010). These surveys were conducted by the Conservation International-Brazil (CI Brazil), as part of the Marine Management Areas Science Program, Brazil Node.

## Results

**Reef condition**: the following parameters were considered to define the status of the Eastern Brazilian reefs: percent living coral cover, density of larger corals (> 20 cm diameter), density of coral recruits (≤ 2 cm diameter) and percent of macroalgae. The reefs surveyed on the North Coast in 1998 revealed very low values for living coral cover (<2.5%), number of coral colonies (< 2 per reef site) and density of coral recruits (< 1 $m^{-2}$). The abundance of macroalgae was not evaluated during this investigation (Kikuchi & Leão 1998, Kikuchi 2000). In the Tinharé and Boipeba reefs, the live coral cover reached values between 2 and 5.2%, the density of larger corals ranged from 13 to 32 colonies per reef site (60 $m^2$); coral recruits values varied between 2 and 5 colonies per square meter and the percent of macroalgae was above 27. Reefs from the Cabralia area presented values of coral cover ranging between 2.3 and 9.4%, coral colonies with diameters higher than 20 cm reached values from 11 to 75 colonies per reef site, coral recruitment was very low (maximum 3 individuals $m^{-2}$), and macroalgae presented percentages up to 62. In the Itacolomis reefs, which were assessed in 2005, the live coral cover reached 14.2%, the density of larger corals was 93.3 colonies per reef site, coral recruits reached values of 38.4 colonies per square meter and the percent of macroalgae was 17.6.

**Table I.** Occurrence of coral and hydrocoral species in reefs from Eastern Brazil.

| | **North Coast** | **Todos Santos Bay** | **Tinhare/ Boipeba** | **Cabrália** | **Itacolomis** | **Abrolhos coastal** | **Abrolhos islands** | **Abrolhos offshore** |
|---|---|---|---|---|---|---|---|---|
| *Agaricia agaricites* | X | X | X | X | X | X | X | X |
| *Agaricia fragilis* | X | | X | X | | X | X | X |
| *Astrangia braziliensis* | | X | | | | | | X |
| *Favia gravida* | X | X | X | X | X | X | X | X |
| *Favia leptophylla* | | X | | X | X | X | X | X |
| *Madracis decactis* | X | X | X | X | | X | X | X |
| *Meandrina* | X | | | X | X | X | X | X |
| *Montastrea cavernosa* | X | X | X | X | X | X | X | X |
| *Mussismilia* | X | X | X | X | X | X | X | X |
| *Mussismilia harttii* | X | X | X | X | X | X | X | X |
| *Mussismilia hispida* | X | X | X | X | X | X | X | X |
| *Phyllangia americana* | | | X | | | X | | X |
| *Porites astreoides* | X | X | X | X | X | X | X | X |
| *Porites branneri* | X | X | X | X | X | X | X | X |
| *Scolymia wellsi* | | X | X | X | X | X | X | X |
| *Scolymia cubensis* | | | | | | | | X |
| *Siderastrea stellata* | X | X | X | X | X | X | X | X |
| *Siderastrea radians* | X | | | | | | | |
| *Stephanocoenia* | | | | | | | | X |
| *Millepora alcicornis* | X | X | X | X | X | X | X | X |
| *Millepora nitida* | | | X | X | X | X | X | X |
| *Millepora braziliensis* | | | | | X | | X | X |
| *Stylaster roseus* | | | X | | | | | X |
| **# Species** | **14** | **14** | **16** | **16** | **15** | **17** | **17** | **22** |

In the Abrolhos area, average values for the reefs from the coastal area were as follows: living coral cover ranged from 5.6 to 11%, the density of large corals varied from 11 to 144 colonies per reef site (60 $m^2$), the number of coral recruits per square meter was 13.6 to 35, and values for macroalgae abundance varied from 0.6 to 11.9%. In the fringing reefs bordering the Abrolhos islands, coral cover values ranged from 6.8 to 17.3%, the density of larger corals varied between 57.7 and 155.3 colonies per reef site, coral recruits ranged from 13.6 to 35 $m^2$, and the abundance of macroalgae ranged from 0 to 22.5%. In the chapeirões of the Parcel dos Abrolhos, the values of the reef indicators were: 14.9% for living coral cover, 107.5 for number of large coral colonies per reef site; 32.1 $m^2$ for density of coral recruits and 6.3% for macroalgae abundance (Kikuchi *et al.* 2010). Comparing these data averaged for the inshore and offshore reefs, which were acquired along belt transects that covered an area of 60 $m^2$ in each reef site (Tab. III), one sees that the values of the measured coral parameters (living cover, density of larger colonies and of recruits) for the inshore reefs (North Coast, Tinharé / Boipeba and Cabrália) are much lower than those for the offshore reefs (Itacolomis and Abrolhos), which are opposite the average values of the abundance of macroalgae.

