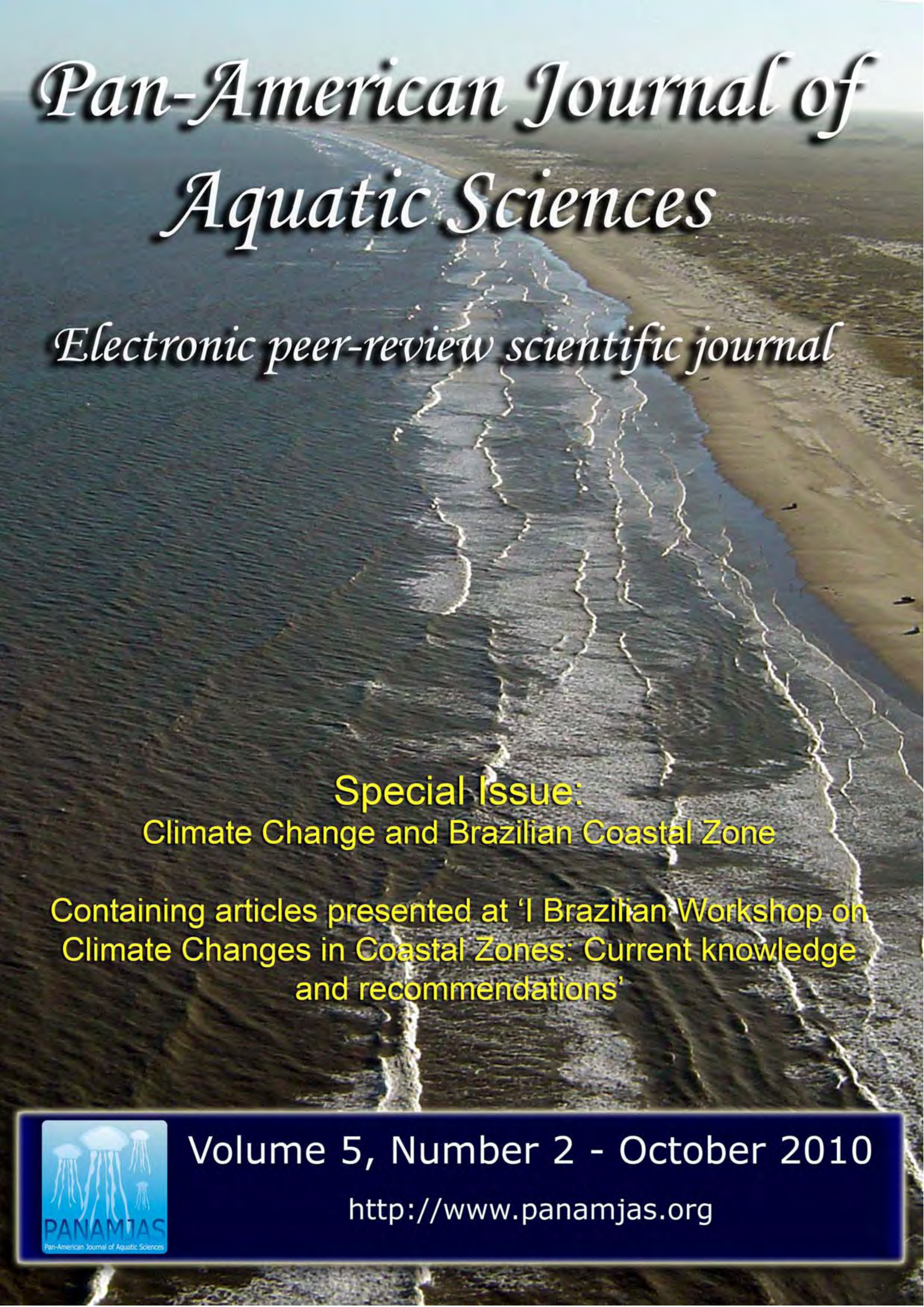

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Introduction to the Special Issue on Climate Change and Brazilian Coastal Zone

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Abstract. The multidisciplinary Coastal Zone (CZ) network from the National Institute of Sciences and Technology (INCT) for Climate Change, aims to evaluate the state of knowledge and coordinate projects dealing with the effects of global climate changes in the country's coastal zone. During its first year, CZ focused on literature review, historic data analysis and vulnerability studies. The studies were presented during the ***I Brazilian Workshop on Climate Change and Coastal Zones***, and resulted in the fifteen scientific articles that comprise this Special Issue. Based on regional case studies and a few broad national assessments, results showed how the large Brazilian coast and their ecosystems are highly vulnerable to climate variability, and which parameters and regions may be more impacted by global climate change. With only a few studies aiming to evaluate the vulnerability of biological, ecological and socio-economic parameters, along with the many deficiencies on basic knowledge, the country's coastal and marine zones are still neglected by climate change policies. Although a series of scientific goals still need to be achieved to better evaluate the effects of climate change on the Brazilian coastal zone, the present volume constitute a first step towards the provision of guidance to managers and policymakers.

Key-words: Global Climate Change, impacts and vulnerability, oceanography, coastal geology, marine ecology.

Resumo. Introdução ao Volume Especial sobre "Mudança Climática e Zona Costeira Brasileira". A rede Zona Costeira do INCT para Mudanças Climáticas, de caráter multidisciplinar e interinstitucional, objetiva de avaliar o estado do conhecimento e coordenar projetos que investiguem os efeitos das mudanças climáticas em zonas costeiras brasileiras. Em seu primeiro ano, os projetos focaram em revisões da literatura, análises de banco de dados e sobre vulnerabilidades dos ecossistemas. Os resultados foram apresentados durante o ***I Workshop Brasileiro de Mudanças Climáticas em Zonas Costeiras***, resultando também nos 15 artigos deste Volume Especial. Tendo como base estudos de caso regionalizados e algumas avaliações nacionais, os resultados mostram como a extensa costa Brasileira e seus ecossistemas são altamente vulneráveis a variabilidade climática, e quais parâmetros e regiões poderão ser mais impactados pelas mudanças climáticas globais. Com poucos estudos específicos que avaliem a vulnerabilidade de parâmetros biológicos, ecológicos e socio-econômicos, associado às inúmeras deficiências de conhecimento básico, as zonas costeira e marinha brasileiras são ainda negligencias pelas políticas de mudanças climáticas. Ainda que uma série de metas científicas necessite ser alcançadas para melhor avaliar os efeitos das mudanças climáticas em zonas costeiras brasileiras, os artigos apresentados neste volume constituem passos preliminares para guiar a gestão e a elaboração de políticas públicas sobre o tema.

Palavras-chave: Mudança Climática Global, impactos, vulnerabilidade, geologia costeira, ecologia marinha.

Introduction

Global Climate Change (GCC) has been at the centre of scientific debate during the 21st century and has received substantial attention from society, governments and the private sector worldwide. Despite active debate and recognized climate uncertainties, the scientific evidences for global warming remains robust and the conclusion that human activities are affecting the climate cannot be undermined (*e.g.* Schiermeier 2010). Indeed, evidences from hundreds of studies are suggesting that the pace and scale of changes and its impacts are surpassing the predictions outlined by the Intergovernmental Panel on Climate Change Fourth Assessment Report (IPCC 2007) (McMullen & Jabbour 2009, Hoegh-Guldberg & Bruno 2010, Nicholls *et al.* 2010, Stroeve *et al.* 2011). Global Climate Change (GCC) is recognized now as a planetary crisis, which impacts represent an unprecedented risk for natural ecosystems and human civilization.

Because coastal areas are directly affected by sea-level rise, increases in air and sea temperature, exposure to extreme events and ocean acidification, these areas will be impacted most severely by the predicted GCC (Trenberth *et al.* 2007). However, despite the significance of the climate-related risks affecting the low-lying habitats, the paucity of scientific publications dealing with specific and regional problems is remarkable (Nicholls 2007) and coastal and marine systems are vastly underrepresented in comparison with terrestrial systems (Richardson & Poloczanska 2008, Hoegh-Guldberg & Bruno 2010). Studies and predictions relating to the impacts of climate change on coastal and marine ecosystems are limited by the lack of long-term data, by the lower observational capacity and by a lack of integrated approaches to link diverse aspects of science and society. The lack of information at the regional and local scales produces uncertainties about climate, and these uncertainties hamper efforts to plan for the future (Malone *et al*. 2010). Furthermore, no coastal and marine region on earth is exempt from anthropogenic modifications and impacts that affect the ecosystem equilibrium and capacity to buffer climate change (Halpern *et al.* 2008).

Brazil is a globally important country in the context of climate change. Owing largely to its historical deforestation rate, the country is the world's fourth-largest greenhouse-gas emitter (Nepstad *et al*. 2011). Moreover, Brazil depends strongly on its very abundant natural resources. Because of that, the country has therefore great potential to contribute to the reduction of GCC risks. Most of the discussion about Brazil's contribution to mitigate global climate (Santili *et al.* 2005), as well as studies about impacts and vulnerability of natural ecosystems to climate change, has been focussed on terrestrial ecosystems (e.g., Salazar *et al.* 2007, Lapola *et al.* 2009). However, the country's large coastal and marine zones as well as the country's role in buffering climate change impacts and mitigating emissions are still neglected by many national and international climate change forums and policies (Copertino 2011). The Brazilian coast, as many other coasts, is highly vulnerable to present-day climate variability and may be profoundly impacted by the projected climate change (Muehe 2006, Neves & Muehe 2008). These impacts would pose serious threats to coastal biodiversity, ecological functions and services to society, including the coastal zone's carbon sequestration capacity. However, studies on Brazilian coastal vulnerability to GCC were few and isolated, owing in part to the fact that the country's coastal zone is very extensive.

In an attempt to fill this gap in current information, a Coastal Zone (CZ) project was established within the framework and aims of the National Institute of Sciences and Technology (INCT) for Climate Change and the Brazilian Network for Global Climate Change (Rede CLIMA). The full historic context of these large research programs and their first results are found in their activity report (INCT for Climate Change, 2010). A brief overview is given by Garcia & Nobre in the foreword of this volume. Formed by nearly 50 scientists, the multidisciplinary and interinstitucional CZ network aims to evaluate the current state of knowledge, identify deficiencies, establish protocols, integrate/coordinated projects and design scientific questions in several GCC-related research topics. The goals of the project are to investigate the impacts of climate change on the Brazilian coast and to determine the coast's vulnerability to these changes. The CZ project also seeks to propose mitigation and adaptation measures to compensate for and to buffer the impacts of climate change.

To achieve these goals, the CZ project organised the "First Brazilian Workshop on Climate Change and Coastal Zones", which was hosted by the Federal University of Rio Grande (FURG) (Figure 1). The workshop brought together experts from fourteen national institutions and took important steps that facilitated the attainment of the first project goals. In this three-day workshop, experts evaluated the status of the current knowledge of Brazilian coastal systems and processes and presented their preliminary results. In addition, participants offered recommendations for future studies. The information gathered in the workshop resulted in fifteen scientific articles that comprise this Special Issue of the *Pan-American Journal of Aquatic Sciences*. In this editorial paper, we provide an overview and we also highlight the main findings of these articles, placing their importance and relevance in the perspective of Brazilian coastal zones facing climate change.

Overview of the volume content

The Brazilian coastline is almost 9,000 km long and includes a variety of coastal features such as sedimentary cliffs, large and deeply incised estuaries, crystalline headlands and low-lying coastal plains. By conducting a broad introductory review on the morphology and vulnerability of the Brazilian coastal zone, Muehe explores how each coastal region will respond in different ways to the expected climate changes and associated sea-level rise. The author concludes that erosion, although irregularly distributed, is affecting the entire shoreline. The risk of erosion can be magnified by sea-level rise and by the increase in the frequency and intensity of storms. The southern Brazilian coastline, for example, is exposed very often to extreme events, *i.e.*, storm surges and storm waves, mostly associated with extra-tropical cyclones. The frequency and intensity of these extreme events and their effects on erosion over the past 30 years is analysed by Machado *et al*., who report a total of 40 extreme events associated with maximum erosion and surge elevation in Rio Grande do Sul State. If the predicted sea-level rise occurs, the rise will certainly increase the importance of the already-existing storm surge hazards by intensifying inundation and the resulting erosion. In another contribution, Muehe *et al*. show that erosive trends are not evident for some coastal-plain areas in Rio de Janeiro State. However, the lack of sediment sources can make the system highly vulnerable to sea-level rise. The sandy dune system is highly vulnerable to changes in water balance. These changes can affect the sparse foredune vegetation cover and have drastic consequences for sediment transport and coastal morphology. The study has profound implications for predicting the effects of temperature increases and rainfall on the fragile morpho-sedimentary balance in these coastal plains.

The vulnerability of the Brazilian coastal zone to climate change and the hazards and risks involved are evaluate by Nicolodi & Petermann, who take into account the natural, social and technological characteristics of each coastal geographic region. Based on broad-scale and detailed information for each region, the authors indicate the main economic sectors likely to be affected and identify different levels of vulnerability. The areas identified as high and very high vulnerable should be at the top of the priority list for climate change policies and plans. One of the most vulnerable areas affected by sea-level rise is the Recife (Pernambuco State) metropolitan centre. This intensely populated area is highly exposed to coastal erosion and inundation and is the site of several land use conflicts. Based on optimistic and pessimistic IPCC emission scenarios, Costa *et al*. conduct a vulnerability and impact assessment for the region. They define coastal and estuarine flooding zones and discuss the natural, historical-cultural and economic resources at risk. Both studies provide guidance for preventive strategies to adapt to the effects of climate change.

The overall consensus seems to be that different Brazilian coastal regions will certainly be affected and will respond in different ways to climate changes. However, further predictions, particularly concerning sea-level rise, are very limited. Lemos & Ghisolfi show that most of the tide-gauge measurements performed along the coast are not accurate. This widespread inaccuracy thus places a serious limitation on attempts to clearly define the effects of global warming on the mean sea level along the Brazilian coast. These authors investigate the causes for this lack of accuracy and report that methodological, technological and institutional problems need to be addressed to provide better estimates of the sea level.

Brazil is home to the third-largest mangrove area in the world (Giri *et al*. 2011). Brazilian artisanal fishers are highly dependent on these mangrove systems, which occupy 80% of the coastline and have been threatened by several anthropogenic impacts. Faraco *et al*. propose an innovative methodology to assess the vulnerability of mangrove system to climate change, adapted to Brazilian reality. The proposal includes not only sea-level rise estimates but also resilience and adaptation capacity of the communities and the impacts of Brazilian conservation policies. The integrated socio-ecological diagnosis and approach may lead to a challenge in the development of management practices and more flexible policies, which are made with the stakeholder´s participation, including mitigation and adaptation strategies.

Also important for conservation, fishing and tourism, Brazilian coral reefs are exposed to several kinds of natural and anthropogenic impacts. Corals have been degraded worldwide by eutrophication, pollution and overfishing (Hughes et al. 2007). They are also seriously threaten by climate changes impacts such as ocean acidification and warming that are leading to decreased growth rates and increasing bleaching and diseases (Anthony et al. 2008, De´ath et al. 2009, Wild 2011). The status of the coral reefs of Brazil is reviewed by Leão *et al*., who identify the reefs that are more stressed by anthropogenic impacts and more vulnerable to climate change effects. The review provides an important basis for establishing priorities for future research and conservation plans for these unique Brazilian marine systems, which are marked by a resistant relict coral fauna and a high level of endemism.

The study of modes of large-scale climate variability in relation to regional climate and oceanographic parameters can reveal trends that are fundamental to GCC studies. Focusing on the responses of large marine ecosystems (LMEs), Gherardi *et al.* explore spatial patterns of correlation between several climate indices (Pacific Decadal Oscillation, ENSO, North and South Atlantic and Antarctic Oscillation Index) and sea surface temperature anomalies (SSTA) for the Southwest Atlantic. Their findings reveal distinct correlation patterns for the Brazilian LMEs. The authors point out that the response of LMEs to climatic variability may not be controlled by the ecological criteria used to define the LMEs. The characteristics of the dependence on the SSTA of productivity and trophic relations in each of the Brazilian LMEs are such that mixed responses are likely to be produced at the ecosystem level. Therefore, despite the great importance of this framework for marine resource assessment and management, the use of LME responses for monitoring GCC impacts requires great caution.

Changes in global primary production have been showed by several studies over the past decades, in association with multi-decadal climate and ocean variability (Chavez *et al.* 2011). Climate driven changes in ocean temperature, nutrients and light lead to changes in phytoplankton biomass and structure, but the relative importance of the impacts and the biological responses are regionally varying (Marinov *et al*. 2010). The lack of long-term biological observations makes it difficult to detect robust changes with time at regional scales. Ciotti *et al.* used satellite data to conduct a first comparative evaluation of surface chlorophyll over the entire Brazilian continental shelf (BCS), characterising each region. The authors conclude that the detection of long-term trends is currently still not feasible for the BCS. Despite the paucity of *in situ* measurements and the optical complexity associated with Brazilian coastal waters, remote sensing of ocean color is undoubtedly the best available tool for a global description of chlorophyll and to predict the effects of GCC on marine primary production. The use of these techniques in Brazilian science should be enhanced.

Rainfall distribution and hydrological balance are likely to be affected by GCC (Meehl *et al.* 2007). Lake and lagoon levels are among the most apparent signals of change in water quantity. The water catchment surface area is much greater than the lake itself, and the water level can therefore visibly reflect the influence of climate on a relatively large area (Williamson *et al.* 2009). By analysing 90 years of water-level records for Mirim Lagoon (Brazil-Uruguay frontier), Hirata *et al.* find long-term changes strongly associated with ENSO and identified two regime shifts, apparently related to the cold and warm phases of the Pacific Decadal Oscillation during the previous century. The last warm phase, between 1977 and 1998, significantly affected the water balance of a wide region in Southern South America (Haylook et al. 2006, Agosta and Compagnucci 2008). Hirata and co-authors work provides key insights for predicting the possible effects of trends in regime shifts and of climate change on the water balance of the coastal lagoons and wetlands of southern Brazil.

Fisheries may be impacted by climate changes in several ways. They may be affected by the increasing temperature, changes in salinity and ocean currents, and also through the changes in nursery habitats and ecosystem primary production. Combining IPCC emission scenarios with regional climate models, climate and biological time series data, and accounting for local anthropogenic alterations, Shroeder & Castello evaluate the future impacts of global warming on the fisheries of Patos Lagoon. They predict that the main factor affecting fisheries in this region will be the acceleration of the outflow current at the mouth of the lagoon. This hydrological change will have important cones-quences for the population dynamics of valuable fish resources and may produce changes to the fishing calendar. Exploring a series of cause-effect relationship, the authors call attention for the fact that climate changes impacts on the local fisheries can be both negative and positive, depending on the factor and on the considered species.

Global warming is expect to affect the distribution of marine communities and many evidences of species shifting and changing abundance are raising from literature (Hoegh-Guldberg 2010). Previous biological knowledge and a comparison of present and past data allow De Faveri *et al*. to find important changes in an intertidal macroalgal community in southern Brazil (Santa Catarina State). The results include the appearance of tropical and opportunist species not previously described in this region, and the disappearance of local common taxa that used to occur in the 70´s decade. Many marine population responses to temperature increases are expected to be pronounced or to be initially detected in transitional warm-temperate regions, such as Southern Brazilian region. On rock shores, however, climate change may not lead to a simple poleward shift in the distribution of intertidal organisms but may cause localized extinctions, due to the inability of species to move into suitable habitats (Hawkins et al. 2008).Therefore, monitoring marine populations, with a focus on stenothermic species, can provide useful indicators of climate change effects, particularly where historical temperature data are not available.

The contributions appearing in the present volume deal mainly with climate variability and its potential impacts during the previous decades or the past century. In contrast, Medeanic & Correa go further back through recent geological time. Based on radiocarbon and palynomorphic data from cores, these authors make a preliminary paleore-construction of climate, sea-level oscillation and environmental changes in the coastal plain of the southernmost state of Brazil during the Holocene (~10,000 B.P.). Their work highlights the potential of palynomorph proxies as a tool to predict future scenarios based on climatic change periodicity.

The crucial role of scientific communication and media coverage on the GCC issue is also considered in this volume. Hellebrandt & Hellebrandt review the coverage of GCC by the Brazilian media and identified critical points. Among these points is the predominance of issues set by an international scientific and political agenda. The Brazilian media reproduces information provided by international agencies and news sources connected with this agenda, which overlooks both local reality and scientific expertise. Failure to communicate key messages about climate change, particularly if the regional context is not considered, can have negative implications for public awareness and for establishing climate change policies.

Final remarks

If the physics of climate change still involves many uncertainties, the impacts of climate change on coastal and marine ecosystems are still very much controversial, particularly in the case of analysis at the regional level. It seems relatively less complicated to predict the effects of a changing parameter (*e.g.*, rising temperature, acidification and decreasing light) on isolated species from previous knowledge about their physiology, ecology and reproductive biology. However, many challenges arise when predicting the responses at the community and ecosystem level, in addition to the complexity added by synergistic effects (Walther et al. 2002, Williams *et al.* 2008, Russel *et al.* 2009, Hoegh-Guldberg & Bruno 2010). Therefore, the challenge posed to the worldwide scientific community working with GCC and its impacts is paramount and will demand the best of our talent and creativity.

The papers presented in this Special Issue constitute a first step towards the provision of guidance to managers and policymakers who must address the impacts of GCC in the Brazilian coastal zone, particularly in relation to the Climate Change National Plan. However, a series of scientific goals still need to be achieved to evaluate the effects of climate change on the Brazilian coastal zone. These goals include the analysis and integration of historical data, the application of standardised protocols, hypothesis testing, and continuous data acquisition programmes specifically designed to observe the coastal environments.

For most Brazilian coastal ecosystems and regions, temporal and large spatial data is scarce for both biotic and abiotic parameters. Where available, information is isolated, punctual in space, with short and incomplete time series (if any). Most studies also lack integrated or comparative protocol consistency. Scientific evaluations and future planning on the impacts of climate change along Brazilian coastal zone will achieve development if observational systems are implemented and improved to allow systematic monitoring programs of physical, chemical, biological and social parameters. Experimental approaches can help climate change science and management, but only after a better determination of questions and hypothesis, that are specific to each regional condition.

By researching GCC, science and scientists cannot be apart from society. Public awareness and education may affect, at middle and long term, society opinion, behaviour and political decisions, contributing for the advance of climate change policies and actions. The *Rio Grande Declaration*, an open letter released soon after the Workshop and now officially published in this volume, constitutes a preliminary attempt of CZ members and meeting participants to contribute to awareness and influence public policies. The letter warns about climate change problems, particularly the ones affecting the coast, and claims for society and political action.

By indicating deficiencies and revealing scientific hurdles, and pointing out the consequences for ecosystems and society, the present volume is expected to offer new insights and stimulate future studies of impacts, mitigation measures and adaptation strategies for Brazilian coastal zones facing Global Climate Change. It is also envisaged that this initial step will foster new knowledge that will represent a significant Brazilian contribution to international scientific forums addressing this important issue.

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Figure 1. Participants of the I Brazilian Workshop on Climate Changes in Coastal Zones, hosted by the Federal University of Rio Grande, between September 14th and 16th 2009. The event was promoted by Coastal Zone Network from National Institute of Science and Technology (INCT) for Climate Change, and supported by CNPq.

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F O R E W O R D

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The Intergovernmental Panel on Climate Change (IPCC) projections for this century would certainly result in a suite of biophysical and socio-economic impacts on the Brazilian coastal zone that would ultimately affect several sectors, including natural ecosystems, fisheries, transportation, tourism and recreation, infrastructure and local communities.

Global climate change will affect coastal zones where approximately 40% of world's population lives within 100 km of the coastline. The anticipated climate-related changes include an accelerated sea level rise, a further increase in sea surface temperature, an intensification of tropical and extra-tropical cyclones, large extreme waves and storms, alterations in the precipitation and run-off rates, ocean acidification, among others. These phenomena will vary from place to place at different time scales, but their impacts are most certainly to be negative on coastal societies.

Coastal zones will face socio-economic and environmental problems, especially in low-lying areas, which can be severely affected by seawater intrusion and local wave climate changes. For instance, the IPCC expects that, globally, mean sea level may rise as much as 88 cm by the end of the 21st century. One clear message that emerged from the last IPCC report is the urgent need to understand the impacts and assess the vulnerability of coastal zones to climate changes around the world.

Although there has been a considerable increase in the understanding of the impacts of climate changing on coastal zones and their ecosystems, there are still substantial knowledge gaps. The vulnerability to climate change is highly variable, depending on the region and ecosystems under investigation. The capacity of adaptation of marine and coastal ecosystem will vary among species, communities, geographical regions and levels of system health and degradation. Rising in sea level and increase in both frequency and intensity of storms would amplify the impacts on the detected areas under risk. Coastlines under stress from human activities are particularly susceptible to global warming impacts and their vulnerabilities have to be urgently assessed. In highly urbanized areas floods rather than coastal erosion can cause strong impacts. Even worse, the historic drainage problem in certain coastal cities can be magnified due to intense flooding causing a serious public health problem with groundwater contamination, mosquito proliferation, and associated spread of diseases.

The Brazilian Climate Change Research Programs: Rede CLIMA and INCT for Climate Change

In late 2007, the Brazilian Ministry of Science and Technology (MCT) created the Brazilian Research Network on Climate Change (Rede CLIMA) with the following objectives: (a) generate and disseminate knowledge and technology for Brazil to meet the challenges represented by the causes and effects of global climate change; (b) gather data and information necessary to support Brazilian diplomacy in negotiations on the international regime for climate change; (c) develop studies on the impacts of global and regional climate change in Brazil, with emphasis on the country's vulnerability to climate change; (d) consider alternatives for the adaptation of Brazil's social, economic and natural systems; (e) investigate the effects of changes in land use, and in Brazil's social, economic and natural systems to the country's emissions that contribute to global climate change, and (f) contribute to the formulation and monitoring of public policies on global climate change within the Brazilian territory, g) contribute to the conception and implementation of a Brazilian climate-related disaster monitoring and alert system, h) carry out studies regarding Brazilian greenhouse gas emissions in support to the periodic national greenhouse gas inventories stipulated by the Presidential Decree n.º 7.390 of September 9th 2010. One of the first products of Rede CLIMA will be to produce regular analysis of Brazil's climate and predicted climate change, with better precision for South America than the models developed in other countries that are available nowadays, and with more specific analysis in certain strategic areas, among them Coastal Zones, for the formulation of national policies.

From the scientific point of view, Rede CLIMA interacts closely with the National Institute of Science and Technology for Climate Change (INCT for Climate Change), which began in 2008, and with the São Paulo State Research Funding Agency (FAPESP) Research Program on Global Climate Change also established in 2008. The INCT for Climate Change is funded by Brazil's National Council for Scientific and Technological Development (CNPq) and by FAPESP. It brings together the largest and most far-reaching interdisciplinary network of environmental research institutions in Brazil, involving over 90 research groups from 65 institutions and universities from Brazil and abroad, with over 400 participants. The main goal of the INCT for Climate Change is to provide high quality and relevant scientific information needed to (a) understand climate functioning, variability and change, and (b) inform adaptation and mitigation at local, national and international levels. The INCT for Climate Change is structured in three scientific and one technological axes: scientific basis for global environmental change; research on impacts, adaptation and vulnerability; mitigation; and technological developments and products. FAPESP Research Program on Global Climate Change has objectives that are similar to those of the INCT for Climate Change and of Rede CLIMA, with a particular emphasis in the development of new technologies to mitigate and adapt to climate change.

The Coastal Zone Network

With about 8.500 km, the large Brazilian coastal zone presents a variety of climates and coastal morphologies, including several ecosystems such as sandy beaches and dunes, rock shores, coral reefs, estuaries, mangroves, salt marshes and seagrass meadows. The Brazilian's coastal zone is a significant national environmental benefit that is also fundamentally important to our lifestyle and economy. About 20-30% of the Brazilian population lives by the coast, where several pressures already exist such as sea reclamation, flooding, erosion and extreme weather events.

Climate change will certainly affect in different ways the various coastal cities and coastal ecosystems in Brazil. Due to its complexity, the Brazilian coastal zone cannot be investigated under the perspective of small projects addressing only few scientific questions. Dense population occupies the region at sea-land interface with complex infrastructure in certain areas, added to a mosaic of different ecosystems, which are exposed to anthropogenic and natural impacts.

Therefore, a coordinated research team was needed to investigate vulnerability, impacts and adaptation of the Brazilian coastal zone to climate change. To address this need, the Coastal Zone network was created within the context of Rede CLIMA and INCT for Climate Change. The first and major effort was made towards establishing a multidisciplinary research team, comprising both regional and institutional representativeness, aiming at achieving national and international scientific impact. Coordinated by the Institute of Oceanography at the Federal University of Rio Grande (IO-FURG), Coastal Zone is formed by more than fifty researchers from 23 institutes, covering about 11 Brazilian coastal states. Taking into account that the analysis of the impacts of climate change on the Brazilian coastal zones is limited by a number of deficiencies, especially by basic knowledge about the physical, geological and ecological dynamics of these environments, the main CZ goals are: 1) to evaluate the state of knowledge and identify the gaps; 2) to recommend future studies; 3) to establish protocols and 4) to coordinate/integrate projects that investigate the vulnerability and the effects of climate change in coastal areas of Brazil in order to propose adaptive actions with the organized sectors of society. The CZ researchers focused first on making a preliminary assessment of the studies, including reviews, analysis of past data and vulnerability assessment of ecosystems and regions to climate.

I Brazilian Workshop on Climate Change and Coastal Zones

The Coastal Zone netwport has planned workshops to run on biennial basis, to better integrate the finds. The "First Brazilian Workshop on Climate Change and Coastal Zones", one of the first CZ achievements, was held from September 14th to 16th 2009 at the IO/FURG. The Workshop aimed the divulgation of Coastal Zone preliminary results, consolidating the research group, stimulating the integration of its members and discussing methodological protocols and future research. The Workshop covered topics within the areas of geology, geography, physical, geological and biological oceanography, ecology, fisheries, socio-economics, scientific divulgation and education. The event was attended by 200 people, including scientists and students, from several national institutions. The Workshop successfully achieved its goals, and its results were highlighted by the national scientific community and by the media and society in general. By bringing together different research areas and institutions, new collaborations were established. Moreover, the Workshop established scientific basis, new and promising collaborations and leaded the future of climate change research in Brazil.

The Workshop also resulted in this Special Issue of the *Pan-American Journal of Aquatic Sciences* (PanamJAS), which includes 15 peer-reviewed scientific articles covering several physical, biological and social aspects of the Brazilian coast. The Issue is the first of several steps toward a detailed assessment of the impacts and vulnerability of the Brazilian coastal zone to climate change.

Based on Workshop discussions, we released the *Rio Grande Declaration*, an open letter signed by Coastal Zone members and meeting participants. Forwarded to the main national media groups and public sectors, and also published in this volume, *Rio Grande Declaration* is a manifest from the scientific community present or represented during the Workshop, warning about climate change impacts, particularly those affecting the coast. The letter highlights a series of scientific goals that still needs to be reached to adequately assess and monitor the effects of climate change on coastal ecosystems in Brazil. The successful implementation of the recommendations depends on political will and decisions, which must be long-term committed to the theme of Climate Change.

We hope that this Special Issue will heighten the interest of the scientific community, managers and policy-makers, because a wide range of climate changes impacts are expected to influence the Brazilian coastal zones. Human response and our scientific capacity will play a major role in determining the success of the adaptation of the Brazilian coastal zone to climate change.

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Brazilian coastal vulnerability to climate change

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Abstract. The coastal zone of Brazil includes a variety of coastal forms, such as wide occurrence of sedimentary cliffs, large and deeply incised estuaries, crystalline headlands and low-lying coastal plains. These forms will respond in different ways to the expected climate changes and associated sea level rise. The potential vulnerability of the distinct coastal types along the Brazilian coast to climate change is evaluated. Due to the low occupation of large sectors of the coastline, the risks are concentrated in the urbanized areas. The largest impacts are expected to be caused by floods. The absence of long-term observations of oceanographic data or detailed altimetric maps presents a major difficulty for the evaluation of different risk scenarios at the local level and consequently for the application of measures to minimize these impacts over the population.

Key words: Coastal vulnerability, climate change, coastal classification, Brazil

Resumo: Vulnerabilidade da costa brasileira a mudanças climáticas. A zona costeira brasileira se caracteriza por amplos domínios de falésias sedimentares e de rochas do embasamento com alternância de baixadas costeiras e margens ao longo de estuários inseridos nos relevos elevados. Considerando os distintos compartimentos geomorfológicos é apresentada uma avaliação da vulnerabilidade potencial em face de uma mudança climática e associada elevação do nível do mar. Os resultados indicam que a baixa ocupação de grande parte da zona costeira faz com que as áreas de risco se concentram nas cidades costeiras, sendo os riscos de inundação os de maior impacto sobre a população. A ausência de observações contínuas de longa duração, assim como a falta de mapeamentos altimétricos de detalhe, representa a maior dificuldade na construção de cenários de risco a nível local e consequentemente para o desenvolvimento e aplicação de medidas de minimização dos impactos sobre a população.

Palavras-chave: Vulnerabilidade costeira, mudança climática, classificação costeira, Brasil

Introduction

The climate changes forecasted by the Intergovernmental Panel on Climate Change (IPCC) will necessarily depend on the time and place being considered.

One of the forecasts for the evolution of the average surface temperature of the planet under different greenhouse gas emission scenarios (IPCC 2007) is that the temperature increase along the Brazilian coast will be less than 1 °C until 2030. But, this increase may be as high as 2 °C or 3 °C for the last decade of this century (Fig. 1). The predicted increase in temperature at higher latitudes is more significant and suggests that ice will melt in Greenland and Antarctica, resulting in rising sea level rates. Sea level rates will already be increasing because of thermal expansion. The most direct result of coastal geomorphological processes will be the adjustment, usually by erosion, of the coastline and the increased vulnerability of low-lying areas to flooding.

This first approximation regarding the climate evolution already allows us to affirm that, from a geomorphic viewpoint, the changes brought about by sea level rise will be small in the next 20 years, and the current trends will be more or less maintained. However, because of the significant rise in temperature forecasted for the end of the century, geomorphic processes are expected to intensify, starting in the middle of the century, as a result of both the sea level rise and the intensification and frequency of subtropical cyclogenesis. This cyclogenesis is associated with an increase in the sea water temperature, changes in sea level, increased wind transport and destabilization of dune fields.

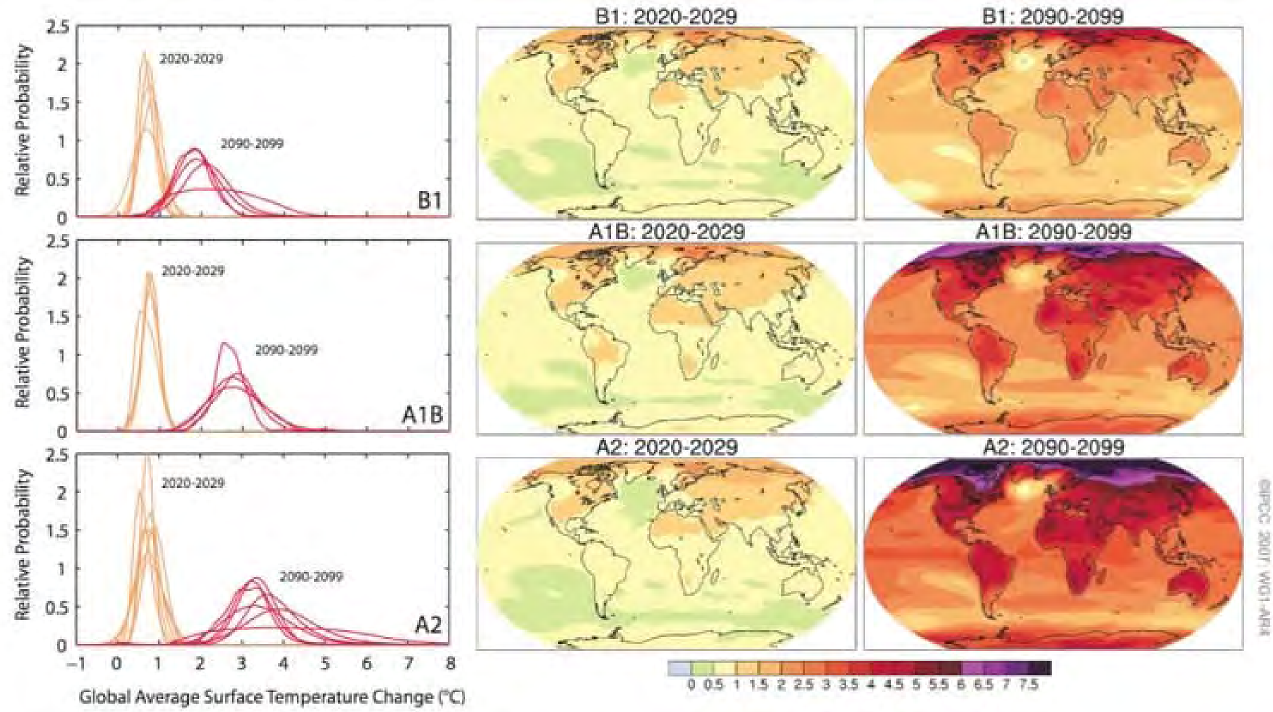

Figure 1. Evolution of the average surface temperature projected by the IPCC in 2007.

Nobre *et al.* (2007) produced climate projections for the next 30 years of the century in South America for various emission scenarios. In terms of precipitation these predictions show discrepancies in the forecasted anomalies in terms of either increase or decrease. Although the discrepancies between the results are small they will affect negatively or positively areas that are already experiencing water deficit as in the Northeast Region of Brazil, where the projections for the coastal zone indicate anomalies varying from very small to an increase and even decrease in the amount of precipitation. However, even with no significative change in rainfall, the augmented evaporation caused by the temperature increase will result in augmented water shortages in the semi-arid regions.

The temperature forecasts by Nobre *et al.* (2007) for the coastal zone are similar to the scenario forecasted by the IPCC (2007) and indicate a temperature increase in the range of 2 ºC to 3 ºC.

The perception of risk from sea level rise was incorporated into the ORLA Project of the Ministry of Environment (Ministério do Meio Ambiente 2004) through the establishment of set-back lines of 50 m in urban areas and 200 m in rural areas. This distance would be measured landward either from the backshore limit or from the dune toe of the reverse side of foredunes when present. The establishment of the width of these set-back lines resulted from a conciliation between the results of the application of the Bruun rule (Bruun 1962, 1988), for an increase of an 1 m sea level rise (Muehe 2001, 2004), and the impossibility of its practical application in areas of very low gradient of the shoreface and inner shelf as in the north and northeast regions where the results of the model indicate very large recession of the coastline (Fig. 2).

The adopted limits represent a first minimum restriction to be considered in the urbanization of coastal areas, and can be expanded according to local geomorphic characteristics such as the known erosion rate and landscape conservation.

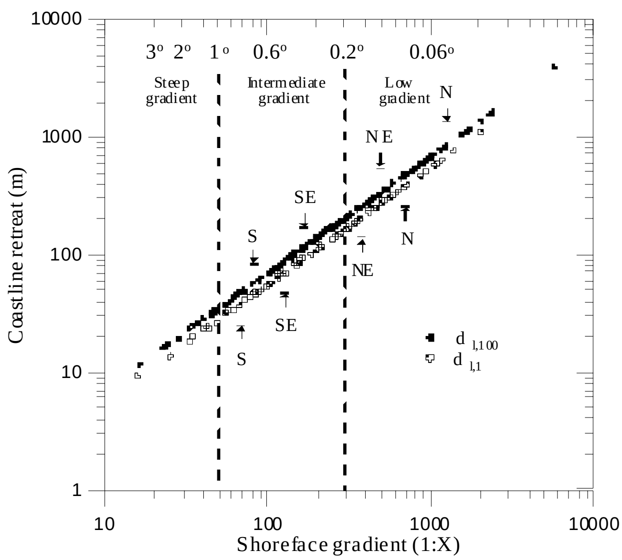

Figure 2. Coastline retreat in response to an elevation of 1 m of relative sea level and a closure depth of the beach profile of 5 m (dl, 1) and 10 m (dl, 100)), (Muehe 2001).

The coastal vulnerability investigations conducted by research groups associated to the Program of Marine Geology and Geophysics (PGGM) (Muehe 2006) indicate that, in general, erosion is more prevalent than accretion, which is restricted to sites with a significant input of fluvial sediments.

Coastal morphology and its response to sea level oscillations

Horizontal adjustments of the coastline are the result of an intricate relationship between the oscillations in the sea level, changes in wave incidence, sediment availability, coastal morphology and rock strength. Accretion of the shoreline may occur locally even during a period of sea level rise, provided there is sufficient sediment supply. Such areas include coastal plains or terraces associated to a fluvial outlet. Nevertheless, large-scale marine transgressions cannot be accompanied by a positive sediment balance and consequently result in coastline erosion. For example, during the last marine transgression, the coastline receded tens of kilometers over the course of about 10,000 years.

The relative sea level elevations of the Brazilian coast 120,000 years BP and 5,600 years BP were on the order of 8 m and 5 m higher than the current level, respectively. During these transgressions, marine sands were deposited in the form of beach barriers and beach ridge coastal plains. The higher sea level, that the present one, of the last transgression resulted, according to Pirazzoli (1996, cited in Bird 2008), from the postglacial isostatic compensation, which was limited, in Brazil, to the coast between Cape Calcanhar and the southern extremity of South America and excluded the Amazonian Coastal Region (Fig. 3).

Curves of relative sea level variation were established by Martin *et al.* (1979, 2003 among others) for Salvador (Fig. 4) and several locations in southern and southeastern Brazil. These curves confirm a sea level elevation of up to 5 m, despite disagreements about the oscillations after the maximum transgression (Angulo & Lessa 1997).

The development of coastal barriers during each of the marine transgressions led to the formation of lagoons at the lee of the barriers and the subsequent formation of coastal plains through sediment infilling of the lagoons. The low altitude and topography of these plains results in difficulty of water discharge, amplified during storms due to the blocking of the channel outlets by waves and tides. Therefore, these plains represent an area with potential risk of flooding due to sea level rise (Fig. 5). The response of a barrier to a sea level rise is to adjust by landward translation, a process that involves wave overwash, the formation of overwash fans and even localized barrier rupture. Overwash does not occur when the barrier was formed during a period of higher sea level or had their height increased by the development of dunes. In any case there will be erosion on the ocean side of the barrier as also at its backside in contact of a lagoon, if present.

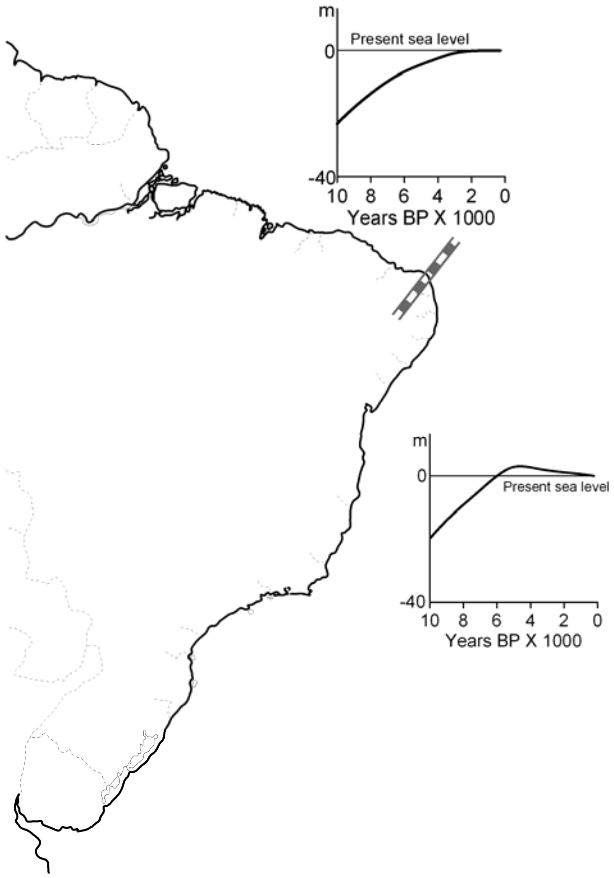

Figure 3. Relative sea level variations during the Holocene. Adapted from Pirazzoli 1996, cited in Bird 2008.

Sediment accumulation may occur in the form of coastal terraces or plains developed through accretion of a succession of beach ridges. This type of accumulation occurred in the delta-shaped plains of the São Francisco, Jequitinhonha, Doce and Paraíba do Sul Rivers (Fig. 6), which were studied in detail by Dominguez *et al.* (1983, 1987, 1989), and Martin *et al.* (1984). Reversals of the longshore sediment transport direction is revealed by the changing alignment of beach ridges as a consequence of

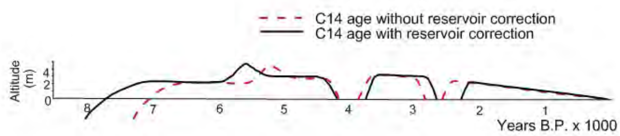

Figure 4. Relative sea level curve for Salvador (adapted from Martin, 2003).

Figure 5. Highly developed double coastal barriers and enclosed lagoons in Barra da Tijuca, Rio de Janeiro. Photo D. Muehe.

Figure 6. Beach ridges of the Doce River coastal plain. Image from Google Earth.

changes in the wave incidence in response to climate changes, and those changes are reflected in adjustments of the shoreline through the process of beach rotation.

In areas of high relief, as represented by the sedimentary deposits of the Barreiras Group and other morphologically similar areas which occur discontinuously from the coast of Amapá up to Rio de Janeiro, the result of transgressions were the formation of coastal cliffs, in some places still active, preceded by narrow beaches and a nearshore and inner shelf of low gradient (Fig. 7). A rising sea level will increase the erosion of the cliffs, a slow process whose speed depends on the cohesion of the material and the amount of sediment released and maintained in the profile. Many of the cliffs that are still active probably represent an incomplete adjustment related to the post-glacial transgression rather than the result of a recent rise in sea level.

The erosion of sedimentary cliffs left vestiges of their past position in the form of lateritic concretions deposited on the continental shelf, and the released sediments represented an important source of sand for the formation of beaches, dunes and coastal terraces.

Figure 7. Active cliffs in sedimentary deposits of the Barreiras Group. Buzios, Rio Grande do Norte. Photo D. Muehe.

Coastal Compartments and Associated Vulnerabilities

Physiographic coastline classifications, for the Brazilian coastline, have been proposed by several authors. The most largely known was proposed by Silveira (1964) who considered geological, geomorphological, climatic and oceanographic aspects. More recent studies (Muehe 1998, 2005, 2006, Muehe & Neves 1995, Dominguez 2004, 2007) are in many aspects coincident with the classification scheme of Silveira but are differentiated by their objectives and level of detail.

The following classification (Fig. 8) is based on the literature mentioned above, with emphasis placed on the prevailing geomorphological aspects and potential vulnerabilities associated with climate change and its consequences (*e.g.*, sea level rise and flooding):

Figure 8. Coastal compartments.

The tide and mangrove dominated coast of the North region

With a wide continental shelf, highly influenced by the water discharge and mud deposition of the Amazon, the coastal zone is submitted to a macro tidal regimen with tidal ranges of locally up to 10 m associated to strong tidal currents.

Mangroves occur widely and correspond about 76% of this formation of the whole Brazilian coastline (Muehe, 1998). They represent an important ecosystem for the maintenance of fishery as also for the protection of the coast. A rise in sea level may be compensated by a backward and lateral expansion of the mangroves, but this expansion is frequently limited by the presence of cliffs along the open coast and estuaries. Depending of the rate of sea level rise the adaption may not be sustained under rates higher that 7 mm a^{-1} as reported by Reed *et al.* (2008) for the Mid-Atlantic coast of the USA.

Coastal erosion has been reported by El Robrini *et al.* (2006) in Mosqueiro in the estuarine coast to the north of Belém and along the Atlantic Coast in the region of Salinópolis, one of the principal resorts of the coast of Pará, and near Ajuruteua, whose beaches are in high demand on weekends and holidays.

According to data from the Brazilian Institute of Geography and Statistics (IBGE) interpreted by Strohaecker (2008), the population on the coast is relatively high in relation to the population of the state (89% in Amapá, 45% in Pará and 27% in Maranhão). However, this population is mainly concentrated in metropolitan areas, while the rest of the coast is almost empty. Over 80% of the coastal municipalities of Amapá and Pará have population densities of less than 50 inhabitants/km^2. Therefore, many erosion or flood events would only have localized socio-economic impacts.

According to a study by Tessler (2008), the flood risk varies from very high to high in the region around Macapá and in the northeast area of Marajó Island and from high to medium in the city of Belém and the coast of Bragança in Pará. The risk is high along the estuary on the island of São Luiz in Maranhão and medium to high in the Parnaíba Delta.

The Sediment Starved Coast of the Northeast

The coast is characterized by the dominance of sedimentary cliffs of the flat topped Barreiras group and can be sub-divided according the degree of water deficit into a semi-arid compartment in the north, including the States of Piauí, Ceará and the West Coast of Rio Grande do Norte and a more humid compartment in the south extending from the South Coast of Rio Grande do Norte to Salvador in Bahia.

Large dune fields occur widely and represent a sink of the sands which otherwise would lead to a progradation of the coastline. An increase in temperature or decrease in precipitation will amplify the eolian sediment transport and increase the vulnerability of the coastline due to the augmented transfer of sediments from the shore to the continent.

Beach rocks occur widely at some distance from the beach and acts like breakwaters, providing some protection against the waves but also avoiding sediments to be carried to the beach, increasing the vulnerability to erosion. The overtopping of these barriers under a higher sea level will increase the wave activity at the beach which will have to adjust morphodynamically to the new level of energy.

In the semi-arid sector the most impacted segments by erosion are in Ceará, to the north of the port of Pecém, and in Fortaleza. In Pecém because of the deposition of sediments at the lee of the port structure, and in Fortaleza because of the retention and diversion of the flow of sediment to the beaches of the city after the construction of a breakwater in order to protect the Port of Mucuripe (Morais *et al.* 2006). In Macau and Guamaré in Rio Grande do Norte, the recession of the coastline is endangering oil pumping stations (Vital *et al.* 2006). According to these authors the construction of structures perpendicular to the beach in Macau, Caiçara do Norte and Touros accelerates the erosion. Segments under erosion of the sedimentary cliffs of the Barreiras Formation are associated to a slow retreat of the cliffs and represent a risk for constructions when located too close to the edge of the cliff. Occasional swell from the Northern Hemisphere reach the coast of Ceará in the summer months triggering erosion (Melo Fo & Alves, 1993, Melo Fo *et al.* 1995). The frequency of these events may increase as a result of climate change, and will contribute to the general trend of coastline destabilization.

The population in the states of Ceará and Rio Grande do Norte is concentrated along the coast and represents almost 50% of the population of these states, with densities ranging from 50 to 200 inhabitants/km^2 (Strohaecker 2008). However, almost 40% of this population is concentrated in coastal metropolitan areas, therefore only 10% is distributed in the rest of the coastal municipalities.

According to Tessler (2008), the areas with the greatest risk of flooding are located in the Parnaiba metropolitan area in the State of Piaui, in the metropolitan region of Fortaleza in Ceará, and along the margins of the Apodi and do Carmo Rivers, between the localities of Areia Branca and Mossoró in Rio Grande do Norte.

On the coast of the sedimentary cliffs, the erosion is widespread and occurs almost along the whole coastline from the south of Rio Grande do Norte along the coast of Paraíba, Pernambuco and Alagoas. The opposite is true on the coast of Sergipe, where the abundant amount of sediment delivered by the rivers causes about 57% of the shoreline to be in equilibrium, while 21% is under erosion (Bittencourt *et al.* 2006).

In Paraíba State, the segments under erosion represents about 42% of the 140 km of beaches (Neves *et al.* 2006).

In Pernambuco, about 30% of the beaches are under erosion. The majority are experiencing severe erosion due to natural factors, such as coastal circulation and sediment deficit, while man-made interventions often intensifies this trend (Neves & Muehe, 1995; Manso *et al.* 2006). The occurrence of beach rocks and algae in the shoreface and innershelf increase the sediment deficit by preventing their transport in direction to the shore. Because of the proximity of buildings, the most critical areas are the beaches of Boa Viagem, Piedade, Candeias and Barra das Jangadas in Recife.

In Alagoas, the vulnerability to erosion is caused by the reduced delivery of fluvial sediments. Erosion is concentrated primarily on the northern coast of the state, where tourist activity is concen-trated (Araújo *et al.* 2006). According to Dominguez (1995), the susceptibility of the coast to erosion is demonstrated by active cliffs of the Barreiras group, the almost absence of coastal plains and Pleistocene terraces as also the occurrence of submerged beach rocks attesting the retreat of the coastline.

In Sergipe segments under erosion are located in Atalaia Nova, north of Aracaju, and to the south of the São Francisco River outlet, where the Vila do Cabeço was completely eroded. Areas of high shoreline variability are located near the outlets of the Real, Vaza Barris and Sergipe Rivers, where erosive episodes have caused significant material damage (Bittencourt *et al.* 2006).

In Bahia, the coast between Mangue Seco, at the outlet of the São Francisco River and Salvador, is in equilibrium (Dominguez *et al.* 2006).

According to Strohaecker (2008) based on IBGE data, the general trend of the State population is to concentrate in coastal municipalities. Around 40% to 50% in Rio Grande do Norte, Pernambuco and Alagoas, 30% to 40% in Sergipe and Bahia and 20 to 30% in Paraíba. The majority lives in metropolitan areas with only 10 % distributed along the remaining coastal municipalities.

The areas under greatest risk to flooding (Tessler 2008) are located in low-laying areas of João Pessoa and Recife, in the urban area of Aracaju, in the coastal plain north of the Vaza Barris River and in the low-lying areas of Salvador.

The Mixed Coast of Sedimentary Cliffs and Wave Dominated Deltas

The presence of the sedimentary cliffs of the Barreiras Group is still dominant but less continuous in the south. Beach ridge plains developed in front of the Jequitinhonha and Caravela Rivers, in Bahia, Doce River in Espirito Santo and Paraíba do Sul River in Rio de Janeiro State (Fig. 6). The changes in the alignment of the beach ridges associated to modifications in the longshore sediment transport indicate the occurrence of alternations in the dominium between waves generated by the trade winds and swell waves generated by cold fronts from the south. Therefore the compartment is located in a region highly susceptible to modifications in the dominium between tropical and subtropical climatic-oceanographic processes.

In Bahia, about 60% of the coast is in equilibrium, and 26% is under erosion, with intense erosion occurring in fluvial outlets. Sediment retention occur in Ilhéus and in unconsolidated capes such as the coastal plain of Caravelas. Long stretches of the cliffs in south Bahia, from Cumuruxatiba to the border of Espírito Santo State, are experiencing long-term negative sediment budget (Dominguez *et al.* 2006). Strong coastal erosion with destruction of houses occurs in Mucuri, in south Bahia near the border with Espírito Santo.

In Espírito Santo the coastline alternates between long stretches under erosion or in equilibrium with few segments of accretion. Accretion is occurring in the coastal plains of Doce River, in the north, and Itabapoana River, at the southern border between the States of Espírito Santo and Rio de Janeiro (Albino *et al.* 2006).

On the coast of Rio de Janeiro near the border between Espírito Santo and Cape Frio, significant erosion is occurring on the south margin at the outlet of the Paraiba do Sul River in Atafona where the sands are being trapped on the inner continental shelf by mud brought by the river and by the predominance of longitudinal transport of sediments towards the south, out of the affected area (Muehe *et al.* 2006). Other areas at risk of erosion in highly urbanized areas include the coast of Macaé and Rio das Ostras (Muehe *et al.* 2006).

The population density of this compartment is low except along the northern coast of Rio de Janeiro, where oil exploration on the continental shelf led to migration to the cities of Macaé and Campos. Other cities with strong growth due to tourism are Armação dos Búzios, Rio das Ostras and Cabo Frio (Strohaecker 2008).

According to Tessler (2008), the critical areas at risk of flooding are the cities of Valença and Ilheus in Bahia, São Mateus and Vitória in Espírito Santo and Campos dos Goytacazes, Macaé and Cabo Frio in Rio de Janeiro.

The Double Barrier-Lagoon Coast

This compartment due to its almost east-west alignment of the coastline is highly exposed to storm waves from the south. The longshore sediment transport tends to be in equilibrium along a year, with the less frequent high energy waves (swell) from south and southwest being compensated by the more frequent waves from the southeast. Seasonally this equilibrium is frequently disrupted by the predominance of one of these wave incidences resulting in short term beach rotation with erosion at one of the beach extremities and accumulation at the other as in the Ipanema-Leblon Beach in the Metropolitan area of Rio de Janeiro.

From Cape Frio to the Marambaia Island, the coastline of this compartment shows signs of instability, with wave overwash and backshore scarp retreat (Muehe *et al.* 2006). Backshore retreat on the order of 10 to 15 m were recorded in several places and resulted largely from an exceptional storm that occurred in May 2001. This storm destroyed houses, kiosks and streets, mainly in the municipalities of Maricá and Saquarema. Erosion also occurs at the lagoon side of the more landward located Pleistocene barrier in contact with the Araruama lagoon, a long lasting geomorphological process that has gradually reduced the width of this barrier associated to an increase in the width of the lagoon.

The extreme west of the compartment is characterized be a long and narrow barrier separating the large Sepetiba Bay from the ocean. Localized overwash and gradual erosion of the lagoon shore of the barrier may result in temporary disruption of the barrier during exceptional storms and sea level rise. This disruption, in turn, will lead to the propagation of waves into the bay, with possible effects on the port of Sepetiba.

The occupation of the coastal barriers are concentrated in the towns of Maricá, Saquarema, Figueira and Monte Alto and in the metropolitan area of Rio de Janeiro. The expansion of the urbanization in these areas is moving very close to the beach, increasing their vulnerability to erosion.

In the metropolitan area of Rio de Janeiro, which includes the coast of Niterói, the increased population density makes the oceanic and estuarine coast more vulnerable against erosion, flooding and landslides. The expansion of urbanization over low lying areas of previously existing lagoons (*e.g.*, Barra da Tijuca) with limited drainage capacity represents risks that will significantly increase under a raised sea level and increased storm activity (Muehe & Neves 2008). Other critical areas identified in the municipality of Rio de Janeiro are located next to the Meriti and Pavuna Rivers and in the Sepetiba Bay.

The Rocky Coast of the Southeast

This compartment, which extends from Ilha Grande Bay in Rio de Janeiro to the Cape Santa Marta in Santa Catarina is characterized by the proximity of the Serra do Mar mountain range which extends up to the coastline between Ilha Grande Bay in Rio de Janeiro and São Vicente in São Paulo resulting in a drowned landscape with a sequence of high cliffs of Precambrian rocks and small coves. Coastal plains are small and sometimes absent. From São Vicente to the North of Santa Catarina, therefore including the coast of Paraná, the coastline is formed by long beaches and wide coastal plains with important estuaries as in Santos and Cananéia in São

Paulo, Paranaguá and Guaratuba in Paraná and São Francisco do Sul in Santa Catarina. From the north of Santa Catarina to the south of Santa Catarina Island the coastline becomes irregular with outcrops of the crystalline basement and small coastal plains. Southward of Santa Catarina Island and cape Santa Marta, in Santa Catarina, the coastline is formed by a sequence of beaches limited by rocky promontories with wide coastal plains and lagoons.

Longshore sediment transport tends to be directed to the north. The occurrence of extra-tropical cyclones with strong winds, heavy rain and high waves has been a main threat and seems to increase in frequency. Associated to an increase in temperature of the ocean water their occurrence will increase and may also affect the coastline up to Rio de Janeiro.

Modifications of the coastline due to erosion are, in São Paulo, usually isolated and associated with natural or artificial obstacles that interrupt the flow of sediments (Tessler *et al.* 2006).

In Paraná, the most significant modifycations of the coastline occur on the estuarine outlets (*e.g.*, the Superagui channel, Peças island, Mel island, Pontal do Sul, Ponta de Caiobá and Guaratuba). These modifications include both retreat and advance of the shoreline and occurred on the order of hundreds of meters in less than a decade (Angulo *et al.* 2006). The ocean coastline is presently stable. Areas most impacted by erosion are the beach resorts of Flamengo and Riviera and the central beach of Matinhos, restored through beach nourishment.

In Santa Catarina, investigations were concentrated on the central north coast (Klein *et al.* 2006) and on the island of Santa Catarina (Horn 2006). On the continental coast, the risks associated with coastal erosion result from inappropriate land use and frequent storms. The most critical points are located in Barra Velha, Piçarras and Penha. These areas are experiencing medium-intensity erosion, and Bombinhas is experiencing low-intensity erosion. On the island of Santa Catarina, erosion is occurring throughout the ocean coast. The greatest risk is to the urban areas on the north coast of the island (*e.g.*, beaches of Canasvieiras, Cachoeira and the Ingleses) and on the northwest coast in the Barra da Lagoa. Urbanized areas on the east and south coast with medium to high risk of erosion include Campeche, Armação and Pântano do Sul (Horn 2006).

Areas with the greatest risk of flooding are identified by Tessler (2008) and include the estuarine region of São Vicente and Santos in São Paulo, Paranaguá at the Bay of Paranaguá in Paraná, and in Santa Catarina at the southern shore of the Babitonga bay, at the estuary of the Itajaí-Açu River and at the localities of Palhoça and São José on the west shore of the South Bay and Florianópolis at the margins of the North and South Bay.

Strohaecker (2008) call attention to the high rate of population growth in the urban areas extending hundreds of kilometers along the coastline.

The Sandy Coast of Multiple Barriers of Rio Grande do Sul

From cape Santa Marta to Chui, at the border between Brazil and Uruguay, the coastline is formed by a long, wide, fine grained and monotonous beach in front of a multiple barrier-lagoon system, with the widest lagoons represented by the Patos and Mirim Lagoons. Active dune fields develop on top of the coastal barriers with dominant sand transport to southwest. Storm surges are frequently submitting the shoreline to a harsh wave climate.

The beach shows a high morphodynamic mobility alternating between long stretches of retreat and advance (Toldo *et al.* 2006) and reversal of this trend over time (Esteves 2008). This mobility has been in most cases limited to the beach without a definite retreat of the backshore. Very localized segments of coastal erosion were described by Calliari *et al.* (1998) and Speranski & Calliari (2006) and were related to wave convergence in Mostardas, to the south of the Mostardas lighthouse, between Bojurú and Estreito and at a small segment near Cassino and in the far south near Chuí.

The distribution of population along the coast is low and mostly concentrated in urban centers of second homes that attract nearly 100,000 visitors during the summer. The main urban center is located at the estuary near the mouth of the Lagoa dos Patos in Rio Grande. With about 200,000 inhabitants the city is located in low laying areas of the coastal plain and present the highest risk of flooding of the entire Brazilian coast (Tessler 2008). The port of Rio Grande is one of the most important in the country because its depth, its favorable location in relation to MERCOSUL countries and the presence of important industrial and petrochemical complexes.

Final Considerations

The Brazilian shoreline is experiencing erosion along the entire coast, but the erosion is irregularly distributed and often associated with river outlets. Large segments of the coast are formed by sedimentary cliffs in areas of low occupation where erosion is slow. On beaches the erosion becomes a risk when buildings are constructed to close to the shore. Numerous low-lying coastal plains formed by the sedimentary fill of old lagoons and estuaries are very susceptible to the effects of flooding and represent a risk to urban areas.

The already detected areas under risk will be magnified by rising sea levels and the increase in frequency and intensity of storms associated with an elevation in ocean temperature. These risks will be most significant in urban areas and especially in large coastal cities. In general flooding presents a greater risk than coastal erosion. Areas susceptible to flooding already have drainage problems, which will become more critical with a rise in sea level which in turn leads to groundwater contamination and the spread of diseases both through water as also due to the proliferation of mosquitoes and other transmittting agents. The implementation of appropriate actions by the various levels of government are difficult to make because of the uncertainty of the timing and magnitude of climate changes, the lack of observations of long-term temporal oceanographic variables and the absence of a well established observational network, the absence of detailed altimetric surveys required to model and identify the areas at greatest risk as also the small time window of the administrative mandate of each government in relation to the time required for the climate change to become effective. Nevertheless, the potential risk of erosion and flooding that will result from the expected climate change is significant. However, the situation in Brazil is less critical than in many countries in terms of the magnitude of potential impacts to the population due to the reduced occupation of large parts of the coastal area. Nevertheless, the establishment of integrated networks of continuous monitoring of oceanographic and climatic variables as also of the geomorphologic changes in response to coastal processes is crucial in order to build up convincing evidence of the direction and intensity of climatic-oceanographic changes which will give the justifycation to formulate appropriate actions for coastal management at the different levels of government.

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Potential vulnerability of the Brazilian coastal zone in its environmental, social, and technological aspects

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Abstract. Climate change caused by human action can be considered a major challenge facing human kind in the 21st century. Its potential to cause economic and social impacts is considerable, as it directly affects standards of living of coastal populations. This challenge can only be overcome through integrated actions taken by various sectors of society and supported by a deep knowledge of current and expected scenarios. This paper is a contribution to this knowledge, as it defines the vulnerability level of the Brazilian coastal zone based on a combination of environmental, social, and technological standards set forth in *Macrodiagnóstico da Zona Costeira e Marinha* (Macrodiagnosis of the Coastal and Marine Zone) by the Ministry of the Environment in 2008. Low-lying, densely populated, socially underprivileged regions with intricate technological networks are the most vulnerable and require a prioritized integrated action from policymakers. Throughout the entire country, several areas were rated as vulnerable or highly vulnerable, particularly the metropolitan regions of Belém, capitals of the Northeast, Rio de Janeiro, and Santos. Its potential to cause economic and social impacts is considerable, as it directly affects standards of living of coastal populations. This challenge can only be overcome through integrated actions taken by various sectors of society and supported by a deep knowledge of current and expected scenarios.

Key words: climate changes, natural risk, social risk, technological risk

Resumo. Vulnerabilidade potencial das zonas costeiras brasileiras em seus aspectos ambientais, sociais e tecnológicos. Considerado um dos grandes desafios a serem enfrentados pela humanidade no Século XXI, a resposta das sociedades aos efeitos de alterações nos padrões climáticos é fundamental no planejamento territorial, principalmente no que diz respeito às zonas costeiras. Mesmo alterações de pequena intensidade possuem potencial para causar impactos econômicos e sociais consideráveis, com efeito direto na qualidade de vida das populações costeiras. Este desafio somente poderá ser enfrentado a partir de ações integradas entre os diversos setores da sociedade e fundamentado no conhecimento profundo dos cenários atuais e previstos. O presente artigo apresenta uma contribuição a este conhecimento, definindo o grau de vulnerabilidade da zona costeira brasileira (em escala da União), com base em uma combinação de critérios ambientais, sociais e tecnológicos, definidos quando da publicação do Macrodiagnóstico da Zona Costeira e Marinha por parte do Ministério do Meio Ambiente em 2008. Regiões de baixa altitude, densamente povoadas, socialmente carentes e com intrincadas redes tecnológicas são as mais vulneráveis e que demandam prioridade de ação integrada por parte dos tomadores de decisão. Ao longo de todo o país diversas áreas foram classificadas com grau alto ou muito alto de vulnerabilidade, com destaque para as regiões metropolitanas de Belém, capitais dos estados da região nordeste, Rio de Janeiro e Santos.

Palavras chave: mudanças climáticas, risco natural, risco social, risco tecnológico

Introduction

Coastal zones, in their seemingly simple landscapes and usual dynamics, require at least the same - or possibly a more complex - level of consideration as inland spaces, for they involve issues related to changing sea level, paleoclimate, and vegetation history. In other words, the coast, like many other areas with ecological landscapes, may always be considered a heritage from earlier processes, redesigned by the now-prevailing coastal dynamics. Therefore, one can say coastal areas are three-way contact zones: land, sea, and climate, in addition to the remarkable showcases of individual ecosystems found in the land/sea mosaic comprising the total coastal space (Ab'Saber 2000).

The Brazilian coast, 8,698 kilometers long, and covering some 514,000 square kilometers, is a perennial challenge to management, due to the multiplicity of situations existing in such territory[1]. There are approximately 300 coastal municipalities facing the ocean, with privileged beaches for the development of tourist activities including leisure, fishing and many others. This dynamic landscape of fast physical and socio-economic changes is home to approximately 18% of the country's population, inasmuch as 16 out of 28 metropolitan regions lie along the coast. These densely populated areas coexist alongside large, sparsely populated areas. These are the areas of small-scale commercial or subsistence fishing communities, descended from *quilombolas* [dwellers of communities of descendants of fugitive African slaves], indigenous tribes, and other groups living in their traditional lifestyles. Considering the high level of preservation of their ecosystems, these areas will be the most relevant for preventive environmental planning.

In addition to the familiar environmental issues affecting this part of Brazil's territory, particularly with regard to causes and effects, there arises a new potential development in the shape of climate change. The need to adapt to this new development and mitigate the problems it has caused should figure prominently on the agenda of legislators and decision makers.

Within this context, it is important to understand the interactions between oceans and coastal zones and the climate change-related variables. Moreover, it is essential to build a strategic vision of this part of the territory, so that steps may be taken in response to new scenarios of global warming, rising sea levels and coastal erosion.

UNESCO, through its Intergovernmental Oceanographic Commission (IOC) has been concentrating efforts to establish methodologies to help Member States in the difficult task of identifying hazards brought about by climate change in coastal zones and making adaptations and acting to mitigate its undesirable effects.

That has been a priority among IOC's initiatives, after the disaster of December 2004, when a tsunami hit several countries along the Indian Ocean. Together with the World Meteorological Organization (WMO), IOC is starting to develop an initial multi-hazard warning system to guide governments in their decisions, especially with regard to integrated coastal management (IOC 2009).

In Brazil, efforts to build a technical and institutional structure able to withstand the effects of climate change are just getting underway. A recent study by TCU (the Federal Audit Office, similar to the GAO in the USA) titled *Auditorias de natureza operacional sobre políticas públicas e mudanças climáticas* (Operating audits on public policy and climate change) has concluded that the country lacks a national-scale study on the vulnerability of its coastline to climate change impacts (TCU 2009).

TCU emphasizes that, among the few existing Brazilian coastal vulnerability studies, a highlight is *Macrodiagnóstico da Zona Costeira e Marinha* (MDZCM), an instrument set forth by Law 7661/88, which established the National Coastal Management Plan.

The MDZCM diagnosed the main aspects on the Coastal and Marine Zone, mostly the changes in the energy policy, which led to a considerable increase in oil drilling, development, and extraction in this part of the territory, particularly after the state monopoly was broken up. The current and potential dimensions of the urban-manufacturing facilities and their interaction with other activities also went into this diagnosis, which included information on infrastructure, household and industrial wastewater, and toxic elements present in coastal municipalities, among others. The sources are identified by geographic type of receiving bodies (estuaries, bays, beaches, etc).

By combining a broad array of information, environmental hazard figures were generated which, in turn, measure threats to the living standards of Coastal and Marine Zone populations. Locations with a flooding potential, social risk potential, and technological risk potential could thus be identified (Nicolodi & Zamboni 2008).

This paper attempts to identify, based on data generated by MDZCM, the regions in the Brazilian coastal zone most vulnerable to the effects of climate change, and thereby provide support for a thorough assessment of the country's vulnerability, and help fill the gaps identified by the Federal Audit Office.

[1] An extension value which takes into account the irregular coastline forming bays and recesses, among other landforms. Of its 514,000 km^2 area, some 450,000 km^2 cover 17 coastal states, and 395 municipalities, including inner water surfaces – while the rest consists of Brazil's Territorial Sea (MDZCM 2008).

Vulnerability Analysis and the Environmental Risk Concept

The concept of risk is usually associated with an event which may or may not happen. However, the actual risk only occurs when assets are valuable, whether materially or not, since there is no risk if the perception of losing something does not exist. Therefore, one cannot envision risk if there is no danger of losing something. In this case, society faces a risk.

The notion of "possible loss", which is intrinsic to risk, can be broken down into several components. When we examine spatial location, or even spatial distribution of hazards, the connection with cities – or more precisely, urban centers – becomes more evident. This is because they are the specific site of production and reproduction of manufacturing processes and a lifestyle which favors population concentration, encourages manufacturing output, business relationships, and service provision (Castro *et al.* 2005).

In this sense, risk assessment is based on the relationship between reliability and criticality of complex systems, where the dynamic behavior of numerous variables must be captured in a select set of indicators capable of monitoring the interactions that actually occur along different time scales, i.e., in the near, medium, and long term (Egler 2005).

Environmental risk analysis must be seen as a dynamic indicator of relationships between natural systems, the productive structure, and the social conditions of human reproduction at a given place and time. It is therefore important to consider the assessment of environmental hazards as the consequence of three basic categories:

a) Natural Risk: related to processes and events of a natural origin, or resulting from human activities. The nature of these processes is quite diverse on time and spatial scales, so the natural risk may present differing levels of loss, as a result of intensity (magnitude), spatial extent, and time of activity of the processes under consideration.

b) Technological Risk: The technological risk is inherent in productive processes and manufacturing activities. The idea of technological danger derives chiefly from manufacturing technology, as a result of inherent flaws, as opposed to natural dangers, perceived as an external threat (Castro *et al.* 2005). Technological risk may be defined as a potential event that can be life-threatening in the near, medium, and long term, as a result of investment decisions in the manufacturing structure.

c) Social Risk: This category can be analyzed and developed from different standpoints. It is often considered as the damage society (or part of it) can bring about. Another approach stresses the relationship between deprivation and vulnerability to natural disasters. For the purposes of this study, we have adopted the bias proposed by Egler (1996), where Social Risk is seen as the result of deprivation of social requirements for full human development, a fact that contributes to deterioration in standards of living. Its most obvious consequences are the lack of adequate living conditions, expressed in terms of access to basic services such as treated water, wastewater, and trash collection services. In the long term, however, these can affect employability, income, and technical development of the local population, as key elements to a full, sustainable, human development.

Taking these three basic dimensions as a starting point for a broader concept of environmental risk, a methodology for its evaluation must build on three basic criteria (Egler 1996):

a) Vulnerability of natural systems, seen as the level between the stability of biophysical processes and unstable situations where there are substantial losses of primary productivity;

b) Density and potential expansion of the productive structure, which attempts to express fixed and flowing economic aspects in a certain area of the country in a dynamic concept;

c) Criticality of housing conditions, in terms of the gap between current standards of living and the minimum required for full human development.

These definitions are in agreement with UNESCO's IOC, which defines coastal vulnerability as the state of coastal communities (including their social structure, physical assets, economy, and environmental support) that determine which are affected to a greater or lesser extent by extreme events (IOC 2009).

The same Commission further establishes that vulnerability analyses be conducted according to different – macro to micro – scales, depending on the approach to be given by the national integrated coastal management programs.

In this study, the macroscale will be used to define Brazilian coastal vulnerability by region, thus providing inputs for planning responses for their mitigation and adaptation.

Methodology

According to IOC's proposed methodology, five stages are necessary to make national and regional climate change adaptation plans: 1) Identifying and quantifying the hazards; 2) Measuring vulnerability; 3) Assessing the risk; 4) Enhancing awareness and preparedness; 5) Mitigating the risk. This study addresses stages

1 and 2, which are the basis of the necessary knowledge to define the other stages.

Information generated by MDZCM (Nicolodi & Zamboni 2008) was used to prepare the overview map on the vulnerability of the Brazilian coastal zone with relation to natural risk, social risk, and technological risk. To the crossing of such results were added spatial information on population dynamics, geomorphology, use and occupation of the Exclusive Economic Zone (EEZ) and biodiversity[2]. In all cases, specific geoprocessing routines were resorted to, along with IDRISI and ARCGIS9[3] software.

The analysis scale of the issues addressed in MDZCM and the vulnerability analyses of the coastal zone proposed by this paper is 1:1,000,000. This scale corresponds to the scope of the area of study and enables practically all existing map bases to be included in the analysis context.

Natural risk charts are a direct product of a combination of altimetry aspects[4] with population data, added to assessment of vulnerability levels to inundation caused by extreme weather events, heavy rains, and prospects of a higher sea level.

The altimetry information was modeled into geographic information systems[5], and became a digital model of the Coastal Zone, to which data on the local population were added by subdistricts, provided by IBGE, the Brazilian Institute of Geography and Statistics, according to the census update provided by IBGE in 2006.

Upon refining the five levels of potential natural risk,[6] coastal process information was considered, through the use of statistical techniques (weighted averages). Eroded coastal areas added value by showing the regions more prone to flooding, since erosion tends to destroy natural barriers such as *restingas* (beach ridges with scrubby vegetation), dunes, sea cliffs, mangroves, etc. On the other hand, coastal areas with a sediment accretion and, consequently, shoreline progradation, subtracted value when determining risk ranges (Muehe 2006).

When weighting the factors, the combination of land elevations below 10 m above sea level and marine erosion was considered the most critical indicator of coastal environment vulnerability to floods. The risk potential could then be assessed by cross-referencing this information against the population data by subdistrict. An example of a natural risk map can be seen in figure 1.

Regarding social risk definition, the level of income of that part of the population earning up to three (3) times the minimum wage was used as background data, based on IBGE 2000 census results by district. Area ranking according to social risk potential[7] was obtained by crossing income data with the number of homes lacking garbage collection and wastewater services. The ranking system thus considered dwellings where wastes are disposed of in rudimentary cesspools, ditches, rivers, lakes, or into the ocean to be “lacking basic sanitation”. Regarding the destination of solid waste, the ranking system considered those dwellings where garbage is burned or buried, thrown into backyards or streams, the ocean, or ponds as “homes lacking garbage collection”. An example of a social risk map can be seen in figure 2.

As to technological risk, the data came from sources referred as technological, such as, for example, power generating units or manufacturing facilities. Their construction methodology resulted from the number of industry employees per city in relation to the industry’s polluting potential. The definition of polluting potential followed the methodology proposed by RAIS, the Annual List of Social Information issued by the Labor Ministry (2002)[8].

The data resulting from the crossing of this information were grouped into four categories representing technological risk potential levels (low, medium, high, and very high). Moreover, the maps include the location of thermal plants according to the fuel used, natural gas and oil production and extraction activities, and oil industry-related

[2] The inclusion of these variables did not necessarily occur during the analyses of Geographic Information Systems, but rather, during the descriptive analysis of the results.

[3] Such routines include Boolean operations with maps, attribute analysis of georeferenced databases, and multi-standard evaluations.

[4] The altimetry data came from SRTM-NASA, available on the U.S. Geological Service.

[5] Such modeling took place at the Geography Department of the Federal University of Rio de Janeiro (UFRJ) when the data base’s MDZCM was prepared.

[6] These are: very high, high, moderate, low, and very low.

[7] These can be: very low, low, medium, high, and very high.

[8] Types of industry according to polluting potential: (a) very high: Rubber, Tobacco, Leather, Chemicals, Mining, Non-Metal Ores; (b) high: Metallurgy, Textiles, Foodstuffs and Beverages, Paper and Printing; (c) medium: Mechanics, Rolling Stock, Footwear, Wood and Furniture; (d) low: Electronics and Communications, Civil Construction, Public Utilities. It should be pointed out that IBAMA measures the polluting potential of manufacturing activities, especially with regard to the *Cadastro Técnico Federal* (a mandatory registration list of companies in polluting, or potentially polluting, industries) (http://www.ibama.gov.br/cadastro).

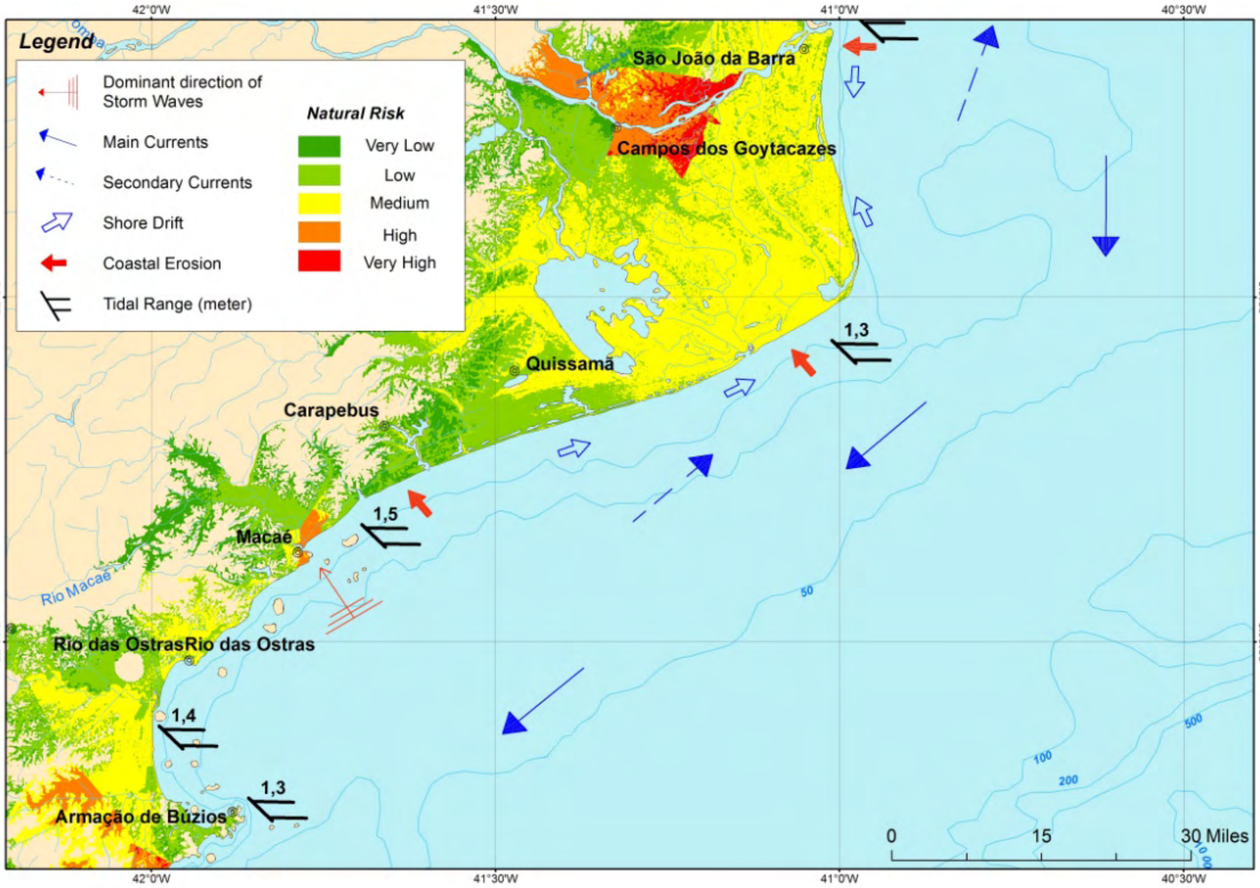

Figure 1. Example of a Natural Risk Map.

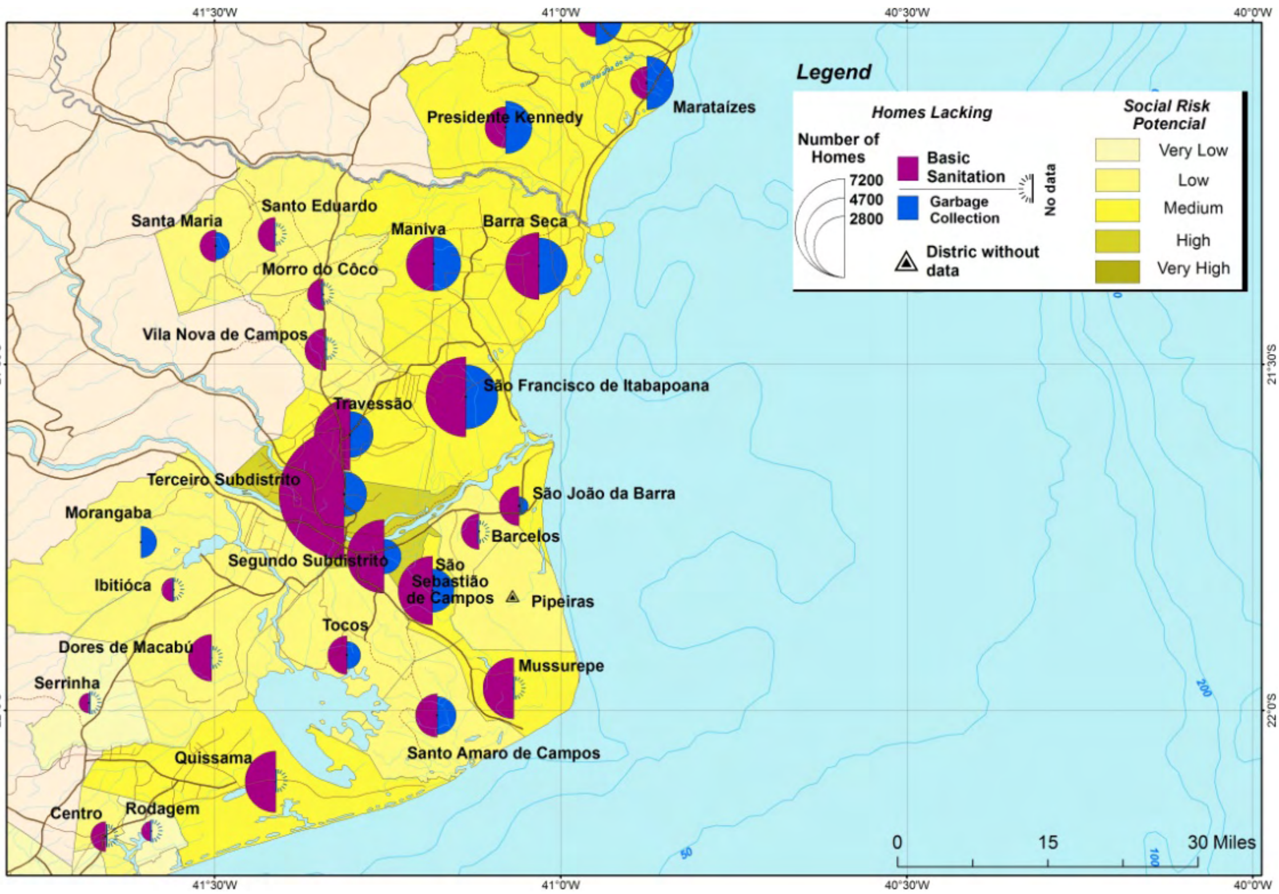

Figure 2. Example of a Social Risk Map. The risk potential is shown in yellow at subdistrict level.

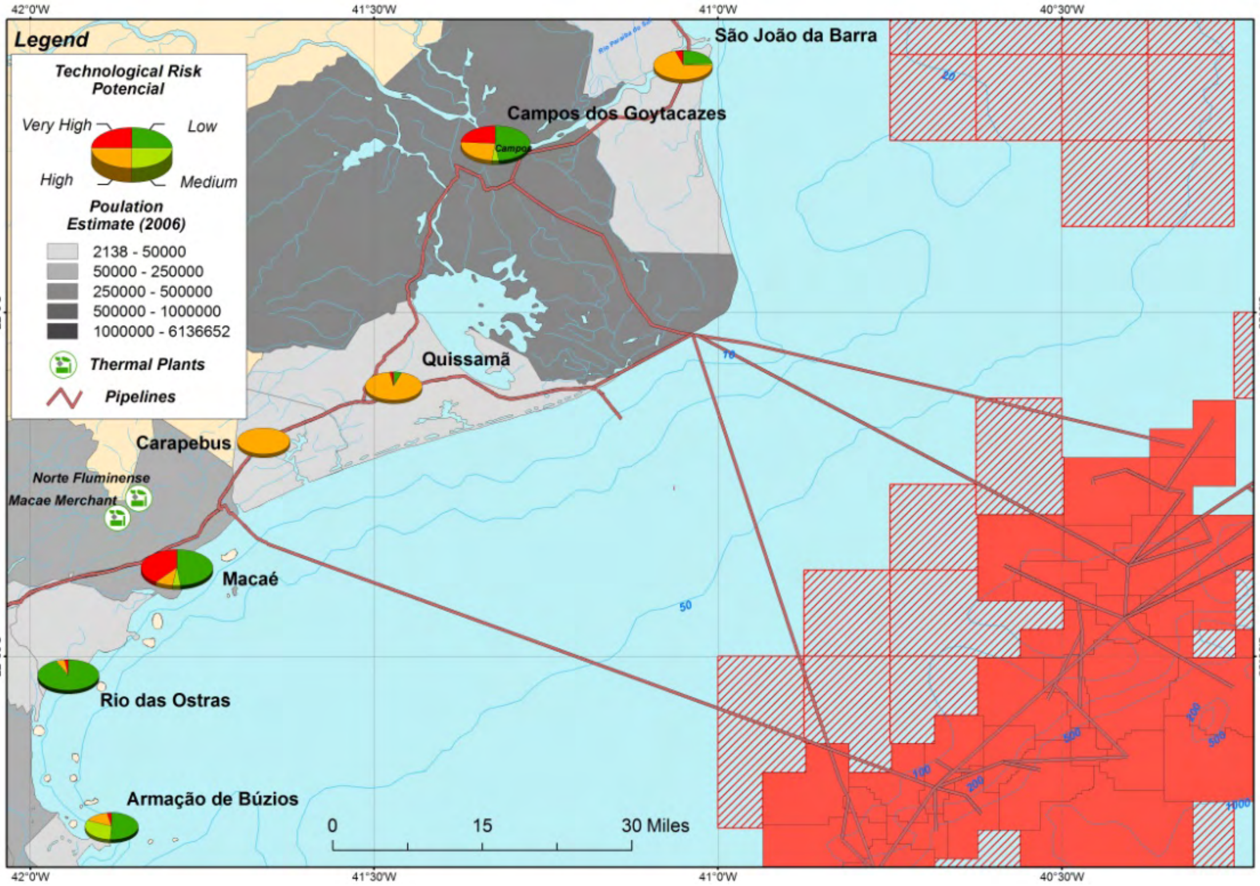

Figure 3. Example of a Technological Risk Map. The pie chart indicates the risk potential at each municipality. The town population appears as a gray background.

facilities (pipelines, refineries, etc). This mapping activity is based on population estimates by municipality, made in 2006, which give an idea of the number of people potentially affected by an accident involving technological risk. This is related to the various stages of the productive activity, from the extraction of raw materials to the marketing of goods. An example of a technological risk map can be seen in figure 3.

The definition of Brazilian coast vulnerability was made in five hierarchical levels, following the same categories as for Social Risk, Technological Risk, and Inundation Risk. For data-crossing operations the following values were established per category: Very Low ≤ 1, Low >1 and ≤ 2, Medium >2 and ≤ 3, High >3 and ≤ 4, Very High >4 and ≤ 5.

The first stage consisted in establishing a sole Technological Risk rating for the municipalities. This was calculated by the weighted average between risk potential categories. A process example may be seen in Table I.

The results were ranked in five intervals using the *Geometrical Interval* algorithm, available as an ArcGIS function. In this system, the class intervals are based on a geometrical series. The geometric coefficient in this classifier can change once (to its inverse) to optimize the intervals. The algorithm creates these geometrical intervals by minimizing the square sum of elements per class.

The reclassified technological risk potential can then be spatially crossed with the social risk and the natural risk data. To this end, phrases and sentences similar to those used in mathematics were used to describe Boolean operations. The model used to describe the GIS sentences, involved the logical combination of the vector maps through conditional operators which supported the assumption to which the analysis was directed. The Vulnerability Index obtained from this crossing was developed through the simple average between the three types of risk involved (Fig. 4).

Results and Discussion

From the onset of European colonization, the establishment of populations and socio-economic utilization of coastal areas have been increasingly intense. This territory occupation by about one quarter of the Brazilian population, has begun with the appropriation of common spaces in the Coastal

Table I. Example of weighted average calculation for the new categories of Technological Risk.

Municipality	V. High Risk	High Risk	Medium Risk	Low Risk	Final Risk (Weighted Average)
Araruama	3605	1536	4608	2614	3087.2
Armação de Búzios	60	192	576	310	244
Arraial do Cabo	3565	220	660	266	1515.5
Cabo Frio	4615	3324	9972	3234	5196.7
Casimiro de Abreu	230	828	2484	1744	1100.1
Iguaba Grande	90	4	12	156	58.1
Macaé	63535	13608	40824	32586	39982.2
Maricá	1335	1040	3120	934	1575.9
Rio das Ostras	275	452	1356	3432	1008.2
Saquarema	565	440	1320	296	652.6

Final Risk = [(V.High Risk*5)+(High Risk*4)+(Medium Risk*3)+Low Risk*2)]/(5+4+3+2)

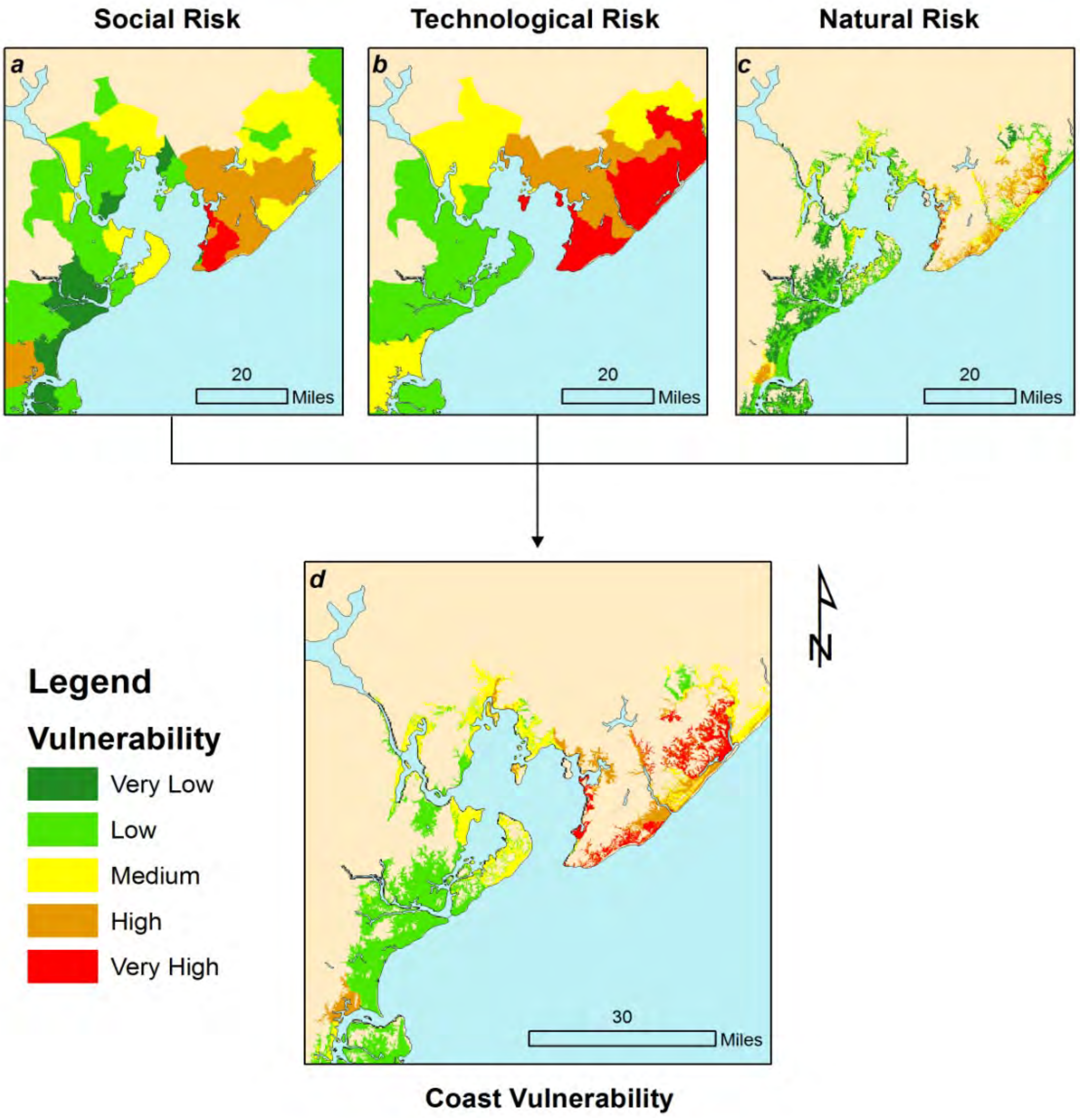

Figure 4. The spatial crossing made between the three risk types: (a) Natural Risk; (b) Social Risk; and (c) Technological Risk. The result is shown by (d) Coast vulnerability, obtained by simple average.

Zone, through its typical activities and uses, and its main inducing vectors relate to port, manufacturing, oil, and tourist activities.

Intrinsically linked to human occupation due to its cause and effect relationship, the coast's geomorphological characteristics, associated with climate and ocean processes, impart a unique relevance to flooding-related issues. Therefore, the resulting loss of physical space to the development of economic and social activities that are inherent to it stand out from an a priori analysis of the risks of natural disasters to which these continental and marine transition areas would be exposed (Tessler 2008).

The analysis of the Brazilian coastal vulnerability to the effects of climate change studied herein will be presented in a regionalized form to organize the results of this work.

North Region

The Brazilian North Region generally displays a low vulnerability level, with exceptions in the vicinity of its three large capital cities: Macapá, Belém, and São Luís. In these cases, vulnerability was rated high or very high (Fig. 5).

This ranking is explained by a combination of factors, mainly physical (coastal dynamics and geomorphology), socioeconomic (average population income, lack of basic services) and technological (types of industry, types of pollution, and their representativeness of the number of workers).

In geomorphological terms, the coast and continental shelf of the North Region are dominated by mud sediment from the Amazon, with significant coastal stretches under accelerated erosion while others – due to the buildup of sediment from the local river network – have prograded.

The emerged coastal region is formed by a low-lying Holocene plain, its width varying between 10 and 100 km, while the inner portion is dominated by older plain deposits and rocks of the Pre-Cambrian Guyana shield, with an altitude below 500 m, forming the source areas of part of the coastal river network. Tidal influence is quite strong. For example, on Maracá Island, macrotides, predominantly semidiurnal, exceed 9.8 m, while to the north, at Oiapoque Bay, this amplitude is lower (about 2.7 m).

In its southern portion, the coast shows a finger-like muddy progradation, which emphasizes the irregular coastline. Its appearance is of a sea-drowned coastline, typically a succession of small

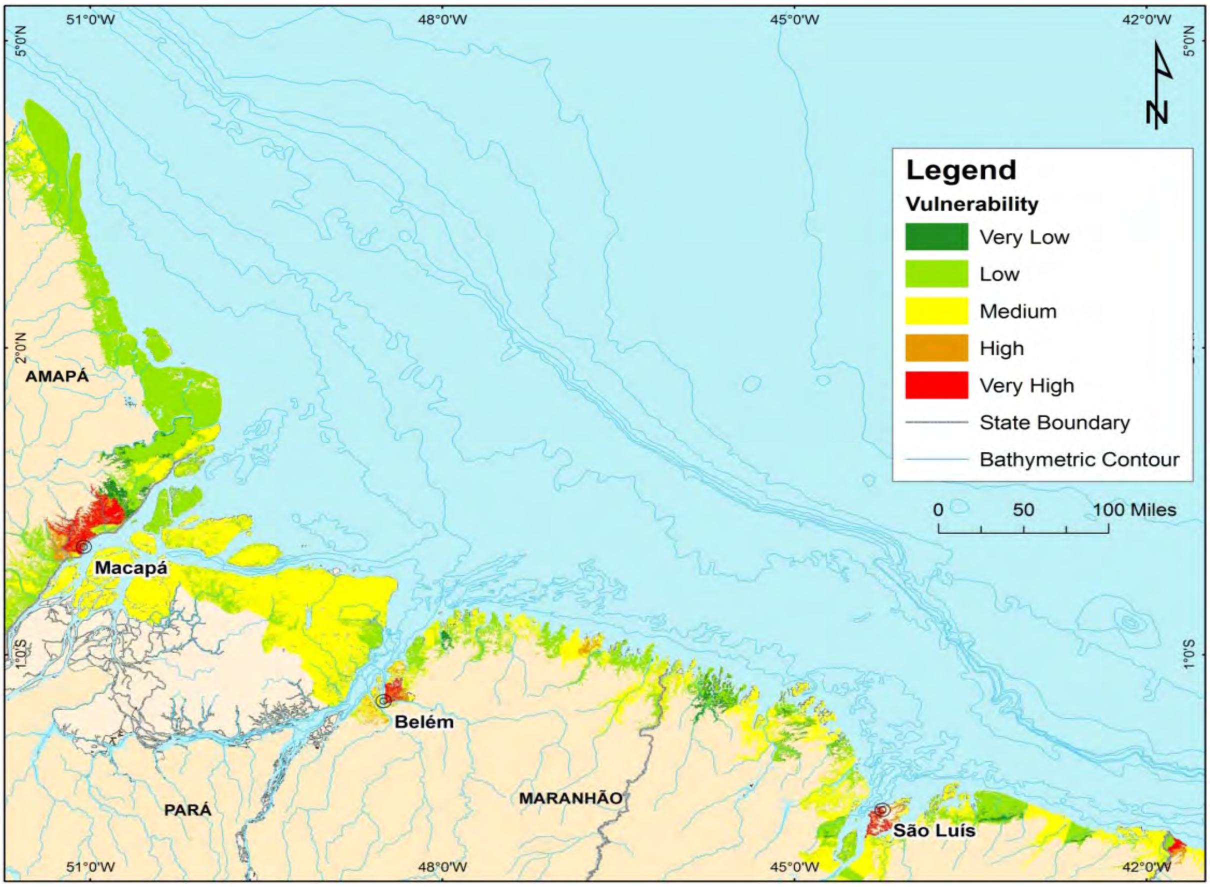

Figure 5. Vulnerability of the Brazilian North Coast. Low vulnerability level, except in the vicinity of three large capitals: Macapá, Belém, and São Luís.

estuaries and sediment accretions which jointly look like *rias* (drowned river valleys), and the reason why they are called *re-entrâncias* (recesses) in Maranhão state. Many of them resulted from prograded muddy deposits, forming long landforms more or less perpendicular to the coast. The North coast, here shown from Oiapoque (in Amapá state) to the south of Maranhão, is a high energy segment, with a strong sediment mobility, very much influenced by the intense water and sediment discharge from the Amazon River and the hydrodynamic factors of the ocean, particularly tides (Muehe & Nicolodi 2008).

Such characteristics provide low vulnerability levels to this area, which change when analyzing the existing metropolitan regions. The North coast of Brazil is characterized by scanty human presence, consisting mainly of traditional extractive and foraging communities, large empty areas, dozens of municipalities with a small population density, but with important regional complexes such as Macapá and metropolitan concentrations in Belém and São Luís (Strohaecker 2008).

The geomorphologic characteristics of the north coast of Pará form a physical barrier to an intensive process of population settlement on the coast. But a few parts of this segment have had a disorderly population growth. Population density in this area is approximately 27 inhabitants per km^2, in contrast to other sections with a density of 3.5 inhabitants per km^2. Significant values can be noticed just in the Belém area and its surroundings (of about 220 inhabitants/km^2).

São Luís is located in the Golfão Maranhense (Maranhão's Big Gulf) region. São Luís has the state's only significant population concentration (> 170 inhabitants per km^2) on this coastal lowland. Therefore, only the area around the Maranhão state capital is highly vulnerable.

In addition to this analysis of population dynamics, it should be noted that the coverage of waste collection services seen in the North Region is much lower than in other regions of Brazil, and it is also the one with the worst provision of this basic service: 6,790 tons/day.

This situation, further to the data on basic sanitation, leads to a coefficient ratio between the total population and the population exposed to social risk of 33.7% for the North Region, which, in absolute figures can be translated into 2.206,138 inhabitants, most of them residing in the capitals and their outskirts (Astolpho & Gusmão 2008). This data becomes even more relevant when considered a few results of global assessments made by IPCC, which confirm the fact that disadvantaged populations, who are less able to adapt, are the most vulnerable (Marengo 2006).

Adding to high levels of vulnerability of the metropolitan areas in the North, is the association between the metal-mechanical complexes and the paper and pulp industry on the coast of the Pará and Maranhão states, with massive investments in the production of metallic minerals such as iron and aluminum, and extensive planted land used to produce pulp. This is a determining factor that increases the technological risk and vulnerability of the Coastal Zone at critical points, as is the case of Barcarena, in Pará state, and São Luís, in Maranhão (Egler 2008).

Northeast Region

The Coastal Zone of the Northeast Region, marked here by the coast between the north of Piauí state and the south of Bahia state, features a great diversity of ecosystems, with distinct physical and geomorphologic characteristics affected by a broad range of pressure vectors, which ultimately define the region's vulnerability.

Unlike the North, where only metropolitan areas were found to be highly vulnerable, the Northeast alternates between the five vulnerability levels which do not necessarily have a direct relationship with population dynamics.

In geomorphological terms, the upper part of the region is dominated by sedimentary deposits of the Barreiras group, in front of which numerous dune fields have developed, fed by sediments coming from the inner continental shelf, as, for example, the Parnaíba River Delta and Jericoacoara, in Ceará.

In Rio Grande do Norte state one can see the Barreiras Group sea cliffs and a wide development of active dune fields along the entire coast. One can notice the natural barrier formed by the dunes on the river estuaries, which leads to insufficient drainage and forms swampy valleys, in addition to an increased number of estuaries and mangroves starting in Paraíba state, as a result of a higher precipitation volume.

To the east of this dune field, the Parnaíba River estuary displays a coastal stretch considered medium to highly vulnerable, particularly due to the strong erosion caused by the cyclic floods that hit the Parnaíba River downstream during the high-water season (Fig. 6).

The coast of Ceará, marked here and there by higher land, has a large number of eroded coastal sections linked to moving barchan dune fields, the Barreiras terrace deposits, and outcrops of the crystalline basement. In addition, the Ceará coast has a low population density, except near Fortaleza, where this density is higher, and the vulnerability level is also high. In the Aracati area, where vulnerability is medium to high, the factors affecting this ranking are related to the significant shortage of basic sanitation, the accelerated manufacturing development, and the increase of shrimp farming activities and tourism.

Another especially vulnerable area is the vicinity of Mossoró, in the innermost portions of the coastal region. This situation occurs due to a number of factors, including the existing low-lying areas that tend to flood owing to the drainage of Apodi and Mossoró rivers, an acute shortage in the provision of basic services, and an intricate logistic oil and gas network, which extends all the way to the area near Macau, where the Guamaré Natural Gas Plant is located. In this section, the highlight is the coastal erosion, which is so strong, that it is already affecting oil industry equipment installed in the area (Muehe 2006).

When analyzing this region's social risk, one can see that the situation is critical in large centers, particularly in Natal, João Pessoa, and Fortaleza.

The lack of sanitation in these areas is significantly greater than the lack of garbage collection services. In Fortaleza, the data on the shortage of garbage collection services show a tendency toward solving the problem, while the sewerage situation is of extreme concern in almost all municipalities and districts. This same situation, although less severe, can be noticed in Maceió, Aracaju, and nearby areas (Astolpho & Gusmão 2008).

In the Northeast, the population exposed to social risk is 25.71% of the total population, which, in absolute numbers, may be translated into 12.286,455 inhabitants potentially more vulnerable to the effects of climate changes.

In the central part of the Northeast, the main areas of higher vulnerability include the metropolitan areas of Natal, João Pessoa, and Recife (Fig. 7). According to Neves *et al.* (2006) about 42% the coast of Paraíba is exposed to the effects of erosion. Similar geomorphologic characteristics extend to the coast of Pernambuco, which has a higher population density, compared with the coast of Paraíba and Alagoas. Along this entire segment, low to medium natural risks predominate, with the exception of the areas with the highest urban concentration (João Pessoa and Recife) and deeply eroded segments (Paulista, Itapojuca, Suape, Cabo de Santo Agostinho, and Recife).