In Todos os Santos Bay the data about coral diversity originated from the survey performed in 2003 by Dutra and collaborators (2006) compared with the information given in Laborel's description from the 1960's (Laborel 1969, 1970), show that the major differences between these two surveys are the identified coral species present in the reefs from the interior of the bay. Some species cited in Laborel's description were not found in the 2003 survey, such

**Table II.** Information of coral reefs surveyed along the coast of Eastern Brazil. n = number of reef sites. SST = Sea Surface Temperature

| Reefs | Location | Depth range (m) | Date of survey | SST Anomaly | Measured parameters | Method |
|---|---|---|---|---|---|---|
| North Coast<br>n=6 | 12.3805º S<br>38.0200º W | 4.5-8.5 | 1998 | 1.0 ºC > 1 week | Coral cover, colony diameter, # coral species, coral recruits | Belt transect<br>(3x1m wide x 20m long)<br>60m²/site |
| Tinharé /<br>Boipeba<br>n=4 | 13.4910º S<br>38.9024º W | 3.5-4.0 | 2003<br><br>2004 | 1.0 ºC > 1 week<br><br>0.25 ºC < 2 weeks | Coral cover, colony diameter, # coral species, coral recruits, coral dead surface, bleaching, disease, algal abundance | Belt transect (AGRRA)<br>(6x1m wide x 10m long)<br>60m²/site |
| Cabralia<br>n=6 | 16.2397º S<br>38.9526º W | 4.8-6.8 | 2004 | No SST anomaly | Coral cover, colony diameter, # coral species, coral recruits, coral dead surface, bleaching, disease, algal abundance | Belt transect (AGRRA)<br>(6x1m wide x 10m long)<br>60m²/site |
| Itacolomis<br>n=3 | 16.8976º S<br>39.0909º W | 2.0-3.5 | 2005 | 0.75 ºC > 2 weeks | Coral cover, colony diameter, # coral species, coral recruits, coral dead surface, bleaching, disease, algal abundance | Belt transect (AGRRA)<br>(6x1m wide x 10m long)<br>60m²/site |
| Abrolhos<br>coastal reefs<br>n=20 | 17.4670º S -<br>18.0203º S<br>39.0004º W -<br>38.9883º W | 2.0-8.0 | 2001<br>2002<br>2003<br>2005 | 0.50-0.75 ºC<br>< 1 week<br>1.0 ºC > 2 weeks<br>0.75 ºC > 2 weeks | Coral cover, colony diameter, # coral species, coral recruits, coral dead surface, bleaching, disease, algal abundance | Belt transect (AGRRA)<br>(6x1m wide x 10m long)<br>60m²/site |
| Abrolhos<br>islands<br>n=12 | 17.9673º S -<br>17.9794º S<br>38.7018º W -<br>38.7080º W | 3.5-8.0 | 2000<br>2001<br>2002<br>2005 | 0.25 ºC < 2 weeks<br>0.50-0.75 ºC<br>< 1 week<br>0.75 ºC > 2 weeks | Coral cover, colony diameter, # coral species, coral recruits, coral dead surface, bleaching, disease, algal abundance | Belt transect (AGRRA)<br>(6x1m wide x 10m long)<br>60m²/site |
| Abrolhos<br>offshore reefs<br>n=6 | 17.9977º S<br>38.6713º W | 6.0-9.0 | 2000<br>2001<br>2002<br>2003 | 0.25 ºC < 2 weeks<br>0.50-0.75 ºC<br>< 1 week<br>1.0 ºC > 2 weeks | Coral cover, colony diameter, # coral species, coral recruits, coral dead surface, bleaching, disease, algal abundance | Belt transect (AGRRA)<br>(6x1m wide x 10m long)<br>60m²/site |
| Todos Santos<br>Bay<br>n=32 | 12.4720º S-<br>13.1037º S<br>38.3134º W-<br>38.4532º W | 3.0-8.0 | 2003<br>n=9<br>2007<br>n=23 | 1.0 ºC > 2 weeks<br><br>No SST anomaly | Coral cover, # coral species, algal abundance, other benthics (sponge, zoanthus, soft coral) | Belt transect (Video)<br>(10x0.20m wide x 20m long)<br>40m²/site |
| Salvador City<br>Yatch Club | 12.5900º S<br>38.3100º W | 2.0-4.5 | 2006 | No SST anomaly | Rate of coral growth and bleaching | In situ measurement in 30 coral colonies of *Siderastrea* sp and *Montastrea cavernosa* |
| Abrolhos<br>several reefs<br>N=14 | 17.4701º S-<br>17.5732º S<br>39.0141º W-<br>38.3020º W | 4.3-15.0 | 2006<br>2007<br>2008 | No SST anomaly<br>No SST anomaly<br>No SST anomaly | Coral bleaching progression | In situ measurement in colonies of *Montastrea cavernosa* |

as *Mussismilia braziliensis*, *Meandrina braziliensis*, *Porites branneri*, *Stephanocoenina michelini* and *Millepora nitida*. The most common species that occurred in both the 1960 and the 2003 surveys are *Montastrea cavernosa*, *Siderastrea stellata*, *Mussismilia hartti*, *M. hispida* and *Favia gravida*. There are also some species that Laborel did not identify but were found in 2003: *Madracis decactis*, *Agaricia agaricites*, *Porites astreoides* and *Scolymia wellsi*. Comparing data from the living coral cover of the same reefs investigated in 2003 by Dutra *et al.* (2006) with a survey performed by Cruz in 2007 (Cruz 2008, Cruz *et al.* 2009), it seems that the values found for five of these reefs in 2007 are lower than the ones registered in 2003 (see Table IV). Regarding the presence of the coral species, Cruz (2008) and Cruz *et al.* (2009) report the same species that Dutra *et al.* (2006) registered in their earlier survey of the reefs located in the interior of the bay.

**Coral bleaching events:** the first record of coral bleaching in Bahia occurred in 1994, in the area of Abrolhos, affecting an average of 70% of coral colonies (Castro & Pires 1999). In 1998, a sea surface temperature anomaly started in mid January (summer in the southern hemisphere), attained its climax in mid March and early April, and faded away at the end of May. During this event, two hotspots were registered, one on the North Coast of the State (Dutra 2000) and the other in Abrolhos (Leão *et al.* 2008). In both areas, the estimated sea surface temperature anomaly, at about 1 °C, matched measurements of sea temperature in the field, which ranged between 29.5 °C and 30.5 °C. An evaluation during 13 months in a reef from the North Coast registered an average of 60% corals bleached (Fig. 2).

During surveys performed from 2000 to 2005, the average of corals bleached ranged from 0.2% during years with short-term sea surface anomalies, equal or less than 0.75 $^{o}$C, to up to 50% in years with anomalies equal or greater than 1$^{o}$C for more than one week.

**Table III.** Average values of coral parameters and macroalgae abundance of inshore and offhore reefs from Eastern Brazil, measured along belt transects covering an area of 60 m$^2$ in each reef site. Inshore reefs = North Coast, Tinharé / Boipeba and Cabralia. Offshore reefs = Itacolomis and Abrolhos.

| | Living coral cover % | Density colonies > 20 cm #colonies . 60 m$^2$ | Density coral recruits #colonies . m$^2$ | Macroalgae % |
|---|---|---|---|---|
| Inshore reefs | 3.6±2.4 | 22.0±22.4 | 1.6±1.8 | 43.2±18.4 |
| Offshore reefs | 11.6±3.5 | 102.0±42.7 | 27.1±8.5 | 8.2±6.7 |

**Table IV.** Average (± SD) living coral cover measured during the surveys of 2003 (Dutra *et al.* 2006) and 2007 (Cruz 2008) in reefs located in the interior of Todos os Santos Bay.