Another factor that adds to the region's high vulnerability is the displacement of the chemicals complex to the Northeast coast along Salvador, Aracaju, and Maceió, due to the expansion of the energy boundary on the coast. This fact has brought a massive concentration of pipelines, terminals, and plants. The surroundings of the Recôncavo Baiano area and the cities of Aracaju (SE), Maceió (AL) Recife-Cabo (PE), and Macau-Guamaré (RN) are highlights in this process, where the energy production equipment increases the exposure to environmental hazards (Egler 2008).

In the southern portion of the Northeast Region, the most outstanding morphological feature is the São Francisco River delta, site of the country's worst coastal erosion. Bittencourt *et al.* (2006) indicate as likely causes the embankment interventions to contain the river flow upstream from its mouth, mainly those related to the construction of hydroelectric plants, which implies great potential inundation of inner drainage areas, which rates this section as of high risk.

From the São Francisco River to the Caravelas River plain, there is a general tendency for the coastline to prograde and stretches with sea cliffs of the Barreiras Group to erode. Dune fields appear near the mouth of the São Francisco and on the northern coast of Bahia. Near Salvador, the Barreiras River is replaced by outcrops of Pre-Cambrian and Cretaceous crystalline basement.

Higher-than-average coastal sections, coupled with a low density population, have a medium to low vulnerability. At some places, this level is high only where population density is higher and basic sanitation is deficient, i.e., at Valença, Ilhéus, and Porto Seguro - urban centers combined with river mouths (Fig. 8).

In the Salvador metropolitan area, the high vulnerability levels are not only related to these factors, but also to high technological risk posed by the Camaçari manufacturing complex, namely the oil industry, and particularly the Landulpho Alves Refinery, the Candeias Natural Gas Production Unit, and the Termobahia, Rômulo Almeida, and Camaçari thermal plants (Fig. 9).

Southeast Region

The coast of Espírito Santo state and the north coast of Rio de Janeiro state are geomorphological boundaries of the Northeast coast. This stretch is dominated by Tertiary terraces and the sea cliffs (Barreiras), Pre-Cambrian crystalline promontories and Quaternary plains of river and sea origin. Between the mouths of São Mateus and Itabapoana rivers, the Barreiras terraces and sea cliffs extend along the entire coast, displaying live and dead

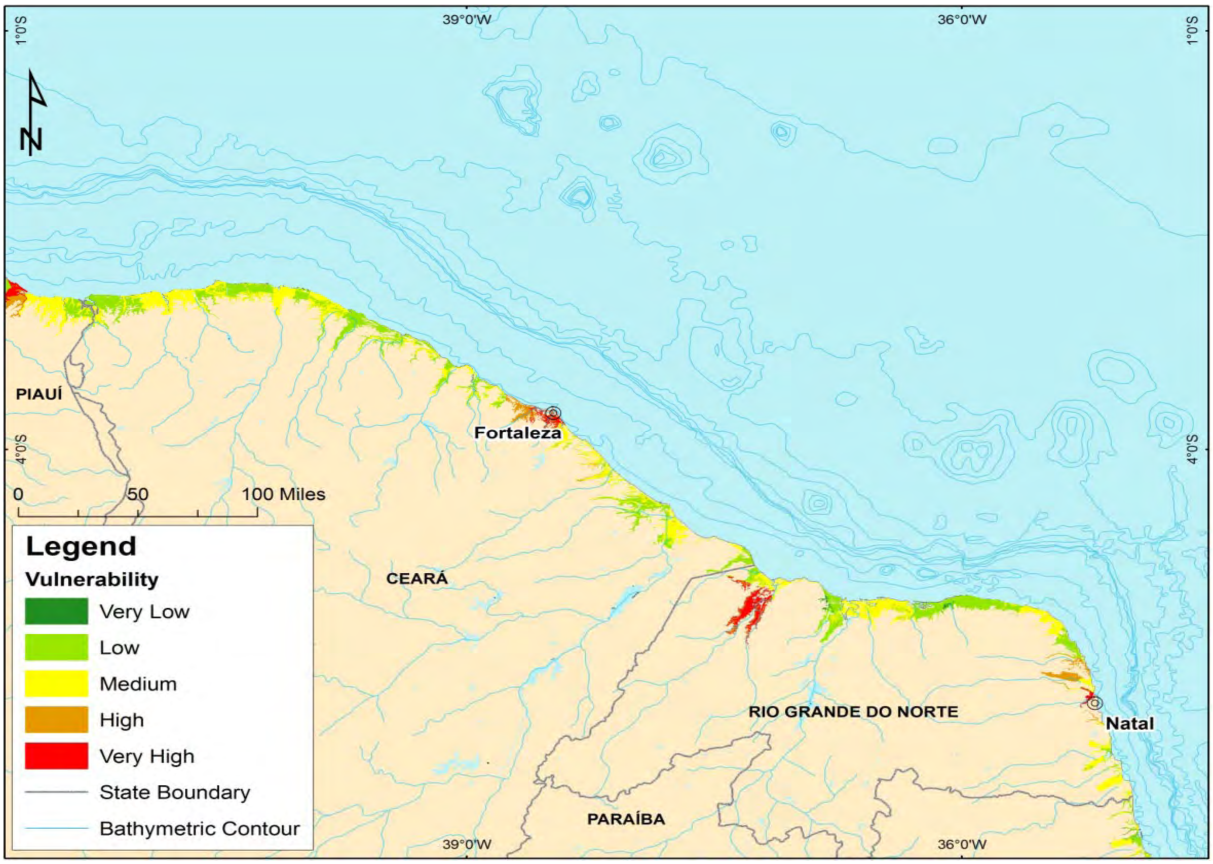

Figure 6. Vulnerability Map of the North Region, showing the states of Piauí, Ceará, and Rio Grande do Norte.

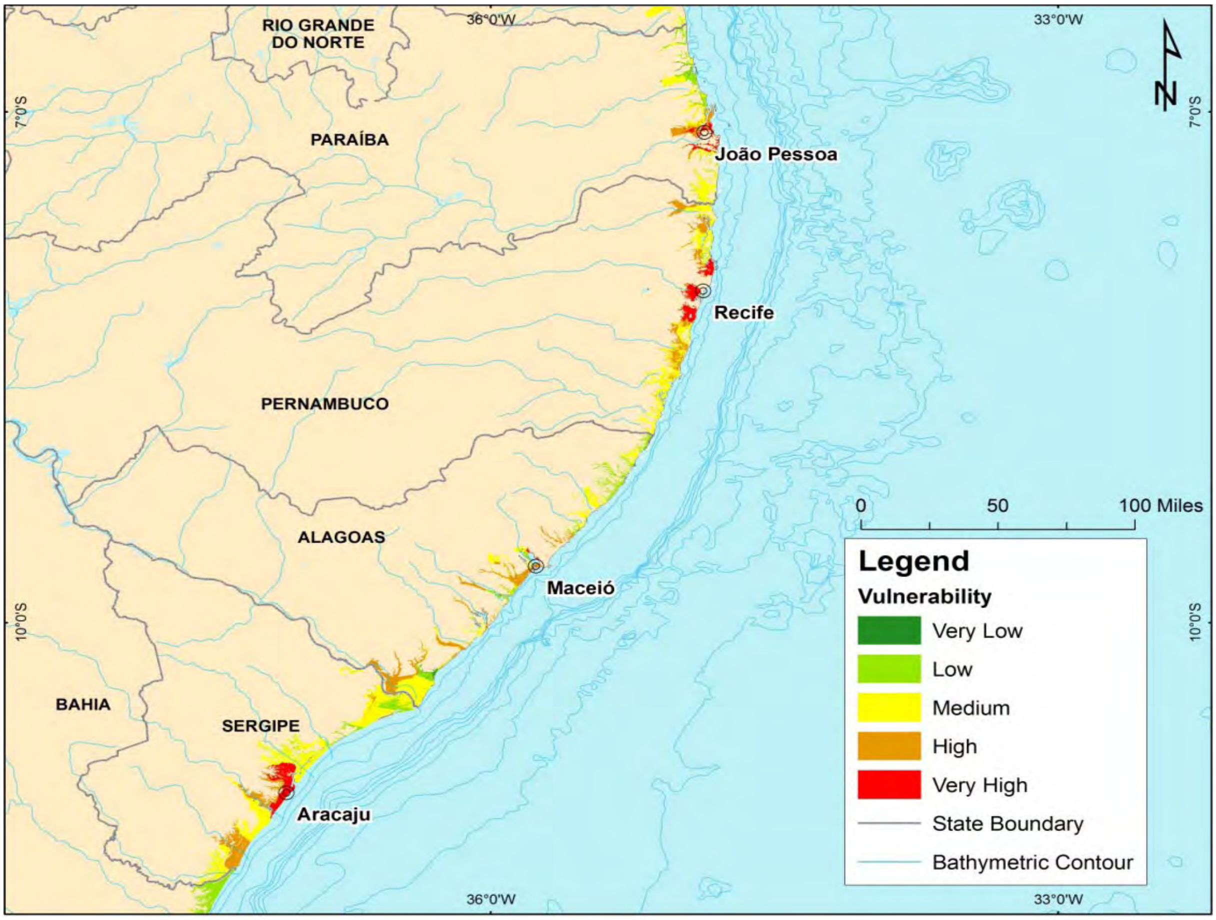

Figure 7. Coastal vulnerability of Paraíba, Pernambuco, Alagoas, and Sergipe states.

cliffs, and marine abrasion terraces. The sedimentary coastal plains are little developed, and the plain at the Doce River mouth is the most relevant.

This stretch consists of sections of medium to low coastal vulnerability. Only three sites were ranked as vulnerable (medium to very high levels): the Doce River, Vitória, and the inner drainage areas of the Paraíba do Sul River (Fig. 10).

In the case of the Doce River, one can see that the combination of the above-mentioned conditions, coupled with high levels of coastal erosion, make the region of São Mateus and Conceição da Barra more vulnerable.

What adds to this situation is the fact that the stretch of the Coastal Zone between Mucuri, on the southern coast of Bahia, to the center-north of Espírito Santo, especially near Linhares and Aracruz in Espírito Santo, is specializing in the production of pulp for the foreign market, as can be seen from the concentration of equipment used by the paper and pulp industry, particularly the continuous dimensions of the area involved (Egler 2008).

The Doce River drainage at the end of its flow at Linhares occurs on low ground showing marginally to its main flow a number of tributaries connected to ponds. Attributing higher risk levels relates to inundation potential for low land with a rate of human occupation slightly above the region's average. Vitória, Vila Velha, and Guarapari have the highest population densities in low coastal areas, with population densities above the Espírito Santo state coast average.

The drainage of the Paraíba do Sul River, in the Campos dos Goytacazes area, occurs at near sea level land, through densely populated areas bound by the Pre-Cambrian crystalline complex. This geomorphologic setting, associated with the population density of northern Rio de Janeiro state, are typical of the vectors leading to high vulnerability levels in the area. The town of Atafona, on the south bank of the Paraíba do Sul River mouth, has one of the most intense erosive phenomena of the entire Southeast coast of Brazil (Muehe *et al.* 2006).

The stretch between Cabo Frio and Guanabara Bay has a rim formed by narrow ridges separated by rocky headlands, with the development of lagoons behind the ridges. This section is also known as the Lake Region. The general direction of the coastline, which directly exposes this coastal stretch to the south (with waves from the south quadrant) and, from time to time, to the action of heavy storms, which explains the strong erosion.

The highest levels of vulnerability identified on the eastern coast of Rio de Janeiro state are in the areas of São João da Barra and Macaé, which, in the last two decades, have experienced a sharp urban development linked to oil prospecting activities on the contiguous continental shelf (Fig. 11). In Cabo Frio, the increase in population in the urban areas, in a land that displays higher landforms (promontories and hills) and low-lying coastal plains, lead to an increased potential hazard to which the area is exposed (Tessler 2008).

The Guanabara Bay region is one of the most emblematic cases in Brazil, with regard to vulnerability. Its low topography lies along a geological fault that extends toward the ocean from the crystalline complex. To this depression converge all drainage networks from Serra do Mar mountain range at the back of the bay, which were blocked at their low flows by high sea levels during the Holocene.

In contrast with the ocean beaches located at its outer edges, constantly exposed to storm cycles originating from south quadrants, the inner bay coastline is affected only occasionally by more powerful events. Its vicinity, however, concentrates one of the highest population densities in the country[9], sometimes along the lower river streams that flow into the system. In extreme tidal situations followed by heavy rain on the mountain range (associated with the passage of frontal systems which drown the drainages in their lower flows) the inner bay coastline, which is lower, is exposed to inundation events (which increases the volume of rivers).

In addition to this context, Rio de Janeiro has the highest ratio in Brazil, between the exposed population (78%) and its total population, equivalent to 11.194,150 people – some 5 million of which in the capital alone. Data on the social risk of this portion of the Brazilian territory are alarming, as shown in (Fig. 12).

In addition to these factors which lead to high vulnerability, the Rio de Janeiro metropolitan area holds a petrochemical complex, with an intricate network of refineries[10], natural gas plants[11], gas pipelines, and offshore oil fields.

The location of a coastal mountain range near the existing shoreline, west of Guanabara Bay, with its promontories marking small individual beaches and conspicuous inlets and sedimentary plains

[9] Rio de Janeiro is the state with the greatest total population residing in metropolitan areas (75.2%). Additionally, the state includes most coastal municipalities with population densities over 1,000 inhabitants/km^2, as is the case of Rio de Janeiro City and Niteroi, the towns of *Baixada Fluminense* (in the state's low-lying area) and the outskirts of the metropolitan area.

[10] Duque de Caxias and Manguinhos Refineries.

[11] REDUC I and II and Cabiunas I, II, and III.

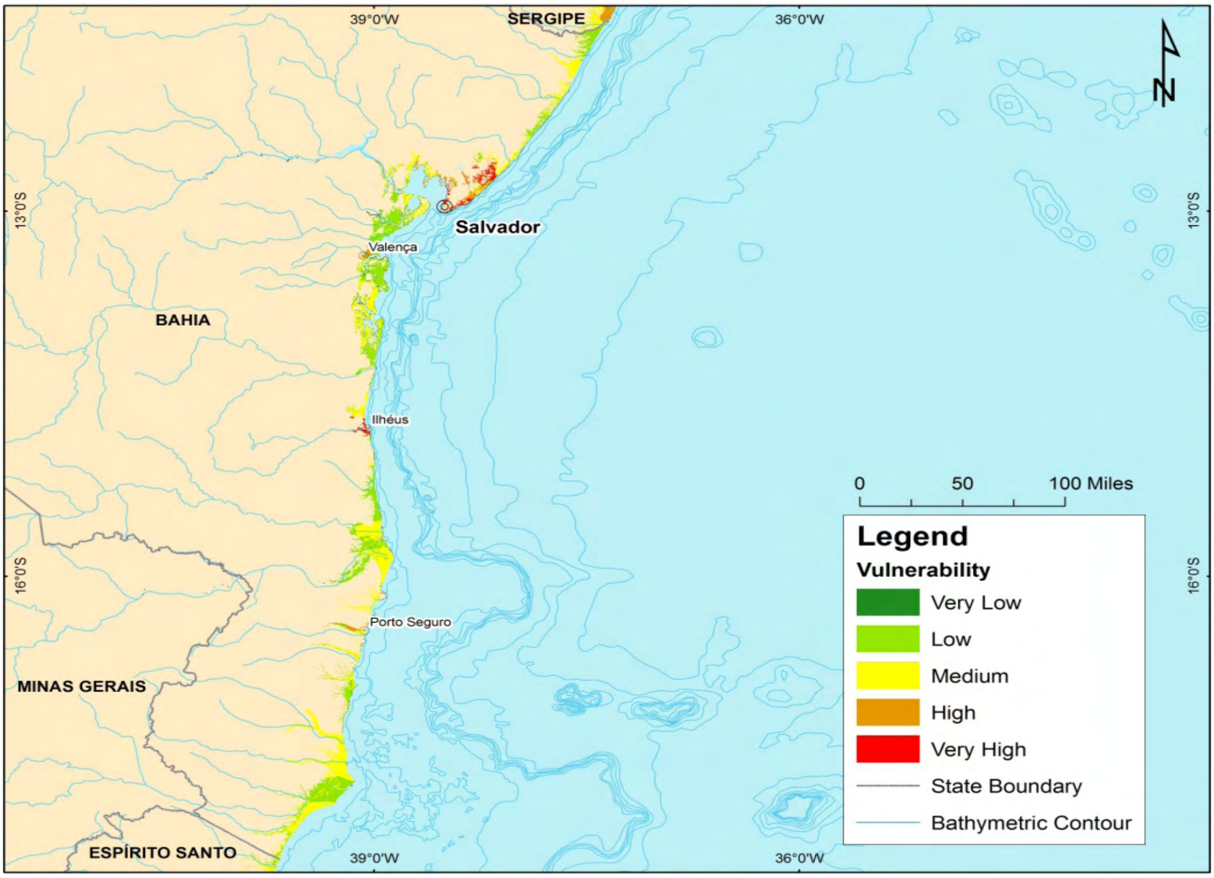

Figure 8. Urban centers in Bahia state, where vulnerability is high due to a high population density and an inadequate basic sanitation service.

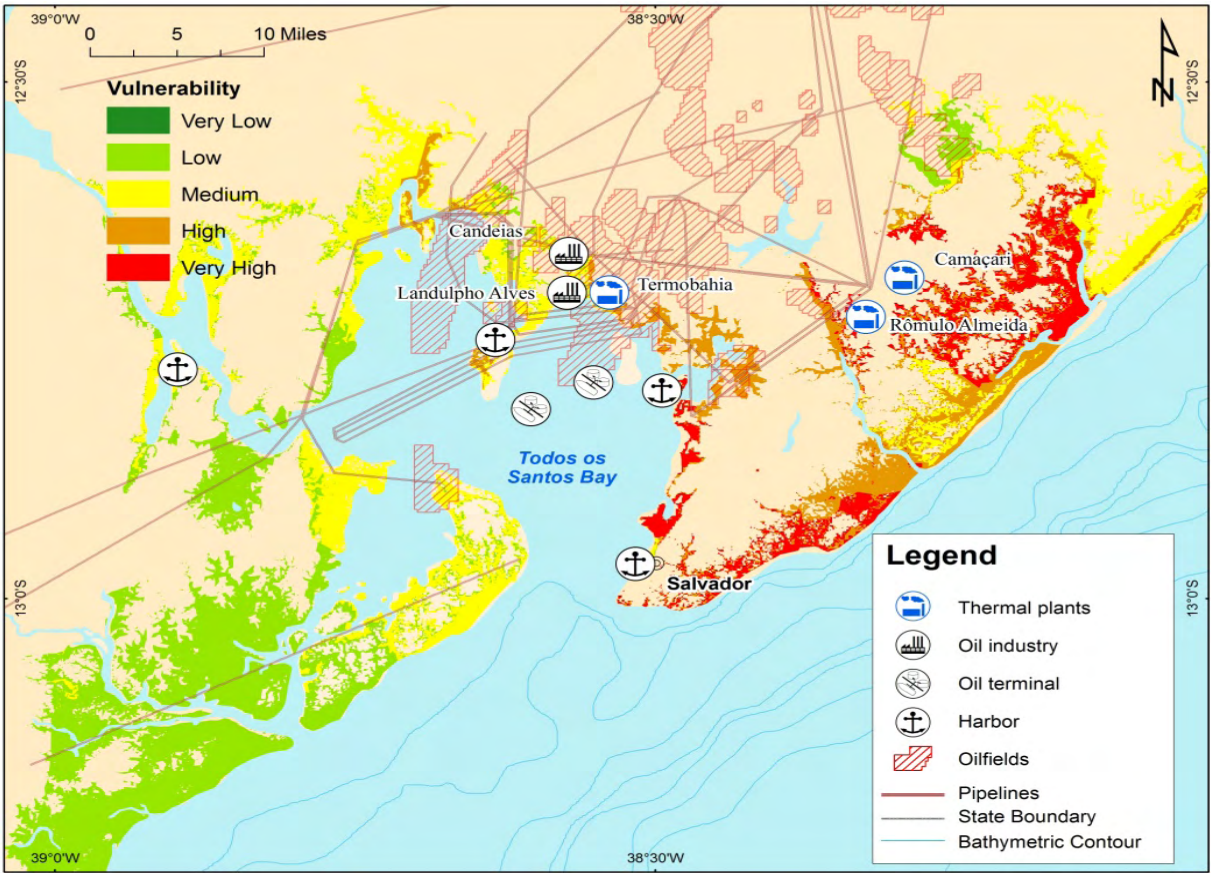

Figure 9. The metropolitan area of Salvador. High vulnerability levels linked to high technological risk.

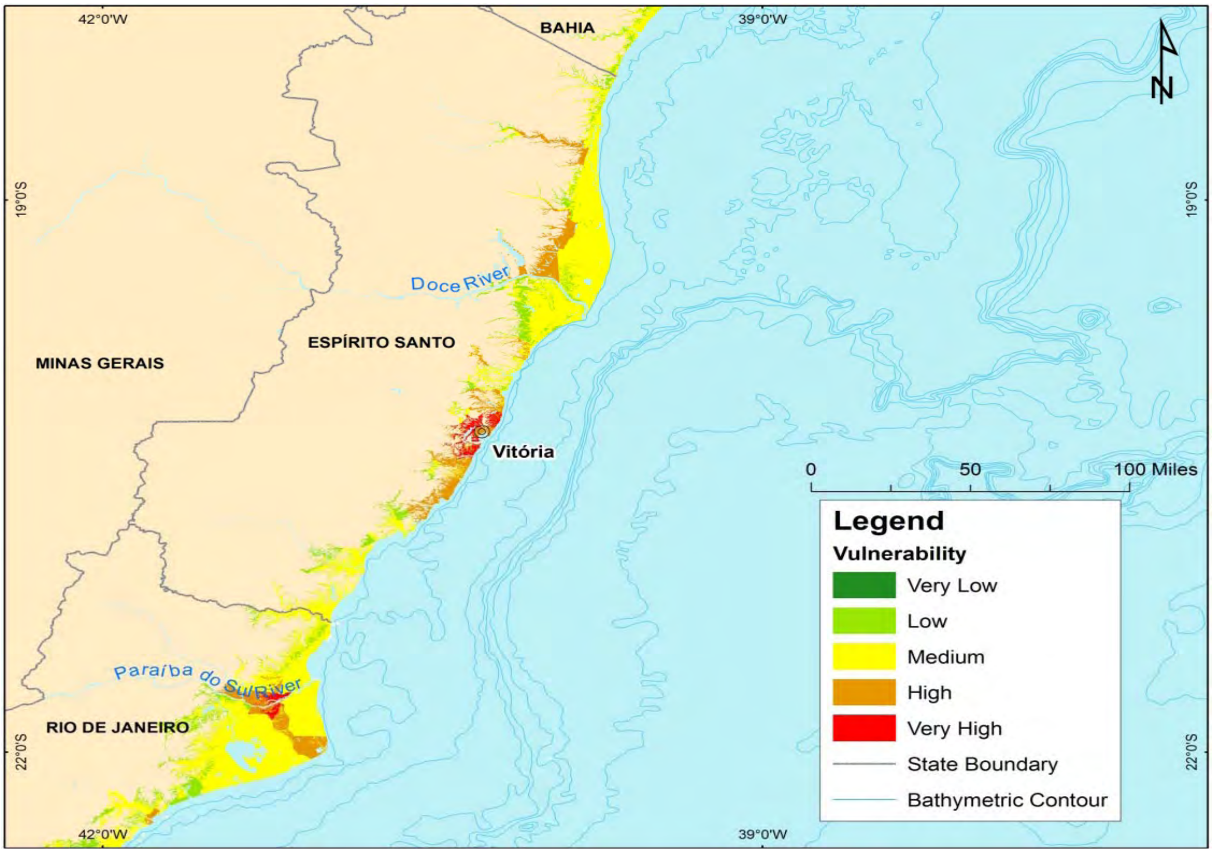

Figure 10. Medium to very high vulnerability level locations: the Doce River, Vitória and the inner drainage areas of the Paraíba do Sul River.

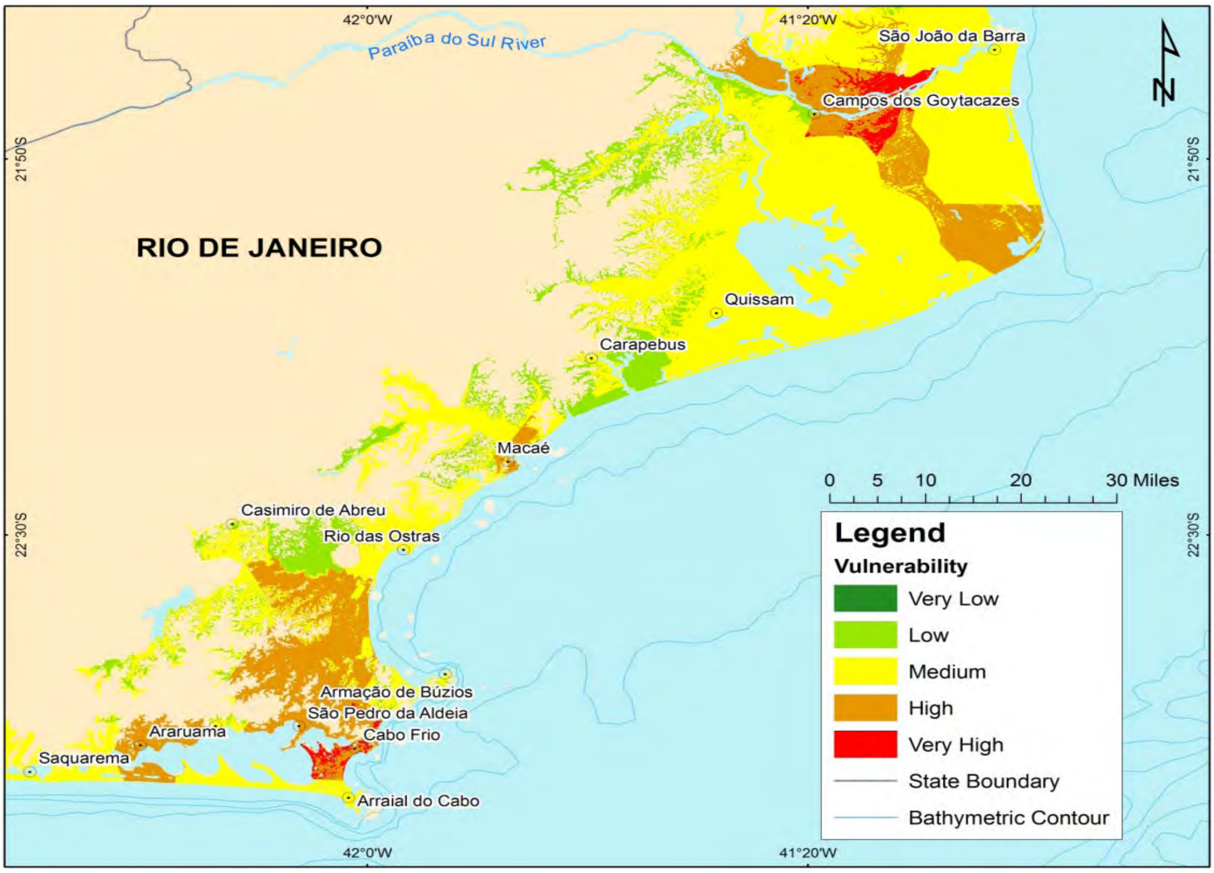

Figure 11. Higher vulnerability levels identified on the eastern Rio de Janeiro state coast associated with the São João da Barra and Macaé areas.

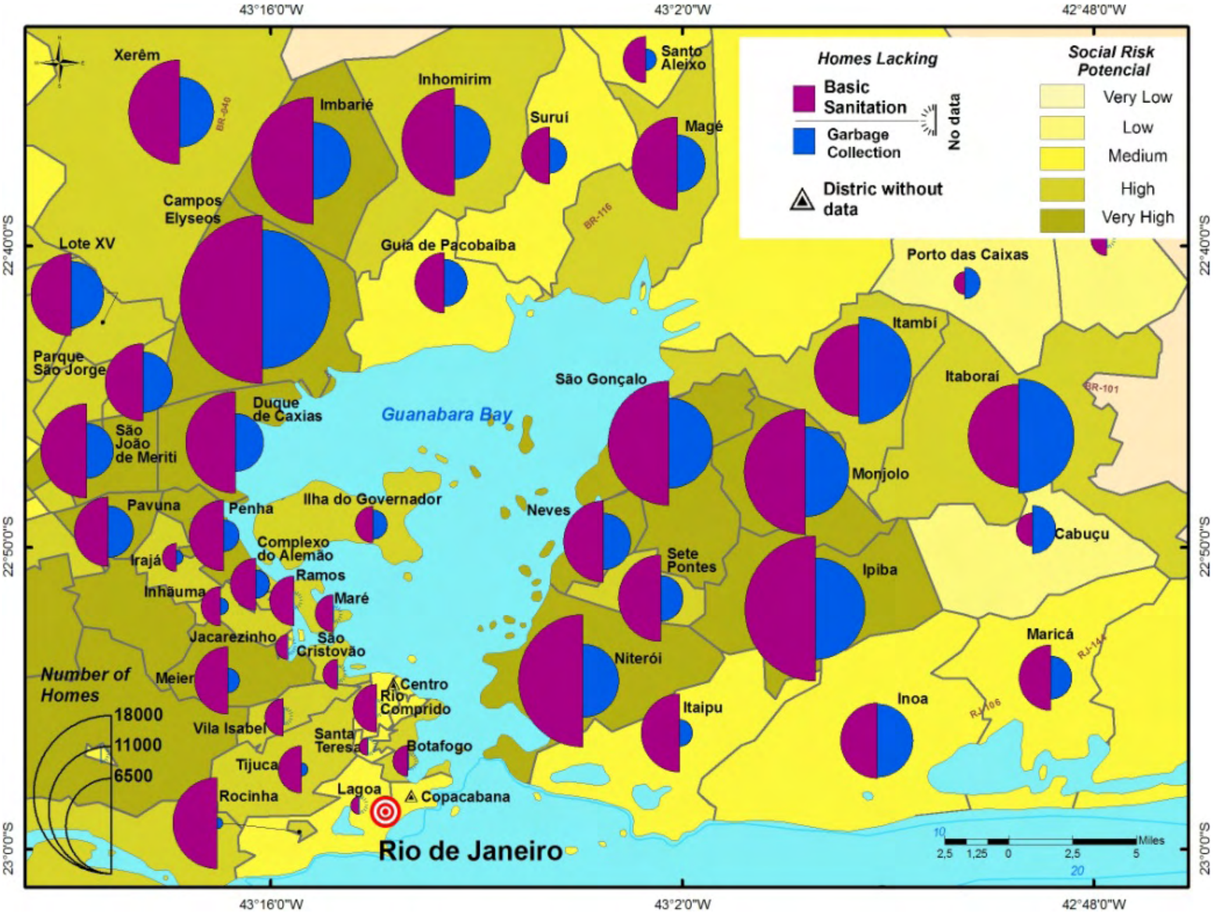

Figure 12. Social risk map of Guanabara Bay, in Rio de Janeiro. Graphic forms in purple represent the lack of sewers in subdistrict households. The shortage of garbage collection services is shown in blue. (Adapted from MDZCM, 2008).

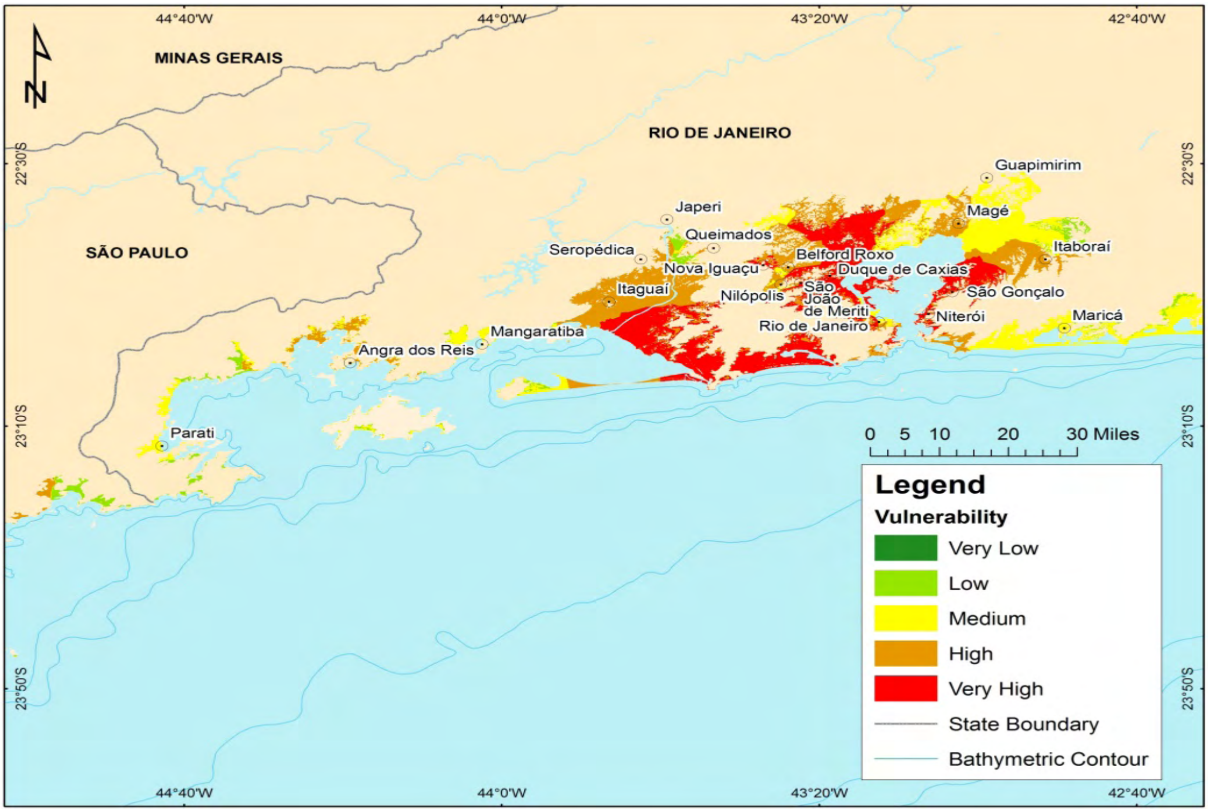

Figure 13. High vulnerability level in the metropolitan Rio de Janeiro area. The coastal area south of Guanabara Bay has a low vulnerability.

formed in the mountain range recesses, shape a geomorphologic region of many different ground levels occupied by permanent, low density populations.

As is common during summer on most of the Brazilian coast, beaches that are far from big cities get a large inflow of temporary population. Therefore, most of this coast does not present a high vulnerability level (Fig. 13).The group of cities near Santos known as *Baixada Santista*, which includes the Santos bay and estuary, as well as the surrounding urban areas, contain Brazil's largest sea port and manufacturing complexes on the small estuary and coastal plains, which have developed around channels, on the foothills of Serra do Mar. The region's high population density, its typical socio-economic features, and its geomorphologic configuration of a pronounced retreat in the crystalline complex, determined, for almost the entire area, a high vulnerability level (Fig. 14).

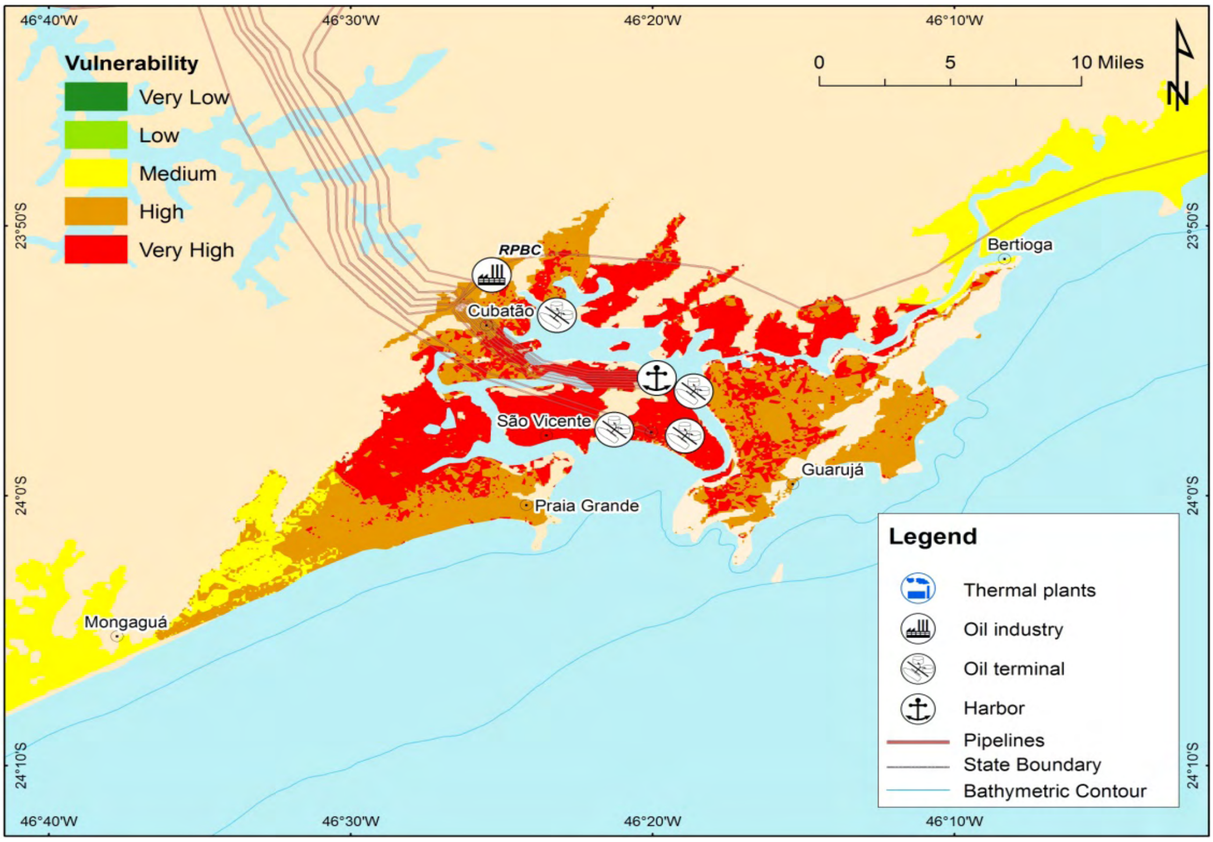

Figure 14. Baixada Santista and the Santos estuary. A combination of socio-economic, technological and geomorphologic features resulted in high vulnerability.

Another factor that makes the entire region more vulnerable is a visible concentration of manufacturing facilities between Santos and Macaé where there are oil and gas extraction fields, terminals, and pipelines, thermal and nuclear power plants, and a host of chemicals, metal and mechanical complexes. Furthermore, energy boundaries are being expanded toward the South coast, with an increase in oil prospection in the Santos Basin, plus the construction of pipelines, and an expanded chemical industry in Paranaguá.

South Region

A scenery of broad amphitheaters is the predominant geomorphologic feature in the Paranaguá Bay region, which includes the coastal area south of *Baixada Santista* to Itajaí, on the coast of Santa Catarina state. This segment contains three major seaports (Paranaguá, São Francisco do Sul, and Itajaí). These municipalities and/or their surroundings have significantly higher population densities than the average population per km^2 of the Southeast coast of Brazil. This mixture of topographic and population factors, the socio-economic importance of these urban centers, plus the instability factors affecting the shoreline, produce medium to high vulnerability levels (Fig. 15).

On the coast of Santa Catarina, the Joinville area, the Itajaí Valley, and Greater Florianópolis have very high vulnerability levels, because of their high urban concentrations in areas below 10 meters above sea level. Floods as those that occurred in 1983, 1984, and recently in the November 2008 disaster, in which 135 people perished and over 1.5

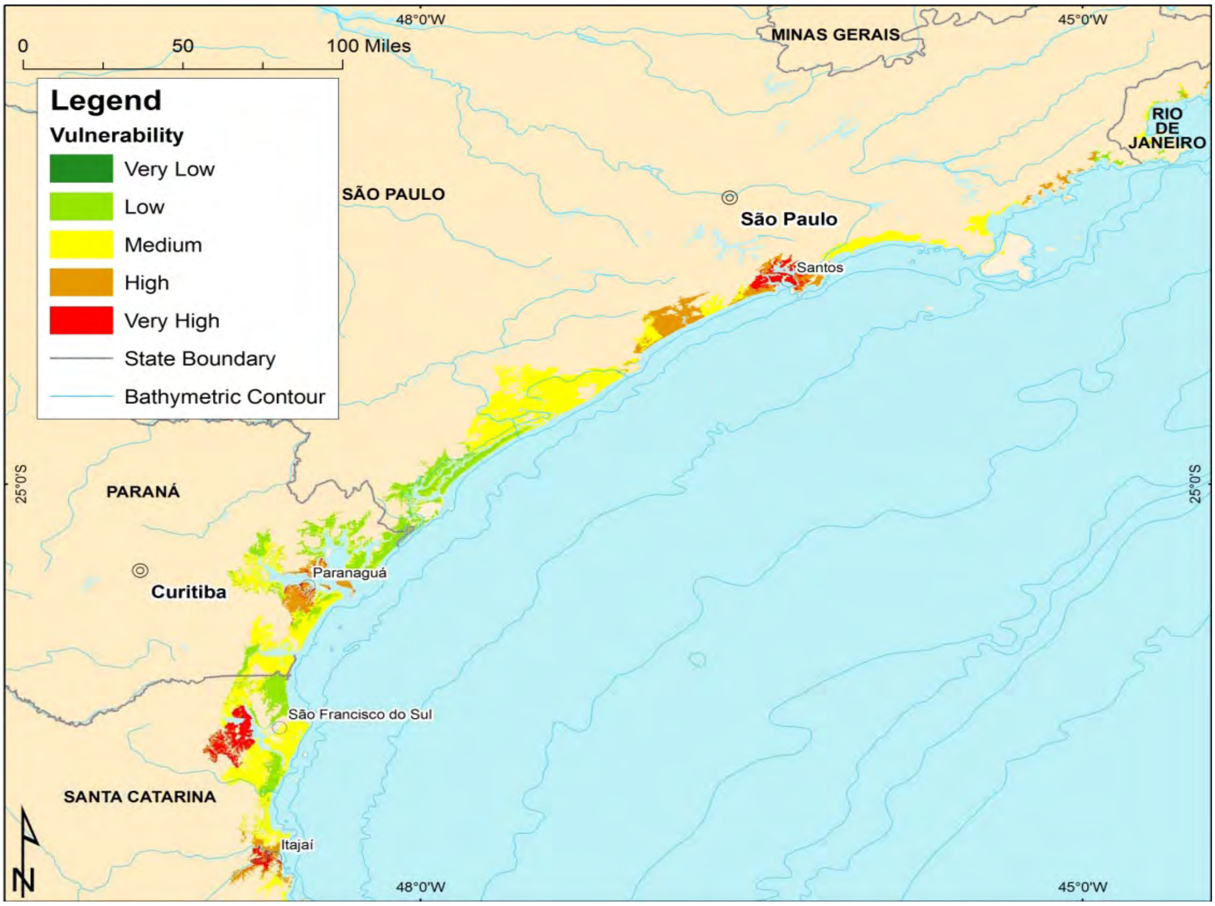

Figure 15. Vulnerability of the northern part of the South Region. The topography, population density, and socio-economic factors of urban centers generate medium to high vulnerability levels.

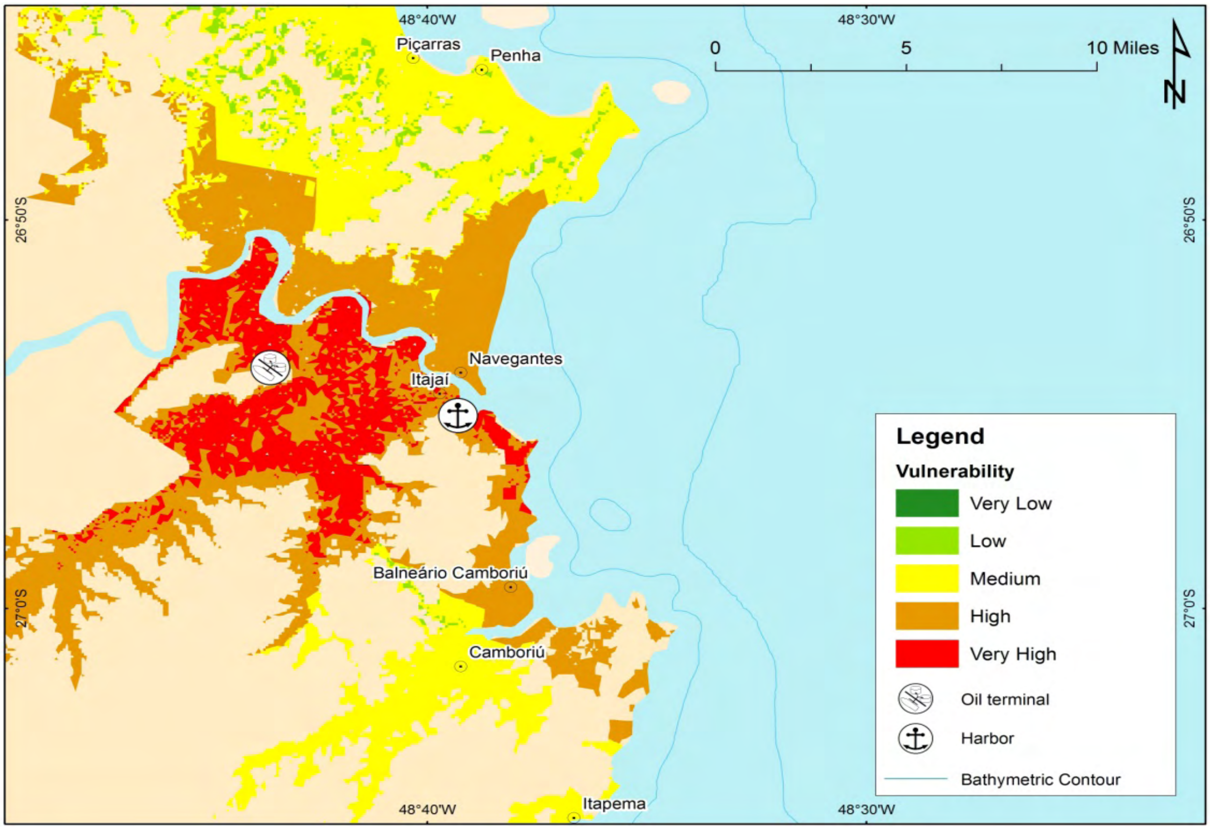

Figure 16. The high and very high vulnerability region corresponds to the distal portion of the Itajaí-Açu River basin, which has undergone frequent inundation in recent years, particularly during recent events in 1983, 1984, and 2008.

million people were injured, fully confirmed this vulnerability (Fig. 16).

The southern part of Santa Catarina state up to the border of Uruguay, is characterized by sandy barriers highly exposed to a strong wave and storm regimen with a tidal range of less than 1 m. Numerous lagoons developed behind the barriers with only few outlets.

Although the geomorphological context alone cannot explain the high vulnerability levels, it is important to emphasize that this region is critical for the occurrence of uncommon, extreme events of great magnitude, as was the case of Catarina Hurricane, which struck in 2004 and all but wiped out the bordering area between the two southernmost states of Brazil.

The only place defined as highly vulnerable in Rio Grande do Sul state is the Rio Grande area near the Patos Lagoon outlet, which is kept open through two 4.5 km long jetties (Rio Grande bar piers). This scenario includes the main urban center in the inner estuary, with a population of around 200.000 inhabitants living on low, flat ground and over areas expanded by the water surface landfill. The land occupied by housing coexists with spaces dominated by the activities of one of the country's most important ports, combined with an expanding manufacturing and petrochemicals complex of great relevance to the state (Fig. 17).

The role of the port of Rio Grande in this part of the area of high vulnerability, should be considered in conjunction with the Metropolitan Area

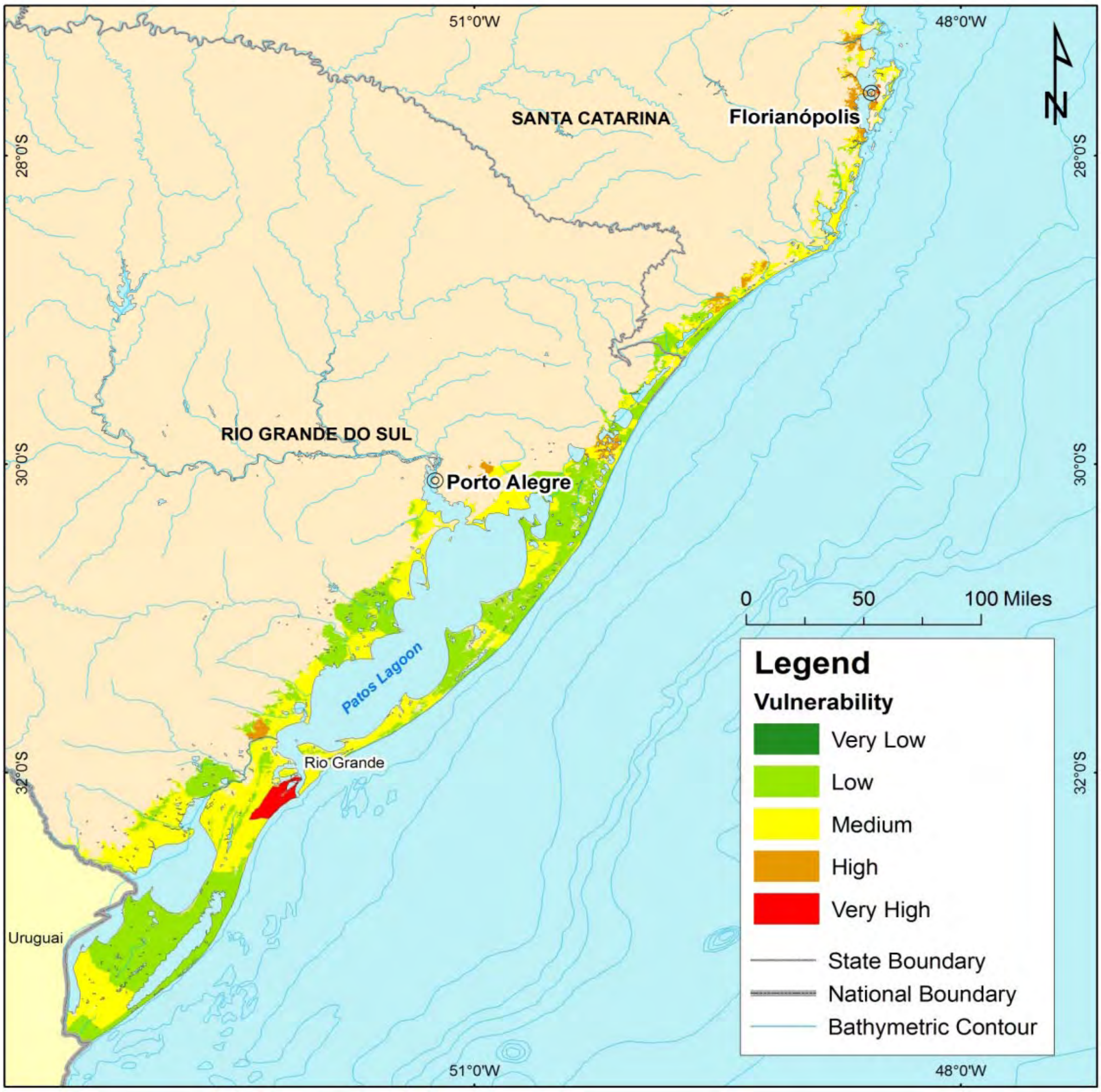

Figure 17. From the south of Santa Catarina state to the border of Uruguay, vulnerability is relatively low, with the exception of the urban area of Rio Grande. This region is subject to weather events of great magnitude, such as Hurricane Catarina in 2004.

of Porto Alegre, as regards the lagoon area where they are located. The likelihood of an increased trading of energy, goods and services and the implementation of new plants in the area due to its Mercosur standing, are specific elements that will probably increase the threat of technological hazards on the South coast in the coming decades (Egler 2008).

Conclusions

The Coastal Zone is the most dynamic geographical area in the country, since the time when the country was a colony of Portugal, and connections from structural centers directed internal flows directly to seaports, next to which the first urban centers were established (Moraes 1999).

The analysis of the combination between a likely unchanging tendency of this scenario in the near future and the context of global climate changes, points inevitably to the importance of undertaking a realistic coastal management, with priority actions, and human and financial resources.

Knowing about the mesoregions more or less vulnerable to the impacts of the direct effects of climate change is essential for the public authorities to make their decisions. These effects are directly linked to three major types of causes, defined in this paper as natural risk, social risk, and technological risk. The combination of these concepts, when applied to the national territory have enabled the definition of the five levels of vulnerability used, illustrating the scene presented as a challenge to be faced by integrated coastal management in Brazil, especially in the current context of climate change.

From this standpoint, the Intergovernmental Oceanographic Commission (IOC) has defined the climate change-related risks as shown in Table II. With the exception of tsunamis, Brazil is exposed to varying levels of the other risks defined by IOC.

In addition to the risks to which the Brazilian coast is directly exposed, other factors are expected to indirectly influence the dynamics of this part of the territory. According to Marengo (2006), modeling carried out by IPCC indicate possible significant changes to the outflow of the largest Brazilian rivers: an increased volume in the Plata and Paraná River basins and a decrease in the Amazon and the Pantanal basins. The variation in those water volumes will lead to a

Table II. Definition of climate change-related risks to Coastal Zones, according to the Intergovernmental Oceanographic Commission (IOC, 2009). and the relations with the observed in Brazil.