| Reefs | Mangueira | Pedras Alvas | Dentão | Cardinal | Poste 1 | Poste 4 | Poste 5 | Poste 6 |
|---|---|---|---|---|---|---|---|---|
| 2003 Survey | 13.5±4.7 | 27.9±1.8 | 7.7±6.5 | 23.1±2.3 | 8.9±0.2 | 18.7±1.5 | 8.1±1.5 | 10.1±0.7 |
| 2007 Survey | 8.4±5.7 | 13.1±5.8 | 0.7±0.4 | 27.0±5.4 | 2.3±1.2 | 21.0±8.7 | 4.6±2.3 | 19.2±4.3 |

Sea surface anomalies of 1 °C or a little higher occurred in 2003 in Tinharé/Boipeba and Abrolhos. In Tinharé/Boipeba, the sea surface temperature rose at the end of February and dissipated at the end of April. Coral bleaching was registered at the beginning of May, reaching an average of 27%. In Abrolhos, a sea surface temperature anomaly started in mid February, reached its climax during the whole month of March and dissipated at the end of April. Coral bleaching was observed in mid March, with an average of 13% colonies bleached (Fig. 2). During the hotspot event that occurred in Southern Bahia in 2005, two reef areas were affected, Itacolomis and Abrolhos, with an average of 25% of coral colonies bleached. A less extensive coral bleaching event was observed in the Itacolomis reefs, where an average of 11% of corals was found to be affected (Fig. 2). In those areas, the sea surface temperature started to rise in mid March, reaching anomalies of 0.75 to 1 $^{o}$C at the beginning of April, and being completely dissipated at the end of the month.

During years with short term sea water anomalies with maximum values of 0.75 ºC, the surveys performed in the Abrolhos area (2000, 2001, 2002), and in reefs from Tinharé and Boipeba (2004), revealed values of coral bleaching of less than 10% (Fig. 3).

During the investigation performed in fixed coral colonies at the entrance of Todos os Santos Bay in 2006, when sea water temperature anomalies did not occur, the average number of colonies of *Montastrea cavernosa* with signals of bleaching were from 3.5 (out of a group of 30 colonies – 11.6%) per month during the summer, and three colonies per month (10%) during the winter. *Siderastrea* spp did not reach more than two bleached colonies (within a group of 30 monitored colonies – 6.6%) per month during the summer, and less than that during the winter months (Chaves 2007). The investigation of the Abrolhos reefs with fixed colonies of *Montastrea cavernosa*, from 2006 to 2008, a period without sea water temperature anomalies along the coast of Brazil, revealed that bleaching events affected less than 10% of the investigated coral colonies (Meirelles 2009).

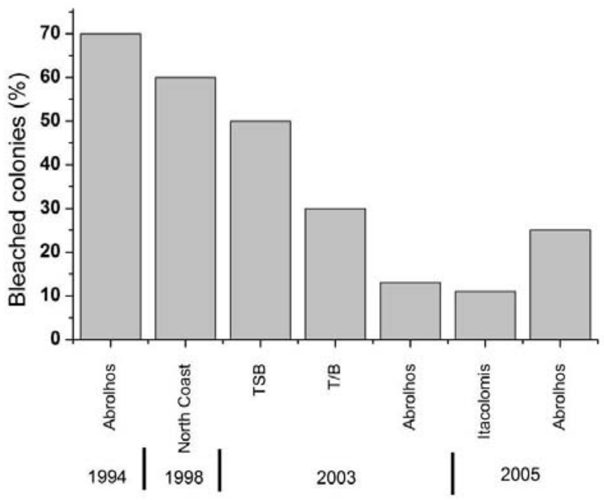


**Figure 2**. Average percentages of bleached coral colonies measured during longer term events of sea water temperature anomalies ≥ 1 ºC, along the coast of Eastern Brazil. TSB = Todos os Santos Bay, T/B = Tinharé and Boipeba islands.

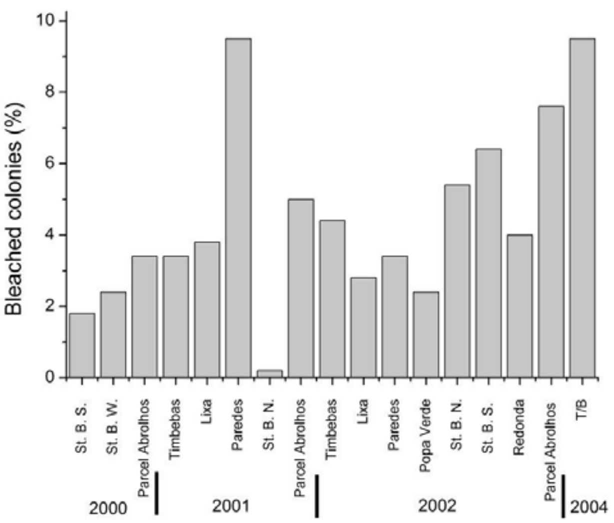


**Figure 3.** Average percentages of bleached coral colonies measured during short term events of sea water temperature anomalies ≤ 0.75 ºC. St. B. S = Santa Barbara South; St. B. W. = Santa Barbara West; St. B. N. = Santa Barbara North; T/B = Tinharé and Boipeba islands.

**Occurrence of coral diseases:** according to the description given by Francini-Filho *et al.* (2008), the first coral disease detected in the Abrolhos reefs was in January 2005, comprising only a few affected colonies of *Siderastrea* spp and *Mussismilia braziliensis*. Since then, the number of sites showing diseased corals increased sharply. Four types of diseases were detected affecting the reef-building corals: black-band, red-band, white plague and dark spots. The most affected coral species were: *Favia gravida*, *F. leptophylla*, *Mussismilia braziliensis*, *M. hartti*, *M. hispida*, *Porites astreoides* and *Siderastrea* spp. Because *Mussismilia braziliensis* is an important coral constructor of reefs in Abrolhos, the white-plague like disease prevalence and progression rate was investigated. At two sites (Leste and Timbebas reefs), this disease prevailed during the sampling period, and its linear progression rate was estimated at 0.18±0.06 (SE) $cm^2 day^{-1}$, while the area progression rate was estimated at 0.21±0.07 (SE) $cm^2 day^{-1}$. According to the above authors, a model estimating the loss of *M. braziliensis* based on these numbers predicts that if the current rate of mortality of *M. braziliensis* is maintained, about 40% of this coral cover will be lost in the next 50 years, and if there is an increase in disease severity in successive decades, *M. braziliensis* will be nearly extinct in less than a century. Francini-Filho *et al.* (2010) identified a seasonal prevalence of the white plague-like disease in the summer compared to the winter, which means that the disease is temperature dependent. According to these authors, this result supports the hypothesis that warmer oceans are facilitating the proliferation of coral diseases worldwide.

## Discussion and Recommendations

**The reef condition:** overall, inshore reefs of Eastern Brazil (North Coast, Tinhare and Boipeba and Cabralia), which are located less than 5 km from the coast, are in poorer condition than the offshore reefs, which are located more than 5 km off the coast (Itacolomis and Abrolhos) (see Table III). Previous works have shown that the inshore reefs are experiencing stress resulting, chiefly, from higher sedimentation rates and water turbidity (Dutra *et al.* 2006), an abnormal increase in nutrients associated with sewage pollution in the coastal waters (Costa Jr *et al.* 2000, 2006), and an elevated rate of bioerosion (Santa-Isabel 2001, Reis & Leão 2003), besides being highly used by fishing and tourism. These inhospitable conditions must have been deleterious to the reef-building corals of these reefs. Although the vital conditions of the offshore reefs seem to be quite stable, both in the Archipelago and in the Chapeirões, there are two sites (Leste and southern St. Barbara), where the values of the selected coral indicators are rather low. Leste is the closest reef in the Abrolhos area to the coastline (~10 km) and, therefore, the most exposed to processes acting in the continent coastal zone, besides being one of the reefs most affected by coral disease (Francini-Filho *et al.* 2008). The southern part of St. Barbara Island is located inside the limits of the Abrolhos National Marine Park, but it is the preferred site of tourists for diving and snorkeling, because of the protection it offers for anchoring (Spanó *et al.* 2008).Thus, the set of parameters assessed show that there is a clear distinction between the inshore and offshore reefs, with some sites from the latter group already decayed to conditions quite similar to those of the inshore reefs. These sites must be closely monitored and need to be target of management actions.

**Occurrence of coral bleaching and disease:** The strongest coral bleaching events registered along the coast of Eastern Brazil have been associated with warming of the sea surface temperature. When sea surface anomalies reached values of 1 ºC during one to two weeks, as occurred in 1998, 2003 and 2005 along the whole coast of the state of Bahia, more than 30% of bleached corals were registered in the inshore reefs along an extent of about 500 km. In these periods, the reefs located in the northernmost part of the state (e.g., the North Coast and Todos os Santos Bay) were the most affected. In this area, the average bleaching of colonies reached values above 50% (see figure 2). In the offshore reefs of Abrolhos, the percentage of bleaching was milder, ranging from 8 to 18% in 2003 and reaching an average of 25% in 2005.