Risk	Definition		Vulnerable areas
Rapid onset hazards	Tsunami	A series of ocean waves generated by displacement of the ocean floor from an earthquakes, volcanic events, or large asteroid impacts.	Because the Brazilian coast is a "passive" coast, such events aren't expected, although they can't be discarded.
	Storm surge	Temporary rise in sea level caused by intense storm associated with low pressure and strong onshore winds.	The entire coast, especially the southeast and south, due to greater energy involved in the dynamics of this coastal region.
	Extreme wind-forced waves	Extreme instances of waves generated by winds somewhere in the ocean, be it locally or thousands of kilometers away.	The entire coast, especially the states of Santa Catarina and Rio Grande do Sul.
Cumulative or progressive hazards	Long-term sea level rise	Global sea level rise due to a thermal expansion of oceans and increased melting of land-based ice.	There's no availability long data series in the country, with the exception of Rio de Janeiro and São Paulo. In these cases, there is evidence of elevation about 3 mm/year.
	Coastal erosion	Loss of coastal land caused by waves, tides currents or drainage that can be enhanced by each of other hazards.	There is evidence of coastal erosion in several areas of the Brazilian coast. The phenomenon is more complex when it comes to urban coasts.

new sediment transport regime and its consequences on the shoreline.

These effects were identified by Neves & Muehe (2008). They include: a) coastal erosion and progradation; b) damaged coastal protection works; c) structural or operating losses at ports and terminals; d) damaged urban construction work in coastal cities; e) damaged structural or operating sanitation work; f) exposure of underground pipelines or structural damage to exposed pipelines; g) saline intrusion in estuaries; h) saline intrusion in aquifers; i) mangrove evolution; j) damaged coral reefs.

The scene has been set and there is no doubt the challenge of adapting and mitigating the consequences of such events is enormous, and cannot be faced without a detailed technical reference study consisting of micro- and macroscale vulnerability assessments.

The results obtained are included in this reference study based on a georeferenced data base, and can potentially assist in dealing with two of the various issues raised by the Federal Audit Office during its audit of public policies and climate change (TCU 2009):

1 – Brazil has no vulnerability study of its coast against the impacts of changing climate on a national scale.

2 – The country's available data are insufficient to build climate change impact scenarios in coastal areas.

The main sectors likely to be affected in a climate change scenario include ports and tourism. Brazil has a port sector that moves an annual 700 million tons of various goods and accounts for over 90% of all exports. One example was the destruction of the Itajaí seaport by heavy rains that hit Santa Catarina state in November 2008. Port reconstruction work will require over R$ 320 million, in addition to downtime losses estimated at US$ 35 million per day.

In the case of tourism, it is worth noting that the largest investments have been made in infrastructure work in coastal zones. For example, of the 14 tourist centers covered by the PRODETUR / NE-II program, with a US$ 400 M funding, 12 are located in the Coastal Zone[12].

These are examples of situations which the Brazilian society should be prepared to handle. The analysis of coastal zone vulnerability should guide the priority given to government actions. The areas defined as of high or very high vulnerability should be on the top priority list when decisions and plans are made.

In terms of institutional planning, Nicolodi & Zamboni (2008) analyzed the main actions undertaken by the Federal Government in the coastal zone and found that, although the management tools developed between 1996 and 2006 have brought some advance[13], integrated strategic planning is still incipient.

An integrated strategic planning must include the variables related to climate change vulnerability, especially when analyzing geographic action priorities.

Neves & Muehe (2008) reported the following actions that should make up the mentioned integrated strategic planning:

- permanent (long term) environmental monitoring;
- proposing effective municipal legislation governing urban occupation;
- effective state policies on coastal management;
- directing federal action efforts: legislation and education;
- action monitoring and coordination;
- identification sources of funds, their application, and forms of control;
- planning and prioritization of studies to undertake traditional actions (retreat, accommodation, and protection).

Key initiatives to address the "climate change in coastal areas" theme, such as the Global Ocean Observation System (GOOS)[14], linked to the Intergovernmental Oceanographic Commission (IOC), or the surveys on coastal erosion made by the Marine Geology and Geophysics Program (PGGM)[15] must be encouraged as a way of maintaining a structural base for decision-making by institutions responsible for the country's coastal and marine management.

[12]Source: http://migre.me/3H24g access on 11/27/2008.

[13]The authors identified as main instruments: *Projeto Orla* (Rim Project) Agenda 21, *Planos Diretores Municipais* (Municipal Master Plans), *Conselhos Municipais de Meio Ambiente – CMMA* (Municipal Environmental Councils), *Zoneamento Ecológico Econômico Costeiro – ZEEC* (Coastal Ecological and Economic Zoning), *Áreas de Exclusão Temporária de Óleo e Gás* (Areas of Temporary Oil and Gas Exclusion), *Sistema Nacional de Unidades de Conservação* (National System of Conservation Units), *Mapeamento da Sensibilidade do Litoral ao Óleo* (Mapping of the Coastal Sensitivity to Oil).

[14]The Brazilian component of this program may be accessed from: www.goosbrasil.org

[15]The results are organized in the book *Erosão e Progradação do Litoral Brasileiro* (Muehe 2006).

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A methodology for assessing the vulnerability of mangroves and fisherfolk to climate change

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Abstract. Mangroves are putatively vulnerable to climate change, especially sea level rise, depending on factors such as coastal topography and the presence of barriers to landward migration. Usage patterns of mangrove resources can also affect their ability to respond to change. Brazilian artisanal fisherfolk are highly dependent on mangrove resources and services, which makes them also vulnerable to climate change. These populations have to cope with high levels of uncertainty related to the availability of natural resources, and to social and political contexts, such as biodiversity conservation policies. Besides being protected by many different laws, mangroves are also included in no-take protected areas. This may contribute to their resilience as natural systems, but can enhance the vulnerability of human populations. We propose herein a research methodology for assessing the vulnerability to climate change of the social-ecological system mangroves - fisherfolk, by analyzing exposure to sea-level rise, sensitivity and adaptive capacity, and the impacts of conservation policies on these elements, particularly the effects of coastal protected areas in southern Brazil. An integrated social-ecological diagnosis may lead to more flexible policies, elaborated with stakeholders' participation, more adequate to local realities and more inclusive of strategies for mitigation and adaptation to climate change.

Keywords: adaptive capacity, sea-level rise, Brazil, protected areas, social-ecological systems

Resumo. Metodologia para análise da vulnerabilidade de pescadores e manguezais às mudanças climáticas. Os manguezais são vulneráveis às mudanças climáticas, especialmente à elevação do nível do mar. Sua capacidade de resposta depende da topografia costeira, da presença de barreiras à migração e de padrões de uso dos recursos naturais. Pescadores artesanais no Brasil são dependentes de recursos e serviços ambientais dos manguezais, sendo também vulneráveis às mudanças climáticas. Eles lidam com incertezas relacionadas à disponibilidade destes recursos, e a contextos sociais e políticos. Mesmo protegidos por diversas normas, os manguezais também são incluídos em unidades de conservação de proteção integral. Isso pode contribuir para sua resiliência, mas pode, por outro lado, aumentar a vulnerabilidade das populações humanas. Propomos nesse trabalho uma metodologia para avaliar a vulnerabilidade de manguezais e populações costeiras às mudanças climáticas, usando como estudo de caso uma área no litoral sul do Brasil. A metodologia baseia-se na análise da exposição à elevação do nível do mar, da sensibilidade e da capacidade adaptativa, e dos impactos das atuais políticas de conservação, especialmente as unidades de conservação, sobre esses elementos. Um diagnóstico sócioecológico integrado pode contribuir para políticas mais flexíveis, elaboradas com a participação de todos os interessados, mais adequadas às realidades locais e que incluam estratégias de adaptação às mudanças climáticas.

Palavras-chave: capacidade adaptativa, elevação do nível do mar, Brasil, áreas protegidas, sistemas socioecológicos

Introduction

Vulnerability of coastal populations and ecosystems is a multi-concept which includes *hazard exposure, sensitivity* (the magnitude of losses that potentially result from exposure to the hazard) and *adaptive capacity*, or the capacity to respond to impacts and prepare ahead of them, through coping strategies and long-term adaptation to a certain threat (Kelly & Adger 2000, Brooks 2003, Turner *et al.* 2003, Füssel 2007).

In projected climate change scenarios, the main threats to coastal populations and ecosystems are sea-level rise, the intensification of extreme weather events and ecosystem changes (Nicholls *et al.* 1999, Nicholls *et al.* 2007, Gilman *et al.* 2008). Other expected impacts are a rise of up to 3 ºC on sea surface temperature, changes in precipitation and fresh water input, salt water intrusion into soils and coastal aquifers, and ocean acidification (Sterr *et al.* 2000, Adger *et al.* 2005, Nicholls *et al.* 2007). These climate alterations will have varied effects on coastal ecosystems and human populations, with a likely increase on flooding and loss of wetlands (Nicholls 2004), flooding of populated areas and infrastructure, resulting in severe economic impacts (Zhang *et al.* 2004, Wu *et al.* 2008), and changes in the availability of natural resources, with consequences for the livelihoods of those that rely directly on them for survival, such as traditional or neo-traditional coastal populations, including fisherfolk (Badjeck *et al.* 2010).

Exposure to these threats is directly linked to the position of human settlements and ecosystems on which they depend in relation to the sea and to regions prone to the occurrence of sea-level rise and extreme weather events (Smit & Wandel 2006). Sensitivity, often treated as equivalent to exposure, depends on the number of people, the infrastructure and the extension of ecosystems exposed to the hazard, and on the level of dependency on natural resources of the considered population (Tuler *et al.* 2008). Adaptive capacity depends, in the case of human populations, on a series of factors linked to access to assets. In the case of ecosystems, adaptive capacity can be treated as analogous to ecological resilience, which is the capacity of a system to recover after a disturbance while maintaining its functionalities (Walker *et al.* 2004). It will be affected, among other factors, by the degree of ecosystem degradation and the exploration levels of its natural resources. In any case, adaptive capacity is a result of the system's ability to self-organize, learn and adapt (Walker *et al.* 2004, Adger 2006).

In this article we aim to present a methodology for assessing the vulnerability to climate change of both mangroves and fisherfolk, jointly conceived as a Social-Ecological System - SES (Folke *et al.* 2002, Folke *et al.* 2003).We do this by first presenting a general review of the main elements that determine the vulnerability of these ecological and social systems to the major expected effects of climate change on coastal areas. We then present a case study of the coastal region of the State of Paraná, southern Brazil, where artisanal fishing villages coexist with extensive mangrove forests. This scenario is rendered more complex by the existence of several protected areas on the region. We suggest that the strict preservation of these areas, mainly for biodiversity conservation, can have both negative and positive effects on the vulnerability of mangroves and artisanal fisherfolk to climate change. Furthermore, these varying effects can work in opposite directions, for example, enhancing the vulnerability of fishing villages, by diminishing their options for livelihood diversification, while lowering the vulnerability of mangroves, by protecting adjacent land and allowing them to adapt to sea-level rise.

Based on this case study we propose a methodology to assess the joint vulnerability to climate change of mangroves and fisherfolk, which we believe can be used in other settings and is based on the so-called vulnerability or contextual approach (Ford *et al.* 2010). In this perspective, which considers vulnerability of social-ecological systems as a starting point, studies must focus on defining the current processes related to the social construction of vulnerability. That is, how different social, economic and political characteristics, processes and trends determine, in the present, distinct levels of vulnerability. The goal is to develop policies that are able to improve future perspectives considering social and environmental changes (Kelly & Adger 2000, Van Aalst *et al.* 2008). This approach becomes more relevant if we consider that, in general, lack of adaptive capacity is the main factor contributing to increase the vulnerability of human societies, although physical exposure to hazards is also an important component of vulnerability of social and natural systems (Nicholls *et al.* 2007).

On a second level of analysis we propose specific indicators to analyze the impact of the protected areas on the elements that compose vulnerability. Most protected areas in the world were established based on availability of space or political viability, without considering climate, or based on a static view of climate issues. Even though climate change will probably affect the distribution of species, so that many of them may move out of protected areas, these will continue to be an important tool for biodiversity conservation. However, in this new context, it becomes more urgent to integrate conservation policies with other general strategies for management of landscapes and natural resources. And it also becomes essential that the selection of areas to be protected and the management of them and of the landscapes in which they are inserted are done with climate change as an explicit parameter (Hannah *et al.* 2002, Hannah *et al.* 2007).

Conservation actions should not be limited to protecting large tracts of ecosystems, but should also consider dynamics of change and adaptation of social-ecological systems and the building of adaptive capacity in human communities, including actions aimed at diversifying income sources so that these populations become less dependent on natural resources and are better able to cope with and adapt to the expected and unexpected impacts of climate change (McClanahan *et al.* 2008). For this to be achieved, there is a need to identify which elements of climate change will bring the most important effects on each ecosystem and human population, and what will these effects be (Sterr *et al.* 2000, Hulme 2005). Thus, it is of great importance to understand how social and natural systems currently respond to climate-related disturbances, in order to provide a basis for the development of these new adaptive strategies capable of achieving biodiversity conservation, both inside and outside of protected areas, together with the social and economic sustainability of human populations.

Mangroves and their vulnerability to climate change

Among coastal ecosystems, mangroves are of great ecological, economic and social importance. Occupying most of the protected and semi-protected coasts in tropical and subtropical regions, they stabilize coastlines, prevent erosion and function as a barrier to storms. They provide refuge, feeding and reproduction sites for a great variety of animals, including commercially important species, and ultimately help to sustain and restore fishing stocks. Mangroves are also a source of organic matter for other coastal ecosystems; they provide adequate sites for aquaculture; their sediments are sinks for pollutants and terrigenous sediments; and they have aesthetic and spiritual value for many human groups. Besides these functions, many mangrove products are directly explored by coastal populations, especially wood, used as fuel and building material, but also tannins and other plant extracts (Lacerda 2002, Agrawala *et al.* 2003, Walters *et al.* 2008, Valiela *et al.* 2009).

Mangroves are amongst the most threatened coastal ecosystems. In the Americas, an estimated 38% of mangrove areas have already been lost, at an annual rate of 3.62% (Valiela *et al.* 2009). However, South America had the lowest rate of mangrove loss among all world regions, only 0.18%, or 4,000 hectares, in the 2000 - 2005 period (FAO 2007). Threats to mangroves have two main origins: on the one hand human occupation and unsustainable patterns of resource usage threaten their existence and limit available space for migration, besides affecting factors such as sediment supply, the volume of groundwater and the discharge of nutrients and pollutants. On the other hand, the effects of global climate change, especially sea-level rise, pressure the frontward margin of mangroves, causing erosion, tree mortality and loss of forest area. As active contributors to the degradation of mangroves, coastal populations may end up eliminating the very ecosystem that provides them resources and protection against the impacts of climate change (Taylor & Sanderson 2002).

The ability of mangroves to respond to sea-level rise depends on many factors, including coastal topography and the presence of barriers to landward migration. This response depends on their ability to accumulate sediments and promote accretion, a process which is regulated by a series of geomorphological, climatic and hydrological controls over sediment supply, primary production, decomposition, subsidence and autocompaction, all of which are extremely variable from one site to another (Cahoon & Hensel 2006). Vulnerability also depends on their ability to migrate, following sea-level variations. Though significant increases in total mangrove area have been recently reported for the northeastern Brazilian coast (Maia *et al.* 2006, Lacerda *et al.* 2007, Lacerda 2009), migration and colonization of new areas may be limited by human occupation of adjacent areas, which restricts this ecosystem's capacity to adapt to new conditions (Scavia *et al.* 2002). Mangroves are unable to follow sea-level rise when the surface elevation rate is lower than the relative sea-level elevation rate. This has been observed in some recent studies (Gilman *et al.* 2008), although some other studies have shown the opposite (Alongi 2008), indicating there is a need for more long-term observations in a larger number of sites.

Mangroves will probably suffer a combination of positive (rise in atmospheric temperature and CO_2 concentration) and negative (rise in saline intrusion and erosion) effects of climate change, and the balance between the two will largely depend on site-specific factors (Saenger 2002). Because of the multiplicity of expected responses of mangroves to these changes, a more realistic approach would be to categorize and delimitate forests according to their level of vulnerability.

Less vulnerable mangroves would be those located in areas with high tidal range (> 5 meters), in humid tropical coasts and/or in areas close to the mouths of large rivers or on their margins, in remote areas with little human occupation, in areas with large nutrient supply, those growing on deep soils, with available space for landward migration and in regions with large extensions of well developed mangrove stands, which are a source for propagules and seeds. These conditions are found, for example, on the northern coast of Brazil. Highly vulnerable mangroves would be those situated on small islands, growing on calcareous soils, in regions without large rivers, in arid regions, in places subject to ground subsidence, in areas with low tidal range and with no sediment supply, and mangroves whose expansion is blocked by human occupation or a steep slope (McLeod & Salm 2006, Alongi 2008, Lovelock & Ellison 2007). Therefore, the main variables that should be considered for the analyses of mangrove responses to relative sea-level rise are: topography, sediment sources, rate of sediment supply, area of the drainage basin, tidal range, coastal dynamics and the mean rate of sea-level rise (Soares 2009).

Even though the predicted impacts of climate change on mangroves will vary between different ecosystems and regions, it is important to consider that they will combine with, and even intensify, other stress factors, potentially aggravating overall conditions. Thus, the survival of these ecosystems in a climate change scenario depends on their adaptive capacity, but also on the intensity with which human activities are undermining this capacity (Scavia *et al.* 2002). For example, in comparison with prior sea-level rise events in Earth´s history, nowadays most coastal regions are affected by human activities, including cities and infrastructure, which limit the possibility of mangroves migrating towards the continent in response to climate change. In addition, if we consider the large number of people living close to mangroves and depending directly on them for survival, and at the same time functioning as a source of impact and contributing to lower their resilience, it becomes of surmount importance to analyze these systems together, hence our SES approach. The development of management policies and strategies for land occupation and resource use in coastal environments must consider these multiple elements, or otherwise, there is a risk that both mangroves and human populations will lose (Walters *et al.* 2008).

Fisherfolk and their vulnerability to climate change

Among coastal populations, those that depend on the direct use of natural resources, such as fisherfolk, are especially vulnerable to climate change. Worldwide, an estimated 120 million people depend directly on fishing for their survival, 95% of which live in developing countries, where the great majority is engaged in artisanal fisheries (Allison & Ellis 2001). Artisanal fisherfolk in tropical and subtropical regions are usually highly dependent, directly or indirectly, on resources and services provided by mangroves, which makes them jointly vulnerable to climate change, since those that depend on marine resources as a source of food are highly vulnerable to its impacts, both in terms of health and food security, and in economic terms (Nicholls *et al.* 2007).

It is important to discriminate the different dimensions that compose the vulnerability of fisheries systems. This vulnerability is dynamic over time due to changes in the characteristics of threats, the exposure to them, the sensitivity of the system and the adaptation actions. A "fisherfolk-mangroves" SES may be exposed to different kinds of threats (environmental, economic and political), may have distinct sensitivities to these threats and may also be more or less resilient (Tuler *et al.* 2008).

Small-scale fisheries face a permanent state of uncertainty, due to the natural variability of fish stocks and because these stocks are declining as a result of overfishing, bad management practices, and other factors (Jackson *et al.* 2001, Mullon *et al.* 2005, Pauly *et al.* 2005). For these populations, which usually have lower adaptive capacity, social and biophysical resilience are closely connected and climate change can increase the uncertainties regarding the availability of natural resources (Dolan & Walker 2004), and, as a consequence, threaten their biological survival and social reproduction. Climate change will bring direct impacts on marine biodiversity, such as changes in reproduction and migration periods of several species, an increase in diseases, changes in latitudinal and longitudinal distribution patterns, changes in population size and community composition and changes in the hydrological cycle, with effects on biodiversity and environmental services (Gitay *et al.* 2002). Much of this is already evident in different ecosystems and biomes all over the planet (e.g. Walther *et al.* 2002, Parmesan & Yohe 2003, Parmesan 2006). These changes can alter seasonal and distributional patterns of fish species that are explored by artisanal fisheries, potentially impacting local livelihoods. Faced with the restrictions imposed on them by the natural environment, these fisherfolk are forced to adapt to the seasonal distribution and the ecology of fish, both strongly influenced by climate (Iwasaki *et al.* 2009).

Climate change will also bring greater variability and uncertainty regarding weather conditions, which impact directly on artisanal fisherfolk, whose fishing gear limit their mobility and ability to operate in adverse conditions. In face of these changes in the environment, traditional knowledge accumulated by these populations, which used to guide them during their fishing activities in an efficient and safe way, may become useless (Ford & Smit 2004).

Uncertainties also derive from political, economic and social contexts. Market variations and changes and inadequacies of the rules that regulate fishing activities are sources of variability and stress that constantly threaten the livelihoods of fisherfolk (Marschke & Berkes 2006). Other factors such as the lack of external institutional support and erosion of traditional resource use systems can lead to a rise in the vulnerability of these livelihoods (Kalikoski *et al.* 2010). In addition to fisheries management rules, small-scale fishermen are also subject to the effects of other types of rules, such as those concerned with biodiversity conservation. For the sake of biodiversity, many restrictions are imposed on the access to and usage of coastal environments and resources. These actions may function as factors that increase the vulnerability of the system by making it more sensitive or by limiting its capacity to respond.

These factors (environmental laws, environmental degradation, increase in variability and uncertainty related to climate and fish stocks) may result in a reduction of the adaptive capacity of coastal populations, potentially aggravating the effects of climate change. As an example, fishing villages that depend on a small number of species, and that have few options for diversifying their income sources, tend to be very vulnerable to changes in fish stocks. On the other hand, the consequences of climate change can make the implementation of biodiversity conservation policies ever more difficult, if they fail to take into account this new scenario, and if they fail to include in their elaboration and implementtation processes those that are directly affected by them.

A case study: the coast of Paraná State, southern Brazil

With environmental problems and land occupation patterns partially similar to other developing countries, the coast of Brazil is also exposed to extreme climatic events, such as storm surges and flooding, with risks for natural systems, infrastructure and human settlements. The rise of mean sea-level in Brazil, which is already occurring in most measuring sites, although still small, tends to add to the effects of these other phenomena, bringing such consequences as an acceleration of coastal erosion, a magnification of flooding events, the rise of water tables and increased salinization of rivers, estuaries and aquifers (Szlafsztein 2005).

Most human occupation on the Brazilian coast derives from urbanization and the expansion of activities such as tourism, ports, commerce and industry, which are concentrated on the roughly 55% of the coast which are more densely populated (Neves & Muehe 2008). In these areas, the impacts of extreme events and climate change tend to be economically and socially important, as they affect great concentrations of infrastructure and human populations. On the remaining parts of the coast, there is a predominance of SES in which human populations, such as artisanal fisherfolk, depend directly on the exploration of natural resources, with many of them still using traditional practices.

A fundamental interface between the social and the ecological components of a fisheries system is the relation between fishing populations and the coastal environments from which they extract the resources that sustain their livelihood. In Brazil, mangroves play an important role on supporting both coastal ecosystems and human populations. Mangroves occur along most of the Brazilian coast, from the extreme north (Cabo Orange, Amapá, 04º30’ N) to the city of Laguna, in the southern state of Santa Catarina (28º56’ S), covering most intertidal areas (Schaeffer-Novelli *et al.* 1990). Coastal populations in Brazil who rely on the direct exploration of marine resources are highly dependent on mangrove ecosystems. As an example, in the northern state of Pará, at the estuary of the Caeté River, in the city of Bragança, over 80% of the population base their livelihoods on mangroves, and around 68% obtain income directly from mangrove products (Glaser 2003).

In spite of their importance for human populations, there are few studies dealing with the vulnerability to climate change of coastal ecosystems in Brazil. Even less common are studies that analyze both biophysical and socioeconomic aspects in an integrated manner. Some studies focused on observing changes in the distribution of mangroves as a response to relative sea-level rise (Almeida *et al.* 2008). Gathering results from this and other studies, Soares (2009) has proposed a conceptual model for the study of the response of mangroves to climate change, but it focuses, fundamentally, on biophysical aspects.

In the extensive mangrove forests of the northern coast of Brazil, many long-term studies have been developed, especially as part of the MADAM project (Berger *et al.* 1999). Some of these focused on biophysical dynamics, such as the temporal analysis of mangrove distribution by Cohen & Lara (2003), who concluded that mangrove stands are losing area in the seaward margin and migrating landward, possibly as a response to relative sea level rise, but that this migration is limited by local topography. Other studies analyzed the dependency of local populations on mangrove resources (Glaser 2003), while there were also studies that related the response of mangroves to sea-level rise to socioeconomic matters such as land use and occupation (Lara *et al.* 2002). In other regions of the Brazilian coast, studies have measured extension, retraction and migration of mangrove forests, but without relating them directly to climate change (*e.g.* Lacerda *et al.* 2007).

The coast of the Brazilian southern state of Paraná is dominated by the Paranaguá Estuarine Complex (PEC), whose physical, chemical and biological properties were described by Lana *et al.* (2001). It has extensive intertidal flats, which totalize around 295 km^2, mostly covered by mangroves (Fig. 1). The whole region is part of a Biosphere Reserve and of the Atlantic Rainforest Biome. Around 70% of the region's surface area is still covered by this type of forest and associated ecosystems, in stark contrast with most of the Brazilian coast, where this ecosystem has been largely destroyed (SOS Mata Atlântica/INPE 2009).

The study case site (Fig. 1) is centered around the northern part of the PEC, in the municipality of Guaraqueçaba, where there are two coastal protected areas (PAs), managed by the Brazilian Federal Government: Guaraqueçaba Ecological Station (created in 1982, it encompasses

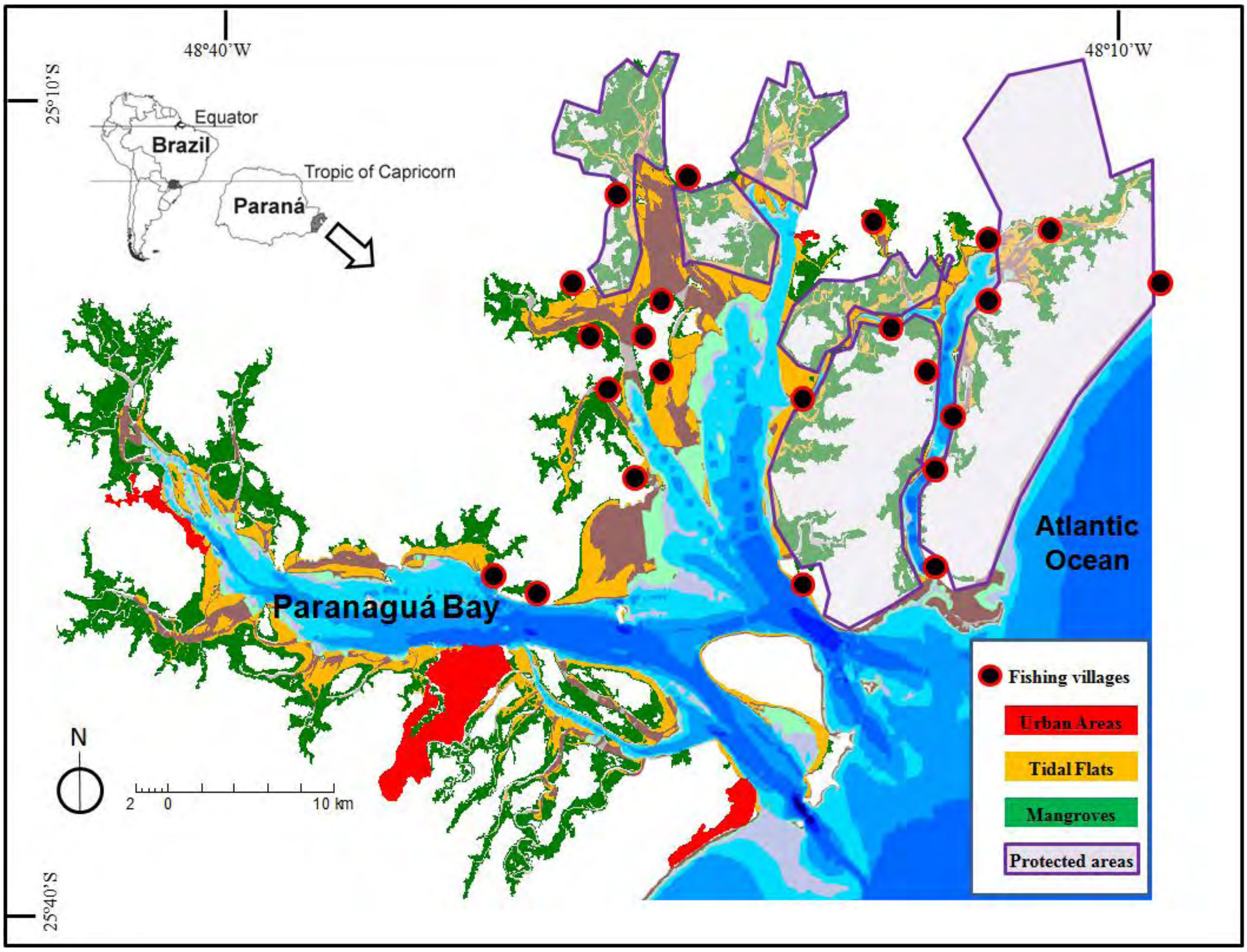

Figure 1. The Paranaguá Estuarine Complex, its extensive mangroves, numerous fishing villages and the no-take protected areas that dominate the northern part of the estuary. Source: Adapted from an original map designed by Prof. Mauricio A. Noernberg, CEM/UFPR.

around 11,500 hectares of mangroves around the Bays of Laranjeiras and Pinheiros) and Superagüi National Park (created in 1989, it protects around 34,000 hectares in the islands of Superagüi and Peças, which include a variety of coastal ecosystems).

Guaraqueçaba is a sparsely occupied area with a population of 7,890 inhabitants distributed over 2,315 km^2. It is one of the poorest municipalities in the state of Paraná, with a Human Development Index of 0.659 (IPARDES 2010). Fishing is the main activity in around 40 villages located on the margins of the estuary where there are an estimated 2,100 families of artisanal fisherfolk, most of them living close to mangroves and the aforementioned PAs (Martin & Zanoni 1994, IPARDES 2010). Although of little regional economic importance, fishing is locally of high social and economic importance (Borges *et al.* 2006).

Artisanal fisheries in this area have been changing over time due mainly to factors such as market changes, demographic dynamics (immigration) and technical innovation, which led part of the local fisheries to more intensified and market-oriented practices, while some of the other practices have disappeared (Andriguetto-Filho 2003, Andriguetto-Filho *et al.* 2009).

Environmental problems in the coasts of Brazil and Paraná affect fisherfolk in diverse ways, causing a series of conflicts, such as the displacement of these populations to inappropriate areas, disputes over fishing grounds among artisanal and industrial fisheries and aquaculture, contamination and depletion of fishing stocks, among others. Cleavages are also observed among artisanal fisherfolk, between those that are traditionally linked to fishing and the opportunists, and between those that use predatory techniques and those that avoid them (Andriguetto-Filho 1999). These problems threaten the survival and socioeconomic reproduction of these populations.

Besides environmental degradation and the disputes with industrial fisheries, there are evidences of conflicts between environmental regulations and the economic activities of local populations, especially those engaged in small-scale fishing and agriculture. Many studies point to environmental conflicts associated with the creation of PAs in the coast of Paraná, especially in the municipality of Guaraqueçaba (Andriguetto-Filho 1993, Martin & Zanoni 1994, Zanoni & Miguel 1995, Pedroso Jr. 2002, Cunha *et al.* 2004, Miranda 2004, Teixeira 2004).

Brazilian mangroves are also included in no-take PAs, besides being protected by many different laws (Martin & Lana 1994). This may contribute to the resilience of natural systems, but can also affect the vulnerability of human populations. Large tracts of Atlantic Rainforest and mangroves in Paraná compose an area of high priority for biodiversity conservation, being classified as of extremely high biological importance by the Brazilian Ministry of Environment (MMA 2007). A great variety of ecosystems and species of interest for conservation is reflected in the existence of many PAs in this region. These areas have been created here since the 1980s and include no-take reserves as well as "sustainable use" ones. They cover a large portion of the region: around 76% of the northern coast of Paraná is included inside PAs, of which 13% (59,440 hectares) in no-take reserves such as National Parks and Ecological Stations. There are also specific rules to protect the Atlantic Rainforest, which also limit the possibilities for occupation of the land and usage of natural resources. This stands in stark contrast with the process of rapid destruction of natural ecosystems that characterized the first centuries of human occupation of the Brazilian coast (SOS Mata Atlântica/INPE 2009).

In no-take PAs, and especially on those that include mangroves, there is a prevalence of strict conservation rules, which aim at completely banning the direct use of natural resources. Mangroves were the first ecosystem in the region to be included in a no-take PA (the above mentioned Guaraqueçaba Ecological Station is composed mainly of mangroves). For this ecosystem, strict no-take rules applied equally to all mangroves represent a simplistic view of the ecosystems structural and functional characteristics, because they are based on the misconception that all mangrove stands are equally productive, that resources are equally distributed and even that human groups access and explore all areas in the same way and with the same intensity. This last assumption also ignores territoriality relations between human groups and even the community conservation mechanisms that may be in use by them. All of this makes these rules not only inadequate but also inefficient, and even unfair, paradoxically resulting in open-access situations and in the environmental degradation of these ecosystems. Extensive discussions on the novel conflicts created by environmental legislation, mainly in the northern sector of the Paranaguá Estuarine Complex, were provided by Martin & Zanoni (1994), Lana (2003) and Raynaut *et al.* (2007).

In spite of the fact that most mangroves in this region are located inside no-take PAs, local populations use mangrove fishing resources on a regular basis. Although mangrove products, such as crabs (*Ucides cordatus*), oysters (*Crassostrea rhizophorae*) and shrimp (*Penaeus schmitti*), account for a relatively small percentage of total artisanal fish production, there are some communities that rely on crab extraction and oyster semicultivation as their main economic activities. It is also evident that a practical situation of open access to these resources has lead to overexploitation. Additionally, a general crisis in fisheries in the region has led to an increase in these activities in local mangroves. In some areas there is a direct relation between the fishing village and the nearby mangrove, with examples of locally established rules of access. But in many cases mangrove resources are explored by people coming from distant places, which is a source of conflicts between different groups of fisherfolk in this region (Miranda 2004).

Even when they are not included in no-take PAs, the direct exploration of mangrove resources, except fishing resources, is considered illegal in Brazil, which is also a source of conflicts with those populations that traditionally explore them (Glaser & Oliveira 2004). In the end, this situation of permanent illegality experienced by those that explore mangrove resources results in a normative insecurity and in a reduction of acceptance of environmental rules, with growing hostility between local populations and environmental authorities. It results also in the adoption of economically inefficient, ecologically inappropriate and socially unequal practices by these populations (Glaser *et al.* 2003).

Therefore, although they might have contributed for the conservation of natural resources in this region, land management and biodiversity conservation policies also generate conflicts when they restrict occupation of certain areas and prohibit exploration of resources. The impacts of these rules are unevenly distributed among different social groups. This situation results in negative impacts on the livelihoods of the populations that inhabit areas considered important for conservation. This is one of the reasons why official management actions are, more often than not, inefficient in protecting natural resources, especially common pool resources such as fishing and mangrove ones.

In a context such as the one observed in the coast of Paraná, one of the poorest regions in the state (Pierri *et al.* 2006), this scenario becomes even more problematic, as local small-scale fishing populations have limited access to political, financial and social assets, which aggravates the impacts that even small fluctuations in natural resources availability, or restrictions on the access to these resources, can have on their livelihood and survival. Therefore, environmental regulations become one of the sources of variability and disturbance for these livelihoods, acting together with other environmental (variations in fish stocks, environmental degradation, extreme weather events) and economic (market fluctuations, low income, lack or inadequacy of support mechanisms) factors, and contributing to increase the vulnerability of populations and ecosystems to climate change. The vulnerability of the SES of small scale fisheries in this context puts at risk the survival conditions of thousands of people, compromising their social reproduction.

As we recognize the connections between coastal ecosystems and human populations, there is a growing need for interdisciplinary research on the effects of climate change and to translate research results into better policies. It is important to comparatively understand these dynamics, analyzing how this multitude of factors affects the livelihoods and adaptive capacity of coastal populations and ecosystems, in order to better adapt conservation strategies, with an eye to both biodiversity conservation and social reproduction of human populations. Research in this domain must find ways to influence the making of environmental policies and rules.

A methodology for assessing vulnerability to climate change and the impacts of protected areas

The development of conservation policies for coastal zones must consider the need to understand the different systems - socioeconomic, geomorphologic and ecologic - in an integrated manner, so that vulnerability can be analyzed for the coastal area as a whole. Although climate is one of the main sources of hazards for the coastal zone, it is not the only source of change and vulnerability. It needs to be considered together with other factors so that management instruments are useful for integrated coastal management. Thus, while developing methodologies for analyzing vulnerability, the components of this analysis must provide information about all the processes that define the behavior of the whole system (McFadden & Green 2007).

A research framework aiming to analyze the relations between social and ecological systems has to face the challenge of understanding cross-scale interactions between phenomena and processes. Nevertheless, considering that responses to the impacts of climate change will consist primarily of individual responses to day-to-day changes on a local scale, there is a need for this type of study to have a multiscale perspective which can be applied to the analysis of adaptive capacity on the level of the communities (Dolan & Walker 2004).

Therefore, the proposal for working with a local case study as the starting point is based on the idea that the information to be collected can form the basis for a bottom-up analysis aimed at elucidating some of these interactions, contributing with studies of global change, which have usually focused on global scale models as the starting point, then extrapolating to the regional and local levels (Wilbanks & Kates 1999). With a focus on the local context, extrapolations could work on the opposite direction, emerging from comparisons between different communities – for example, using proximity to no-take protected areas as the independent factor – or even between different societies, comparing the results of the small-scale study with similar realities in other countries – for example, where artisanal fisherfolk and mangroves may coexist under different conservation policies.

These comparisons would aim on identifying those characteristics of communities and their environments that contribute to enhancing or lowering vulnerabilities, and the elements of the adaptation strategies that turn out to be more efficient (Smit & Wandel 2006). This would result in scientific explanations of the specific realities, but not necessarily on guidelines that could be universally applied to the formulation of policies, because the great variety of social and ecological contexts makes it difficult to develop homogeneous management solutions.

Supported by this logical background, we propose herein a research framework to assess the vulnerability to climate change of mangroves and fisherfolk. Using the case study of the Paranaguá Estuarine Complex in southern Brazil as an example we further include in the proposed methodology indicators to analyze the impacts of biodiversity conservation actions, especially no-take PAs, on this vulnerability. Following this perspective, the framework aims to understand how fisherfolk respond to changes in the status of the assets (biophysical, cultural, political and institutional) on which they base their livelihoods, and if this status is affected by environmental changes or changes in access and entitlements to these assets, specifically as a result of climate change and the implementation of no-take PAs.

Specific steps in the methodology include: (a) Evaluation of the vulnerability of mangroves to climate change, especially regarding their exposure and sensitivity to sea-level rise, and their adaptive capacity; (b) Evaluation of the vulnerability of fisherfolk populations to climate change, considering the exposure of villages to sea-level rise and extreme climatic events, their position in relation to no-take PAs, and the elements that enhance or diminish their adaptive capacity; and (c) Analysis of the effects of no-take PAs on these vulnerabilities, through impacts on sensitivity and adaptive capacity of both fisherfolk and mangroves. Such an approach can also be useful to analyze regional biodiversity conservation policies regarding their adequacy to deal with climate change related dynamics, aiming to identify how they can be adapted to contribute to building adaptive capacity, both of mangroves and fisherfolk, to respond to these changes.

To achieve these objectives, we propose an analysis of vulnerability in two sections, corresponding to two different scales (regional and local) and considering the main components of vulnerability: exposure, sensitivity and adaptive capacity. By analyzing the components of vulnerability in different situations we aim to understand which elements of the system are directly affected by change, being it regulatory, environmental, social or economic (Tuler *et al.* 2008), but with an emphasis on the impacts of existing PAs on the factors that condition vulnerability.

Preliminary steps in the research project should include the definition of the spatial and temporal scales for the study, considering biophysical and socioeconomic criteria, and the time scale in which management decisions are taken; collection of information on the biophysical environment and on socioeconomic and cultural characteristics of the area; identification of specific rules and policies that affect the area; and, choosing the specific sites for detailed data collection, according to the population, ecosystems and policies of interest (Harvey *et al.* 1999).

We divide the analysis according to the three components of vulnerability and the three subsystems being considered: social (fisherfolk), natural (mangroves) and social-ecological (representing the interaction between the other two subsystems; in our case study, it concerns mainly the fisheries production system, or the patterns of utilization of natural resources by coastal populations). It should also be considered that factors influencing vulnerability can be both social and ecological, and internal or external to the system (Füssel 2007).

Vulnerability should always be measured in relation to specific environmental hazards, which can vary according to the specific characteristics of the setting under consideration. For the coastal populations and environments of our case study, we defined three expected effects of climate change as the main threats: relative sea-level rise, an increase in the frequency and intensity of extreme climatic events, and an increase in uncertainty and variability related to the availability of fishing resources.

Exposure to these threats is mainly related with the characteristics of the sites where villages and mangroves are located, especially their proximity to the sea and the topography and slope of the terrain. Thus, for the analysis of this element a digital elevation model (DEM) of the coastal area needs to be constructed. This can be accomplished through the use of remote sensing, with a high-resolution satellite image of the region, or, ideally, with LIDAR (Light Detection and Ranging) data (Gesch 2009).

To improve the quality of the model, the upper boundary of mangrove forests should be delimitated and considered as equivalent to the mean high tide in the region. The DEM can then be constructed through interpolation of existing elevation data, considering this high tide line and the first topographic contour available in local maps (10 meters in the case of the Brazilian coast). To further improve the accuracy of the model, the interpolation can be fed with a series of elevation data points established along the margins of the estuary, in the area between the sea and the first topographic contour.

This digital elevation model, even if not accurate enough to produce detailed scenarios of areas prone to future flooding, especially if LIDAR data is not available, will allow a classification of the coastline in categories representing different levels of exposure to sea-level rise and flooding. The main goal is to identify the location and topography of mangroves and villages and the land-use patterns in the low-lying areas, up to 10 meters above sea-level. This focus on topography and on the existence of barriers to mangrove migration is justified by the lack of consistent data on local and regional sea-level rise. In this case, the analyzed factors work as surrogates or indirect indicators of this dynamics, producing information about the response of these ecosystems to climate change (Gilman *et al.* 2007). The last component of exposure to be measured is the magnitude and frequency of occurrence of extreme climatic events. Information on these events can be obtained both from meteorological and historical records and from interviews with local inhabitants. We suggest as a proxy for this the measurement of the number of fishing days lost due to bad weather conditions.

For the analysis of exposure, we can already identify opposite effects on the social and natural subsystems. A gentle slope means a higher exposure to sea-level rise and storm surges, increasing the vulnerability of villages, considering that the flatter the land the larger the area that would be flooded. But, for mangroves, a gentle slope in adjacent landward areas means that they have available space to migrate towards the continent, although land-use patterns may create barriers to this migration. In our specific setting, this spatial analysis of land adjacent to mangroves will also evaluate the situation of local fishing villages regarding their sensitivity to mean sea-level rise and the impacts of protected areas which exclude human occupation. In this case, the factor that will be analyzed is “coastal squeeze”, that is, if a rise in sea-level will put pressure on human occupations and if these will be able to respond. Many villages in this region are placed between the ocean and the PAs, being susceptible to coastal squeeze if sea level rises.

Still regarding sensitivity, which relates to effects that hazards can have on the systems, the general housing, health and food conditions of human populations should be measured, together with their dependency on climate-influenced resources (such as fish). For this, we propose, based on the Livelihood Vulnerability Index methodology (Hahn *et al.* 2009), to focus on water and food sources and storage capacity, the percentage of household members that lost work or school days due to health problems, and the distance to the closest health service (Table I). For mangroves, mapping of the total area occupied by the ecosystem and the forest types potentially affected are indicators of this component.

Following this analysis of exposure and sensitivity, some villages, and the mangroves associated to them, identified as potentially highly vulnerable, can be chosen for a more detailed evaluation of factors affecting their adaptive capacity. That is, besides exposure and sensitivity to biophysical risk, the other main component of vulnerability will be analyzed: the capacity of these populations and ecosystems to cope and adapt to change, the factors that contribute to it, and, in our specific case, how the existence of no-take PAs affects these factors.

This analysis of adaptive capacity can be divided in two steps. The first one focuses on current vulnerability, considering exposure to risks and coping strategies observed in the present, and based in knowledge of the environment, available resources and existing strategies. A second step aims to create future scenarios by estimating changes that might occur and possible adaptation actions based on behaviors already demonstrated in the past, and their adequacy to these scenarios. What is considered is how communities have dealt with extreme events and disturbances, what conditions may change and what opportunities exist for future adaptation (Ford & Smit 2004).

This type of analysis considers current conditions in these communities, with factors and processes that contribute to enhance or diminish their capacity to respond to changes, to variations and to the unexpected. This perspective recognizes the importance of factors that are not directly connected to climate, such as sources of subsistence, assets, access to resources, institutional arrangements, etc., that condition the vulnerability of these populations. This means that vulnerability to climate change is analyzed together with other sources of stress, with emphasis on the ability of people to respond to risks, changes and threats, potentially generating adaptation proposals that diminish vulnerability to climate change through the reduction of exposure or minimization of other adverse factors. Therefore, besides identifying the most relevant matters for the adaptive capacity of communities, the aim is also to understand the importance of climatic stresses in comparison to other sources of disturbance to these livelihoods (Tschakert 2007).

McClanahan *et al.* (2008) proposed an index of adaptive capacity composed of the following variables: recognition by the population of the causalities; anticipation of changes; mobility and occupational multiplicity of the population; social capital; material assets; and available infrastructure and technology. In a similar way, Yohe & Tol (2002) developed a method to estimate adaptive capacity using eight factors linked to technological options, availability of resources and their distribution in the population, structure of institutions that are important in decision making, the stock of human and social capital, the access to risk spreading processes, characteristics and abilities of the decision makers and the perception of the public in relation to the causes of stress and the meaning of being exposed to it.

Other authors applied and discussed the pertinence of more specific and detailed methodologies such as "Community Risk Assessment" and "Participatory Rapid Appraisal" (Van Aalst *et al.* 2008), or the "Sustainable Livelihood Approach" (Iwasaki *et al.* 2009). What these methods have in common is a bottom-up approach, the direct involvement of communities and a focus in analyzing vulnerability to current events, as well as strategies and policies based on current and real experiences, in different scales.

The "Sustainable Livelihood Framework" (Adato & Meinzen-Dick 2002, Baumann 2000, Divakarannair 2007) is a widely used approach for the study of the livelihoods of these communities that depend directly on natural resources, as well as the study of the importance of biophysical, social, cultural, economic, political and institutional factors that determine the options held by these populations. This method considers that livelihoods are linked to assets composed of human capital (education, knowledge, health, nutrition, workforce), natural capital (the natural resources explored by the community), physical capital (the available infrastructure, such as fishing gear and housing), financial capital (savings, credit, income), social capital (networks, cooperation, access to opportunities, organization) and political capital (policies, institutions and processes that link the individual or group to external power structures).

It is also important to include in this analysis elements of Environmental History, through, for example, interviews with elders and analysis of aerial photographs of the region, that may indicate historical patterns of land usage and occupation. The aim is to understand how the measured factors behaved prior to the existence of PAs, and in this way, relativize the impacts of them on these factors.

Considering the studies already mentioned, and the objectives of this work, and also considering other sources that discuss indicators and criteria for the evaluation of vulnerability and resilience in SESs (Marschke & Berkes 2006, Tschakert 2007, Tuler *et al.* 2008, Hahn *et al.* 2009, Kalikoski *et al.* 2010), we selected a number of indicators, linked mainly to income sources of fishermen and their relation to mangroves. Among the indicators usually utilized in vulnerability assessments, we considered the following to be more informative and useful regarding the objectives of this work:

- Income: total income, income distribution in communities, diversification of income sources, existence of stable income sources (retirement payments, etc.), proportion of economically active population.

- dependency of communities on fishing and mangrove resources: importance of these resources for their subsistence, access conditions and tendencies of variation on their availability, considering environmental degradation, overexploitation, climate change, and the restrictions imposed by environmental rules.

- fishing strategies: types of boats and fishing gear available; number of days they are prevented of going out to sea by bad weather; safety regarding availability of assets related to their livelihood (property of means of production, natural resources and housing, including conditions of access to them); if they have experienced changes in fishing activities (diversification, dislocation of fishing grounds) in response to economic, political and climatic changes.

- Market relations: whether they trade the products they capture or produce only in local markets, only in external ones, or in both; level of dependency on middlemen.

- Organization capacity of the community: means of organization and participation in discussion forums, associations, etc.; perceptions regarding the efficacy of these forums; responses of the community to previous catastrophic events (storm surges, oil spills).

- Adaptation and learning strategies, including social cohesion mechanisms: relations of help and exchange of information inside the community and between communities, regarding livelihood activities; participation of younger members on livelihood activities (knowledge transmission).

- Environmental and fisheries management policies and institutional factors: impacts of these policies on livelihoods; existence of financial support programs (loans, unemployment insurance, fishing ban period insurance) and the level of fishermen participation in these programs.

To assess the linked elements that compose the adaptive capacity of the SES, we propose a measurable index of the stress level or anthropization level of those mangroves that are used by these populations. Estimates on the present state of mangrove forests and fishing resources, such as oyster, mussels and crabs, including the availability of resources and how, where and in what intensity they are explored, can be used as a proxy of the impacts of human activities on the ecosystem's resilience.

This information will help to characterize the main component of the relation between mangroves and fishermen: the usage patterns of mangrove resources by these human populations. Additionally, the level of human usage of a particular mangrove shows its importance for that population. If a highly explored and useful mangrove has a low resilience to current disturbances and projected climate change, it must be the object of adequate management, one that contributes to increase the resilience of the SES as a whole.

The effect of protected areas, or other factor of interest, on the vulnerability of mangroves and fisherfolk should be dealt with at a second level of analysis. For our case study, we propose four specific indicators of these effects: (a) the distance of villages to the closest no-take protected area, indicating the probability of them suffering with “coastal squeeze” and of potential conflicts with biodiversity conservation norms; (b) the proportion of the income of local fisherfolk that comes from mangroves located inside no-take PAs, indicating the impact that these areas can have on their livelihood if these strict norms are fully enforced; (c) the proportion of local inhabitants that used to have a more diversified livelihood, practicing agriculture and extractivism, and who abandoned these activities because of the prohibitions brought on them by PAs; and, (d) the proportion of inhabitants that have suffered other type of restrictions on their livelihoods, such as limitations on improvement of housing conditions, due to PAs.

These data can be obtained from a number of different sources and utilizing a variety of techniques. Part of the social and economic data is available in government agencies, from projects developed in the region by non-governmental organizations, and as published scientific literature. Primary data shall be obtained directly on fishing villages using semi-structured interviews, contacts with key informants (such as community leaders and protected area managers) and direct observation of specific forums. Biological data from mangroves can be collected directly on site, using scientific sampling techniques, or with the help of local fishermen.

Table I summarizes the steps that are proposed in this methodology. They are divided in two scales (regional and local) and categorized according to the component of vulnerability they refer to, the type of capital (human, social, political, financial, natural and physical), the type of information to be collected and analyzed, the method and the source and type (quantitative or qualitative) of data.

After gathering the data it must be decided whether they will be summarized into an index of vulnerability. Most of the indicators proposed in this methodology are quantitative and can be parameterized and used to compose such an index. Although a focus on quantitative indicators and building of a composite index can oversimplify a

Table I. Summary of the indicators that compose the proposed methodology, considering the case study described above.

Vulnerability component	Subsystem	Type of Capital	Indicator	Information collected/analyzed	Method	Data source	Data type	Scale
Exposure	Mangroves	Natural	Topography/ Slope	Surface elevation data; contour curves; upper limit of mangroves; location of PAs; relative sea-level rise scenarios	Remote sensing; spatial analysis; digital elevation model	Satellite images; LIDAR data	Quantitative	Regional
Exposure	Fisherfolk	Natural Physical	Slope; distance from village to the sea	Surface elevation data; contour curves, upper limit of mangroves; location of Pas; location of fishing villages; relative sea-level rise scenarios	Remote sensing; spatial analysis; digital elevation model	Satellite images; LIDAR data	Quantitative	Regional
Exposure	SES	Natural Physical Social	Historic occurrence of extreme climatic events	Frequency of climatic events that significantly affect the villages; number of fishing days lost due to bad weather	Collection of secondary data; interviews with local inhabitants	Government agencies; scientific publications; fisherfolk	Quantitative and qualitative	Local
Sensitivity	Fisherfolk	Social	Food and Water	Type of water source; water storage capacity; food storage capacity, percentage of food coming from own production; number of months a year when there is shortage of food	Secondary data; field observations; household surveys	Government agencies; scientific publications; fisherfolk	Quantitative and qualitative	Local
Sensitivity	Fisherfolk	Social	Health	Percentage of members of household who lost work or school days due to health problems; distance to closest health service	Household surveys	Fisherfolk	Quantitative	Local
Sensitivity	Mangroves	Natural	Mangrove type	Total area and mangrove types potentially affected by sea-level rise	Remote sensing; spatial analysis	Satellite images	Quantitative and qualitative	Regional
Sensitivity	SES	Natural Physical Social Political Human	Dependency on fishing resources/ diversity of income sources	Proportion of income derived from fishing and mangroves resources; location of exploited resources	Secondary data; household surveys	Government agencies; scientific publications; fisherfolk	Quantitative and qualitative	Local
Adaptive capacity/Ecological resilience	Mangroves	Natural	Ecosystem health	Abundance of fishing resources in mangroves and usage patterns; signs of stress in the ecosystem	Sampling of primary data	Direct measurement in mangroves	Quantitative	Local
Adaptive capacity/Ecological resilience	Mangroves	Natural	Capacity to cope with sea-level rise	Presence of barriers/patterns of occupation of landward areas; level of protection of mangroves and landward areas; proximity to rivers and size of drainage basin	Remote sensing; spatial analysis; field surveys	Satellite images; direct observations	Quantitative and qualitative	Local

Table I. Continued.

Vulnerability component	Subsystem	Type of Capital	Indicator	Information collected/analyzed	Method	Data source	Data type	Scale
Adaptive capacity	Fisher folk	Financial	Income level, distribution and diversity	Diversity of income sources; percentage of income coming from external/stable sources; dependency rate	Sampling of secondary data; household surveys	Government agencies; scientific publications; fisherfolk	Quantitative	Local
Adaptive capacity	Fisher folk	Physical	Fishing strategies diversity	Number of fisheries practiced in the village; percentage of fisherfolk that own boats and fishing gears; frequency of usage of mangrove resources	Secondary data	Government agencies; scientific publications;	Quantitative	Local
	SES	Social			Household surveys	Fisherfolk		
					Interviews with key informants			
Adaptive capacity	Fisher folk	Financial	Market connections	Number of places where fisherfolk trade their products; percentage of those that depend on middlemen	Secondary data	Government agencies; scientific publications;	Quantitative	Local
		Social			Household surveys	Fisherfolk		
					Interviews with key informants			
Adaptive capacity	Fisher folk	Social	Community organization	Existence and number of community organizations; perception of effectiveness of external help during catastrophic events; responses of community during previous catastrophic events.	Secondary data	Government agencies; scientific publications;	Quantitative and qualitative	Local
					Interviews	Fisherfolk		
		Political			Direct observation of forums			
					Focal group discussions			
Adaptive capacity	Fisher folk	Human	Adaptation and learning strategies	Frequency and type of help and exchange of information inside the community and between communities, regarding livelihood activities; percentage of inhabitants with knowledge of the threats related to climate change	Interviews; focal group discussions	Fisherfolk	Qualitative and quantitative	Local
		Social						
Sensitivity/ Adaptive capacity	Fisher folk	Political	Impacts of biodiversity conservation policies	Distance of villages to no-take protected area; proportion of income of local fisherfolk that comes from mangroves located inside no-take PAs; proportion of local inhabitants who abandoned livelihood activities and suffered restrictions because of PAs.	Interviews; focal group discussions	Fisherfolk; key informants	Quantitative and qualitative	Local
		Financial						
		Social						

complex reality, this can be useful for comparisons between villages regarding their vulnerability to climate change, the effects of protected areas and the relative importance of each vulnerability component, which can help in defining management priorities. Furthermore, qualitative information can also be used to guide interpretations of the observed situation. An important decision for composing a vulnerability index is whether each sub-component should have a different weight. This demands careful judgment of the reality being studied. We propose to follow the “balanced weighted average approach” used in composing the Livelihood Vulnerability Index (Hahn *et al.* 2009), where each sub-component contributes equally to the overall index. This allows for a clear identification of the contribution of each indicator for the composition of the overall vulnerability of a population or ecosystem, facilitating comparisons and pointing management actions towards the most relevant situations.

Conclusions

Such a complex situation as the one described requires adequate management measures, focused not only on understanding and managing of immediate sources of impact on social and ecosystem process, but also on increasing the resilience of SESs so that they can support these impacts, especially those derived from global climate change. The challenge is to develop new practices and management policies which allow for the adaptation of productive systems to change, and, therefore, their viability and sustainability. For this to be achieved we must acquire sound knowledge about the elements that compose the vulnerability to climate change of the SES formed by mangroves and fisherfolk and the effects of biodiversity conservation policies on these elements. In this context, interdisciplinary research becomes essential in the characterization and analysis of the different types of impacts, the social and economic practices of human populations, and the vulnerability of ecosystems, of the environmental services they provide and of coastal populations. A sound diagnosis may lead to more flexible policies, elaborated with stakeholders’ participation, more adequate to local realities and more inclusive of strategies for mitigation and adaptation to climate change.

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Status of Eastern Brazilian coral reefs in time of climate changes

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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 acqui-red 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).

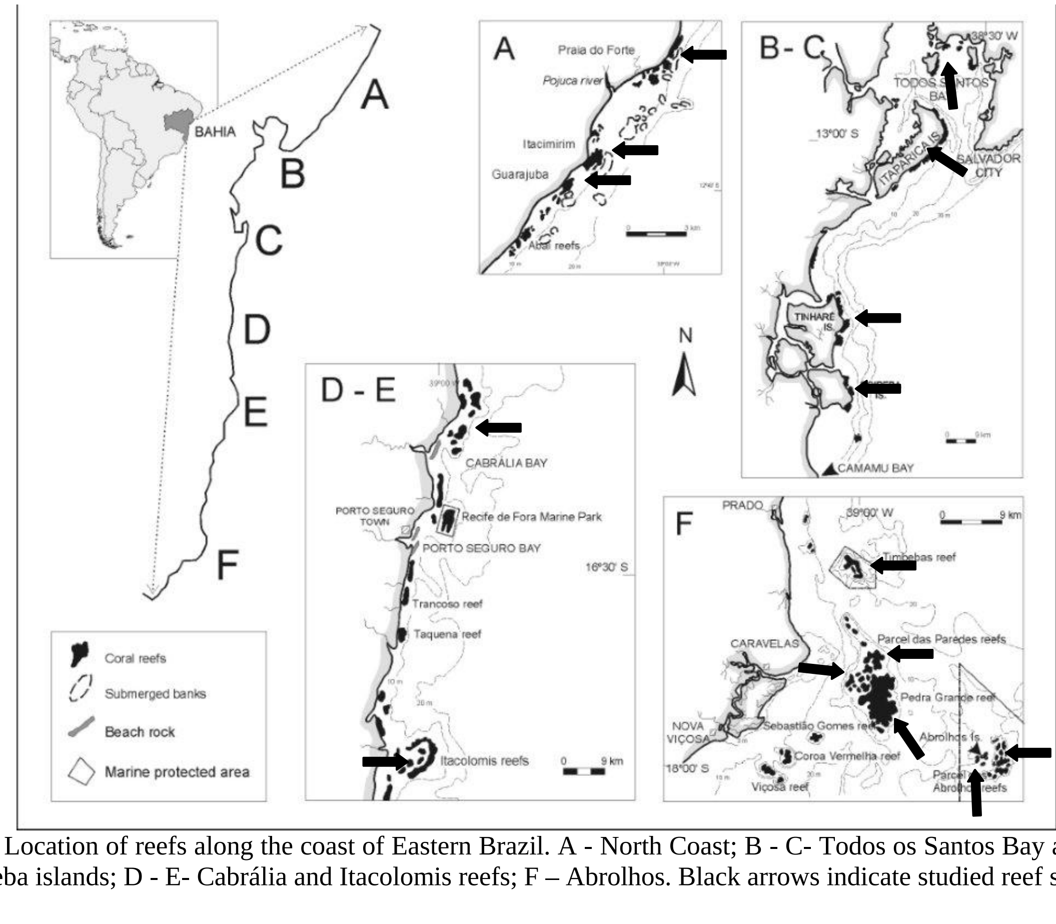

Figure 1. Location of reefs along the coast of Eastern Brazil. A - North Coast; B - C- Todos os Santos Bay and Tinharé and Boipeba islands; D - E- Cabrália and Itacolomis reefs; F – Abrolhos. Black arrows indicate studied reef sites.

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 ^oC). 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 n=6	12.3805º S 38.0200º W	4.5-8.5	1998	1.0 ºC > 1 week	Coral cover, colony diameter, # coral species, coral recruits	Belt transect (3x1m wide x 20m long) $60m^2$/site
Tinharé / Boipeba n=4	13.4910º S 38.9024º W	3.5-4.0	2003 2004	1.0 ºC > 1 week 0.25 ºC < 2 weeks	Coral cover, colony diameter, # coral species, coral recruits, coral dead surface, bleaching, disease, algal abundance	Belt transect (AGRRA) (6x1m wide x 10m long) $60m^2$/site
Cabralia n=6	16.2397º S 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) (6x1m wide x 10m long) $60m^2$/site
Itacolomis n=3	16.8976º S 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) (6x1m wide x 10m long) $60m^2$/site
Abrolhos coastal reefs n=20	17.4670º S - 18.0203º S 39.0004º W - 38.9883º W	2.0-8.0	2001 2002 2003 2005	0.50-0.75 ºC < 1 week 1.0 ºC > 2 weeks 0.75 ºC > 2 weeks	Coral cover, colony diameter, # coral species, coral recruits, coral dead surface, bleaching, disease, algal abundance	Belt transect (AGRRA) (6x1m wide x 10m long) $60m^2$/site
Abrolhos islands n=12	17.9673º S - 17.9794º S 38.7018º W - 38.7080º W	3.5-8.0	2000 2001 2002 2005	0.25 ºC < 2 weeks 0.50-0.75 ºC < 1 week 0.75 ºC > 2 weeks	Coral cover, colony diameter, # coral species, coral recruits, coral dead surface, bleaching, disease, algal abundance	Belt transect (AGRRA) (6x1m wide x 10m long) $60m^2$/site
Abrolhos offshore reefs n=6	17.9977º S 38.6713º W	6.0-9.0	2000 2001 2002 2003	0.25 ºC < 2 weeks 0.50-0.75 ºC < 1 week 1.0 ºC > 2 weeks	Coral cover, colony diameter, # coral species, coral recruits, coral dead surface, bleaching, disease, algal abundance	Belt transect (AGRRA) (6x1m wide x 10m long) $60m^2$/site
Todos Santos Bay n=32	12.4720º S-13.1037º S 38.3134º W-38.4532º W	3.0-8.0	2003 n=9 2007 n=23	1.0 ºC > 2 weeks No SST anomaly	Coral cover, # coral species, algal abundance, other benthics (sponge, zoanthus, soft coral)	Belt transect (Video) (10x0.20m wide x 20m long) $40m^2$/site
Salvador City Yatch Club	12.5900º S 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 several reefs N=14	17.4701º S-17.5732º S 39.0141º W-38.3020º W	4.3-15.0	2006 2007 2008	No SST anomaly No SST anomaly 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).

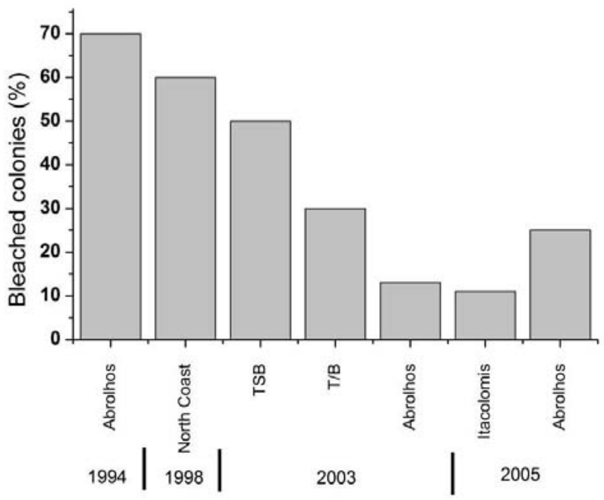

Figure 2. Average percentages of bleached coral colonies measured during longer term events of sea water temperature anomalies ≥ 1 ºC, along the coast of Eastern Brazil. TSB = Todos os Santos Bay, T/B = Tinharé and Boipeba islands.

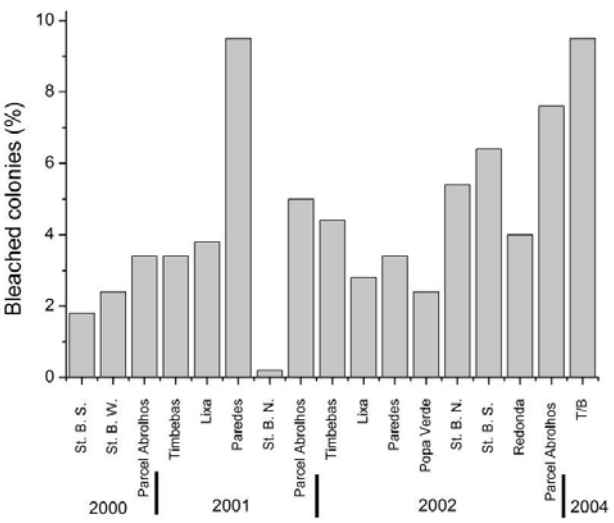

Figure 3. Average percentages of bleached coral colonies measured during short term events of sea water temperature anomalies ≤ 0.75 ºC. St. B. S = Santa Barbara South; St. B. W. = Santa Barbara West; St. B. N. = Santa Barbara North; T/B = Tinharé and Boipeba islands.

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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Temporal and meridional variability of Satellite-estimates of surface chlorophyll concentration over the Brazilian continental shelf

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Abstract. Forecast of biological consequences of climate changes depend on both long-term observations and the establishment of carbon budgets within pelagic ecosystems, including the assessment of biomasses and activities of all players in the global carbon cycle. Approximately 25% of oceanic primary happen over continental shelves, so these are important sites for studies of global carbon dynamics. The Brazilian Continental Shelf (BCS) has sparse and non-systematic *in situ* information on phytoplankton biomass, making products derived from ocean color remote sensing extremely valuable. This work analyzes chlorophyll concentration (Chl) estimated from four ocean color sensors (CZCS, OCTS, SeaWiFS and MODIS) over the BCS, to compare Chl and annual cycles meridionally. Also, useful complementary ocean color variables are presented. Chl gradients increased from the central region towards north and south, limited by estuarine plumes of Amazon and La Plata rivers, and clear annual Chl cycles appear in most areas. In southern and central areas, annual cycles show strong seasonal variability while interannual and long-term variability are equally important in the remaining areas. This is the first comparative evaluation of the Chl over the BCS and will aid the understanding of its long-term variability; essential initial step for discussions of climate changes.

Keywords: South West Atlantic, ocean color remote sensing, chlorophyll concentration, Annual Variability, CDOM index, Fluorescence Line Height

Resumo. Variabilidade temporal e meridional de estimativas de Satélite da concentração de clorofila superficial na plataforma continental brasileira. Previsões de conseqüências biológicas nos oceanos às alterações do clima dependem de bases de dados longas e da quantificação das trocas de carbono nos ambientes pelagiais, incluindo a caracterização das biomassas e atividades de organismos-chave do ciclo global de carbono. Cerca de 25% da produtividade primária global acontece nas plataformas continentais, assim essas são regiões de estudo essenciais na dinâmica ciclo de carbono. Na Plataforma Continental Brasileira (PCB), as informações sobre a biomassa do fitoplâncton são esparsas, tornando dados de satélite da cor do oceano valiosos. Nesse trabalho, analisamos concentrações de clorofila (Chl) estimadas por quatro sensores (CZCS, OCTS, SeaWiFS e MODIS) sobre a PCB para compará-la meridionalmente e sazonalmente. Apresentamos ainda duas variáveis (linha de fluorescência e o índice de Matéria Orgânica Dissolvida) que podem ser usadas para a interpretação da Chl. Os gradientes de Chl enfatizam duas áreas extremas, influenciadas pelas plumas dos rios Amazonas e La Plata, e forçantes interanuais nas regiões centrais. Os resultados são a primeira comparação da Chl na PCB, que poderá guiar estudos futuros para o entendimento de suas variabilidades em longa escala, etapa inicial fundamental para estudos sobre mudanças climáticas.

Palavras-chave: Atlântico Sul Ocidental, Cor do Oceano por sensoriamento remoto, Concentração de Clorofila, Variações Anuais, Altura da Linha de Fluorescência, Índice de MODC

Introduction

The discussion of effects of climate change in oceanic biological processes remains controversial. While reports show fast increases in both CO_2 concentrations in the atmosphere and in ocean's temperatures (IPCC 2007), the biological consequences directly related to these changes are often questionable. Detailed budgets for the global carbon cycle are oversimplified (Houghton 2007), and current predictive models do not accommodate the role of biological processes. More importantly, the lack of long-term biological observations makes it difficult to detect robust changes with time in the oceanic biota. Therefore, efforts are needed to quantify abundances and distributions of key biological marine players in the carbon cycle, such as phytoplankton (Anderson 2005), and to describe quantitatively the processes in which they participate (Le Quere *et al.* 2009).

In the open ocean, the influence of climate changes in processes mediated by phytoplankton are generally based on trends with time, derived from variables such as chlorophyll concentration or primary productivity (PP) rates (Sarmiento *et al.* 2004). Decreases in PP rates have been related to enhancement of vertical stratification in warm waters (Polovina *et al.* 2008), while increases are associated with increases in sea water temperature in cold regions (Rysgaard *et al.* 1999). Biological effects are also link to episodic events such as increases on chlorophyll concentration after passages of hurricanes (Goldenberg *et al.* 2001). In continental shelves, expected changes include altering freshwater outflows (Belkin 2009) and the strength and temporal scales of costal upwelling events (Bakun 1990, Mote & Mantua 2002), and hence nutrient inputs and circulation patterns. All these biological processes will vary regionally, making it imperative to characterize them within these scales.

Long-existent observational sites that include systematic acquisition of biological data are infrequent in the global ocean, but recent international programs and funding efforts (Dickey *et al.* 2009, Johnson *et al.* 2009) will certainly change this panorama the future (*e.g.* complementary sensors in Argo floats, see http://www.argo.ucsd.edu/). Nonetheless, a key source for observing and understanding the upper ocean layer remain satellite data, which provide sinoptic views of biological oceanographic processes through variables retrieved from ocean color sensors. The spectral reflectance emerging from the oceans are used in empirical algorithms and modeling techniques to estimate phytoplankton biomass (i.e, chlorophyll concentration; see O'reilly *et al.* 1998) and other dissolved and particulate components (Carder *et al.* 1986, Ciotti *et al.* 1999, Lee *et al.* 1998, Maritorena *et al.* 2002, Roesler & Perry 1995). Ocean color data combined with information on sea surface temperature, downwelling irradiance and mixed layer depth allow for estimates of primary production rates (Campbell *et al.* 2002, Carr *et al.* 2006, Friedrichs *et al.* 2009). More recently, a number of bio-optical models were designed to discriminate among phytoplankton types or communities (Alvain *et al.* 2005, Ciotti & Bricaud 2006, Sathyendranath *et al.* 2004).

Freely available ocean color data exists since 1978 (McClain 2009) being global for the past 12 years (http://oceancolor.gsfc.nasa.gov). Logically, decade-long time series are inadequate to subsidize climate change studies, but these data has improved our knowledge on annual cycles of phytoplankton biomass (Kahru *et al.* 2004, Longhurst 1995), and can also be helpful to identify inter-annual variability (Henson and Thomas 2007). It is essential to understand how phytoplankton biomass change in time in order to develop conceptual models on phytoplankton dynamics, and ocean color is still the only source of information in many regions where observational studies have been sparse.

The Brazilian Continental Shelf (BCS) occupies over 40º degrees of latitude (Fig. 1) and contains significant regional differences concerning mainly its extension, the influence of offshore circulation, the overall area of the continental shelf and continent runoff inputs (Castro & Miranda 1998, Castro *et al.* 2006). Thus, the physical processes controlling nutrients and light availability for phytoplankton growth or accumulation vary meridionally. Surveys performed on the BCS describing temporal and spatial distributions of phytoplankton biomass and primary production have been fairly unsystematic, but latitudinal differences were reported and temporal patterns have already been showed in some areas (Brandini 1997, Gaeta & Brandini 2006, Ciotti *et al.* 2006). It is important also to mention that these sparse observations have been derived from a variety of methods, which despite of being standard oceanographic procedures have never being inter-compared to date.

It is acknowledged that ocean color products have been developed for open ocean and their use over continental shelves can be sometimes problematic, especially in areas receiving considerable amounts of continental outflows. The global algorithms that retrieve chlorophyll concentration (Chl) presume a covariance between in situ Chl and the relative contributions of all other optically active components in the light field, thus, so when them effectively absorb blue-light, which is the case for detritus or colored dissolved matter (CDOM), Chl is overestimated. The MODIS/Aqua ocean color sensor has additional spectral red bands that are sensitive to the natural fluorescence for chlorophyll present in living cells (Esaias *et al.* 1998, Gower *et al.* 2004). NASA is currently distributing these data as “evaluation products” named fluorescence line height (FLH). The interpretation of FLH is not trivial (Huot *et al.* 2005, 2007), and many issues regarding the role of phytoplankton physiology and taxonomy over the FLH signal and on the actual efficiency of fluorescence by phytoplankton living at the surface of the ocean remain unresolved (Schallenberg *et al.* 2008). Nonetheless, in a first approximation, FLH registered over continental shelf areas that receive significant continental outflow can be an alternative or a complement for blue-green ratios algorithms’ for Chl estimates, as the contribution of detritus and CDOM to FLH tend to be minimal (Gower *et al.* 2004). Even in the open ocean, CDOM is an important optical component for light absorption (Siegel *et al.* 2002), and recently, an additional bio-optical product has been developed (Morel & Gentili 2009) and distributed by NASA - the CDOM index- that intends to offer a metric option to observe CDOM versus phytoplankton influences in a given area.

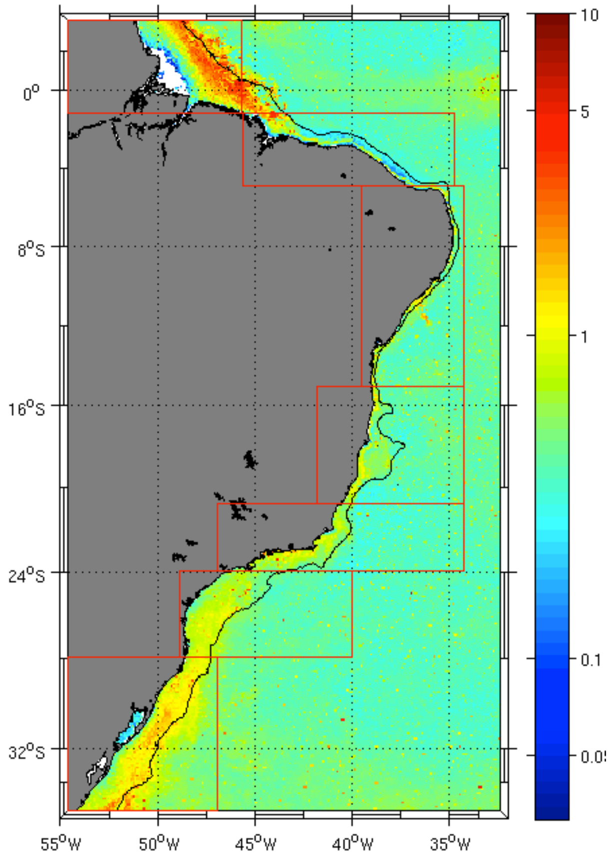

Figure 1. The Brazilian Continental Shelf (BCS) and the subdivision used in this work (Areas 1 to 7 from North to South). Image color gradients show the annual standard deviation of the annual mean chlorophyll concentration ($mg.m^{-3}$) in log scale, for the combined 2000 to 2005 data derived from SeaWIFs. Line represents the 200 m isobath that defines the continental shelf boundary.

The studies conducted over the BCS using ocean color data were mostly regional, except by that from Gonzalez-Silvera *et al.* (2004), which also included observations in the open ocean. Published work comprise studies on the behavior of North Brazil Current (Johns *et al.* 1990, Richardson *et al.* 1994, Fratantoni & Glickson 2002), the confluence of Brazil and Malvinas Currents (Garcia *et al.* 2004, Saraceno *et al.* 2005, Barre *et al.* 2006, Gonzalez-Silvera *et al.* 2006), Amazon & La Plata Plumes signatures (Froidefond *et al.* 2002, Hu *et al.* 2004, Del Vecchio & Subramaniam 2004, Cherubin & Richardson 2007, Garcia & Garcia 2008, Piola *et al.* 2008, Molleri *et al.* 2010), and the tracking of mesoscale features (Bentz *et al.* 2004). Validation and verification of ocean color models have also been conducted (Garcia *et al.* 2005, 2006, Ciotti & Bricaud 2006).

Descriptions and comparative analyses are needed to better understand seasonal and interannual changes of the phytoplankton standing stock over the BCS, as space and time characterizations are crucial initial steps for studies of eventual global change effects. In this work, we gathered all available remote sensing ocean color data for the BCS, derived from 4 ocean-color sensors, to quantify and compare observed Chl, FLH and the CDOM-index over time. We divided the BCS into 7 large regions following Castro *et al.* (2006). Our main objectives were: i) to examine meridional variability in chlorophyll concentrations derived by satellite; ii) to assess the quality of the data available, concerning mainly data coverage; iii) inter-compare chlorophyll products from two sensors (SeaWiFS and MODIS/Aqua); and iv) to establish annual cycles and interannual variability of chlorophyll concentration for all regions. We will also describe spatial and temporal trends of FLH and the CDOM-index over the subareas, and compare these indices to Chl.

Data and Methods

Satellite Data

Data from mapped, 8-Day, global composite images (L3) were downloaded from Ocean Color Home Page (http://oceancolor.gsfc.nasa.gov) and consist of the entire data sets available for Coastal Zone Color Scanner (CZCS), Ocean Color Temperature Sensor (OCTS), Sea-viewing Wide Field-of-view Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer on the Aqua satellite (MODIS/Aqua) up to 31 December 2009 (see Table I). These data sets are reprocessed from time to time, which is necessary for sensor calibration and algorithm improvements. In the present work, data from SeaWiFS refer to reprocessing 2009.1 (December 2009), data from MODIS/Aqua refer to reprocessing 1.1 (August 2005), and data from both CZCS and OCTS were last reprocessed in October 2006. MODIS/Aqua has been fully operational since its launch while a number of gaps for SeaWiFs data, due to problems with the instrument, occurred in 2008 (January 3 to April 3; July 2 to August 18) and 2009 (April 24 to June 15; July 3 to July 17; August 31 to November 5; and November 14 to 30). Further details on each sensor and respective data sets can be found in the official distribution site (http://oceancolor.gsfc.nasa.gov).

Products distributed as Level 3 used in this work included chlorophyll concentration (all sensors), sea surface temperature (MODIS/Aqua), fluorescence line height (MODIS/Aqua) and the CDOM index (SeaWiFS), computed by the respective standard global algorithms and masks. Note that spatial resolutions for L3 images are 4 km for CZCS and MODIS/Aqua, and 9 km for OCTS and SeaWiFS, and were preserved as such.

Images were processed using SeaDAS (v5.4) - a multi-platform software freely distributed by NASA (http://oceancolor.gsfc.nasa.gov/seadas). The bathymetry dataset from SEADAS was used to set apart image pixels occurring over the continental shelf, assumed here as those where local depths ranged from 20 to 200 m. The lower limit of 20 m was set to exclude the effects of both local geography and possible bottom effects. For each satellite product and sensor, the proportion of data coverage was computed as the number of pixels with valid data (i.e., those not masked by land, clouds or algorithm's failures) over the total number of pixels expected between 20 and 200 meters. We used 8-Day spatial resolution of all products and sensors that yielded 46 observations per year. We also grouped SeaWiFS and MODIS/Aqua chlorophyll concentration and data coverage by seasons, so that Fall refers to images starting on days of the year 80 to 162, Winter images from days 168 to 258, Spring images from days 264 to 346 and Summer images from days 352 to 361 and days 1 to 74.

Meridional Division and Basic Statistics

The BCS was divided into 7 (seven) large areas, which are a slight modification of the division into six compartments proposed by Castro and Miranda (1998). The original 6 (six) areas were divided according with physical processes and presence of distinct water masses. Our modification scheme was basically shifting latitudinal boundaries necessary to i) keep the areas more comparable in size; and ii) to accommodate, within each area, similar values for mean and standard deviations of satellite surface chlorophyll (Fig. 1). For each 8-Day satellite product and area, basic statistics (mean, median, standard deviation) were computed, but respective time series represent the median values, rather the mean, in order to focus our discussion on central values and also to avoid extreme or too localized values. Nonetheless, we present the entire statistical distributions by area and ocean color sensor (see Fig. 2).

Annual Cycle and Long-Term Variability of Chlorophyll

Chlorophyll data for SeaWifs were averaged over the 46 8-Day composites to produce a pseudo-climatology, or general mean, for the 12 years (up to 31 December 2009). The 8-Day general means were in turn used to compute 8-Day "anomaly" values for all the composites. The "chlorophyll anomalies" were then log-transformed and used to model the amplitude and phase of the mean annual cycle observed over each area throughout the 12-year series. The annual mean model is based on a nonlinear least square procedure (see Garcia *et al.* 2004 for details), that assumes a sinusoidal form with a single amplitude over the 46 composites registered in a year. The ratio of the variance explained by the annual model to the total variance - correlation of determination (r^2) - for each time series per area was also calculated to verify the goodness of the model, and here describe the consistence of a seasonal variability in the chlorophyll concentration. It is important to note that low correlation of determination observed per area reflects both the inadequacy of the single amplitude (*e.g.*, seasonal cycles can have more than an oscillation per year) and also interannual variability, but in this case we expect the latter to be more important as the majority of BCS is located in tropical and subtropical areas.

To observe long-term variability in SeaWiFS Chl anomaly per area, we first applied a running mean filter (equivalent to 46, or a year of 8-Day mean observations), to create smoothed series, each being normalized by their respective standard deviation. The filtered data were then subjected to spectral analysis, which used the variance-preserving form of the energy spectrum (Emery & Thomson 2004) so to make the total energy of the signals observed among areas comparable. These are simple techniques, that were chosen to accommodate our present goals, but future work should include a number of more sophisticated time-series techniques (*e.g.*, EOFs; wavelets) to better understand the long-term variability of chlorophyll fields in the different

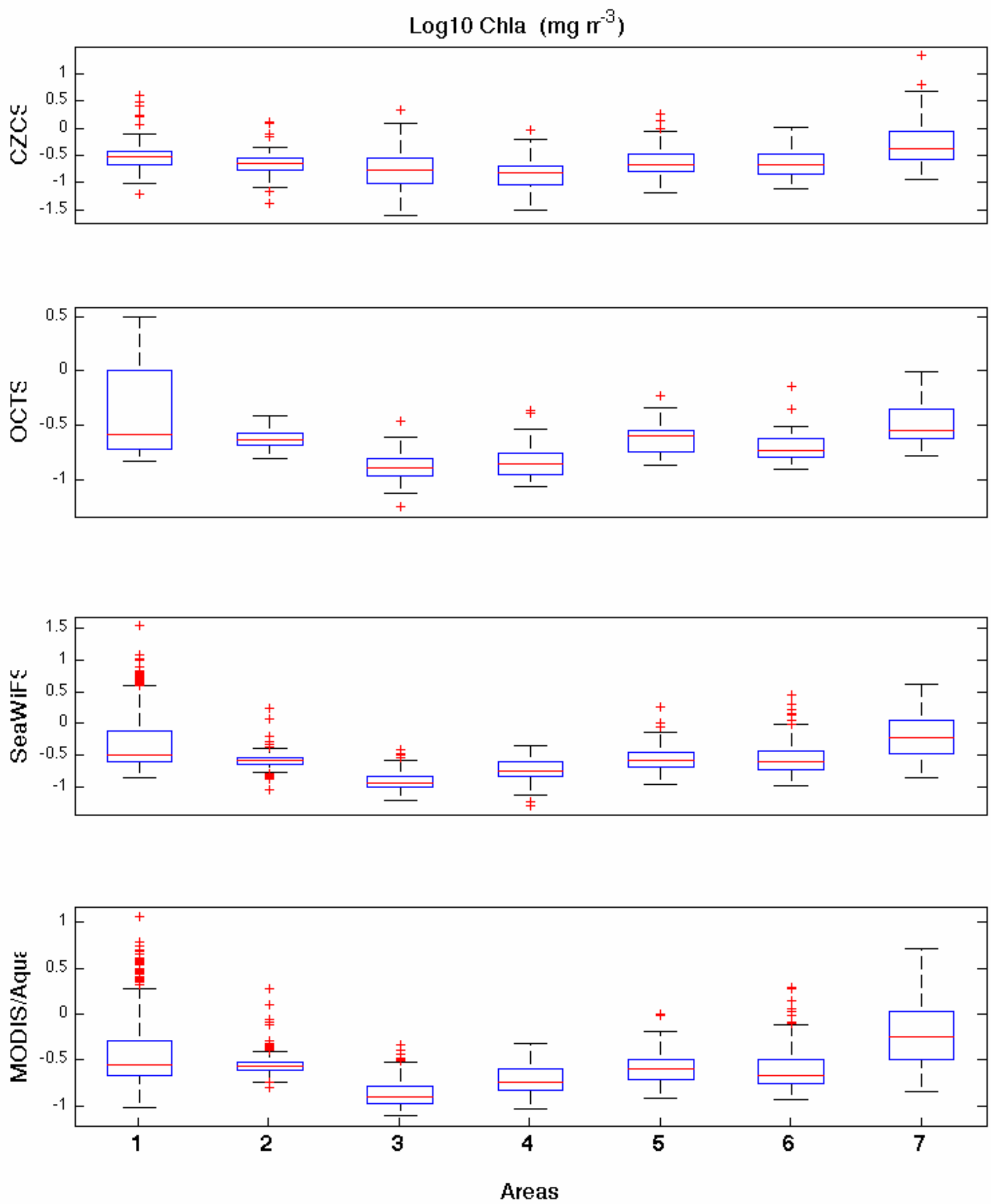

Figure 2. Box plots showing the range and statistics of chlorophyll values observed by the different sensors over the seven subareas of the Brazilian Continental Shelf. Red lines represent the medians and each box represents the 50% percentile (i.e., mean is the center of the box). Note that the distributions are derived from different temporal resolutions from each sensor (see Table I). Red crosses are outliers.

zones of the BCS and their relation to other environmental variables (ex. river discharge, wind stress, surface current, etc.).

Results and Discussion

Despite of the smaller area compared to the open ocean, continental shelves account for about 25% of oceanic global primary production (Longhurst *et al.* 1995). However, it is difficult to quantify time and spatial variability of phytoplankton biomass over these areas. A number of complex, and not yet fully quantifiable processes, interfere on observed phytoplankton standing stocks, usually estimated with chlorophyll concentration (Chl). General spatial patterns for Chl do exist in the surface ocean, resulting from differences in nutrient and light availability for phytoplankton growth (or Chl accumulation) governed by regional and global physical processes (see Holt *et al.* 2009 and references therein). However, other important terms to be considered when Chl distributions are compared in time and space include less understood processes as grazing, sedimentation and advection rates for phytoplankton cells (Banse 1994) because they depend on ecological and physiological components that are difficult to observe. Over continental shelves, all chemical and biological processes are associated with larger Chl in

Table I. Characteristics of the four ocean color sensors that can provide information on the Brazilian Continental Shelf on chlorophyll concentration. Note operating periods.

Spectral Bands (only visible and near infrared only)				
Sensor	Central wavelength (nm)	Spectral resolution (nm)	Spatial resolution (m)	Operating dates
CZCS[1]	443; 520; 550; 670	20	825	24/10/1978 -
	750	100		22/6/1986
OCTS[2]	412; 443; 490; 520	20	700	
	565; 670	20		03/9/1996 -
	765; 865	40		29/6/1997
SeaWiFS[3]	412; 443; 490; 510	20	1100	
	555; 690	20		29/8/1997 -
	765; 865	40		present
	531	5	1000	
	443; 488; 551	10	1000	
	667; 678; 936	10	1000	
MODIS[4]/	412; 748; 869	15	1000	
Aqua	469; 555; 1240	20	500	04/07/2002 -present
	858	25	250	
	905; 1375	30	1000	
	940	40	1000	
	645	50	250	

Obs:[1]Coastal Zone Color Scanner; [2]Ocean Color Temperature Sensor, [3]Sea-viewing Wide Field-of-view Sensor, [4]Moderate Resolution Imaging Spectroradiometer

comparison with the open ocean, within also a more complex physical dynamics (Longhurst 2006). Thus, we stress that the patterns presented here for meridional and seasonal Chl are a result from a number of processes yet to be quantified, so they neither translate directly into primary production nor exportation rates for phytoplankton carbon.

Remote Sensing Chlorophyll Observed in the BCS

The meridional and seasonal distributions of Chl over the large and heterogeneous BCS (Fig. 1) can be related to the equally diverse dominant physical influences (Castro & Miranda 1998). When data from the four ocean color sensors are compared, similar general statistical distributions for Chl (Fig. 2) emerged, especially for SeaWiFS and MODIS/Aqua sensors, which result from almost a decade of their simultaneous data acquisition (Table II). The OCTS sensor operated for less than a year, and there are only about 30 8-Day images available for the BSC. Lacks in data acquisition (Table II) represent besides instrument problems, cloud coverage and algorithm failures.

The highest degree of Chl variability was found in the latitudinal extremes of BCS (Areas 1 and 7) while Chl was remarkable constant in Area 2. The highest and lowest mean Chl values were found in Areas 7 and 3, respectively (Fig. 2) differing about an order of magnitude from each other (*e.g.*, ~1.0 versus ~0.1 mg.m^{-3}). Meridional 8-Day median Chl variability as a function of time and the Chl statistical distribution (Figs. 2 and 3) suggest the importance of the distinct degrees of seasonality in the different areas, but as indicated by some recent studies on physical processes (*e.g.*, Dotori & Castro 2009) we also expect a significant contribution of interannual variability may also be expected.

Data coverage by the distinct sensors also showed important seasonal patterns (Fig. 4) that will be assessed below, but we found no significant statistical relationships between data coverage and Chl for a given Area or sensor. For instance, both SeaWiFS and MODIS/Aqua coverage were remarkable poor in Area 1 during the summer months, period when Chl was also low, while Areas 3 and 7 showed good data coverage year round, and a clear seasonal Chl pattern. Figures 3 and 4 point out the discontinuity for CZCS data coverage in the BSC (see also Table II), which is a result of NASA's strategy of turning off the sensor when it was outside the main interest areas due to limited on-board storage data and to preserve the sensor (Mcclain, 2009). Indeed, CZCS had its life expectancy expanded for several years, but unfortunately, the low data coverage over the BSC prevent studies to integrate its data with those acquired by the current operational sensors (*e.g.*, SeaWiFs and MODIS/Aqua - but see also www.ioccg.org/ sensors/current.html) in order to produce longer time-series. Recent literature show, for areas where CZCS data is available, detectable trends in Chl with time that suggested alterations in the marine biota (*e.g.*, Antoine *et al.* 2005). Studies like these at the BSC are, unfortunately, limited today to 12 years of continuous ocean color data data (i.e., SeaWiFs and MODIS/Aqua), and none our chosen Areas has showed strong positive or negative Chl trends with time. It is worth mentioning that understanding the impacts of global change demands long-term biological observations and that will be jeopardized for the BCS if the current NASA’s programs are discontinued. Thus, it is imperative to create and maintain new ocean color programs and to involve the Brazilian scientific community on using and interpreting its potential products.

Seasonal and Meridional Chl variability

The seasonal mean Chl per area derived by SeaWiFS and MODIS/Aqua (Table III), place Area 3 as a boundary of low Chl that separates gradients towards north and south. Maximum Chl per area increases steeply towards north (3-fold in Area 2 and an order of magnitude in Area 1) occurring during fall while towards south, Chl gradients were gradual and occurred during winter. In Areas 3 and 4, Chl was high and similar in fall and winter, and low and similar in spring and summer. Area 2 showed a single and modest Chl peak in the fall. Periods with minimum Chl values also varied meridionaly, and were observed during spring in Area 1 and during summer in Areas 5, 6 and 7.

The seasonal and meridional distribution of mean data coverage per Area and instrument (Tab. III), showed that only half of the 8-Day composite images were available most of the year in Area 1 and that data coverage was about 13 to 18% during summer and 23 to 27% during fall. Area 2 has also showed poor data coverage during summer (29 to 33%) and fall (44 to 53%).

It was possible to model significant annual cycles in all Areas, except for Area 2 (Table IV). The best fits were found in Areas 7 and 4, suggesting that the main processes for accumulation and loss of phytoplankton biomass operate rather seasonally, especially in Area 7 (r^2=0.78). All remaining Areas showed correlations of 0.52 to 0.58 to the annual model, probably a result of important inter-annual variability as in Area 1 in 2001 and Area 6 during 2007 (Fig. 5), for instance.

The meridional patterns of Chl were indeed related to the main reported seasonal changes in hydrography. In Area 1, the most prominent feature is the Amazon River discharge, which provides seasonally dissolved colored material, nutrients, sediments and detritus to larger extensions of the continental shelf. During the rainy seasons (summer and spring) larger river discharge is combined with changes in both wind direction (from SE to NE) and in transport rates of the North Brazil Current (Molleri *et al.* 2010). Both the size and the orientation of the Amazon plume are responsible for the magnitude and seasonal Chl variability and also reflect the amount of particles and dissolved load that can interfere in the Chl algorithm performance.

Chl changes in Areas 2 and 3 are likely to be associated with variability in the biological processes, probably driven by changes in water temperature and irradiance, since neither major river flow nor relevant oceanographic features (*e.g.*, upwelling) are reported for those two areas, which are the least studied ones of our BSC subdivision. In Area 2, no significant parameters could be found for the annual variability in Chl (Table IV), which showed a fall Chl peak only about 25% higher than that for the remaining of the year. Area 3 showed the lowest Chl in comparison to all other Areas, with a strong seasonal cycle. The annual amplitudes detected by the SeaWiFs time series were 0.04 and 0.12 mg.m^{-3} for Areas 2 and 3, respectively (Table IV). It is important to remember that Area 3 is the smallest despite occupying over 10 degrees of latitude.

Areas 2 to 4 are also under direct influence of the seasonal and meridional migration of the Inter-Tropical Convergence Zone (ITCZ) in the south Atlantic and thus they will likely respond to any mode of change in the wind fields. Northern and weak winds occur in the summer, enhancing vertical stratification that in turn is expected to disfavor Chl accumulation. In the winter, southern and stronger winds have been already linked to increases in Chl in Area 4 due to the erosion of the picnocline and consequent fertilization of the surface layers (Ciotti *et al.* 2006). In addition, Area 4 comprises the Abrolhos region with a shallow continental shelf, allowing addition of nutrients by ressuspension of bottom water masses. The seasonal influence of wind regimes on vertical mixing is suggested by the good adjustment of the Chl series to the annual model (Table IV). Abrolhos, and a number of banks adjacent to Area 4 affect the flow and direction of the Brazil Current (BC). As a consequence, the main flow of the BC shows mesoscale instabilities and meanders (Gaeta *et al.* 1999) that have a significant impact on the circulation of the Areas towards the south (Calado *et al.* 2008, Silveira *et al.* 2008).

Areas 5 and the northern third of Area 6 encompass the most studied regions of the BSC (see review in Castro *et al.* 2006). Areas 5 and 6 were separated at São Sebastião Island latitude because of their important distinct oceanographic features. Area 5 includes Cabo São Tomé and Cabo Frio, where

Table II. Division for the BSC in subareas based on Castro *et al.* (2006). For each sensor and area, columns represent the number of 8-Day images with no data; n is the length of each sensor data sets (up to the end 2009 for those operational) for 8-Day images. Also, the total number of Pixels over the delimited continental shelf (20 to 200 m): 9 km for OCTS and SeaWiFS and 4 km for CZCS and MODIS/Aqua.

Area and latitudinal range	SeaWIFS (n=568)	Modis/Aqua (n=345)	OCTS (n=30)	CZCS (n=353)	Number of 9 Km pixels	Number of 4 Km pixels
1 - 04N-01S	37	3	3	282	1742	6918
2 - 01S-05S	35	2	2	240	561	2237
3- 05S-15S	36	2	0	259	258	1017
4- 15S-21S	39	2	1	285	656	2587
5- 21S-24S	39	2	3	298	689	2727
6- 24S-28S	37	2	0	297	1229	4937
7- 28S-34S	37	2	0	270	1288	5168

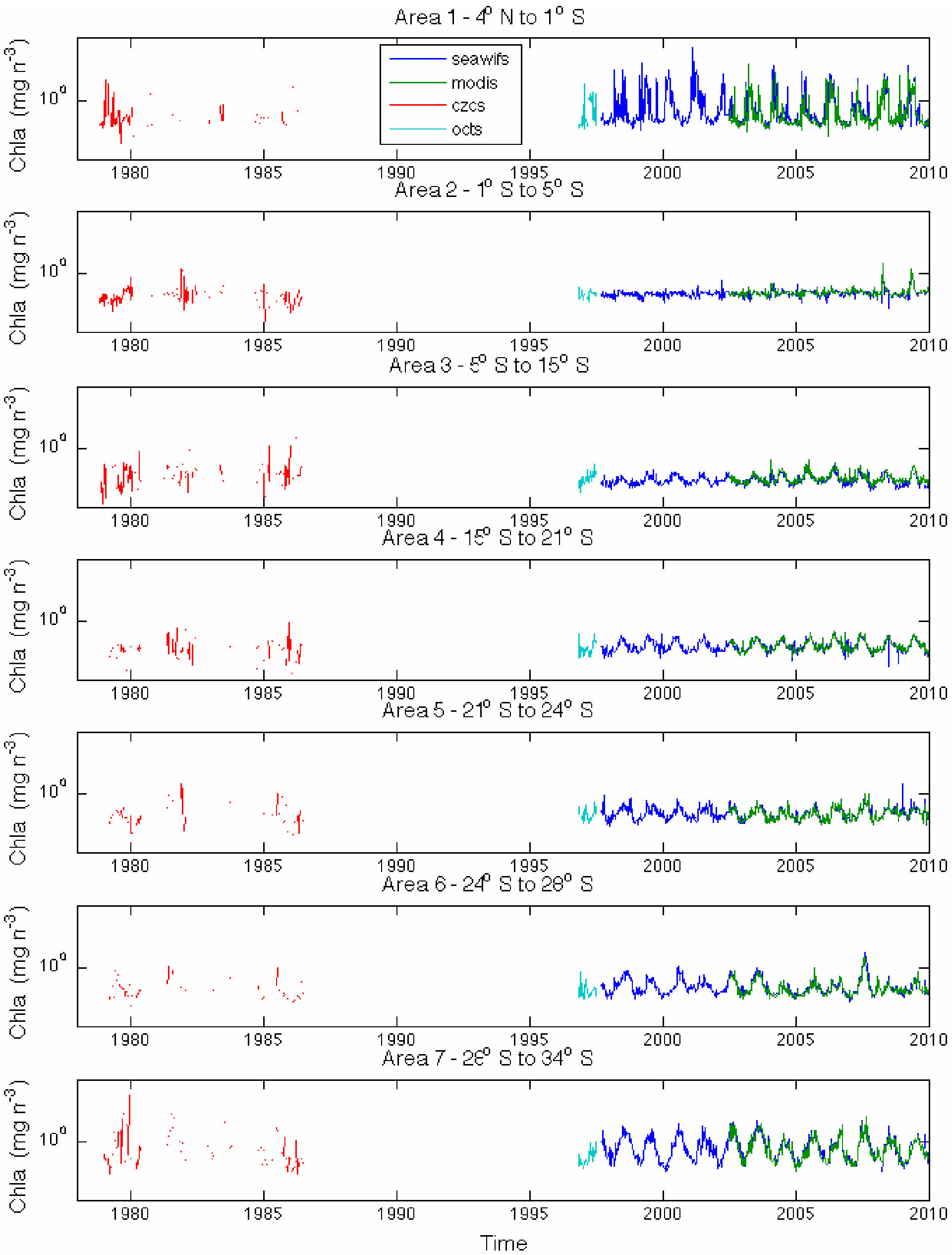

Figure 3. Time series of 8-Day median chlorophyll concentration over the seven Areas of the BCS (see Table I for limits), provided by the four ocean color sensors (see legend) during their respective operation periods.

costal upwelling occurs in the summer (see Guenther *et al.* 2008 and references). The upwelling plumes tend to move offshore in São Tomé, and towards south through the inner and median continental shelves in Cabo Frio. In the revision by Guenther *et al.* (2008), it is presented that the upwelling of the South Atlantic Central Water (ACAS) to the surface, shifs the system from oligotrophic to eutrophic conditions, and thus, Chl accumulation would be expected during the summer (period where the upwelling events are more intense), which was not shown in the present analyses (Table III). Indeed, maximum Chl occur in winter in Area 5. Numerical models and observations, however, show that the shelf currents respond to mesoscale wind fields, which are most intense during winter in response to passages of atmospheric cold front systems (Dotori & Castro 2009). Also, it is important to note that a strong deep Chl maximum associated with the permanence of ACAS intrusions at the subsurface have been observed in Area 5 (Sumida *et al.* 2005) which perhaps the ocean color sensors do not not efficiently detect (André 1992). Other possible cause of the seasonal Chl pattern observed in Area 5 (and 6) is related to the flow of BC that in the summer is closer to the coast (Silva Jr. *et al.* 1996) inducing

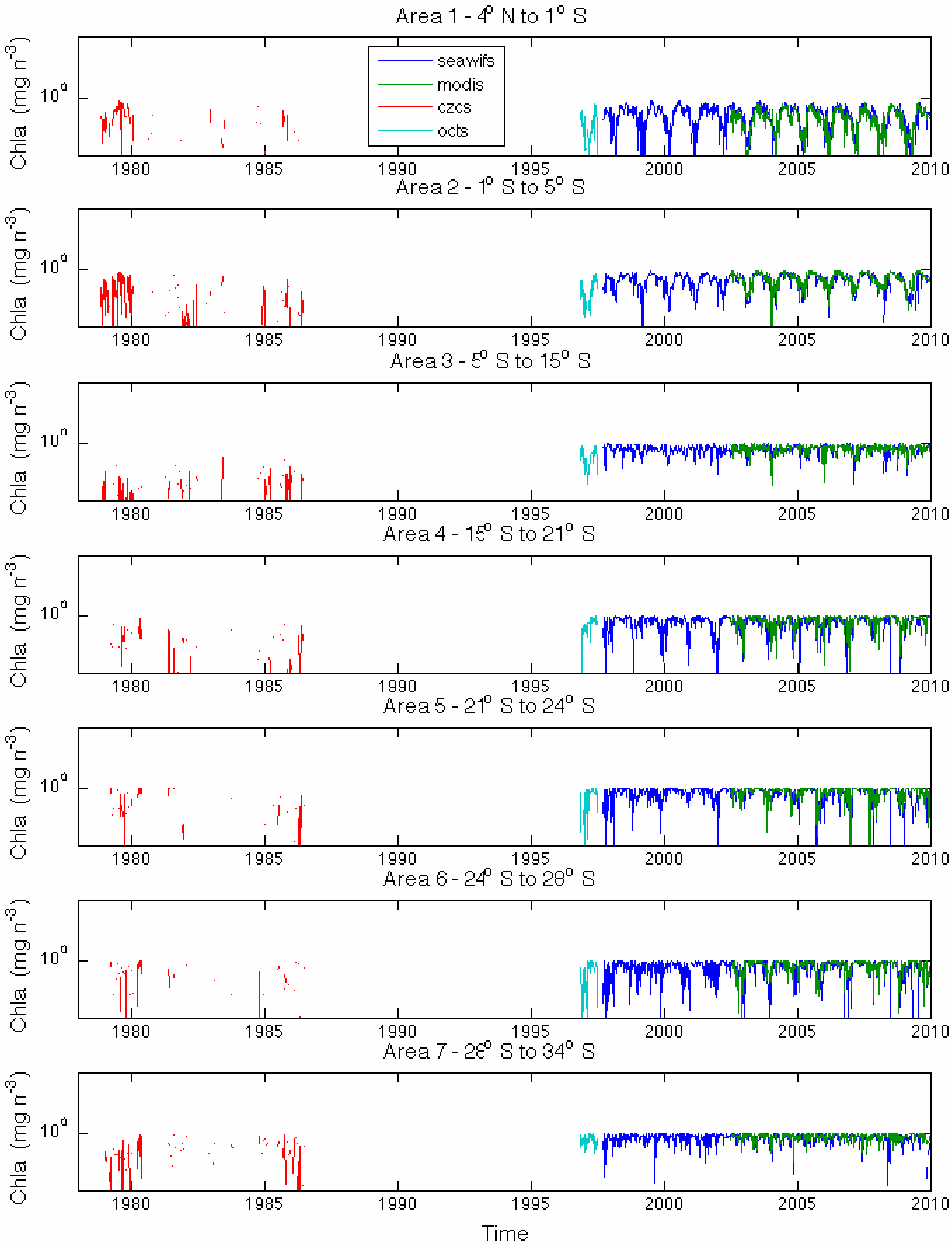

Figure 4. Time series of 8-Day median data coverage (i.e., 1 would represent that 100% of the subarea had valid data) concentration over alternated subareas of the BCS (see Table I), provided by the four ocean color sensors (see legend).

coastal downwelling of oligotrophic warm waters at Areas 5 and 6. Upwelling events in Cabo Frio are usually short, and our approach compared large Areas and 8-Day image composites, therefore, the relative importance of the coastal upwelling process may have been masked. Nonetheless, we cannot exclude the role of biological factors such as grazing and sedimentation explaining these patterns. Note also that the upwelling plumes tend to stay in Area 5, but the modeled annual amplitudes for both Areas 4 and 5 are exactly the same (Tab. IV). Mean Chl is only slightly higher in Area 5 during winter, while the goodness for the annual fit is higher in Area 4, suggesting that interannual influences on Chl accumulation are more important in Area 5 than in Area 4.

In winter, Areas 6 and 7 (but mainly Area 7, as we discussed below) receive a coastal water mass originated from the south portion of Brazil, with nutrients from the outflows of both Rio de la Plata and Lagoa dos Patos (Piola & Romero 2004, Pimenta *et al.* 2005). Indeed, the relative contribution of Colored Dissolved Organic Mater (CDOM) has been showed to be higher in winter in Area 6 (Ciotti unpublished data) which may imply that the Chl values could be overestimated due to presence of CDOM. Note that the goodness for the fit to the annual model in Area 6 is about the same of that observed in Area 5, suggesting important interannual forcing in Area 6 as well.