When thermal anomalies were between 0.50 to 0.75 ºC for less than one week, as occurred in 2001 and 2002, or around 0.25 ºC, as in 2000 and 2004, the average coral bleaching was lower than 10%, even in the inshore reefs of Tinhare and Boipeba (see figure 3). During 2006, 2007 and 2008, no thermal anomalies occurred along the coast of Brazil, and signals of bleaching in coral colonies during experiments on the northern (Todos os Santos Bay) and southern (Abrolhos) coasts of Eastern Brazil were very mild, remaining lower than 12% of the surveyed coral colonies.

Overall, based on these occurrences, we see a strong linkage between strong coral bleaching and periods of elevated sea surface temperatures in Eastern Brazil. Additionally, reefs already impacted by processes operating in the coastal zone, the inshore reefs, are most susceptible to bleaching. Other examples include the reefs of Jamaica and South Florida, which are threatened by anthropogenic impacts and have been strongly affected by successive bleaching events (Hughes *et al.* 2003, Goldberg & Wilkson 2004).

Adding to those pieces of evidence, a Bayesian model developed by Krug (2008), based on the maximum sea surface temperature accumulated in five years, light attenuation in water, rainfall magnitude, zonal and meridional wind fields derived from remote sensing and analysis and reanalysis data, shows the complex nature of bleaching patterns in Eastern Brazil. This model points to a scenario where factors such as the period, the intensity and/or the geographical position of the bleached corals, determine the bleaching pattern. The model shows evidence that high sea surface temperature controlled bleaching events on the North Coast and Todos os Santos Bay. However, in the Abrolhos area, where bleaching events were weaker than the northern reefs, there is a large amount of variability of surface temperature, precipitation and winds, suggesting that, for example, the 2003 bleaching event was mostly influenced by low water transparency and increased rainfall. Thus, the model concludes that the bleaching pattern in Eastern Brazil is a highly complex system that might be responding to both global and regional forcing factors.

Although Brazilian reefs have been coexisting for a long time with natural occurrence of extreme environmental conditions, such as high sedimentation rates, low light penetration levels and periodic thermal stress, coral bleaching has not yet caused coral mass mortality. Such threat could occur in the future, considering that a worldwide intensification of warm sea surface temperature anomalies is expected (Hoegh-Guldberg 1999, Maynard *et al.* 2009). In addition, it is known that there is also a positive link between coral disease incidences and stresses arising from global warming (Selig *et al.* 2006; Bruno *et al.* 2007; Ainsworth & Hoegh-Guldberg 2009). Anomalously higher water temperatures may enhance the probability of coral disease outbreaks by increasing the abundance or virulence of pathogens or by increasing the host susceptibility, as bleached corals are more susceptible to diseases than healthy ones (Muller *et al.* 2008). Moreover, coral bleaching and disease must be also intensified by the rapid deterioration of coastal waters, a factor that will enforce the degradation of the Brazilian inshore reefs.

As stated by Francini-Filho *et al.* (2008), the consequences of a coral decline due the intensification of diseases, for the maintenance of reef integrity, in a region with high endemism levels, are not yet totally predictable. Nevertheless, in the specific case of the relatively low diversity Brazilian reef ecosystem, it may be more catastrophic than previously anticipated. It is therefore important to increase our knowledge of the reef processes and to develop a better capacity in Brazil for implementing strategies that will enhance the chances for the reefs to resist future sea surface temperature warming. Thus, urgent actions regarding the conservation of this reef region is needed. Many initiatives concerned with coral reef protection, management and recovery have been developed in Brazil during the last few years (Rodriguez-Ramirez *et al.* 2008), but much effort is still needed for the effective conservation of the reefs. The survival of these reefs will depend upon an appropriate understanding of all processes involved in the reef ecosystem functioning and maintenance, and on the effective management and sustainable use of their resources. The complexities involving important processes like euthrophication, spread of coral diseases and coral bleaching demand deliberate actions toward a long-term reef monitoring and increase in society's awareness.

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