Area 7 comprises the southernmost portion of Brazilian continental shelf waters. The influence of both La Plata River and Pato's Lagoon discharges on ocean color imagery has been recently reported (Garcia & Garcia 2008, Piola *et al.* 2008). The extent of the La Plata plume over the Brazilian shelf is associated with both surface winds and river discharge (Piola *et al.* 2008, Garcia & Garcia 2008). During winter, the La Plata plume extension is associated with more intense and persistent

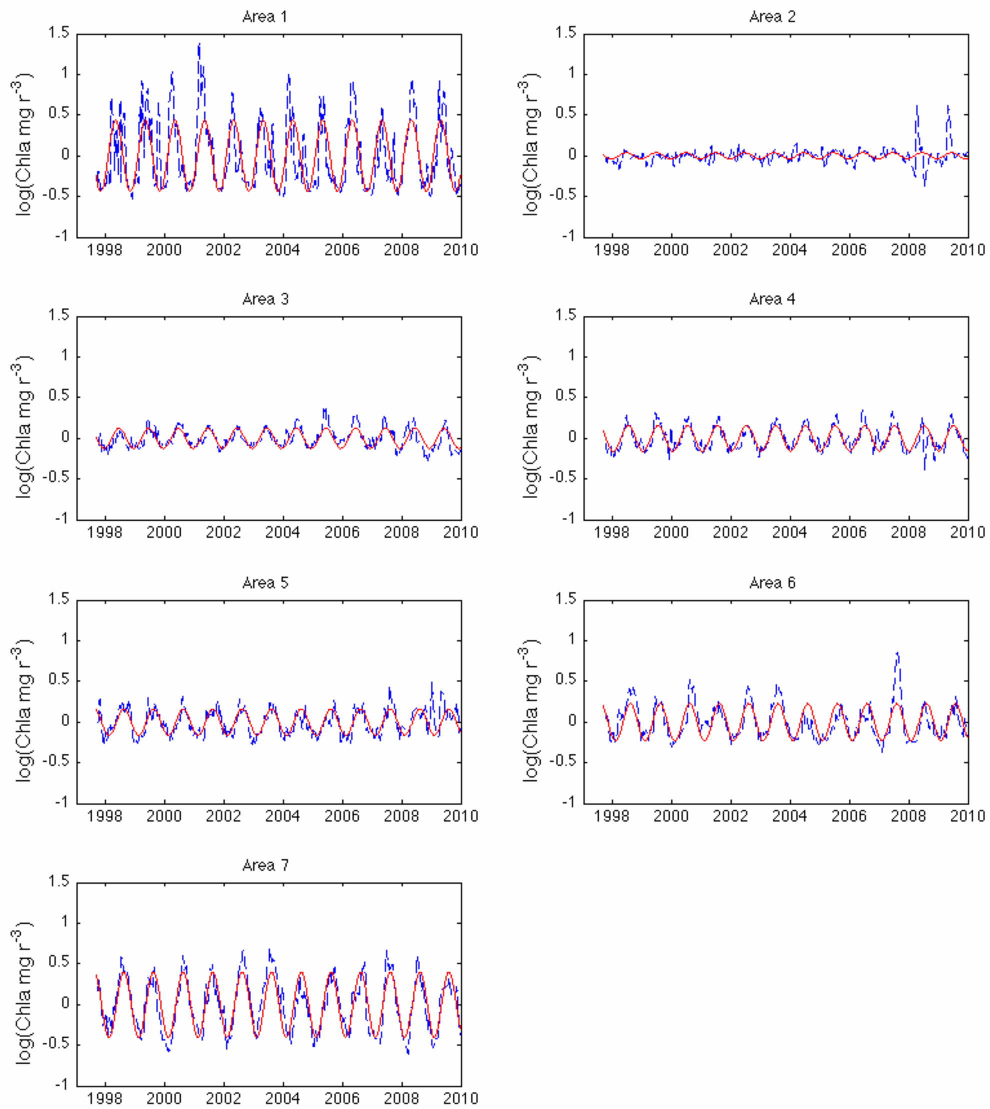

Figure 5. Annual cycles of chlorophyll concentration (Chl, mg.m^{-3}) adjusted for each subarea (red solid line) versus observed Chl values in each 8-Day period (blue doted line).

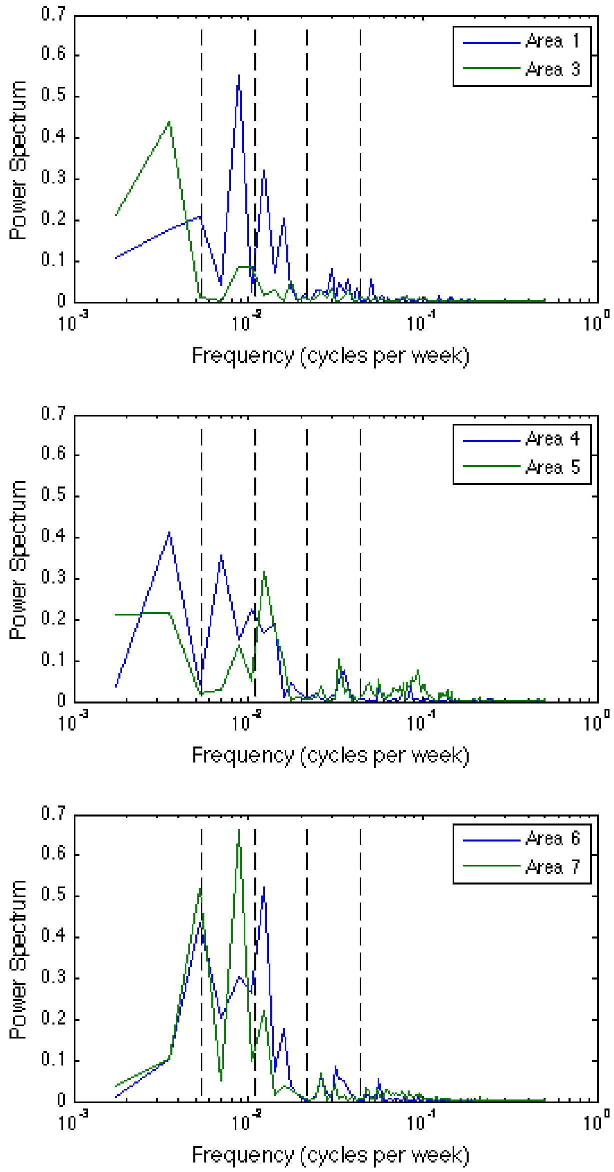

Figure 6. A variance-preserving plot of power energy (in mg2 m-6) for the normalized deseasoned chlorophyll time series from Areas 1 and 3 (above), Areas 4 and 5 (middle), and Areas 6 and 7 (below). The vertical dashed lines stand for ½ year, 1 year, 2 year and 4 years cycles, from right to left, respectively.

northeast winds rather than with increases in discharge by the La Plata River. Garcia and Garcia (2008) demonstrated the annual cycle as the most dominant mode of variability over the southern Brazilian continental shelf, and the associated high amplitude in the annual cycle (see Table IV) is mainly controlled by the seasonal variation in the incursion of La Plata plume. The northward La Plata River plume extension varies from year to year (Piola *et al*. 2008) leading to a strong interannual variability in Chl is also expected in the region. The few observations also show larger in situ chlorophyll concentration during spring and winter in Area 7 (Ciotti *et al.* 1995). The meridional gradient of Chl from Area 7 to Area 3 during winter (Table III) that is probably related to the seasonal migration of La Plata River plume reflected in the amplitudes for the annual fits up to Area 3 (Table IV).

Comparison Between SeaWiFS and MODIS/ Aqua Chl and Data Coverage

Because of the inconsistencies for both CSZC and OCTS data acquisition over the BCS, our seasonal comparisons over the seven Areas were performed only for SeaWiFS and for MODIS/Aqua (Table III), during periods when the 8-Day composite images were available for both sensors. The non-parametric statistical tests to access significant differences between sensors for the same sample size (Table V) show statistically comparable Chl for the two sensors in most, but not in all Areas. Significant differences were mainly related to data coverage, especially during winter and fall, when SeaWiFS data coverage was higher in Area 1 but MODIS/Aqua data coverage was higher in the remaining Areas. Differences in Chl were detected in Areas 1, 2 and 3, with no apparent seasonal patterns. Note that we used data from MODIS/Aqua reprocessing 1.1, performed in August 2005.

Long-term variability of chlorophyll based on SeaWiFS 12-years period

The analyses of the interannual variability in Chl fields given by SeaWiFS dataset (Sept. 1997 to Dec. 2009) show clear seasonal cycles all regions, except in Area 2 (Table IV). In addition, the amount of energy contained in Chl anomalies derived spectra was an order of magnitude higher in Areas 1 and 7 (Fig. 6) due to the presence of Amazonas River (Area 1) and La Plata River (Area 7). Except for Area 2, the results suggest long term variation (> 2 years) in most of BCS. Note that the vertical axis in Figure 6 represent the total energy, given in [chla]2, where the signal variance is preserved within the frequency spectrum. A 4-years signal was observed in Areas 4 to 7 a pattern already detected in southern BCS (Garcia & Garcia 2008), who associated this signal with both cycles of La Plata river discharge and alongshore winds. In the remaining areas, the cycles may be associated with long-term changes on the Trade winds regime and mesoscale features.

Complementary information

It is outside the scope of this work to detail other variables than Chl and data coverage by the four ocean color sensors. However, the presence of a south to north gradient of Chl values in the winter that may be related to the seasonal meridional excursion of the La Plata river plume, lead us to investigate the general patterns observed in two additional ocean color products that may complement and aid the interpretation of Chl patterns (Fig. 7). The hypothesis to test is that the south-north Chl gradient observed in winter reflects partially the influence of continental outflows on over-estimatives for Chl due to the presence of CDOM.

As mentioned before, MODIS/Aqua provides data on sea surface temperature (SST) and chlorophyll fluorescence line height (FLH) that can complement Chl, and a new ocean color product (available for SeaWiFS and MODIS/Aqua) - the CDOM-index – can illustrate the relative importance of this component over phytoplankton. In a first approximation, FLH appears to confirm the trends shown by Chl:i) Area 3 showed the lowest FLH and CDOM-index, while the maximum were observed in both Areas 1 and 7. However, Area 2 is no longer the least variable, being replaced by Area 3 for both FLH and CDOM-index, which suggest that the seasonal variability on Area 3 may be a seasonal contribution of CDOM by changes in wind field. There is a contrast between Area 1 and 7 regarding the CDOM-index, much more evident in the south. Note also that Areas 5 and 6 have different mean FLH but similar Chl, with an apparent larger contribution of CDOM in Area 6 that may explain this divergence. A discussion in depth of these differences among products would require validation programs and the development of semi-analytical regional models. Our goal here is to point out that data are already available for scientific interests in physical and biological processes in the BCS. Although these products are not free of some fundamental errors, they may be used to ask scientific questions and design better surveys.

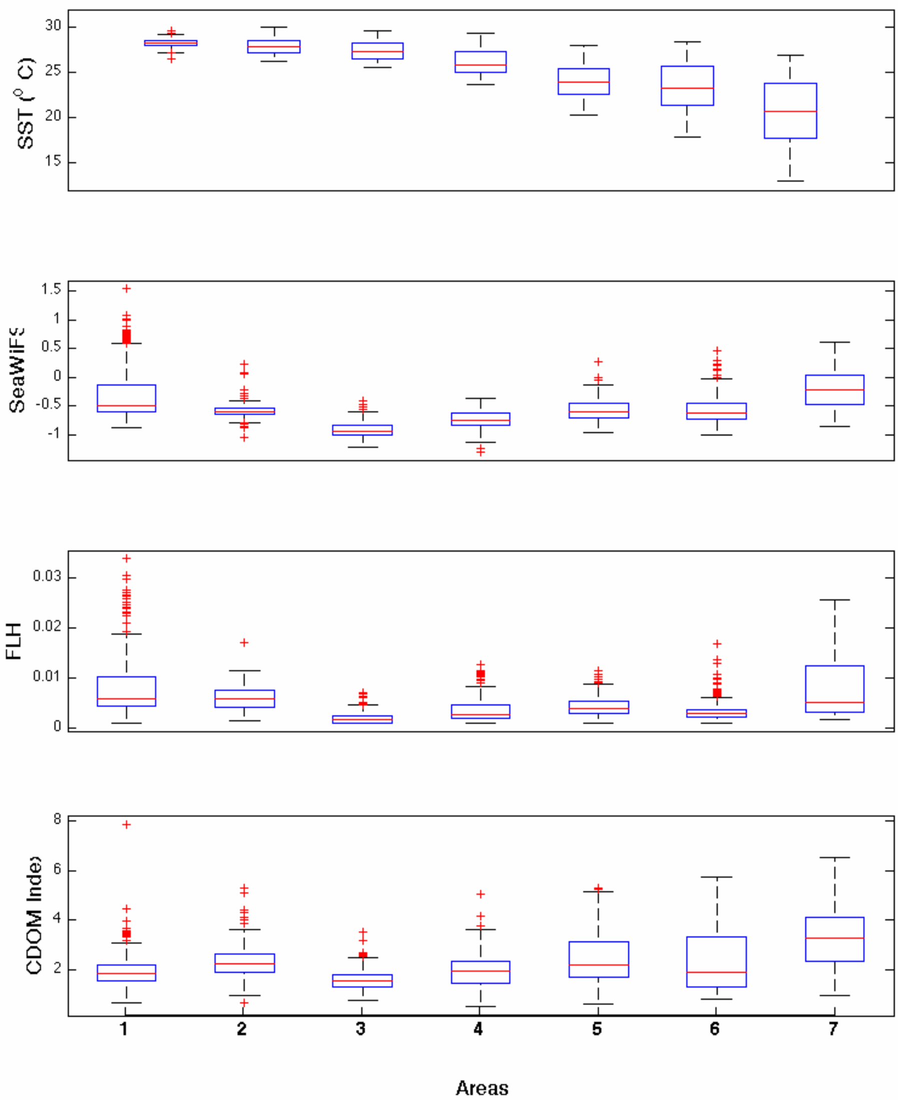

Figure 7. Statistical distributions for all available data per Area for Sea Surface Temperature (SST, MODIS/Aqua), Chlorophyll concentration (log scale; Chla SeaWiFS), Fluorescence Line Height (FLH, MODIS/Aqua) and the CDOM index (SeaWiFS).

Table III. Seasonal chl cycles and proportion of data coverage (i.e., 0 would represent no data while 1 would represent that all pixels had valid data) per region (Seawifs MODIS). Values represent the overall means for all 8-Day median values of Chl observed in each area. These means were computed for periods with concurrent data acquired by both sensors, up to 31 December 2009.

SeaWiFS								
Season	Fall		Winter		Spring		Summer	
Area and latitudinal range	CHL Mean (Std)	COVER Mean (Std)	CHL Mean (Std)	COVER Mean (Std)	CHL Mean (Std)	COVER Mean (Std)	CHL Mean (Std)	COVER Mean (Std)
1 - 4N-1S	2.17 (2.05)	0.27 (0.20)	0.54 (0.57)	0.53 (0.17)	0.25 (0.07)	0.41 (0.12)	0.91 (1.72)	0.18 (0.13)
2- 1S-5S	0.32 (0.23)	0.44 (0.23)	0.27 (0.03)	0.71 (0.15)	0.25 (0.03)	0.58 (0.12)	0.25 (0.07)	0.29 (0.17)
3- 5S-15S	0.16 (0.05)	0.62 (0.18)	0.15 (0.04)	0.70 (0.15)	0.10 (0.02)	0.73 (0.18)	0.11 (0.02)	0.62 (0.24)
4- 15S-21S	0.23 (0.07)	0.74 (0.21)	0.26 (0.07)	0.73 (0.20)	0.16 (0.05)	0.52 (0.30)	0.15 (0.03)	0.58 (0.27)
5- 21S-24S	0.28 (0.11)	0.86 (0.20)	0.38 (0.12)	0.86 (0.21)	0.28 (0.11)	0.57 (0.30)	0.23 (0.21)	0.69 (0.29)
6- 24S-28S	0.27 (0.11)	0.79 (0.21)	0.55 (0.43)	0.75 (0.24)	0.25 (0.11)	0.48 (0.28)	0.18 (0.04)	0.65 (0.28)
7- 28S-34S	0.66 (0.42)	0.72 (0.24)	1.61 (0.79)	0.77 (0.20)	0.78 (0.52)	0.74 (0.25)	0.30 (0.13)	0.78 (0.18)

MODIS/Aqua								
Season	Fall		Winter		Spring		Summer	
Area and latitudinal range	CHL Mean (Std)	COVER Mean (Std)	CHL Mean (Std)	COVER Mean (Std)	CHL Mean (Std)	COVER Mean (Std)	CHL Mean (Std)	COVER Mean (Std)
1 - 4N-1S	1.72 (1.83)	0.23 (0.17)	0.50 (0.69	0.46 (0.14)	0.29 (0.56)	0.28 (0.11)	0.57 (0.85)	0.13 (0.10)
2- 1S-5S	0.36 (0.24)	0.53 (0.23)	0.26 (0.03	0.78 (0.10)	0.26 (0.03)	0.57 (0.11)	0.28 (0.07)	0.34 (0.16)
3- 5S-15S	0.18 (0.06)	0.67 (0.17)	0.17 (0.06	0.73 (0.14)	0.11 (0.02)	0.71 (0.15)	0.13 (0.06)	0.65 (0.21)
4- 15S-21S	0.24 (0.09)	0.83 (0.16)	0.28 (0.07	0.83 (0.15)	0.17 (0.05)	0.61 (0.27)	0.15 (0.02)	0.69 (0.24)
5- 21S-24S	0.27 (0.09)	0.93 (0.10)	0.36 (0.12)	0.91 (0.16)	0.26 (0.11)	0.62 (0.30)	0.20 (0.05)	0.77 (0.23)
6- 24S-28S	0.25 (0.10)	0.87 (0.16)	0.46 (0.32)	0.83 (0.22)	0.24 (0.08)	0.54 (0.25)	0.19 (0.06)	0.70 (0.25)
7- 28S-34S	0.59 (0.32)	0.82 (0.19)	1.47 (0.82)	0.82 (0.17)	0.76 (0.54)	0.77 (0.18)	0.31 (0.11)	0.80 (0.15)

Recommendations and Conclusions

We have shown that the ocean color data are adequate for time series studies but they are currently only a decade-long and quantification of long-term trends is not feasible at present time for the BCS. Our simple analyses have shown however, the presence of long-term and interannual variability that must be taken into account in future studies on BCS. Systematic ocean color measurements from multi-instrument, multi-platform and multi-year observations are needed to understand how annual and decadal-scale climate variability affects the growth of phytoplankton on the continental shelves. It is important to have satellite ocean color data available for the scientific community to access changes in phytoplankton biomass, dissolved material and other derived products. However, SeaWiFS, MODIS, and MERIS sensors are either well beyond or nearing the end of their design lives (Mc Clain 2009). The continuity for these products will only be achieved over the next decades if an effort is made to launch new ocean color sensors.

The data from new sensors have also to be open to all ocean *color* researchers, including the pre-launch characterization and on-orbit calibration

Table IV. Correlation values of the annual model for each region and their respective amplitudes. All values are statistically significant (>99% level) except for region 2.

Area and latitudinal range	R^2 to the Annual fit	Amplitude $mg.m^{-3}$
1 - 4N-1S	0.524	0.44
2- 1S-5S	0.083	0.04
3- 5S-15S	0.567	0.12
4- 15S-21S	0.640	0.16
5- 21S-24S	0.542	0.16
6- 24S-28S	0.576	0.23
7- 28S-34S	0.783	0.40

data, so a critical and constructive discussion is set in place to guarantee the quality of the products and the preservation of the experience from past programs. Among the new planned sensors are the Ocean Color Monitor (OCM-2, India) and the Visible-Infrared Imaging Radiometer Suite (VIIRS, United States). Brazilian and Argentinean governments will also launch an ocean color sensor (SABIA-MAR) and at present the design of potential instruments is under discussion.

For studying the BCS in the future, we must be aware of the necessity of both improving existing ocean color algorithms and validate ocean color products. Regional algorithms may also be needed in certain areas. Recent improvements in field observation capabilities and the increase in number of experts in bio-optical algorithms (empirical and semi-analytical) will definitely push this line of research forward, but programs must be designed and conducted in long term. However, the Brazilian ocean color community is concentrated in few institutions in the South and Southwest Brazilian (*e.g.*, Garcia *et al.* 2005, Kampel *et al.* 2009). Products and models will improve with time, if a long-term program is established for all the necessary steps and not only for data acquisition.

The experience of countries like UK and USA has shown that it is crucial to complement remote sensing programs with a net of observational key locations over the continental shelves where systematic and repeatable surveys are executed for many years. Besides acquiring and validating remote sensing data, we have also to be concerned with the processing and distribution of these data and products to the scientific community. Results of our simple comparison among Chl, FLH and CDOM-index fields are encouraging, but the interpretation of biological and physical mechanisms associated with spatial distributions of these products must be improved. There is also a need to incorporate ecological modeling as part of ocean color data interpretation, and the ocean color groups must invest in this line, or better the different groups should work together.

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Regime shifts, trends and interannual variations of water level in Mirim Lagoon, southern Brazil

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Abstract. Long-term changes of water level in Mirim Lagoon, southern Brazil, are strongly associated with the El Niño-Southern Oscillation (ENSO). However, the relationship between the water lever record and the Southern Oscillation Index changed during the last century. Two different regimes are identified. The first regime (1912-58) is drier than the second (1958-2002). Shifts in variance and wavelet analyses suggest that the extreme floods of 1941 and the subsequent drought of 1943-45 were very unusual climatic events. The following years, from 1945 to 1963, appear to be a transition towards a new climatic state characterized by more frequent El Niños. A positive trend for the entire period (> 1 m) was detected and is significant. The trend is apparently related to the higher frequency of ENSO warm events in the Pacific Ocean during the second half of the last century and references in literature report that this trend affects a wide region in subtropical South America. The record from Mirim Lagoon, spanning over 90 years, is a rare and very important indicator of long-term climatic variations and should be maintained and monitored in order to assess potential environmental changes.

Keywords: El Niño-Southern Oscillation, hydrological cycle, climate changes

Resumo. Mudanças de regime, tendências e variações interanuais de nível na Lagoa Mirim, sul do Brasil. Mudanças de longo período no nível da Lagoa Mirim, sul do Brasil, são fortemente associadas ao El Niño-Oscilação Sul. Entretanto, a relação entre nível registrado e o Índice de Oscilação Sul mudou ao longo do século passado. Dois regimes diferentes são identificados. O primeiro regime (1912-58) é mais seco que o segundo (1958-2002). Mudanças na variância e análise por ondeletas sugerem que a extrema inundação de 1941 e a seca subsequente de 1943-45 foram eventos climáticos singulares. Os anos seguintes, entre 1945-63, parecem ser uma transição para um novo estado climático, caracterizado pela maior frequência de El Niños. Uma tendência positiva maior que 1 m para todo o período foi detectada e é significante. A tendência parece relacionada à maior freqüência de El Niños no Oceano Pacífico durante a segunda metade do século passado e referências na literatura indicam que essa tendência afeta uma vasta região da América do Sul subtropical. O registro da Lagoa Mirim, cobrindo mais de 90 anos, é um raro e importante indicador de variaçõesclimáticas de longo período e deve ser monitorada com a finalidade de avaliar potenciais mudanças ambientais.

Palavras-chave: El Niño-Oscilação Sul, ciclo hidrológico, mudanças climáticas

Introduction

Mirim Lagoon (ML) catchment basin is part of Patos-Mirim hydrographic system, which comprises a portion of Rio Grande do Sul State (southern Brazil) and eastern Uruguay (Fig. 1). The Patos-Mirim system drains an approximate area of 200,000 km^2, with Patos Lagoon alone draining nearly 145,000 km^2. This hydrographic system exerts strong impacts on the adjacent costal area through the input of freshwater and nutrients (Ciotti *et al.* 1995). Its average discharge is 2,400 m³/s. However, during El Niño (EN) years, discharge may rise above 12,000 m³/s (Möller *et al.* 2001) inducing drastic changes in the regional ecosystem and continental shelf circulation and composition. This excessive discharge is associated with large interannual variations of rainfall over the basin. The average precipitation rate over the Patos-Mirim drainage basin is 1,200 mm/year. Above average rainfall in excess of 2,000 mm/year was observed during El Niño events and the lowest average value on record (near 800 mm/year) was observed during the 1988 La Niña (LN) (Beltrame & Tucci 1998). The mean surface area of ML is approximately 3,749 km^2 (185 km long and 20 km wide). Its catchment basin includes almost 55,000 km^2 (47% in Brazil, 53% in Uruguay) and ML is linked to the Patos Lagoon estuary through a 76-km narrow natural channel called São Gonçalo.

The term "coastal lagoon" usually refers to water bodies along the coast with one or more connections with the ocean (Bird, 2008). Therefore, although ML is traditionally known as a coastal lagoon, it resembles more closely an overflowing lake. In the past, Patos Lagoon brackish waters could reach ML through the São Gonçalo channel, damaging inundated rice crops in the region. To avoid salt penetration upstream, a subsurface dam was built across the channel in 1977 to block denser brackish waters but still allowing surface fluxes and navigation. The dam is 3.2 m high and is placed in a cross section where the mean depth is around 5 m. After the dam was built, ML waters remained fresh all the time, with an estimated mean overflow into Patos Lagoon of 700 m^3/s (Machado 2007). Changes of outlet conditions (as the subsurface dam) should only marginally influence mean overflowing lake levels (Bengtsson & Malm 1997).

In addition to rainfall-runoff relationship, the residence time of Patos-Mirim system is also influenced by synoptic scale atmospheric phenomena. With a narrow connection restricting fresh-seawater exchanges, circulation within the system is driven by the combined effect of winds and runoff.

Dynamically, the passage of a cold front and the associated strong south-southwesterly winds drive a water level set up in the northern region of both Mirim and Patos Lagoon (e.g. Möller *et al.* 2001). This could favor ML discharge, but also drives shelf waters against the coast, pushing seawater into the estuary and balancing the pressure gradient. Thus, seawater inflow and the wide flood plains along São Gonçalo channel slow down ML runoff. With the weakening of the southerly component of the winds and the establishment of northeasterlies, seawater retreats and the southward-pointing pressure gradient inside the lagoons acts to equalize the water level throughout the system, driving Patos Lagoon waters towards its estuarine area. This effect, together with the southward movement of ML waters, partially dams ML again, increasing its residence time. Northeasterly winds are predominant during the whole year with increasing importance of southwesterlies during wintertime, associated with atmospheric cold fronts propagating over the region on time scales ranging from 3 to 11 days (Stech & Lorenzetti 1992).

In general, Southeastern South America (SSA - Southern Brazil, Northeastern Argentina and Uruguay) experiences positive rainfall anomalies during EN events and negative anomalies during LN events (Grimm *et al.* 1998, 2000). This association also holds for streamflow anomalies, which present interannual cycles of 3.5 and 6.3 years, coherent with El Niño – Southern Oscillation (ENSO) cycles (Robertson & Mechoso 1998).

The relationship between ENSO and river runoff in Negro and Uruguay Rivers were explored by Mechoso & Perez-Irribaren (1992). They found a tendency for below average streamflow from June through December during LN events and a slightly tendency for above average streamflow from November through February during EN years.

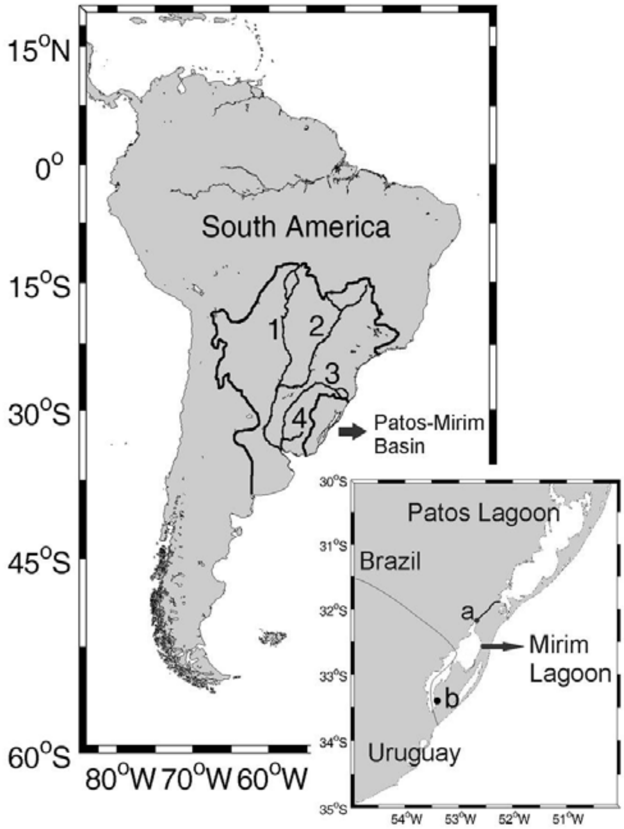

Figure 1. Map showing the La Plata River basin with (1 - Paraguay River, 2 - Paraná River, 3 - Uruguay River and 4 - Negro River) and Patos-Mirim basin. The detail shows the locations where the water level is observed (a - Santa Isabel and b - Santa Vitória do Palmar). The thick black line represents the São Gonçalo channel.

The study of Robertson & Mechoso (1998) also found a near-decadal cycle (approximately 9 years) most marked in the streamflows of Paraná and Paraguay Rivers. The authors pointed out that this cycle is associated with sea surface temperature (SST) anomalies over the tropical North Atlantic Ocean, mostly significant in austral summer. An apparent co-variability of the 9-year cycle and SST anomalies south of Greenland, also suggested a relationship of this cycle with the North Atlantic Oscillation (NAO). Negative SST anomalies would be associated with enhanced Paraná and Paraguay Rivers streamflow. They also suggested a relation to the decadal variability of the summer monsoon system and the southward moisture flux associated with the low-level jet along the eastern flank of the Andes Mountains. This impact would regulate a rainfall see-saw between the region influenced by the South Atlantic Convergence Zone and the subtropical plains of SSA. The see-saw pattern is described by Nogués-Paegle & Mo (1997). Numerical simulations presented by Robertson *et al.* (2000) showed that NAO interannual fluctuations are highly correlated with SST anomalies in the tropical and subtropical South Atlantic Ocean, accompanied by variations in the summer monsoon over South America.

Rainfall is the major source of long-term variability in the hydrological cycle over SSA once variations in evaporation seem to be less important (Berbery & Barros 2002). Positive trends of precipitation were detected over the region and related to a change to more negative Southern Oscillation Index (SOI) conditions in the tropical Pacific Ocean since the 1960's (Haylock *et al.* 2006). Genta *et al.* (1998) focused attention on the existence of long-term trends of streamflow in four major rivers in the region (Uruguay, Negro, Paraná and Paraguay). They reported a general increase in streamflow beginning in the mid-1960s consistent with a decrease in the amplitude of the seasonal cycle. In the case of the Negro River, the positive trend began almost 15 years earlier, just after the extreme drought of 1943-45. Examining SST anomalies in eastern equatorial Pacific Ocean, they suggested that an important component of the observed increase in streamflow is associated with large-scale low-frequency variability of the global climate system and the long-term trend is also possibly associated to changes in the Amazon region.

Long-term behavior of Pacific Ocean SST conditions is usually associated with interdecadal oscillations (Mantua *et al.* 1997, Zhang *et al.* 1997). Abrupt changes from one phase of this interdecadal cycle to another are commonly referred to as regime shifts. In 1977, the leading principal component of SST anomalies of the North Pacific changed from mostly negative to mostly positive values (Mantua *et al.* 1997). Since then, there is uprising ambiguity in the use of the term "regime shift" (Overland *et al.* 2008). According to these authors, confusion arises as a consequence of: (1) the shortness of climatic datasets, (2) the lack of evidence on the existence of different stable modes of the climate system (each stable mode would characterize one regime), and (3) the different usages of the term "regime" amid climate scientists. Therefore, a clear definition of the term is necessary.

Here, we follow the "displacement" viewpoint of regime shifts and use the algorithm designed by Rodionov (2004) to identify them. The displacement concept is solely based on time series analysis of relatively short records (<50 years) in which different multi-year intervals present statistically significant differences in mean relative to their variance (Overland *et al.* 2008). In other words, the mean of one time interval is significantly displaced up or down relative to a subsequent period. Regime shifts described with this definition are dependent on the length of the record, the choice of statistical parameters and may indeed constitute part of a lower frequency cycle. Hence, the regimes defined in the subsequent sections are relative to the period covered by the ML water level record only. Rodionov's algorithm was designed to be operationally used and, as new observations become available, the robustness of the regime shifts may be tested again. Consequently, we reaffirm the importance of continued monitoring and mechanistic understanding of shifts identified by this methodology on several variables (especially in the Pacific Ocean basin), as highlighted by Overland *et al.* (2008).

The aim of the present study is to use the ML water level record to assess the impact of global climatic patterns (ENSO and NAO) over the region, and to verify the existence and temporal structure of long-term trends and regimes of mean water level and variance in the local hydrological cycle. In the next section we describe the data and statistical methods used in this investigation, with special attention to Rodionov's algorithm. Regime shifts, a positive trend and main periodicities are then described and discussed.

Material and methods

The ML monthly water level time series from January 1912 to December 2002 (Fig. 2a) is available at the Mirim Lagoon Development Agency of the Federal University of Pelotas (Rio Grande do Sul, Brazil). The monthly mean is calculated from daily records measured at two locations (Santa Vitória do Palmar and Santa Isabel, see Fig. 1 for reference). The long-term mean was removed before the application of any statistical procedure and from now on we will refer to the ML water level anomalies simply as water level unless otherwise stated.

Statistical analyses described below were carried out in 3 steps. First, the monthly time series was transformed into a mean annual water level series in order to reduce the effects of serial correlation prior to the regime shift analysis. Second, the monthly time series was used to test the existence and significance of a long-term trend. Last, the monthly values were used again to explore the temporal variability of the record through wavelet analysis.

High serial correlation impacts the rejection rate of the null hypothesis of no regime shift. Thus, monthly means were used to construct a series of mean annual water level. This procedure reduced the lag-1 serial correlation from more than 0.9 to nearly 0.30 (Fig. 3). Then, a prewhitening procedure was performed using a lag-1 autoregressive approach (von Storch 1995) corrected by the Inverse Proportionality with 4 corrections (IP4) method (Rodionov 2006). Rodionov (2006) demonstrated that this method keeps the rejection rate of the null hypothesis close to the target significance level (0.1) for series with autocorrelations as high as 0.6 prior to prewhitening. The author considers the analysis with a prewhitening procedure a more conservative method because it increases the chance of missing a true regime shift but, if a shift is detected, its significance can be accurately estimated.

The existence of regime shifts of mean and variance were tested using a sequential data processing technique based on the Student's t test (Rodionov 2004). From the number of independent observations, the Student's test determines the difference in mean necessary for a significant shift of regimes to occur. Considering a time series, for each new observation, the algorithm tests the null hypothesis of the existence of a regime shift using the cumulative sum of normalized anomalies. The parameters of the analysis were the same as those used by Rodionov (2006) in his analysis of the annual Pacific Decadal Oscillation index (cutoff length = 15, Huber weight parameter = 1 and target significance level = 0.1). The test for a shift in variance was applied over the difference between the original mean annual time series and the prewhitened time series using the same cutoff length and significance level.

The algorithm is very sensitive to the choice of these parameters. The cutoff length determines the minimum length of a possible regime. As we are dealing with annual averages, a cutoff length of 15 indicates that a regime, if identified, will have 15 or more years. The choice of 15 years was made in order to avoid the selection of near-decadal cycles as regimes. The Huber weight parameter is a way of reducing the impact of outliers, allowing an even more conservative analysis. The value of Huber's parameter indicates the value above which an observation is considered an outlier (number of standard deviations). Then, any outlier is weighted inversely proportional to their distance from the mean of the regime.

In overflowing lakes as ML, water level observations only allow the conclusion that the climate has been excessively humid (if it is the case) and even drastic climatic changes have minor influences on lake levels and small amplitude interannual variations (Bengtsson & Malm 1997). Still, the circulation and dynamics of the Patos-Mirim system, as discussed in the introduction, induces a higher autocorrelation value with longer lags. This means that ML water level behavior may not resemble that of a pure overflowing lake and may show a clearer impact of climatic forcings. Therefore, our choice of cutoff length and Huber's parameter intend to select regimes longer than 15 years and avoid an excessive flattening of extreme events due to the possible smallness of long period differences in the record.

The trend and its significance were tested using monthly mean values. A linear regression in a least-squares sense was used to estimate the trend and its significance was assessed by a Monte Carlo technique to manage the impact of serial correlation (Livezey & Chen 1983).

Periodicities were explored using wavelet analysis (Torrence & Compo 1998). Wavelet analysis was carried out using a Morlet wavelet (wavenumber 6) with an initial scale of 6 months. The Morlet wavelet was chosen because it is nonorthogonal (better suited for time series analysis with expected continuous variations in wavelet amplitude) and complex (better adapted to capture oscillatory behavior). Moreover, arbitrary choices of different nonorthogonal and complex wavelets do not qualitatively change the results (Torrence & Compo 1998). The variation rate of scales was set to 0.25 corresponding to approximately 271 scales. The maximum scale is 22 years and the series were zero padded before convolutions.

The ML water level time series was then

compared with monthly times series of the SOI and the NAO station based index through cross and coherence wavelet analysis (Grinsted *et al.* 2003). Relative phase relationship in the plots is shown by arrows, where in-phase behavior (no lag co-variation) is denoted by arrows pointing to the right and anti-phase relationship, by arrows pointing to the left. When ML water level leads by 90º, the arrows point straight down. The time lag between the two signals can be estimated by the phase relationship:

$$\text{time lag} = [\ (\Phi \times \pi/180) \times \lambda]\ /\ 2;$$

Where Φ is the angle of the arrow and λ is the wavelength (in this case, the period correspondent to a given frequency band).

The SOI time series used here is the standardized sea level pressure difference between Darwin (Australia) and Tahiti. It was obtained online from the Australian Bureau of Meteorology (BOM) Internet site (http://migre.me/3wXkX). The monthly NAO station based index is provided by Jim Hurrell’s webpage (http://migre.me/3wXtE) at the Climate Analysis Section of the National Center for Atmospheric Research (CAS, NCAR). The index is the difference of normalized sea level pressures between Ponta Delgada (Azores, Portugal) and Stykkisholmur/Reykjavik (Iceland). The probability density function of the NAO index time series is highly bimodal (two discrete peaks) and, as suggested by Grinsted *et al.* (2003), it was transformed to percentiles in order to enhance the results of the analysis.

Results

Before removing the mean of the series, it is possible to observe that the maximum water level of 4.8 meters occurred near the end of the record while the minimum value is reached by the beginning of 1943 (anomalies in Fig. 2a). The 1943-45 period, recognized as the worst drought of the last century in SSA by Genta *et al.* (1998), is also evident in the ML water level time series.

The hydraulic behavior of ML induced by its morphology and dynamics is apparent in the time series. Figure 3 shows lagged autocorrelations for the water level time series with and without the seasonal cycle. The high values and slow decay of the autocorrelation coefficient toward higher lags indicate that the ML water level has strong dependence from month to month. This character-ristic supports the idea that the synoptic scale dynamics that was suppose to drive water exchange between ML and Patos Lagoon estuary is not capable to overcome the long memory of the time series variability.

Rodionov (2004)’s sequential method to detect regime shifts in the annual mean water level series revealed only one shift, in 1958. Before 1958, the annual mean water level was approximately -0.28 m (-0.34 m considering Huber's weighted mean). After the shift, the mean water level jumped to 0.27 m (weighted mean of 0.20 m). The confidence level (CF) of the difference between the means before and after the shift (tested by a Student's two-tailed test with unequal variance) is 6.54×10^{-4}. This very small value indicates that it is very unlikely that this shift had occurred by chance or as a result of red noise. The existence of two different regimes agrees with the hypothesis of Genta *et al.* (1998) for their streamflow series, in the sense that the later period has a higher mean water level than the first one. No signal of shift was detected around 1977, when the subsurface dam was built in the São Gonçalo channel.

The test for a shift in variance resulted in 5 different regimes. The first and last shifts in variance (1919 and 2001) are too close to the record ends, being smaller than the cutoff frequency of 15 years, and should be viewed with caution. From 1912 to 1918 the estimated variance was 0.84. The shift of 1919 has a CF of 5.55×10^{-4}, suggesting that it had not occurred by chance. The following period, from 1919 to 1946, had a smaller variance of 0.10 and, in 1947, a second regime shift was detected (CF = 5.33×10^{-5}). The variance jumped to 1.10 for 15 years. In 1963, the variance decreased to 0.51 (CF = 6.29×10^{-4}) and remained in this level for 38 years, until 2001, when the last shift is detected (CF = 0.57).

The CF in the last shift is poor and the regime is much shorter than the cutoff length. This shift should be taken as "on test" and may be confirmed by new observations. Figure 2b highlights the regime shifts described above. The variance regimes will be later compared with the wavelet analysis results.

After the statistical detection of two regimes with significantly different mean annual water level, the monthly time series is used to detect a difference in the annual cycle between the two periods. Estimating the annual cycle from the mean values for each month of the year results in a shift to higher water levels during the entire year, accompanied by a longer season with positive values (Fig. 4). In this case, the amplitude of the annual cycle is smaller for the second period (1.30 m from 1912 to 1957 against 1.21 m from 1958 to 2002), consistent with the results of Genta *et al.* (1998), who used the same method to present differences in the cycle. If the

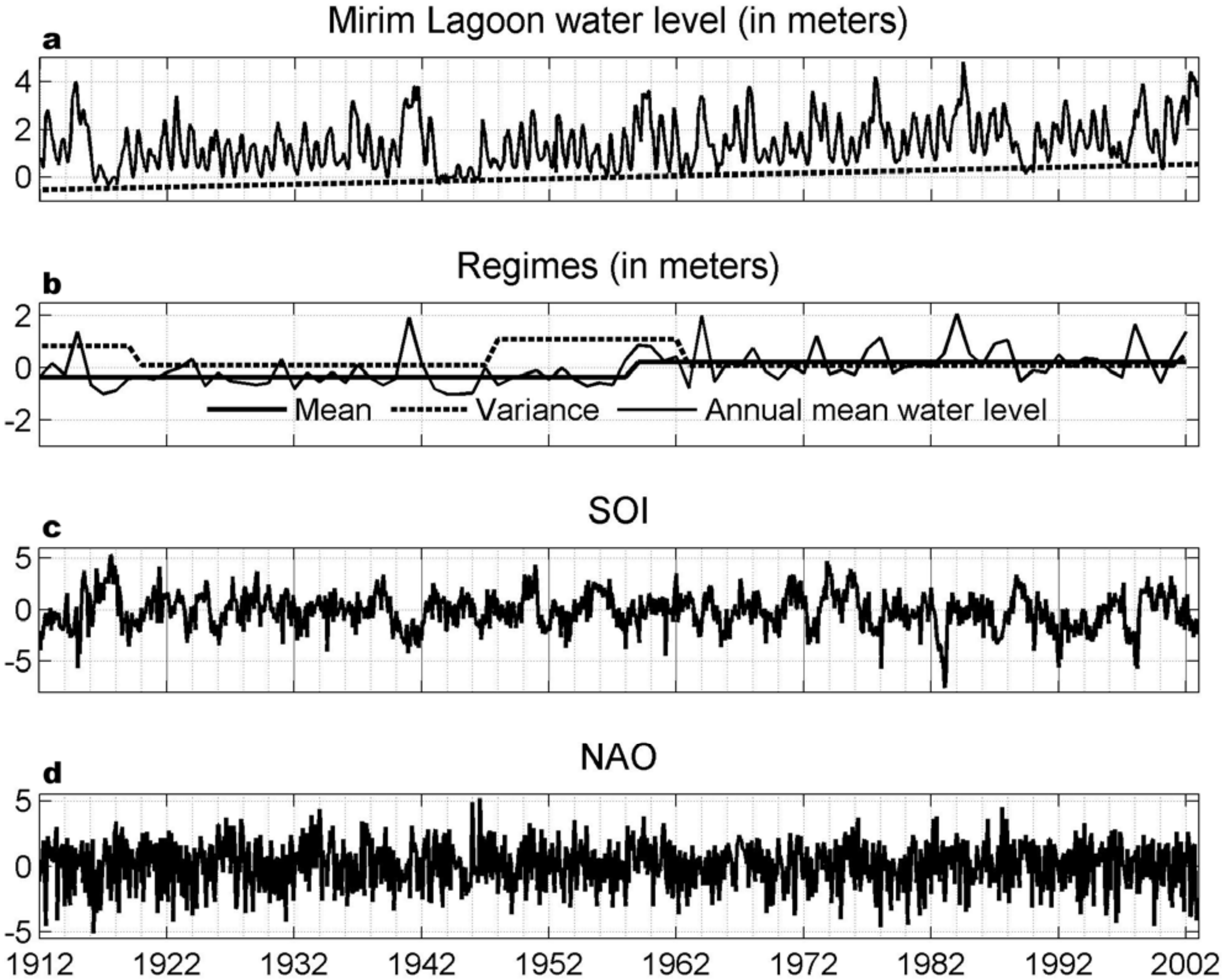

Figure 2. a) Mirim Lagoon monthly water level time series and the linear trend of anomalies (1.06 m from 1912 to 2002, significant at 99% - thick dashed line). b) The average annual water level anomalies and regimes of mean and variance identified by Rodionov's sequential method. c) The Southern Oscillation Index (SOI) time series. d) The North Atlantic Oscillation station index (NAO).

annual cycle is estimated by calculating its amplitude for all years and averaging the respective values, the scenario changes. The amplitude of the annual cycle during the first period becomes smaller than that of the second regime (1.67 m, with a 95% confidence interval between 1.46 and 1.88 m, against 1.88 m with a confidence interval between 1.70 and 2.07 m). A Mann-Whitney U-test indicates that this change in amplitude is not significant at 0.05 significance level, although the same test applied to the two regimes identified by Rodionov's algorithm reveals that their probability distribution function has changed signi-fycantly with the shift in 1957-58. Thus, it is still not clear if the water level annual cycle has changed over the years.

The estimation of a linear trend using the water level anomalies resulted in a positive increase of 11.9 mm/year (1.0669 m from 1912 to 2002), significant at 99% (Fig. 2a). This linear increase was not corrected to take into account vertical motions of the terrain and might be affected by isostatic adjustment or tectonic subsidence. The closest tide gauge station with a near-centennial record (83 years) is in Buenos Aires (Argentina). Raicich (2008) estimated the sea level rise recorded in Buenos Aires from 1905 to 1987 to be around 1.57 mm/year with peaks associated with high freshwater discharges of the La Plata River during EN events. The author also indicated that the United States Geological Survey consider the area between Buenos Aires and Southern Brazil as a region of low seismicity. Jelgersma (1996) argued that subsidence in coastal sedimentary lowlands is slow (a few centimeters/century) and consists of basement subsidence enhanced by subsidence due to isostatic loading. Therefore, even if the increase in ML water level is influenced by both sea level rise and land subsidence, their magnitude would be at least one order smaller than the observed trend.

Using wavelet analysis, it is possible to verify that main periodicities are concentrated in two frequency bands (Fig. 5). There is a broad band centered at 4 years, in agreement with the ENSO periodic band ranging from 2-7 years and commonly found in environmental records worldwide (e.g. Allan, 2000). These periods are also related to large scale atmospheric circulation anomalies that reach South America during ENSO events as described by Grimm *et al.* (1998). This relationship is confirmed by cross wavelet between the water level record and the SOI time series (Fig. 6a). Grinsted *et al.* (2003) pointed out that cross wavelet analysis shows regions in the time-frequency domain where two time series present high spectrum power. If two series are physically related, it is expected a consistent or a slowly varying phase lag. The arrows inside the significant area of Figure 6a suggest an anti-phase relationship in a frequency band ranging from 4 to 5 years (48 to 60 months) and localized in time from the late 1930s to the early 1980s. The anti-phase relationship indicates that when ML water level is positive (negative), SOI is negative (positive). This is expected since negative values of SOI are indicative of El Niño events. The wavelet coherence presented in Figure 6b indicates that both series co-vary in a frequency band ranging from nearly 3 to 6 years around 1940 and after 1990, predominantly showing the same anti-phase behavior inside the 0.05 significance regions.

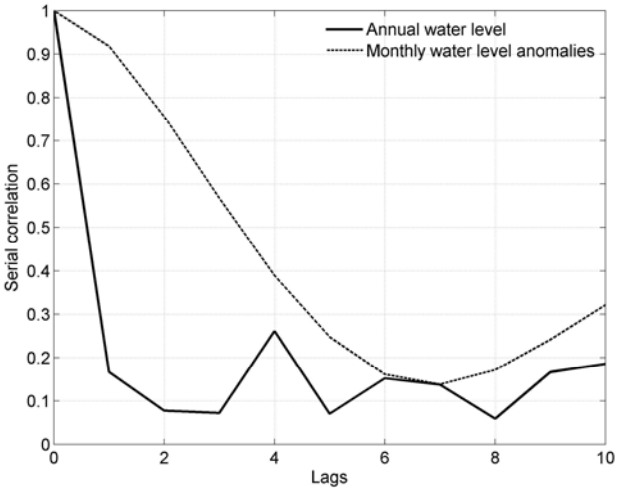

Figure 3. Serial correlations coefficients for Mirim Lagoon water level anomalies (demeaned), for the anomalies with the annual cycle removed (deseasoned) and for the annual mean water level anomaly.

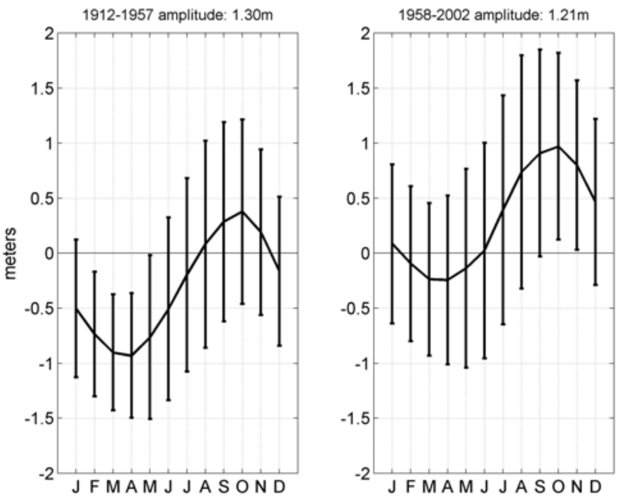

Figure 4. Annual cycles for the two regimes with significant different annual mean water level. Vertical bar indicate the standard deviation for each month.

A near-decadal cycle even more energetic than the ENSO-associated cycles was detected in the analysis. This periodicity was already identified by Robertson & Mechoso (1998) for streamflow series in SSA and was most marked in Paraná and Paraguay rivers. Cross wavelet analysis between SOI and ML water level do not show significant peaks near the 10-year frequency band, but the wavelet coherence presents a wide significant region near the 6-year band. As arrows inside the 0.05 significance level region at this frequency band indicate that SOI leads ML water level by approximately 2 years.

Robertson & Mechoso (1998) suggested an association between SSA streamflow variability and the NAO. Hurrel *et al.* (2003) reported that the NAO has a signal with a period around 8-10 years. When ML water level time series is compared with the transformed NAO index time series, there is a small region in the time-frequency domain, near the 6-year band and localized in time around 1960, where cross wavelet indicates common energy concentration (Fig. 6c). Approximately the same significant region is detected in wavelet coherence presented in Figure 6d, with both time series varying in phase during this period.

Discussion

Statistical analysis of the ML water level time series allowed the detection of two different regimes of mean water level and a significant positive trend. The first regime, with negative mean relative to the record, ranges from 1912 to 1957 and the second, positive relative to the record, spans from 1958 to 2002. The study of Genta *et al.* (1998) showed a significant probability of larger median streamflow for Negro and Uruguay Rivers between 1970 and 1995 than the median before 1940. They also detected a consistent decrease in the annual cycle in the later period for the Uruguay River streamflow. The 30-year running mean for Negro River streamflow (a basin located just next to ML basin) increased monotonically since the late 1940's. The same increasing trend was detected by the author for another neighbor basin, the Uruguay River, but only after the mid 1960's.

In ML, the first regime (1912-1957) embraces two major droughts (1917 and 1943-45). Both events were also observed by Mechoso & Perez-Irribaren (1992), while Genta *et al.* (1998) described the 1943-45 drought period as "extraordinarily strong anomalous climate events". The one in 1917 coincides with a LN year and it is possible to observe that both the ML water level wavelet transform (Fig. 5) and the cross wavelet between the water level series and SOI (Fig. 6a) show significant energy around the 4-year band at that time. The later drought is considered the longest dry event of the last century and was not related to a LN event. However, Figure 5 indicates that there is significant power concentrated in a wide frequency band (corresponding to periods between 4 and 12 years). Cross wavelets from Figures 6a and 6c suggest a significant relationship between ML water level and both SOI and NAO, but on shorter timescales (3 to 8 years). Therefore we conclude that neither ENSO nor NAO are able to completely explain those extreme drier conditions over SSA. However, global-scale tropospheric and stratospheric circulation anomalies during the early 1940's may be a result of a particular state of the climate system associated with the strong 1941-42 EN (Brönnimann 2005) and the long-lasting drought may be related to pre-existent conditions set up by that unusually extreme warm ENSO event.

The existence of two regimes with significantly different means agrees with Genta *et al.* (1998) although a change in the water level annual cycle is not clear. The regime shift in mean is apparently associated to a shift of the ENSO-SSA teleconnection towards higher spectrum frequencies. From 1912 to 1957, when the mean regime was negative, both cross wavelet and wavelet coherence between ML water level and SOI exhibit a high common energy and co-variation in a frequency band centered between 3 and 8 years. During the second regime, when the mean anomaly jumped to a positive value, this frequency band of significant association is concentrated between 1 and 5 years. This supports the idea of Haylock *et al.* (2006) that wetter conditions in SSA are associated with a higher frequency of ENSO warm events. Figure 6c also suggests that even the weak association between ML water level and NAO observed during the first regime is not observed in the second period.

The shift in the ML mean water level is hard to be addressed, but large-scale conditions of the climate system may help to assess its causes. Long-term changes in ENSO are partly described as an interdecadal oscillation of SST anomalies over the Pacific Ocean, with a well expressed El Niño-like regime prevailing from mid-1920s to 1942-43 and again since 1976-77 (Zhang *et al.* 1997). This interdecadal oscillation is also connected to the most powerful principal component analysis mode of streamflow variability calculated using North and

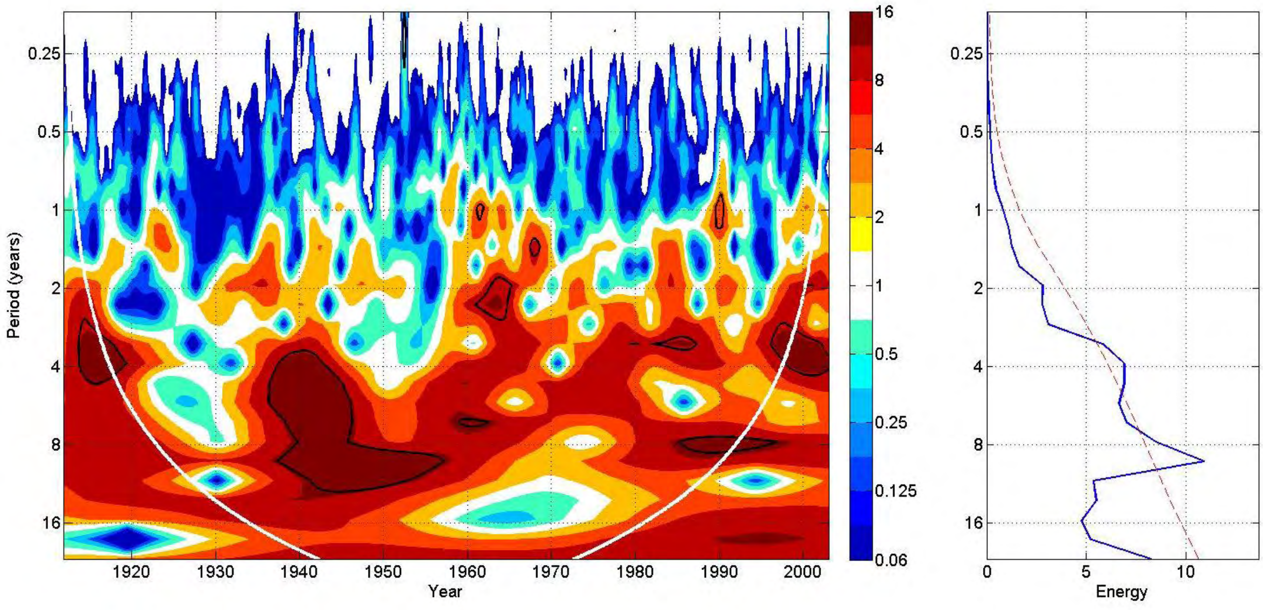

Figure 5. Wavelet transform (left) and global wavelet spectrum (right) of ML water level record. The white line in the wavelet transform plot represents the cone-of-influence and black contours represent the 5% significance level against red noise. The red dashed line in the global spectrum represents a 95% confidence level.

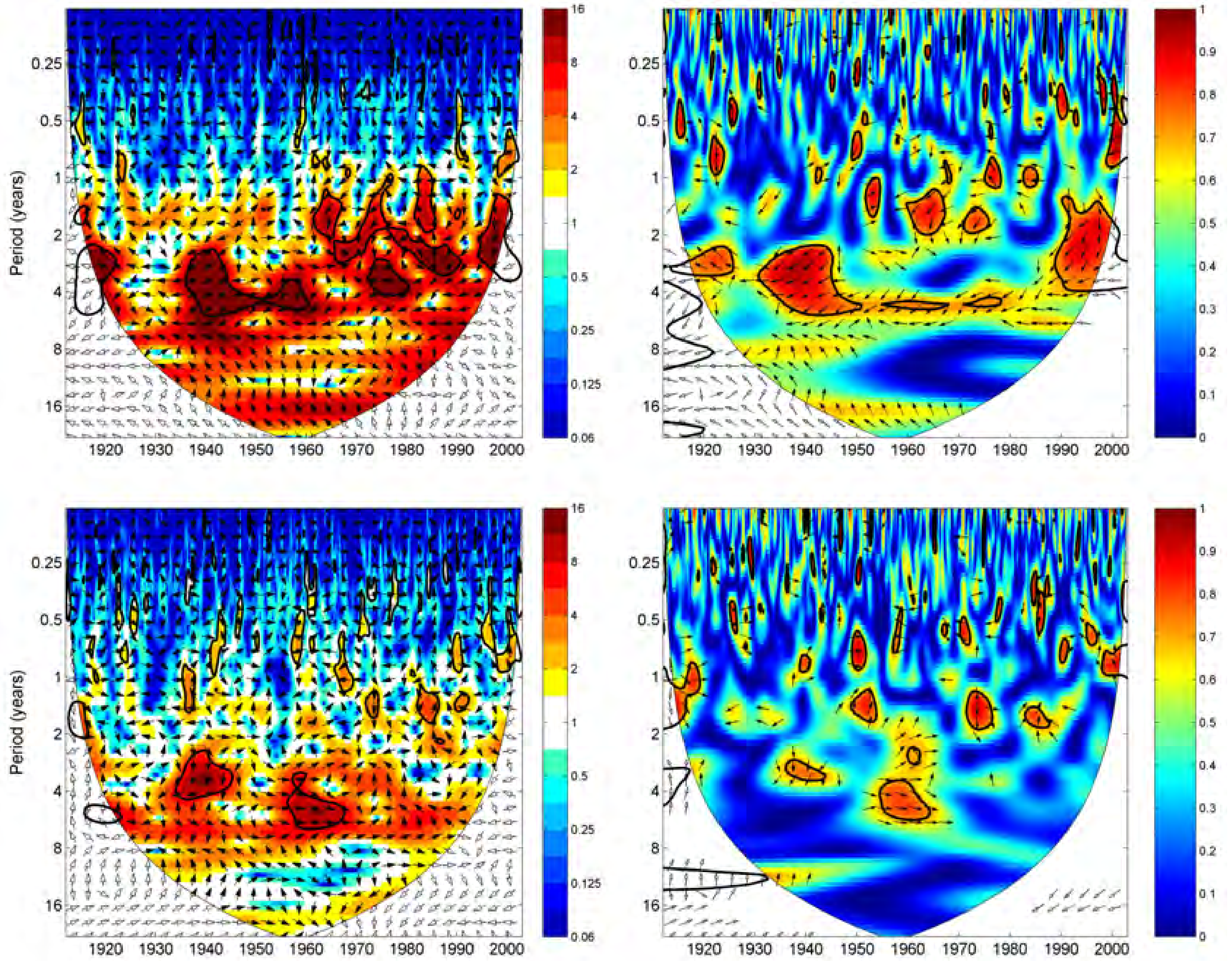

Figure 6. a) Cross wavelet analysis between ML water level and SOI time series (upper left). b) Wavelet coherence between ML water level and SOI time series (upper right). c) Cross wavelet analysis between ML water level and NAO index time series (lower left). d) Wavelet coherence between ML water level and NAO index time series (lower right). The 95% significance against red noise is shown as a thick contour. Relative phase relationship is shown by arrows (in-phase pointing right, anti-phase pointing left and ML water level leading by 90º pointing straight down).

South American rivers together (Dettinger *et al.* 2000). Zhang *et al.* (1997) also pointed out that the interdecadal pattern of the Pacific Ocean presented a change around 1957-58. According to them, this change was analogous to the one in 1976-77 but has received less attention because its subsequent warm phase was shorter. The mid-1950's shift of ML water level regime may be related to these basin-wide changes in the Pacific described by Zhang *et al.* (1997).

Shifts in variance detected in the previous section support the idea of a regime from the early 1920’s until the late 1930’s. The wavelet coherence in Figure 6d suggests a co-variation of the water level and SOI from the 1930’s to the late 1970’s. Allan (2000) reported more robust ENSO periods in the 1910’s, 1950’s, 1970’s and 1980’s and less energetic periods between 1920’s and 1940’s and during the 1960’s. Again, shifts in variance seem to agree with this argument until the 1960’s. Then, the variance decreases in the 1963 shift and remains leveled off until the end of the record. This discrepancy may also be related to the positive shift in the mean that occurred in 1958.

Zhang *et al.* (1997) argued that the interdecadal behavior of Pacific anomalies were different in 1942-43 when compared to the variations that took place in 1957-58 or 1976-77. The high-variance water level regime that began just after the great drought of 1943-45 and lasted until 1963 may reflect a transition period towards a new basic climatic state (considering the observed low variance of the two major regimes of ML water level). Although the nature of the early 1940’s climate anomalies is not known, their strong signal in ML water level record and the Pacific anomalies reported by Zhang *et al.* (1997) suggest a worldwide climatic disturbance as proposed by Brönnimann (2005).

The near-decadal cycle revealed by the wavelet analysis consistently lags SOI by 2 years. The study of Robertson & Mechoso (1998) cited the association of streamflow with SSTa south of Greenland, which would be a possible link to the NAO. Cross wavelet and wavelet coherence between ML water level and the transformed NAO index indicate a sharp region of possible association near the 8-year band around 1960. Hurrel *et al.* (2003) suggested that the 1960's were characterized by anomalously high surface pressures and severe winters from Greenland across northern Europe, during a negative NAO regime. Although the results described here do not reject the hypothesis of association between the NAO and SSA surface climate, the overall signal on ML basin is punctual and barely significant. This may result from the fact that NAO impacts climate mostly during northern winter (austral summer) and this is the dry season in southern Brazil. Decadal variations of the basic state during this season may not be as important as the world-wide ENSO impact on the 7 year timescales.

Whether the positive trend identified here is a consequence of natural oscillations of the climate system or a result of anthropogenic forcing is still unclear. Recently, Church *et al.* (2008) suggested that volcanic activity may be related to a global cooling of the upper ocean and the offset of the increasing rate of sea-level rise between 1963 and 1991. A combination of a robust ENSO period during the 1950's and the subsequent period of high volcanic activity might led to the regime configuration of positive mean and low variance from 1958/1963 to the end of the water level record analyzed here.

Considering human impact around ML basin, surrounding regions in Uruguay have been subjected to intensive cattle and sheep grazing since the early 1940's (García-Rodríguez *et al.* 2002). Overbeck *et al.* (2007) estimated a 25% decrease in natural grassland area in southern Brazil since the late 1970's due to the expansion of agricultural activities (mainly grazing, irrigated rice crops and more recently Eucalyptus sp. plantations). Marques *et al.* (2004) reported that nearly 89% of Uruguayan irrigated rice is cultivated on ML basin. On the other hand, Baldi & Paruelo (2008) used satellite data to demonstrate that ML region presented a small rate of change from grass to cropland when two periods in the last 30 years were compared (1985-89 and 2002-04), suggesting that major changes may have occurred before 1985. Nonetheless, Gautreau (2010) showed evidences that forest loss on the Uruguayan banks of ML could be explained by rice crop extension but improved conditions for forest growth in Uruguay during the last century could be a consequence of increased rainfall. Medeanic *et al.* (2010) used algal palynomorphs from another coastal lagoon in southern Brazil to demonstrate a tendency of increasingly humid conditions during the last century, with a marked anthropogenic impact detected after the 1970's. All these references lead to the conclusion that human impact is important. However, the increase in water level is remarkably high, especially considering that water diverted from ML to irrigated rice production negatively impacts the water balance of the lagoon.

The positive trend in ML is consistent with the trends found by Genta *et al.* (1998) for four major rivers in SSA. A positive trend in rainfall over a large region in SSA is presented by Haylock *et al.* (2006) at least between 1960 and 2000. In the Amazon basin, Marengo *et al.* (1998) found no evidences of changes in the 20th century, whereas slow increases in rainfall were found for northeastern Brazil. Collinschon *et al.* (2001) analyzed river flow and rainfall from 1900 to 1995 on the Paraguay River basin. They detected increased river flow since 1970 associated with changes in rainfall patterns (increased frequency of rainfall events) and suggested that at least part of the runoff increase should be due to deforestation. Moreover, the authors showed that, in Africa, the Congo River flow presented the exactly opposite behavior of Paraguay River throughout the last century, indicating a possible large-scale climatic connection between the continents.

A modeling study by Cook *et al.* (2004) pointed out that the West African Monsoon, in boreal summer, generates a Walker-type circulation with low-level convergence and wet conditions over Africa and divergence and drier conditions over northeastern South America and tropical Atlantic. Thus, a weakening of the African Monsoon would lead to higher precipitation over northeastern Brazil. In fact, the African Monsoon presented a reduction in precipitation during the second half of the last century and numerical modeling experiments indicate Atlantic SST variability as the main driver of the observed rainfall decline (Paeth & Hense 2004). Janicot *et al.* (1998) showed that divergent anomalies over the tropical Atlantic, associated with El Niño events, may lead to a weaker African Monsoon especially if there are positive SST anomalies over the eastern tropical Atlantic as well. Moron *et al.* (1995) showed evidences of stronger El Niño impact over the West African Monsoon after 1970. On the other hand, Diaz *et al.* (1998) demonstrated that the Atlantic Ocean may impact rainfall over southern Brazil and Uruguay and that this impact may be independent of ENSO. In their study, unusually high precipitation was observed in 1959 (a neutral ENSO year) and associated with SST anomalies in the Atlantic basin. It is also worth to note that all trends described by these studies (Genta *et al.* 1998, Marengo *et al.* 1998, Collinschon *et al.* 2001, Paeth & Hense, 2004 and Haylock *et al.* 2006) identify an increasing (decreasing) trend of precipitation or river flow in South America (Africa) starting around 1960. In summary, the tendency of more frequent warm ENSO events and a possible influence of long-term variations of the Atlantic basin may be responsible for these changes in rainfall. Last, the modeling experiments of Paeth & Hense (2004) suggested that increasing concentration of greenhouse gases may lead to warmer SST conditions in the Atlantic and a stronger African Monsoon. If the arguments presented here are correct, the strengthening of the African Monsoon would possibly lead to another shift, now towards a drier regime in South America.

Climatic variations or changes, as described here, impact a wide and important region of the South American continent, with many different ecosystems. Patos Lagoon, for instance, may suffer a strong limnification process of its estuarine area, influencing species distribution and abundance. Ecological changes on interannual timescales such as those observed in shallow-water fish assemblage (Garcia *et al.* 2001, 2004) and algal palynomorphs (Medeanic *et al.* 2010) may become permanent with the abundance of freshwater. Higher discharge of the Patos-Mirim system and the La Plata River would introduce considerable modifications of temperature, salinity and nutrient loads in this heavily fishery-explored continental shelf also affecting the ecological settings of coastal waters (Paes & Moraes 2007). Because different time series spanning such a long period of time are not common in SSA, the ML water level record may be used as an indicator for changes in the regional hydrological cycle and environmental conditions. Its maintenance and operational monitoring is vital to track regime shifts and trends in the region in order to develop environmental policies and to manage the ecosystem and the anthropogenic impact on the neighboring areas.

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Potential vulnerability to climate change of the beach-dune system of the Peró coastal plain - Cabo Frio, Rio de Janeiro state, Brazil

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Abstract. The Peró coastal plain is one of the three morphological compartments located between Búzios and Arraial do Cabo, on the east coast of Rio de Janeiro State, characterized by the occurrence of dune fields, driven by northeasterly winds, obliquely oriented in relation to the coastline. In order to evaluate the stability of the coastline as well as of the dune system a topographical and sedimentological characterrization of the different morphodynamic units was made, consisting of topographic and bathymetric profiling, evaluation of eolian sediment transport through sediment traps, sediment sampling for grain size analysis and comparison of aerial photographs. The results indicate that during the period of investigation sediment transport from the beach-foredune to the main dune field was largely inhibited by the presence of vegetation, and that sediment transport was limited to the reworking of its own sediment stock. Climatic oscillation toward drier periods, whether the result of global climate change or local variation in the duration of the dry period, will probably trigger the eolian sediment transport due to the reduction of the vegetation cover resulting in the migration of the main dune field towards urban areas. No coastal erosion was observed, whether through comparison of aerial photographs of 1970 and 2000 or during one year of monthly topographic profiling. Nevertheless, a rise in sea level might result in an erosive adjustment of the shoreline as well as in an increase in the flooding of the low lying areas.

Key words: Eolian transport, dune stability, beach profile, shoreface profile

Resumo: Vulnerabilidade potencial às mudanças climáticas do sistema duna-praia da planície costeira do Peró - Cabo Frio, Rio de Janeiro, Brasil. A planície costeira do Peró é um dos três compartimentos costeiros localizados entre Armação dos Búzios e Arraial do Cabo, no litoral leste do Rio de Janeiro, que se caracterizam pela presença de campos de dunas dispostas obliquamente à linha de costa por efeito do transporte induzido pelo vento nordeste. Para a avaliação da estabilidade da linha de costa e do sistema de dunas foi efetuada uma caracterização topográfica e sedimentológica das diversas unidades morfológicas. Os levantamentos consistiram de perfis topográficos e batimétricos, avaliação do transporte eólico por meio de armadilhas de areia durante doze meses consecutivos, coleta de sedimentos para análise granulométrica e análise de fotos aéreas. Os resultados mostram que no momento atual o sistema de dunas se alimenta do seu próprio estoque sedimentar, sem aporte significativo do sistema praia-duna frontal. Oscilações do clima para o mais seco, independentemente de mudanças globais, podem reativar o transporte eólico em função da redução do recobrimento vegetal reiniciando a migração das dunas em direção a áreas urbanizadas. A linha de costa não apresentou tendência de erosão, no entanto uma elevação do nível do mar implicará num ajuste erosivo através de retrogradação da mesma, e aumento da dificuldade de escoamento com resultante inundação das áreas baixas à retaguarda das dunas frontais.

Palavras-chave: Transporte eólico, duna, perfil de praia, antepraia

Introduction

The Peró coastal plain constitutes, together with Tucuns and Cabo Frio coastal plains, one of the three geomorphological compartments that stretch from Cape Búzios, herein called Búzios, to Arraial do Cabo, characterized by the presence of sandy dunes, which lie obliquely to the coastline, driven by the prevailing northeasterly wind (Fig. 1). As this is an area of environmental protection, it is still relatively well preserved thus being suitable for a representative case study of the coastal processes operating in the region as related to its present and potential vulnerability to climate change.

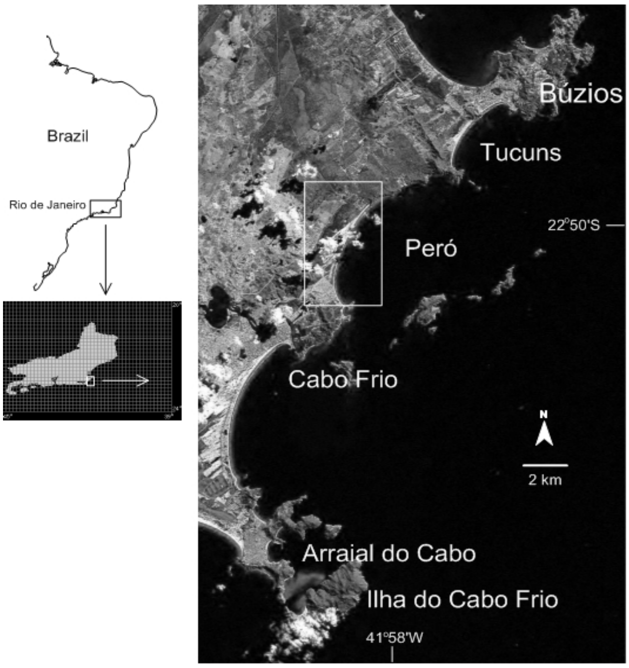

Figure 1. The dune fields of Tucuns, Peró and Cabo Frio, between Búzios and Arraial do Cabo, with location of the study area (white rectangle).

Three distinct geomorphologic units characterize the study area (Fig. 2):

i. The beach-foredune ridge system in front of a deflation plain;
ii. The deflation plain with isolated parabolic dunes;
iii. The active dune field which intercepts and overlaps a paleo-lagoon, currently filled with sediments.

The foredune ridge extends behind the beach from which it receives the sediments. It represents, when depleted of vegetation, a source of sediment for the dune field, which is developing behind it and forms a considerable barrier, with its 7 m high dunes, to the erosion of the coast whose stability depends on its vegetation cover and sediment budget.

The deflation plain is located between the foredune ridge and the active dune field and it presents a few semi-active parabolic dunes.

The active dune field consists of NE-SW trending transgressive dunes and is located in the distal sector of the sandy terrace. Its starting point is located in the northern extremity of the beach and it extends obliquely to the coastline, partially intercepting a paleo-lagoon forming the western limit of the deflation plain. As the dune field moves away from the coastline it becomes wider and encroaches on the lower slope of the coastal range assuming the characteristics of a climbing dune (Rangel & Castro 2005), while its western slip face precipitates towards an urban zone, having already led to the abandonment of a residential estate (Rangel & Castro 2005). The mobility of this dune field has been studied by Dourado & Silva (2005) who estimated a displacement of 125 m between 1965 and 2001 and an average displacement rate of 3.5 m/year, with great variation in the different sectors of the dune field. Because the sediment input from the foredune field, has been almost completely interrupted by the vegetation cover of the foredunes and of the deflation plain, the mobility of the dune field results essentially from the reworking of its own sediment stock. Sediment stability therefore depends essentially on the rainfall regime for the maintenance of the vegetation cover and the consequent inhibition of the wind transport as does the stability of the coastline in terms of coastal erosion.

Local climate, according to Barbiére (1975, 1984), is warm and semi-arid (BSh), with mean temperatures between 25.2 ºC in February and 20.5 ºC in August; mean monthly rainfall of is 60 mm, except in December when it stays above 100 mm; mean monthly evaporation rate is 60 mm. The dry period, when the monthly precipitation drops below

Figure 2. Geomorphologic units of the Peró coastal plain with the location of the foredune ridge, the deflation plain and the active dune field. The dotted line represents the inferred contours of a former lagoon partially intercepted by the active dune field. Image Google Earth.

60 mm, occurs between June and September while the rainy season starts in December, with decreasing amounts of rain up to March. Winds are predominantly from northeast during the whole year alternating with short periods of winds from southeast and southwest associated to the arrival of cold fronts. Wind velocities usually stay between 4 and 6m/s; higher values are observed during the winter.

The present study seeks to identify present-day morphodynamic processes and the possible effects of climate change on them.

Methodology

Monthly topo-bathymetric profiles were measured over twelve months in three positions along the beach arc and along the longitudinal axis of three parabolic dunes; the main goal was to characterize the topography of the foredunes and to assess the mobility of the beach and shoreface as well as that of the parabolic dunes of the deflation plain (Fig. 3).

Topo-bathymetric profiles were measured at positions P2, P5 and P7 (Fig. 3), and adjusted to the average sea-level on the basis of the predicted tides for the Porto do Forno (Arraial do Cabo), following the methodology described by Muehe *et al.* (2003) and Muehe (2004). The profiles extended from the back of the foredune field (profiles P5 and P7) and from the public walk (profile P2), up to the outer limit of the surf zone through conventional topographic leveling. The profiles were extended to greater depths, for the determination of the depth of closure and sediment sampling, with a kayak, a portable echo sounder a hand-held GPS, in accordance with the methodology developed by Belligotti & Muehe (2007).

In accordance with the studies undertaken by Belligotti (2009), the depth of inflection of the bathymetric profile was considered for the determination of the depth of closure, the depth at which vertical variations of topography are negligible (Hallermeier 1981), as a more practical alternative in view of the enormous discrepancy between the values obtained with the different equations proposed in the literature (Hallermeier 1981, Birkemeier 1985, Houston 1995, Wang & Davis Jr 2007) which are, in their turn, greatly influenced by the wave parameters adopted.

The determination of the shoreface equilibrium profile, for purposes of comparison with the measured profile, was obtained with the use of Dean's equation (1991) expressed by the relation:

$$z_x = Ax^{2/3}$$

where the depth "z" at a distance "x" from the coastline is defined as a function of the median diameter of the sediments or of the corresponding settling velocity of (ω_s), expressed by the scale parameter "A", determined in its turn by the relation:

$$A = 0{,}0067 \cdot \omega_s^{0.44}$$

For a rough assessment of a potential retreat of the coastline corresponding to a given rise in sea-level the equation of Bruun (Bruun, 1962, 1988) was employed:

$$R = \frac{SLG}{h}$$

where:

R = erosive retreat of the coastline due to rise in sea-level (m)

S = rise in sea-level (m)

L = length of the active profile (m)

h = height of the active profile (m)

G = proportion of eroded material which is maintained on the active profile

The height of the active profile is determined by the sum of the land height (sand barrier, terrace, foredune) and the depth of closure, and the active length is the horizontal distance between the land height and h. The proportion of material retained on the profile (G) is considered to be 1, because of the difficulty of assessing the quantity of material made available by erosion and retained on the submerged profile. This is certainly one of the sources of error in the assessment of the amplitude of the retreat.

Sediment traps were installed at a few selected locations (Fig. 3) for the assessment of sediment transport from the foredunes to the deflation plain and were monitored during the period of the surveys. The traps were constructed in accordance with Leatherman (1978) and consisted of a 100 cm long PVC tube whose upper half was provided with two openings on each side, one of them being closed with a silk-screen in order to retain the sediments but still allowing the passage of the wind. The lower part was buried and served as support for an acetate cylinder in which the grains collected by the trap were retained. The traps were placed with the opening in the direction of the prevailing wind, of about 60º, well defined in satellite images by the tracks of the trajectory of the sedimentary transport.

Sediment samples were collected for grain size analysis at each of the traps and along the beachface (Fig. 3), where the sampling was carried out at 500 m intervals on the top of the foredune, of the berm and on the beachface. For an adequate representation of the berm sediments 30 cm deep trenches were dug, and one side of the trench was scraped to obtain compound representative samples. Thirteen sediment samples were obtained from the dune field and its associated deflation plain and a further 27 samples were collected from the dune-beach system. Grain size analysis was made through dry sieving according the method described by Folk & Ward (1957).

The stability of the coastline was assessed by means of a comparison between aerial photographs from 1970 with orthophotocharts from 2000/2002.

Climatic data for Arraial do Cabo/Cabo Frio were obtained at following sources: Corpo de Bombeiros Militar do Estado do Rio de Janeiro (CBMRJ) for rain, Centro de Previsão do Tempo e Estudos Climáticos (CPTEC) for cold fronts, and Rede de Meteorologia do Comando da Aeronáutica (REDEMET) for hourly wind direction and speed.

Results

Sediment characterization

Samples collected on the beach (beach face and berm) and on the top of the foredunes, along the beach arc, indicate an increase in median grain size diameter from the southern end toward the center of the beach arc, and a decrease towards the northern end. The median grain size is coarsest in the vicinity of the center of the beach arc (P5), and decreases towards both extremities of the beach. This suggests that the region near the center of the beach is a dispersal center for the finer sedimentary fractions which are displaced preferentially towards the north, possibly being the result of an increase in wave energy under storm conditions (waves from the SE) due to the more exposed position of this segment. The localized increase in the grain size of the beach sediments is not so clearly reflected in the sediments of the foredunes because of the inability of the wind to transport sediments greater than 0.2 mm (2.3 phi) (dashed horizontal line in Fig. 4).

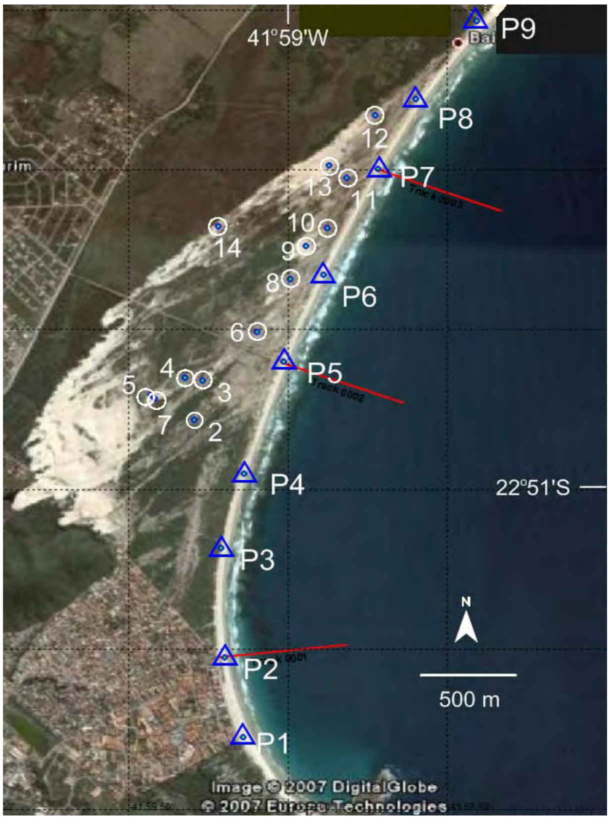

Figure 3. Location of the sediment traps (o), of the topo-bathymetric profiles (Pn) and of the beach-foredune sediment samples (Δ). Image Google Earth.

The finer sands that are more easily transported by wind are found in the final third of the northern extremity of the beach arc (Profile P7), precisely where the beginning of the active dune field is located.

In figure 5 it is presented a correlation between the median diameter and the respective standard deviation of the sediment samples collected on the berm, foredune and on the deflation plain with associated parabolic dunes. The area delineated on the graph by a broken ellipse indicates the grain size characteristics of the foredunes whose sediments present a median diameter equal to or less than 0.2 mm (2.3 phi) and a standard deviation of less than 0.7 mm (0.5 phi). The occurrence of sediments of larger median grain size and higher standard deviation in the dunes of the deflation plain suggests the occurrence of residual deposits resulting from the winnowing of the finer fractions or even a mixture with the sediments of the deflation surface.

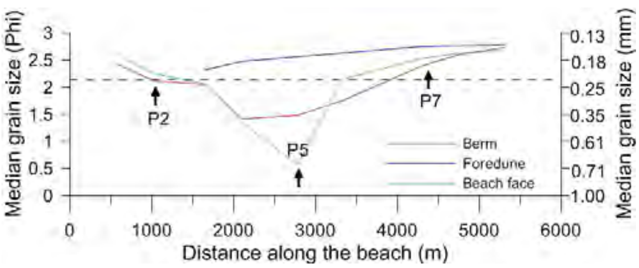

Figure 4. Median grain size distribution along the beach and foredune field. The dashed horizontal line represents the local grain size threshold for eolian sediment transport as depicted in figure 5 indicating a convergence in grain size between beach and foredune sediments toward the northern sector (profile P7) of the beach.

Sediment traps

Through out the monitoring period only three traps, 7, 11 and 14, registered a significant capture of sand. The first two were located on the windward side of parabolic dunes of the deflation plain and the last on the flank of the active dune field. At the other traps, sediment capture was nil or very small. Therefore the few areas of significant wind transport are associated to places without vegetation cover at the inner or lateral flank of the dunes resulting in remobilization of their own sediment stock, suggesting that there is no continuous transport from the foredunes to the deflation plain. This becomes clearer when the traps are grouped by location. Trap 7 presented significant sediment capture while at traps 5 and 4 located, respectively, outside the trailing ridge of the parabolic dune and at the deflation plain upwind from the dune, sediment trapping varied from nil to very small. Trap 11 was also located on the windward side of a reactivated parabolic dune. Trap 14 was located on the flank of the active dune field where sediment transport is active because of a complete absence of vegetation. Trap 12 was placed in a similar position, though closer to the beach, in order to assess the flow of sediment which fed this dune field from the beach. Surprisingly, this trap captured no sediment, suggesting that the main dune field is also largely being fed by its own sediment reservoir without receiving any significant contribution from the beach.

Our results strongly suggest that the maintenance of the vegetation cover is fundamental to inhibit the transport of sand, which is extremely sensitive to the water balance as illustrated by the sediment mobility that occurred in the areas with no vegetation cover (traps 7 and 14). The observed pattern reflects a strong seasonality with expansion of vegetation cover and decrease of eolian sediment transport (Fig. 6).

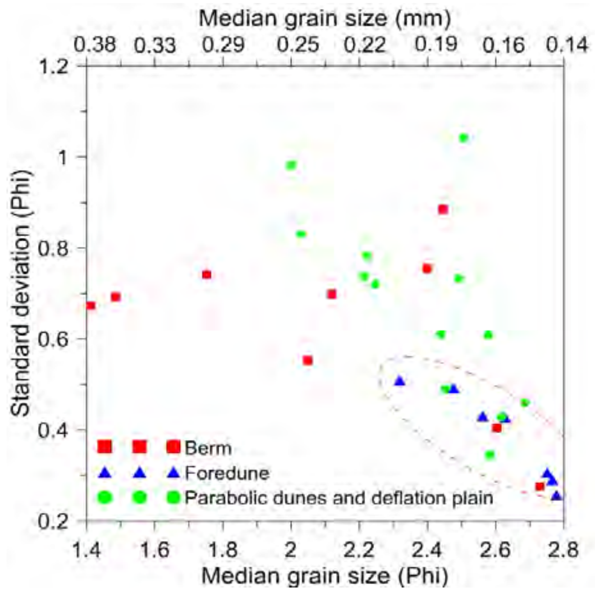

Figure 5. Graphic correlation between median grain size and standard deviation of the beach, foredune and deflation plain sediments. The samples inside the ellipse represent the grain size characteristics of the source sediments that feed the parabolic dune and the active dune field; these sediments are characterized by low standard deviation (well to very well sorted) and median grain size finer than 2.3 phi (0.2 mm).

During the period of investigation the rainy season, with monthly rainfall above 60 mm, extended from November 2007 to April 2008 with the highest levels of precipitation in January and March (Fig. 7) while, according to Barbiére (1975), there is normally a decrease in precipitation after December. The expected relationship between high precipitation and low eolian sediment transport was not found in November, January or August. As shown in figure 7, the number of rainy days in each month was fewer than five, mainly associated with the passage of cold fronts. After the rain the sands deprived of vegetation became once again susceptible to transport by winds. Thus, for the eolian sediment transport, frequency of rainfall is more important than the amount, whereas for the maintenance of vegetation the amount of monthly precipitation is still important.

A better explanation for the observed pattern of eolian sediment transport was found when the monthly duration of the highest wind speeds was taken into consideration. During the period of investigation mean monthly wind speed varied between 7 m/s and 9 m/s, with a constant standard deviation of ±2 m/s, while the highest values ranged between 9 m/s and 14 m/s. When considering only winds from 50º to 70º, which represent the main direction of transport, and velocities ≥ than 9 m/s the relation with eolian sediment transport is significantly higher (Fig. 8). The 9 m/s wind velocity threshold was chosen as being the highest mean monthly wind velocity.

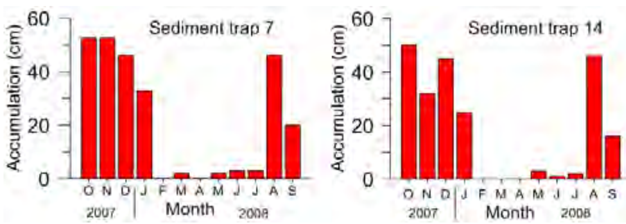

Figure 6. Sediment accumulated in the traps reflects alternating humid and dry weather conditions.

In the light of the preliminary results the importance of the vegetation cover is clear, both in inhibiting sediment mobility and in producing the opposite effect when removed. During the monitoring period it became apparent that the activity of off-road vehicles (buggies and motorcycles) also triggered the remobilization of sediments by damaging the vegetation cover, and resulting in blowouts and modification of the topography (Fig. 9).

Mobility of the Parabolic Dunes of the Deflation Plain

The comparison of the topographic profiles of three parabolic dunes did not indicate any net displacement, despite the intense mobilization of sediments on the windward side of the depositional lobe. This mobilization is reflected in the greater morphodynamic variability of this face as compared to that on the slip face (Fig. 10).

Considering the present climate conditions, the parabolic dunes are reasonably stable, with no input of sediments from the foredune-beach system, due to the, even sparse, vegetation cover of the foredune ridge as also of the deflation plain; in contrast, there is intense sediment remobilization on the windward, vegetation depleted side of the dunes,

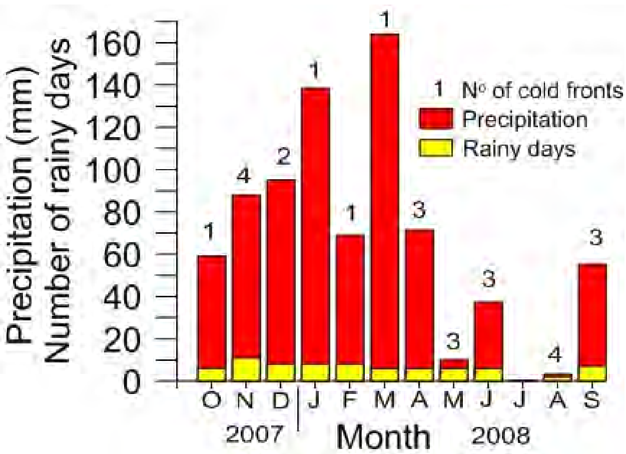

Figure 7. Monthly precipitation and indication of the number of rainy days and number of cold fronts.

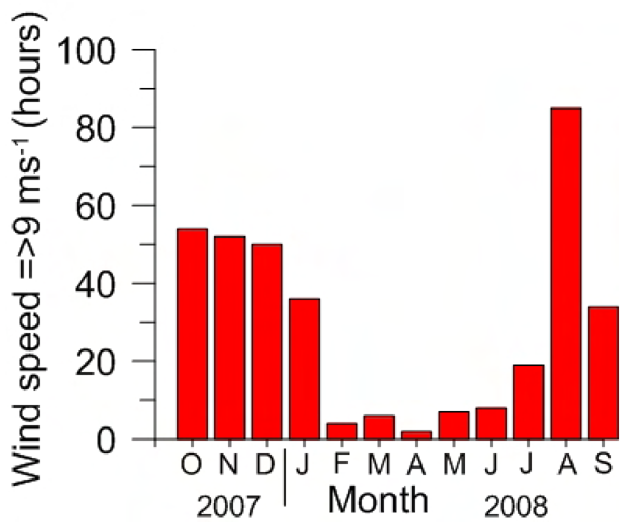

Figure 8. Duration of wind velocities over 9 m/s indicating the close relationship between sediment transport (Fig. 6) and duration of strongest winds from 50-70º.

due to the reworking of their own sediments. The maintenance of the vegetation cover is, however, extremely dependent on the water balance, with longer dry periods leading to the destabilization of the system due to the intensification of the wind transport. This is well exemplified by the 1959 aerial photograph, which indicates sediment transport from the foredunes in the direction of the active dune field, through transgression over the deflation plain (Fig. 11).

When the annual rainfall rates measured in Cabo Frio (from 1921 to 1968) and Arraial do Cabo between (1969 and 1986) are compared with the average rainfall of the same period (Fig. 12) large

Figure 9. Destruction of the vegetation cover and subsequent incision of the terrain due to the traffic of off-road vehicles. Location landward from position P6, figure 3.

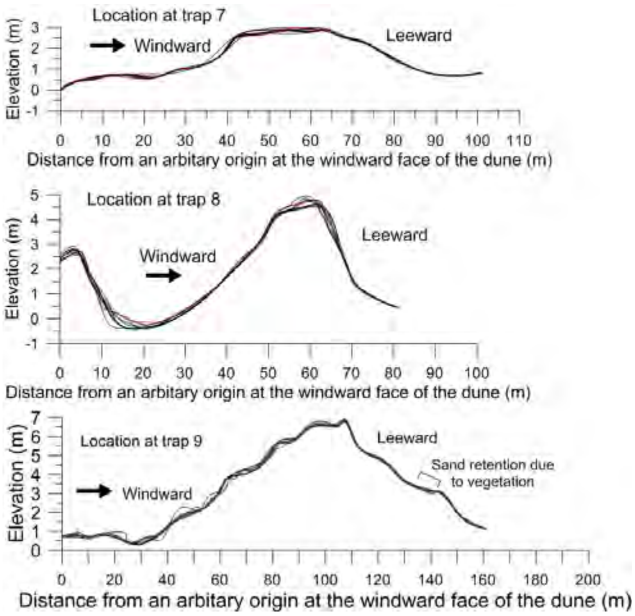

Figure10. Overlay of the 12 monthly topographic profiles along the longitudinal axes of three parabolic dunes located on the deflation plain (see Fig. 3). No net advances of the base of the slip face of the dunes were detected. The last profile of each dune is represented by a red line. Location of profiles in figure 3.

oscillations are observed, with the occurrence of alternating dry and rainy periods. In the 1950´s the monthly rainfall fell far below the average during five successive years what might explain the reactivation of the wind transport as indicated by the 1959 photograph (Fig. 11). This phenomenon may be recurrent during occasions of water deficit: an aerial photograph from 1976 shows some sediment transport in the direction of the active dune field, though less evident than that seen in the 1959 photograph. It must be borne in mind that in 1975 the annual rainfall was above the average value and so the effects of the water deficit were not so remarkable.

Erosion and Coastal Flooding

In the study area, the georeferencing of older aerial photographs is extremely difficult due to the sparse land occupation and the consequent lack of points of reference. Images from 1970 and 2000 were compared by drawing the position of the internal limit of the berm in each image; no evidence of significant change in the position of the coastline was found. Dias *et al.* (2007) had found a different result by inferring erosion of the coastline based on satellite images and a digital terrain model. However, in a later study, Dias *et al.* (2009) reappraised this interpretation as they had then identified a period of coastal advance of some 30m between 1959 and 1976, and of retreat, also of 30m, between 1976 and 2003. This result should be accepted with caution because these analyses were based on aerial photographs by taking the limits of the vegetation cover as points of reference, besides a few roads and buildings, what may lead to significant errors. Beyond that, it is possible that changes may have occurred in the vegetation cover at the foredune-beach interface which could lead to an equivocal interpretation of the position of the coastline. Assuming however, that the amplitude of the erosive process was compensated by progradation of equal extent, the final result does not disagree with the findings of the present study.

The analysis of the time series of the topographic profiles of the foredune-beach system (Fig. 13) did not identify the occurrence of erosion, apart from the morphodynamic variability of the beach with periods of gains and losses typical of beaches of the intermediate morphodynamic stage (Short 1999, Calliari *et al.* 2003). A similar result was obtained by Pereira *et al.* (2008).

The bathymetric profiles present significant landward increase in slope at 9 and 10 m depth. Equilibrium profiles (Dean 1991) despite indicating equilibrium of the upper shoreface are not adjusted to the remaining measured profiles, with “excess” of sand in profile P7 and lack in profiles P2 and P5 (Fig. 14). This may indicate a lack of sediments tending to an erosive adjustment of the profile or a compound profile in which the intermediate shoreface presents a profile with equilibrium of its own, as proposed by Inman *et al.* (1993).

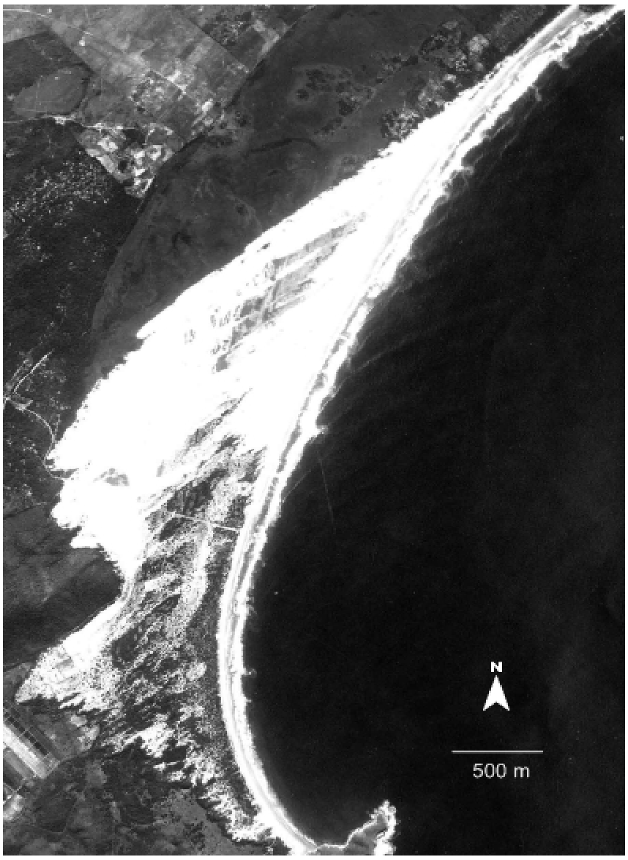

Figure 11. Aerial photograph taken in 1959, by the Cruzeiro do Sul company. The bright white areas at the center and at the northern edge of the beach show sediment transport from the foredunes to the active dune field.

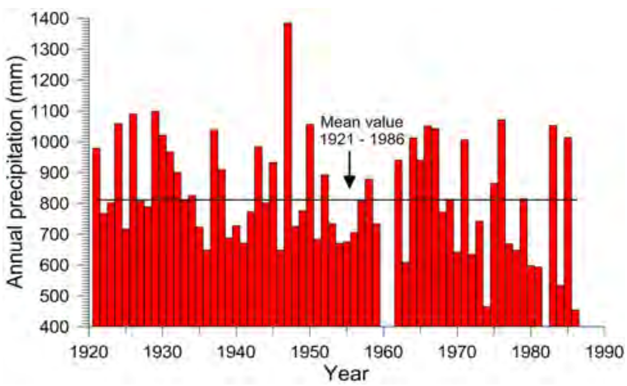

Figure 12. Annual rainfall in Cabo Frio/Arraial do Cabo showing significant deviations from the average of the 1921-1986 period, represented by the black line parallel to the x-axis. No data were collected during the period of 1960 to 1961. In 1982 registered rainfall was only 91.8 mm.

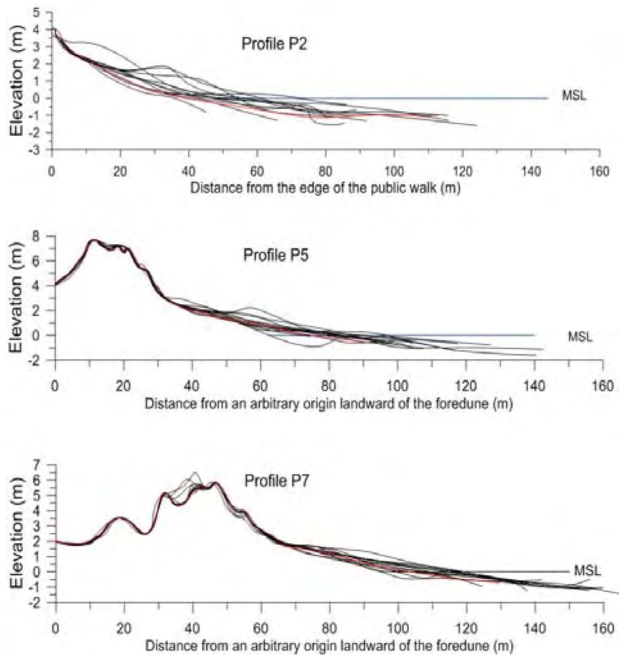

Figure 13. Overlay of the 12 monthly topographic profiles of the foredune-beach system indicating the absence of net erosion during the period of observation. The last profile is represented by a red line. Location of profiles in figure 3.

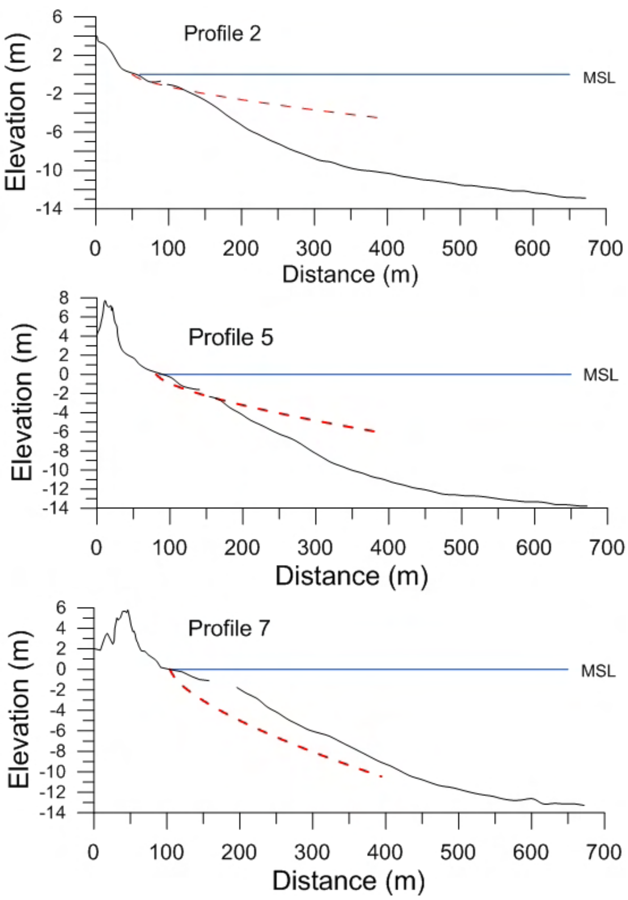

Figure 14. Topo-bathymetric profiles of the foredune-beach-shoreface system compared to the equilibrium profile (broken line) according to the model proposed by Dean (1991).

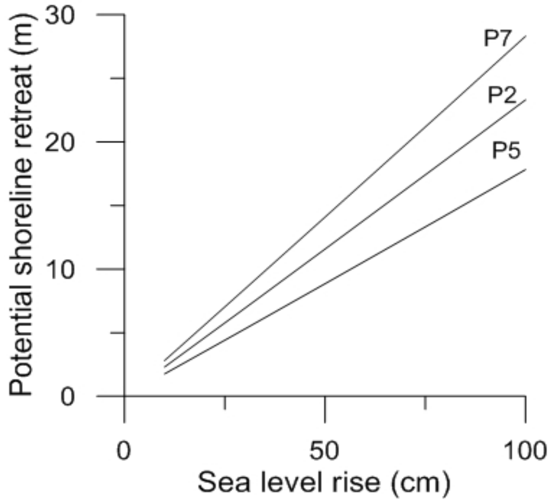

Figure 15. Estimated erosive adjustment of different sectors of the coastline to distinct sea level rise scenarios according to the Bruun rule. Profile locations in figure 3.

The non-identification of an erosive trend of the coastline (not taking into account the possible lack of sediments in the middle shoreface) is auspicious in the sense that it indicates a certain robustness of the coast in the face of the variability of the coastal processes.

However, a rise in sea-level will tend to result in an erosive adaptation of the coastline as there are no sediment sources to compensate for this rise. The application of Bruun´s model (1962, 1988), as described above, to provide a rough estimate of the amplitude of this response to different scenarios of sea level rise, is presented in figure 15; the model predicts an increase in the amplitude of the retreat from the center to the extremities of the beach arc a result that stems essentially from the lower gradient of the shoreface, associated with a smaller grain size in the northern and southern sectors of Peró beach.

For the urban area, behind profile P2, this erosive adaptation will mean the destruction of the public walk in front of the urban area, unless the beach is preserved by means of artificial landfill. Another vulnerability factor arises from the shallow depth of the water table and the poor drainage of the deflation plain with the consequent renewed flooding of the low-lying areas that were extensively flooded during a period of intense rainfall that occurred in the period from January to May 2008.

Conclusion

The Peró coastal plain, with its system of sandy dunes, presents a highly sensitive environmental equilibrium, as climatic oscillations tending to drier weather, independently of global changes, can disturb its delicate morpho-sedimentary balance. Alterations in the water balance, whether by diminished rainfall or increased evaporation, may lead to a reduction of the vegetation cover of the foredunes and of the deflation plain, thus re-starting sediment transport from the foredunes to the active dune field that, in turn, will resume its displacement towards the urban areas. Sea level rise and increased storminess will lead to both, an erosive adjustment of the coastline by means of its retreat and to increased flooding of the low-lying areas of the deflation plain and of the paleo-lagoon located behind the active dune field. Other consequences include the landward displacement of the foredunes and the transference of sediments as blowouts and parabolic dunes towards the deflation plain and the active dune field, as described by Psuty & Silveira (2010).

The observations made on the Peró coastal plain may also be applied to other coastal dune fields that occur in Rio de Janeiro State in areas with higher rainfall rates such as those observed to the north, in the Paraíba do Sul river plain, and to the south, in the beach barriers found in front of Araruama and Saquarema lagoons as well as of Sepetiba bay (Marambaia beach barrier) where localized active blowouts already indicate occasional eolian sediment transport. As some of these areas are experiencing increased occupation adequate setback lines should be established in order to avoid future loss of propriety.

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The authors wish to thank the Departamento de Recursos Minerais (DRM) and AMPLA for their respective authorizations of the use of the aerial photographs and orthophotocharts. We would, further, thank CNPq and CAPES for the graduate and research scholarships as also for two anonymous revisers whose suggestions substantially improved the present document.

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Historical assessment of extreme coastal sea state conditions in southern Brazil and their relation to erosion episodes

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Abstract. Intense cyclonic weather systems in southern Brazil generate ocean storms which can, in a temporal scale varying from few hours to a day completely erode a beach profile from its maximum accretion state. Mid-latitude cyclogenesis with low pressure centers in the deep ocean and along the coast increases the intensity of the Mid-Atlantic storms causing storm surges and storm waves. Preliminary results from a hindcast of wave energy at deep water (100 m), performed with a wave model using winds from reanalysis (period 1979 - 2008), indicated a total of 40 extreme events (wave height above 6 m). These events cause maximum erosion and surge elevation on the order of 62.96m³/m and 1.827 m respectively. Four patterns of synoptic situations capable of generating extreme events were identified. Among the 40 events, 53.66% had the trajectory of Pattern II and 26.82% were associated to Pattern III, representing both 80% of the total. Coastal erosion episodes where mostly associated with Pattern II, while Pattern III caused the highest surges. In a climate change scenario this study shows no important differences in the amount of the extreme events along the last thirty years.

Key words: storm surge, extra-tropical cyclones, wave height, NCEP/NCAR Reanalysis

Resumo. Avaliação histórica das condições extremas de mar na costa do sul do Brasil e sua relação com episódios de erosão. Sistemas meteorológicos como ciclones extratropicais de alta intensidade que ocorrem no sul do Brasil geram ondas de alta energia, que podem levar um perfil de praia de um estágio máximo acrescivo ao máximo erodido em poucas horas. A ciclogênese em médias latitudes, com centro de baixa pressão, contribui para a intensificação das tempestades do Meio do Atlântico, causando marés meteorológicas (storm surges) e ressacas (storm waves). Resultados preliminares para um estudo de energia das ondas em águas profundas (100 m), utilizando um modelo de ondas com dados de vento de reanálises (período 1979 - 2008), indicaram 40 eventos extremos (6 m de altura de onda). Alguns desses eventos geraram erosão de 62,96 m³/m e 1,827 m de elevação do nível do mar. Foram identificados quatro padrões de situações sinóticas geradoras de alturas de ondas acima de 6m. Entre os 40 eventos, 53,66% tiveram a trajetória do Padrão II e 26,82% estavam associados ao Padrão III, ambos representando 80% do total. Episódios de erosão costeira geralmente são associados ao Padrão II. Já o Padrão III é responsável pela maior elevação do nível do mar. Diferenças significativas na quantidade de eventos extremos ao longo dos últimos 30 anos não foram observadas.

Palavras-chave: maré meteorológica, ciclone extra-tropical, altura de onda, NCEP/NCAR Reanálises

Introduction

After the accretion period which occurs between December and March, storms beginning in April start the erosion cycle of the southern Brazilian sandy beaches. Generally, erosion is caused by extreme sea state events which combine high waves and high storm surges. Since astronomical tides have higher amplitude in this region during April, and the storms can last a few days, it is not uncommon that episodes of severe erosion occur during the high water spring tide period (Calliari *et al.* 1998). These storms are mostly associated with high intensity extra-tropical cyclones that generate wind waves which can change a beach profile from its maximum accretion state to complete erosion during a period that can vary from few hours to a few days.

Regarding the occurrence of extra-tropical Cyclones in South America, Gan (1992), analyzing 10 years of data (from 1979 to 1988) has found that the majority of events happen in winter (8 events), followed by autumn (6), spring (4) and summer (3). Gan & Rao (1991) identified two cyclogenesis regions in South America: one in Argentina (42.5° S and 62.5° W) related to the baroclinic instability of the westerly winds and another in Uruguay (31.5° S and 55° W) associated with the baroclinic instability due to the presence of the Andes. Recently, a third region between 20° and in the 35°S located in southern and south-eastern Brazil was identified (Reboita *et al.* 2010).

Mid-latitude cyclogenesis with low pressure centers in the deep ocean and along the coast increases the intensity of Mid-Atlantic storms causing extreme storm surges and storm waves (Calliari *et al.* 1998). The “surge” in a specific instant is represented by the difference between the observed and the astronomical tide and can be either positive or negative causing rapid increase or decrease in sea level, respectively (Pugh 1987).

Storm surges are the major geological risk in low coastal areas. They are often associated with significant losses of life and property. Climate change, with rising sea level and changing storm tracks, will modify the regional distributions of these hazards (von Storch & Woth 2008).

The two main sources of storm surges are: changes in atmospheric pressure and the exchange of momentum between the wind and the sea surface. In general, the effects associated with atmospheric pressure is less than 10% of the total, being the wind shear stress at the sea surface the main component (Marone & Camargo1994). Additionally, sea level elevations at the shore can be further amplified by the presence of shelf waves and by the pilling up of water due to wave breaking processes at the surf zone (known as “wave set up”) (Marone & Camargo 1994).

Observations of synoptic weather conditions and sea level elevation done by Parise *et al.* (2009) showed that the highest sea level elevation events resulted from the action of SW winds which blow parallel to the main NE-SW coastline orientation in the region, a result that can be explained by the pilling up of water at the coast due to the Coriolis effect (i.e. Ekman transport). The monitoring carried out by Saraiva *et al.* (2003) from April 1997 to July 1999 on Cassino Beach indicated the highest frequency of the storm surge in autumn (65%), followed by similar values in summer and spring (15%) and lower values in winter (5%). All the storm surges observed by Saraiva *et al.* (2003) were associated with extra-tropical cyclones.

Coastal erosion has been causing substantial alterations along the coastline of the Rio Grande do Sul (RS) state in southern Brazil for quite some time. In the less occupied areas in the central littoral, coastal erosion caused habitat loss of foredune ridges and inflicted local damage to a lighthouse (Conceição lighthouse) and small beach resorts at Lagamarzinho beach (Barletta & Calliari 2003). In more developed regions of the northern littoral, such as Cidreira, Tramandaí and Imbé beaches, coastal erosion is aggravating, leading to severe loss of public and private property (Esteves *et al.* 2000, Toldo Jr. *et al.* 1993). At the southern littoral, Hermenegildo beach, located near the Uruguayan border, has had homes, roads and power lines systematically destroyed (Calliari *et al.* 1998, Esteves *et al.* 2000). Additionally, in several stretches of the RS coastline, beach erosion causes exposure of peat and muddy lagoonal outcrops leading to a decrease in the quality of beach recreation (Calliari *et al.* 1998) (Fig. 1).

In a climate change scenario, the present study aims at assessing in detail the synoptic situations that give rise to extreme sea state events in Southern Brazil and determining trends in the atmospheric patterns and path lines of meteorological systems associated with them. The erosional impact on the coastline and the storm surges caused by these extreme events are also investigated. Case studies of selected extreme events that generated strong beach erosion are also discussed in detail.

Materials and Methods

Extreme events

In the absence of sufficiently long data sets, we had to resort to numerical models to infer the occurrence of extreme events. The results used herein were extracted from a comprehensive study that is being currently carried out by the third author and are still preliminary (see Melo *et al.* 2010). In that on-going study, the wave generation model Wave Watch III (WW3) (Tolman 2002) forced with reanalysis winds from NCEP (National Centers for Environmental Prediction) was used to reconstruct sea state conditions off the southern Brazilian coast

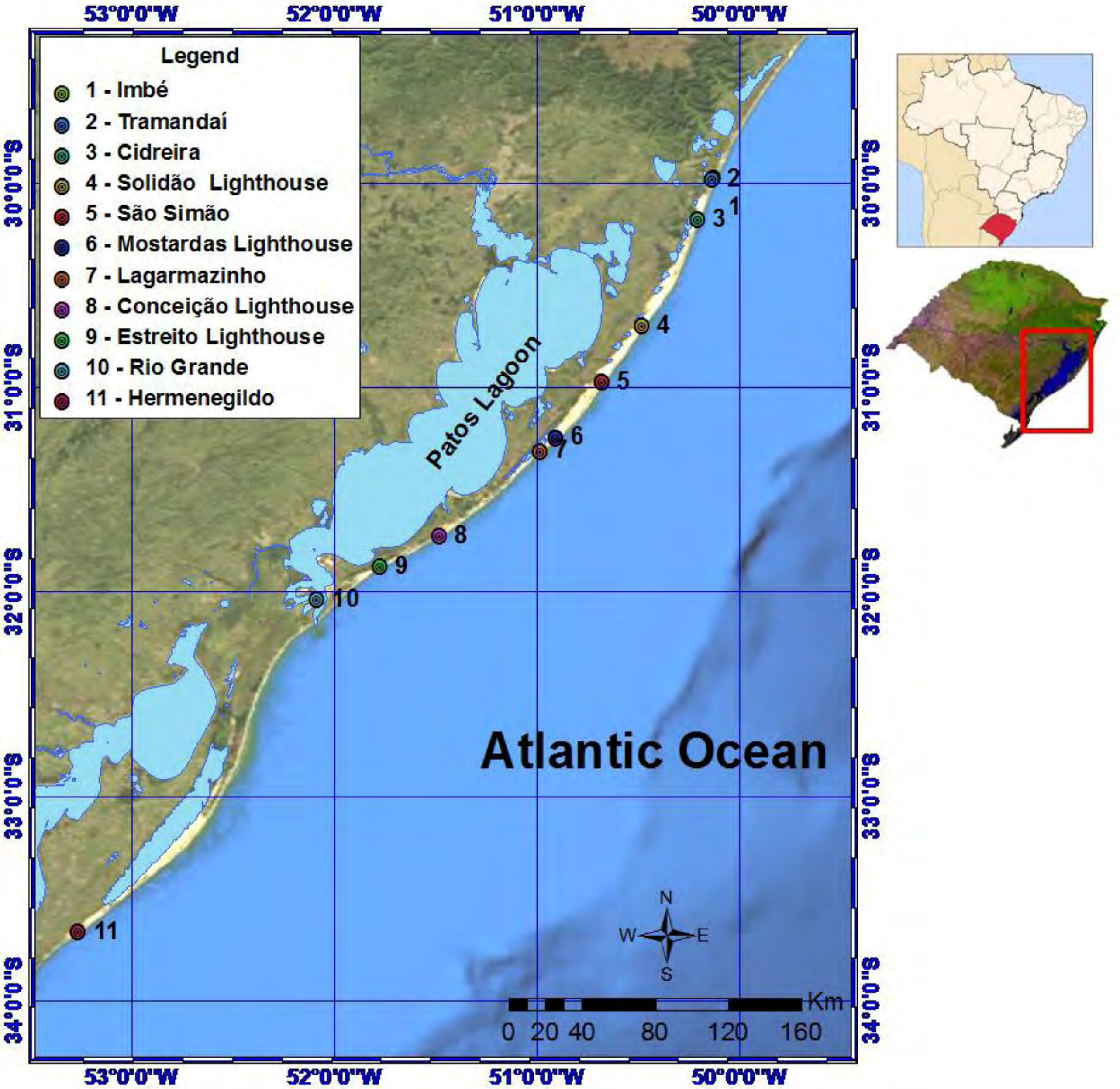

Figure 1. Study area and location of cited sites.

from 1979 to 2008. "Extreme" events were then selected based on the criteria that the reconstructed significant wave height (Hs) at a point in 100 m depth off Rio Grande city exceeded the 6 m mark. Preliminary results indicated that a total of 40 extreme events occurred in the studied period.

Synoptic scenarios associated with extreme events

The reanalysis dataset was created through the cooperative efforts of the NCEP and NCAR (National Center for Atmospheric Research) (Kalnay *et al.* 1996) to produce relatively high-resolution global analyses of atmospheric fields over a long time period. The reanalysis dataset (R-1 of NCEP / NCAR) was used to characterize atmospheric conditions that originated these 40 extreme events. To do so, meridional and zonal components of the wind and atmospheric pressure at the 995 mbar level were used. For both a spatial resolution of 2.5° x 2.5°, and a temporal resolution of 6 hours (0000, 0600, 1200, 1800 UTC) restricted between 60°S - 15°S and 90°W - 20°W was adopted. In order to better characterize the path of the systems that generated extreme events, a threshold vorticity lesser or equal than (ζ_{10}) -5 x $10^{-5}s^{-1}$ was adopted. The reanalysis dataset is available at site www.cdc.noaa.gov

Data analysis

Analysis of variance (ANOVA) was used to verify differences between the numbers of events at 3 years interval along the 30 years. Data normality was tested through the Kolmogorov-Smirnov test and the homogeneity of the same ones through the Levene test (Zar 1999).

Results and Discussion

In the period between the years of 1979 and 2008, 40 events of significant wave height (Hs) above 6 m occurred considering as reference the position of (32°54'S, 50°48'W) at 100 m water depth. The yearly mean number of events was 1.33 with a minimum of 0 events and a maximum of 4 events in the year of 1999. The standard deviation was 0.958/year.

The ANOVA result of the 10 groups joined at 3 years interval shows no significant difference in the number of extreme wave height events along the 30 years period ($F(9, 20) = 1.4815$, $p = 0.22141$) (Fig. 2A). The correlation graphic between the numbers of events and the thirty 30 years period showed a positive but weak correlation ($r = 0.30636$) (Fig. 2B).

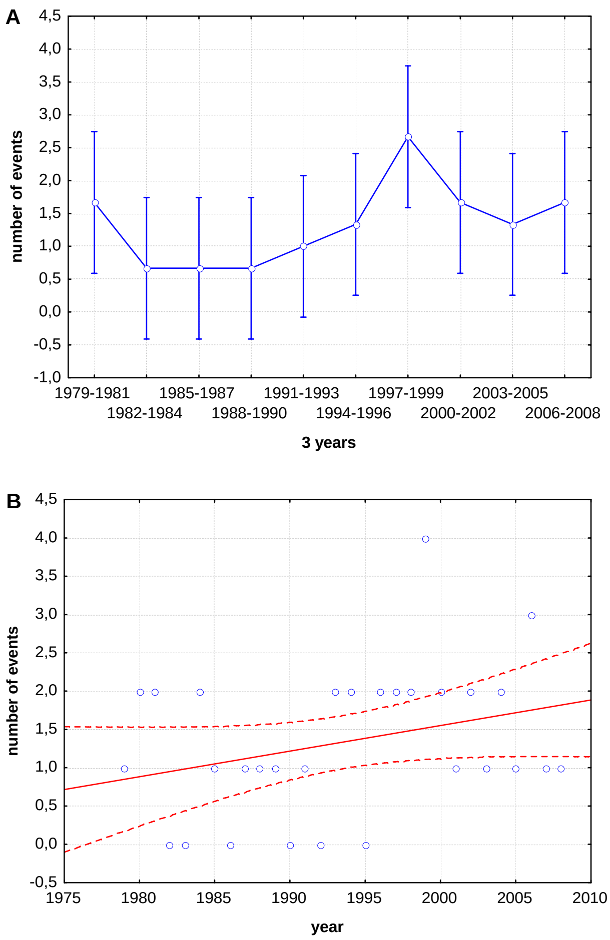

Figure 2. (A) Mean of the number of extreme events of the 10 groups, Vertical bars denote 0.95 confidence intervals, (B) Correlation of the number of extreme events over the study period, the dashed line denote 0.95 confidence intervals and the continuous line denote the regression line.

Webster *et al.* (2005) found an increase in the number of tropical cyclones and cyclone days as well as tropical cyclone intensity over the past 35 years, in an environment of increasing sea surface temperature. A large increase was seen in the number and proportion of hurricanes reaching categories 4 and 5. The largest increase occurred in the North Pacific, Indian, and Southwest Pacific Oceans, and the smallest occurred in the North Atlantic Ocean.

From the analysis of the meteorological scenarios, four patterns of synoptic situations capable of generating extreme events were identified (Fig. 3):

- PATTERN I: Cyclogenesis in the southern Argentinean coast with a displacement to the east and a trajectory between 47.5°S and 57.5°S;
- PATTERN II: Cyclogenesis in the southern Uruguayan coast with a displacement to the east and a trajectory between 28ºS and 43°S;
- PATTERN III: Cyclogenesis in the southern Uruguayan coast with a displacement to the southeast and a trajectory between 32°S and 57.5°S;
- PATTERN IV: High-pressure center generating an easterly wind.

Was not observed at the study area a significant difference in the frequency of the patterns of cyclone trajectories along time. The pattern with the greatest number of extreme events was Pattern II with 22 of the 40 +1 events. Eleven (11) events were associated with Pattern III and four (4) events were associated to both Pattern I and IV. The value of 41 related to the sum of all the patterns is due to an event that occurred on 07/21/1996, in which, two parallel extra-tropical cyclones resembling Patterns I and II occurred simulta-neously.

Case Studies

In this section, a selection of extreme sea state events was used to assess both, the specific meteorological scenarios associated, and the response that was observed on the coast in terms of beach erosion.

July 21th, 1996

An extreme wave height event occurred on July 21th, 1996. The meteorological scenario shows two extra-tropical cyclones parallel to each other representing Patterns I and II. Due to its eastern path and the following of a high pressure system in the rear, a long southwest wind fetch of more than 3000 km was formed over the Atlantic off the South American coast (Fig. 4).

This event caused the maximum erosion profiles recorded in 1996. At places located between Solidão and Estreito lighthouses the maximum eroded volume reached 62.96 m³/m (Barletta & Calliari 2003) (Fig. 5).

April 18th, 1999

The meteorological scenario on this extreme event was unusual since the path of the cyclone that developed off the RS coast formed a loop without much forward motion (Fig. 6).

Severe erosion was observed at Hermenegildo beach. Prior to the storm, this beach resort had 110 beachfront houses. During the storm, 22 houses were destroyed or highly damaged. This single storm was also able to destroy the majority of coastal protection structures including 20% of all beachfront houses. However, as it was later observed, all the coastal protection structures were built on top of the foredunes without any foundation underneath them, being, in this way, susceptible to undermining. Esteves *et al.* (2000) indicated that this was the process that caused most of the structures to collapse (Fig. 7).

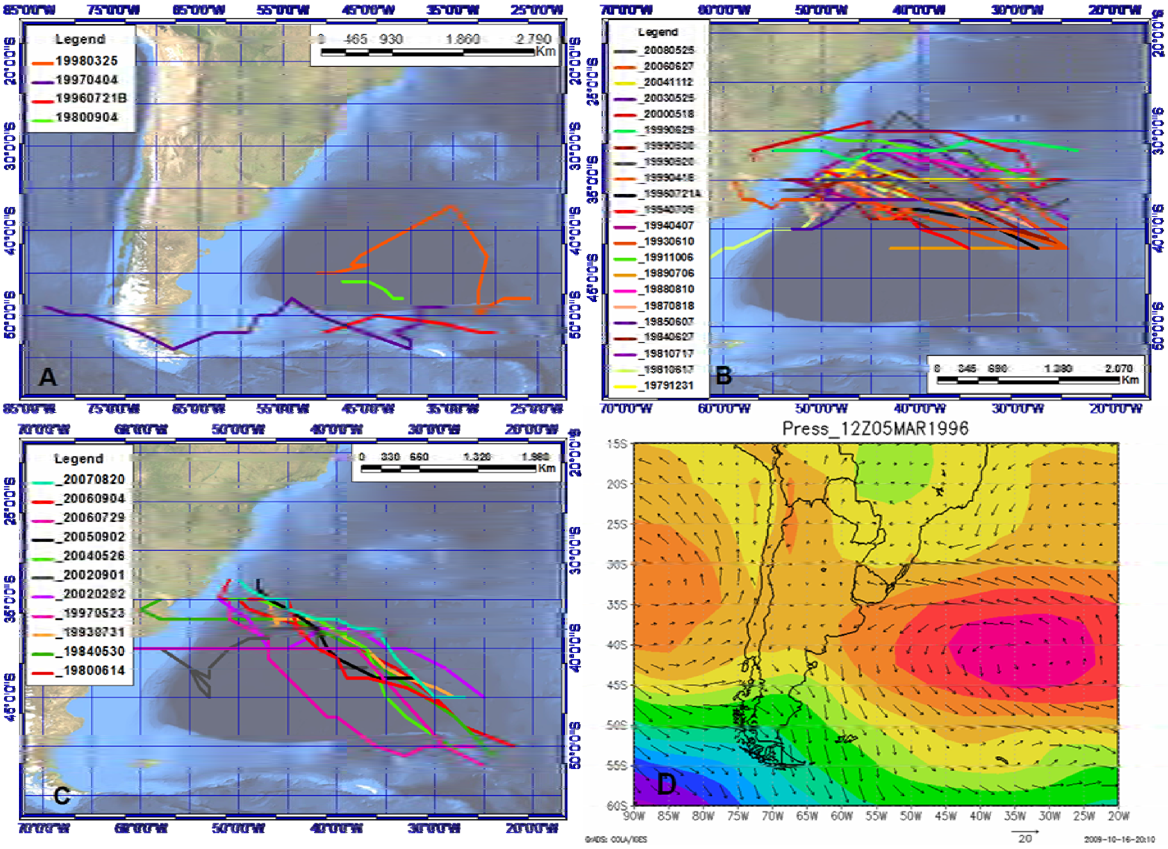

Figure 3. Path of the four synoptic situations: (A) Pattern I, (B) Pattern II, (C) Pattern III, (D) Pattern IV.

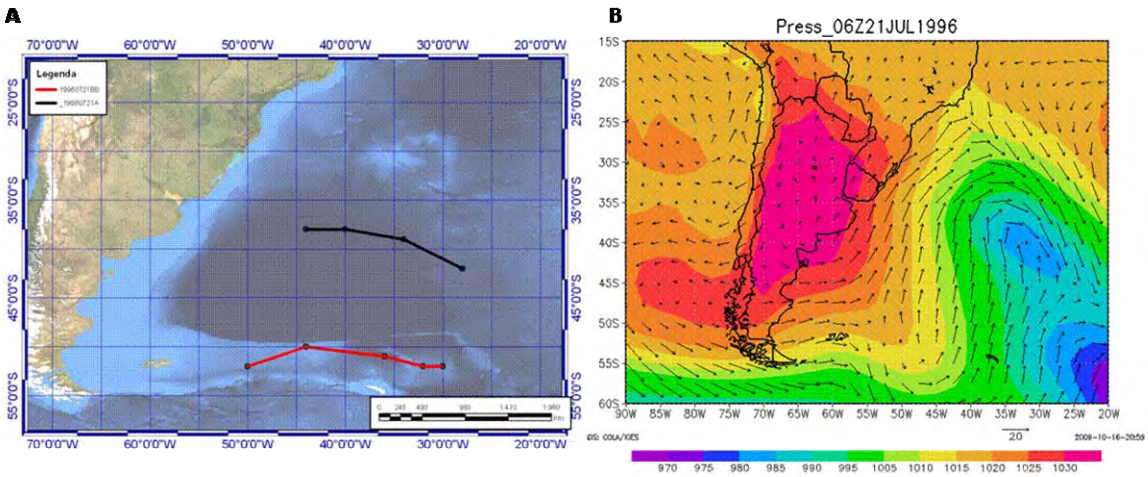

Figure 4. (A) Trajectory, (B) Synoptic situation, wind field (knots) and pressure (mbar).

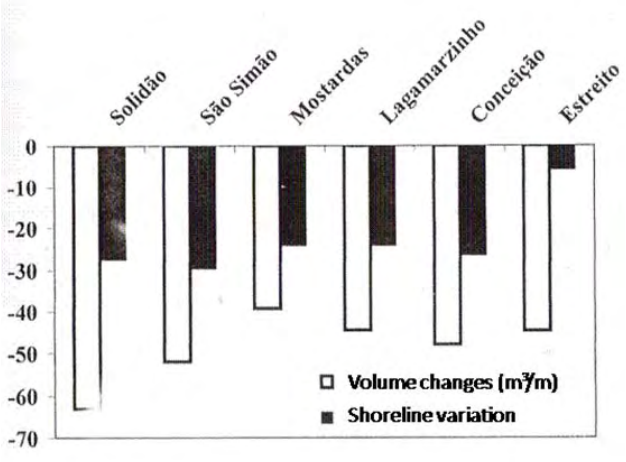

Figure 5. Shoreline (m) and volume changes (m³/m) between Estreito and Solidão lighthouses, after the storm of July 1996. Modified from Barletta & Calliari (2003).

May 25th, 2003

This event was, actually, monitored by an oceanographic buoy moored offshore Rio Grande city (Minuano buoy from the PNBOIA, Program moored at a depth of 70 m) since it caused mud deposition at Cassino beach (Calliari & Faria 2003). Buoy measurements, which did not include direction, are displayed in Table I. Maximum significant wave height came very close to the 7 m mark. The path described by the extra-tropical cyclone on this event resembled Pattern II (Figure 8A). A large low pressure center can be observed moving slowly towards the E (Fig. 8B).

September 04th, 2006

This event coincided with one of the extra-tropical cyclones studied by Parise *et al.* (2009), who shows that this particular storm caused a surge of 1.827 m. Although the surge was very high, beach erosion was low (-8.14 m^3/m) the reason being that the initial profile was already eroded by the winter storms. Regarding the meteorological scenario, it can be observed the development of a long wind fetch from S to SW (Fig. 9). The association between this wind pattern and the NE-SW orientation of the shoreline favored the extra high rise in sea level observed on the coast due to the Coriolis effect (Parise *et al.* 2009).

Table I. Wave data from the Minuano buoy (100 m depth) (Calliari & Faria 2003).

Date/Hours	Wave height (m)	Period (s)
25/05/2003- 00:00	6.9	11.6
25/05/2003- 02:00	6.7	10.7
25/05/2003- 07:00	6.9	11.6
25/05/2003- 13:00	5.6	11.1
25/05/2003- 17:00	5.6	14.2
25/05/2003- 20:00	6.9	16.0

Video-images from an ARGUS system (Holman & Stanley 2007) analyzed before and after the onset of the extra-tropical cyclone allowed the quantification of changes in beach width at Cassino during the event (Parise *et al.* 2009) Timex images from the same system display the surge reaching the dunes and the differences of the surf zone width with a third bar appearing during the storm surge (Fig. 10). Maximum values of storm surges of the order of 1 m, 1.4 m and 1.9 m in the coast of the RS have been found by Calliari *et al.* (1998), Saraiva *et al.* (2003) and Parise *et al.* (2009), respectively. During this event great part of Cassino beach was flooded when the water reached the first avenue close to the beach.

Studies done by Saraiva *et al.* (2003) and Parise *et al.* (2009) pointed out that the maximum elevation of the surge occurs mainly 24 hours after the cyclone formation (Tab. II).

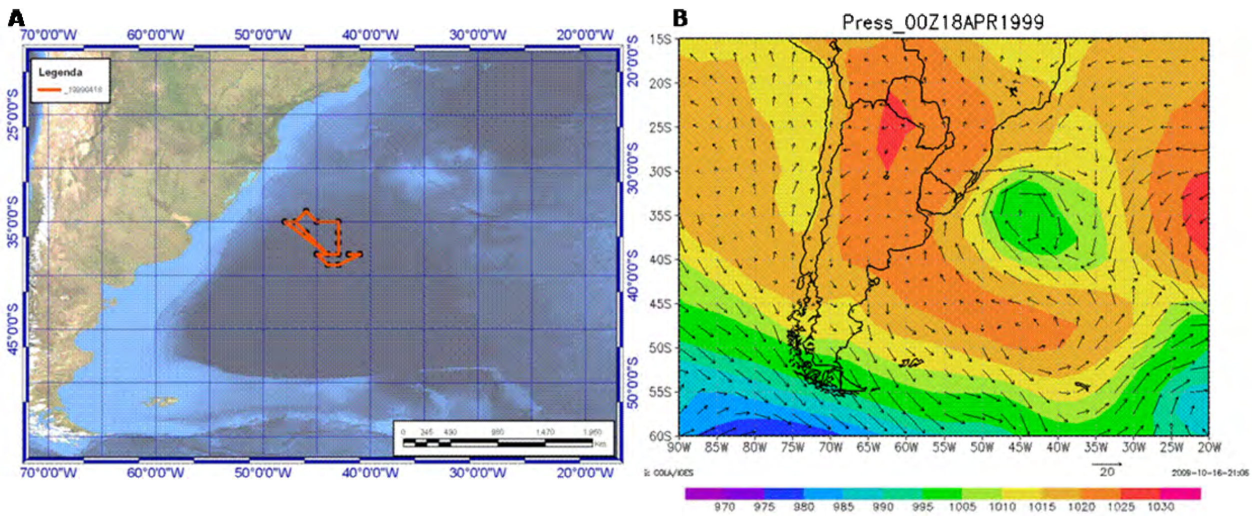

Figure 6. (A) The path in loop, (B) Synoptic situation, wind field (knots) and pressure (mbar).

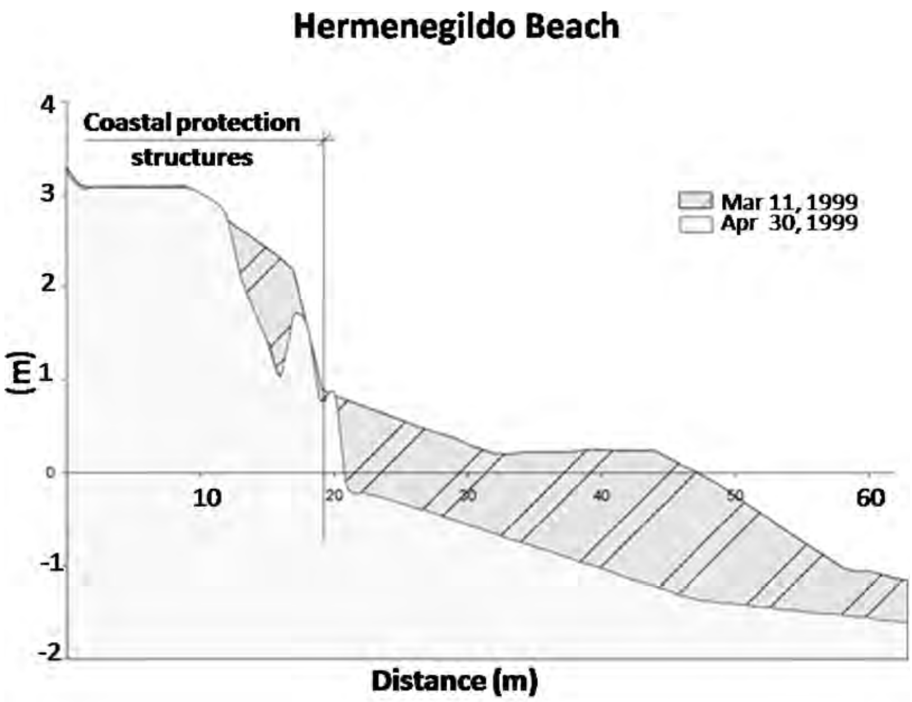

Figure 7. Beach profiles done before and after the event of 18/4/1999. Modified from Esteves *et al.* (2000).

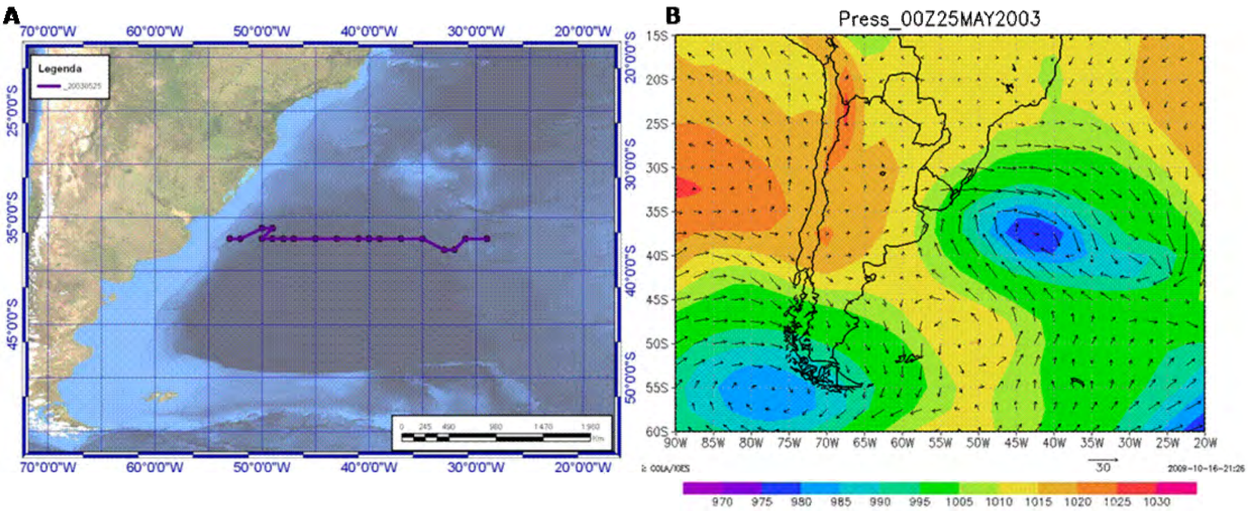

Figure 8. (A) Trajectory, (B) Synoptic situation, wind field (knots) and pressure (mbar).

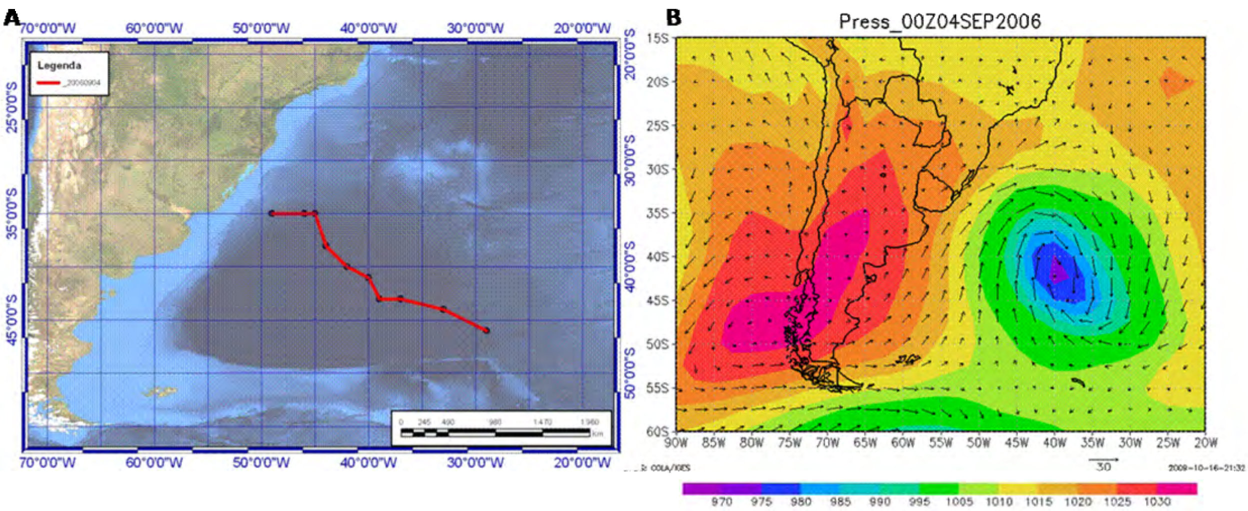

Figure 9. (A) Trajectory, (B) Synoptic situation, wind field (knots) and pressure (mbar).

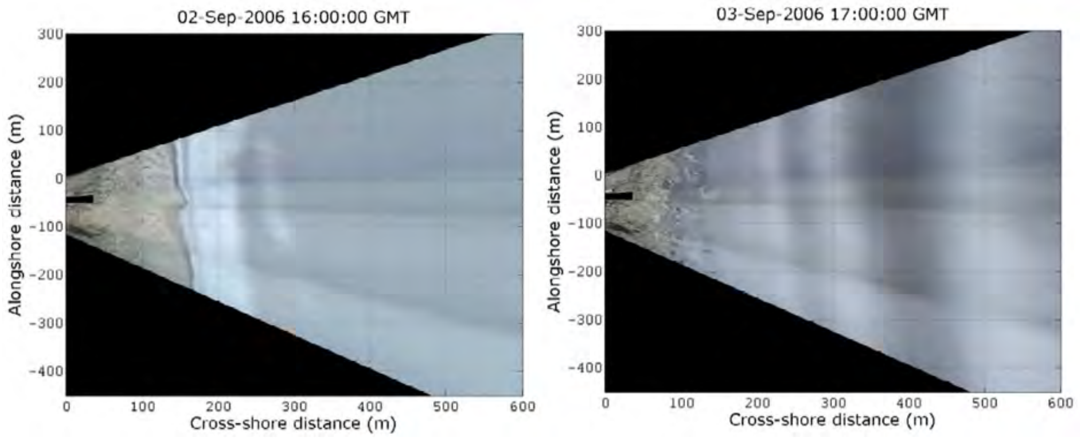

Figure 10. Timex images of the Argus system installed at Cassino beach, during a normal surf-zone (left) and during the storm surge (right). LOG-FURG/2007 - http://www.praia.log.furg.br/

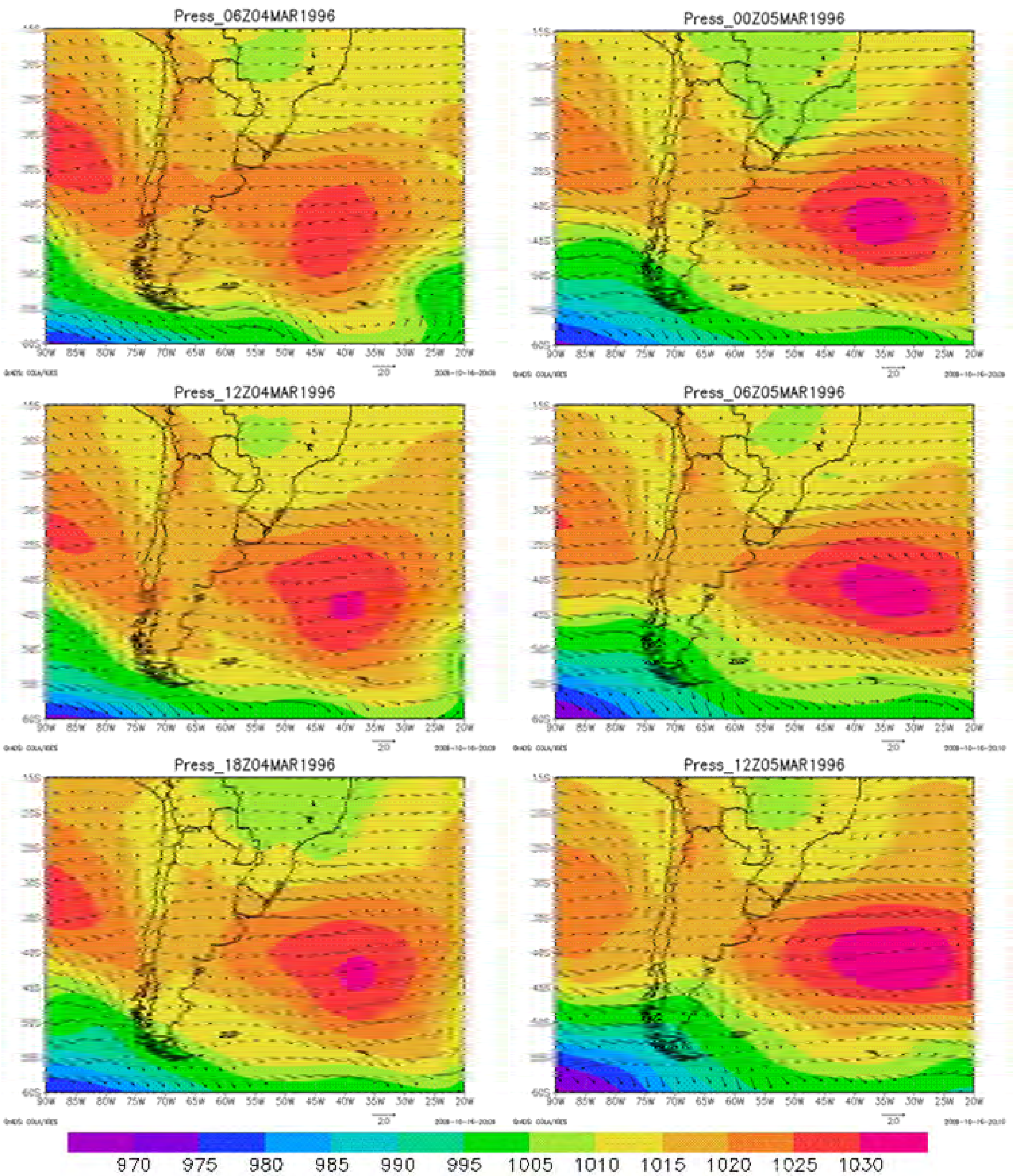

Figure 11. Synoptic situation of the of high pressure center (anticyclone) moving toward the east. Wind (knots) and pressure (mbar)

Table II. Time interval between the formation of the cyclone and the maximum surge elevation.

MONITORING	6h	24h	36h	48h
1997 to 1999 (Saraiva *et al.* 2003)	10%	45%	10%	30%
2006 to 2007 (Paris *et al.* 2009)	9%	39%	26%	26%

Special Cases

Among the 40 extreme wave height events, four were generated by strong easterly winds associated with large anticyclonic system, which also displays the path of the high-pressure center between March 04 and 05 of 1996. This event generated waves from the east quadrant as indicated by the wind field shown in figure 11.

Conclusion

This study shows no important differences in the amount of extreme events along the last thirty years. The mean number of events obtained was 1.33 per year. To these events data of wind velocity and vorticity, atmospheric pressure and sea level elevation were added. Effects of extreme events on the coast caused maximum erosion and surge elevation on the order of 62.96m³/m and 1.827 m, respectively.

Among the 40 events studied, 22 (53.66%) had the trajectory of Pattern II with Cyclogenesis to the south of the Uruguayan coast with a path to the east and a trajectory between 28°S and 43°S. Cyclones associated with Pattern III, represented 26.82% (11 events). Those two types represent 80% of the total extreme events. The relationship between the coastal erosion and these extreme events is clear, as observed from Parise *et al.* (2009), being the cyclones associated with Pattern II the most erosive ones, whereas those associated with Pattern III the ones that cause highest surges.

The reanalysis dataset of NCEP proved very useful in this type of analysis, because although the spacing of the data 2.5 degrees, cyclones and anticyclones studied have diameters above 1000 km, thus presenting a good answer to the synoptic situation that caused each extreme event studied.

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Climatic changes in the coastal plain of the Rio Grande do Sul state in the Holocene: palynomorph evidences

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Abstract. Climatic changes during the Holocene were the principal factors influencing the coastal plain evolution and sea level oscillations. Climatic fluctuations were responsible for littoral sedimentation and palaeoenvironmental changes. Palynological data, obtained from core-drillings, performed at the bottom of the Patos and the Tramandaí lagoons and in adjacent areas, were used for palaeoclimatic reconstructions. Palynomorphs, represented by algal and fungal palynomorphs, pollen and spores of vascular terrestrial and aquatic plants, microforaminifers, and scolecodonts showed their indicative value for palaeoclimatic reconstructions. The samples, dated by ^{14}C method, allowed the comparison of the results when making interpretations. Increase in marine algal palynomorphs indicated sea level rise as a result of global temperature increase. The beginning of the marine transgression was about 10 kyrs BP after the last glacial period when temperature raised. Transgressive maximum (4-6 kyrs BP) was characterized by sea-level rise at about 4-5 m. Posterior regression began as result of temperature fall and drier climate, forcing dune formation in the coastal plain. Palynomorph records from the lagoon sediments in the coastal plains have a great potential and may serve for detail paleoclimatic reconstructions of the past and predictions of climatic changes in the future.

Keywords: Palynology, Palaeoecology, Lagoon sediments, Extreme Southern Brazil

Resumo. Mudanças climáticas na Planície Costeira do Rio Grande do Sul no Holoceno: evidências de palinomorfos. As mudanças climáticas ocorridas durante o Holoceno foram os principais fatores que influenciaram na evolução da zona costeira e nas oscilações do nível do mar. Flutuações climáticas foram responsáveis pela formação dos sedimentos litorâneos e as mudanças paleoambientais. Dados palinológicos, obtidos a partir de furos de sondagens e testemunhos executados no fundo da laguna dos Patos e da laguna de Tramandaí e nas adjacências, foram usados para reconstruções paleoclimáticas. Os palinomorfos representados pelas algas, fungos, grãos de pólens e esporos de plantas vasculares terrestres e aquáticas, microforaminiferos e escolecodontes mostram seus valores indicativos para as reconstruções paleoclimáticas. As amostras datadas pelo método de ^{14}C nos permitiram comparar os resultados obtidos quando foram efetuadas as interpretações. Aumento de palinomorfos de algas marinhas indicou a subida do nível do mar como resultado do aumento das temperaturas globais. Início da transgressão marinha foi a cerca de 10 ka AP depois da última glaciação quando as temperaturas subiram. O máximo transgressivo (4-6 ka AP) foi caracterizado pela subida do nível do mar de 4-5 m. A regressão posterior começou como resultado da queda das temperaturas e aridização do clima, que causou a formação de dunas na zona costeira. Os registros de palinomorfos nos sedimentos lagunares das zonas costeiras possuem um grande potencial nas reconstruções paleoclimáticas do passado e também como previsões de mudanças climáticas do futuro.

Palavras-chave: Palinologia, Paleoecologia, Sedimentos Lagunares, Extremo Sul do Brasil

Introduction

Paleoclimatic changes during the Quaternary (approximately 2.5 Ma BP) were relatively rapid in the past as compared with past climate changes in the last 60 Ma. Understanding of climate oscillations during the Quaternary is important to evaluate variability of the natural environments in the past and probably use of these data for a better understanding of actual climate situation and prediction of the future climate. Climatic changes occurred during the Holocene (10 ka BP till present) were the main factors influencing on the coastal plain evolution of the Rio Grande do Sul state, Brazil. The oscillations of global temperatures caused relatively high frequency changes on sea level. The climatic modifications were also responsible for the littoral sediments deposition in the coastal plains and palaeoenvironmental evolution.

There are many different methods (proxy data) for the Quaternary paleoclimate reconstructions in the world (Bradley 1999). Palynological analysis is one of the most important methods, providing information from continents to complement other proxy data about paleoclimates (Webb 1991, Bradshaw 1994, Ledru *et al.* 1998, Bradley 1999). In addition to pollen and spores of vascular plants, sediments usually include different non-pollen palynomorphs, which are organic-walled microfossils composed of sporopollenin-like or chitin (pseudochitin) polymers (Traverse 1988). These palynomorphs as a rule are more resistant to corrosion and oxidation than pollen and spores composed of sporopollenin (van Geel 1976, Komárek & Jankovská 2001). These palynomorphs are predominantly represented by cysts of Acritarcha (marine phytoplankton) and Dynophyta, zygospores, coenobiums and colonies of Chlorophyta, different fungal palynomorphs, palynomicroforaminifers, and scolecodonts. The forms, usually classified by palynologists as cysts of Acritarcha are *Prasinophycean phycomata* (Colbath & Grenfell 1995). In spite of uncertainties, regarding of their precise biological affinities, acritarchs are considered as remains of cysts of algal protists (Tappan 1980, Strother 1996). Prasinophycean algae are a class of green algae, which are known today from freshwater to marine environments, although in recent forms only the marine taxa produce a fossilized phycomata. The vast majorities of *Prasinophycean phycomata* are recovered from marine sediments and/or are associated with marine organisms. Furthermore, based on their distribution, morphology, and composition, most *Prasinophycean phycomata* are assumed to be phytoplankton, and therefore were the primary producers of the ancient marine ecosystem during the Proterozoic and Paleozoic (Martin 1993).

The study of non-pollen palynomorphs started at the early 1970s in the Netherlands, and since then, the interest in their use for palaeoclimatic reconstructions is growing (van Geel 1976, van Geel & van Hammen 1978, van Geel *et al.* 1980/81, van Geel & Aptroot 2006).

In the Quaternary lagoon sediments of coastal plains, the palynomorph variability is more diverse than in continental deposits. In addition to algal and fungal palynomorphs, there are frequent palynoforaminifers (Zamora *et al.* 2007, Medeanic *et al.* 2009), *Prasinophycean phycomata*, and cysts of Dynophyta (Grill & Quatroccio 1996, Medeanic *et al.* 2001, Weschenfelder *et al.* 2008) indicative of sediments deposited under sea water influence. Scolecodonts are palynomorphs, encountered in sediments formed in shallow water environments near the coast (Lorscheitter 1983, Cordeiro & Lorscheitter 1994).

The different scientific projects regarding Holocene paleoclimate and palaeoenvironmental reconstructions in the coastal Plain of the Rio Grande do Sul State, Brazil based on palynomorph study started in 1980s (Lorscheitter 1983, Cordeiro & Lorscheitter 1994, Lorscheitter & Dillenburg 1998, Medeanic *et al.* 2003, Medeanic 2006, Medeanic & Corrêa 2007). All obtained information so far allowed us to make proxy evaluation of climatic oscillations occurred since the last Pleistocene glaciations. The lowering of temperature that time caused the regression of the ocean with negative amplitude of 120-150 m. The temperature rise at about 10 kyrs BP (the Early Holocene) was the reason of the beginning of the marine transgression. The maximum of marine transgression occurred at about 5-6 kyrs BP (the Middle Holocene) with positive amplitude of sea level rise at about 4-5 m. Posterior marine regression at about 3-3.5 kyrs (the Late Holocene) was characterized by sea level fall at about 2 m. In this paper, we present a revision of our previous published results, based on palynomorph study focusing on the Holocene climatic paleoreconstructions.

Materials and Methods

Study area

The study area is situated in the southern part of the coastal plain of the Rio Grande do Sul state (Fig. 1). The climate of this region is warm-temperate, due to the joint influence of the warm Brazil and cold Falkland currents (Vieira & Rangel

1988). The average annual temperature is 18 °C, with monthly averages of 24.6 °C in January and 13.1 °C in July. The mean annual precipitation is about 1,200 mm. The coastal plain has a diverse geomorphology, with sandy beaches, dunes, freshwater, brackish-water, salt marshes, and wetlands (Costa *et al.* 1997).

In the Quaternary, the coastal plain was subjected by glacio-eustatic sea level oscillations (Villwock & Tomazelli 1995, Corrêa *et al.* 1996). During the Holocene, a vast part of the present Brazilian coastal plain was flooded by sea-waters (Angulo & Lessa 1997, Martin *et al.* 2003). The last glacio-eustatic sea level rise (transgressive phase) began at about 10 kyrs BP. The maximum of that transgression occurred around 5,600 yrs BP characterized by a sea level rise of approximately 5 m above the present sea level. The following regressive stage led to the present sea level.

Sandy sediments along the coast were deposited during regressive-transgressive events in the Quaternary. Lagoon formation was connected to the evolution of the Holocene barrier-lagoonal system (Villwock & Tomazelli 1995). The lagoonal sediment deposits started about 8 kyrs ago (Toldo *et al.* 2000). They consist mostly of mud or muddy sands, having an average thickness of about 6 m.

According to Ramos (1977), the present day vegetation of the coastal plain of the Rio Grande do Sul state consists of the plant communities of dry fields, humid depressions, flooded depressions, peat soils, flooded soils, freshwater marshes and coastal subtropical forests. A great specific diversity of species of Poaceae and Cyperaceae characterizes this region. The modern state of vegetation is a result of the effect of natural factors during the Holocene and the anthropogenic impact, especially during the last century.

Sample collections

A total of more than 100 samples were collected from cores T-64, TBJ-02, B-2, situated in the estuarine part of the Patos Lagoon, and from core FS-20, performed at the Cassino Beach region. Other 35 samples were collected from the cores FS-10 and T-14 performed at the bottom of the Tramandaí Lagoon and adjacent area (Fig. 1). Samples represented by mud and muddy sands were used for the palynomorph study. Samples, enriched by organic matter, were radiocarbon dated at Beta Analytic Inc., Florida, USA. Based on the correlation of the core T-64 (a sample 140 cm deep) with an adjacent core identical in sedimentological and seismical characteristics (Toldo *et al.* 2000), we concluded an approximate age of 5,500-6,000 yrs BP.

The chemical treatment of the samples followed Faegri and Iversen (1975) using HCl (10%) and NaOH (5%). The use of HF was avoided in order to preserve siliceous remains, such as silicoflagellate skeletons and diatoms. Separation of inorganic and organic substances was carried out using $ZnCl_2$ solution with a density of 2.2 g/cm^3.

Results and Discussion

The principal palynomorphs, identified from the Holocene lagoon sediments, were pollen and spores of vascular terrestrial and aquatic plants, algal palynomorphs (zygospores, coenobiums and colonies of Chlorophyta, *Prasinophycean phycomata*, and Dynophyta cysts), fungal palynomorphs (ascospores, hypnodia, fruit bodies), palynoforaminifers, and scolecodonts. Besides, silicoflagellate skeletons of Dictyocha were found in some samples, which were corresponded to transgressive maximum. The microphotographs of the most frequent palynomorphs, identified from the Holocene lagoon samples in the coastal plain of the Rio Grande do Sul state are shown in the plate.

Our reconstructions of paleoclimate were based on the ecological characteristics of all registered and identified palynomorphs taxa. Only the most representative palynomorphs and their ecological characteristics were mentioned for palaeoclimate reconstructions in the Table I. These palynomorphs were zygospores, coenobiums and colonies of Chlorophyta, whose identifications were made according to literature (van Geel 1976, van Geel & van der Hammen 1978, Jankovská & Komárek 2000). They were from freshwater environments, and may also be evidence of freshwater input into saline aquatic environments during pluvial periods (Medeanic *et al.* 2003, Medeanic 2006). Besides, dinoflagellate cysts and *Prasinophycean phycomata* were found, which are indicators of marine environments or sea water influence by tides and/or marine transgressions (Dale 1976, Hoek *et al.* 1995, Grill & Quattroccio, 1996).

The palynoforaminifers represent chitinous inner tests of different benthic and planktonic foraminifers which are widely spread in the oceans and in the seas (van Veen 1957, Pantic & Bajaktarevic 1988). The informal classification of palynoforaminifers was based on morphology, including number of chambers and the types of chambers arrangement. Biological affinities of the different morphological types of palynoforaminifers have not been established yet. Chitinous fungal

Table I. Indicative values of palynomorphs encountered in the Holocene lagoon sediments in the coastal plain of Rio Grande do Sul for paleoclimatic reconstructions.

Palynomorphs	Distribution	Palaeoclimatic implications
Pollen and spores of terrestrial and aquatic vascular plants	All ecosystems of the coastal plains	Increase in frequency, abundance and taxonomic variety from the lagoon samples indicate on augmentation of fresh-water input into lagoons (more humid climate)
MICROALGAE		
Dinoflagellate cysts	The oceans and the seas	Increasing of marine water influence (transgressions) occurred as a results of temperature rise
Prasinophycean phycomata	The oceans and the seas	Increasing of marine water influence (transgressions) occurred as a results of temperature rise
Chlorophyta		
Botryococcus	Freshwater-brackish water environments	Brackish-water lagoon environments, increasing in the past was connected with drier climate
Spirogyra, Pediastrum, Zygnema, Mougeotia	Freshwater fluvial, lacustrine environments	Significant freshwater input into lagoons may serve as indicator of humidity increase
Pseudoschizaea	Grow at the edge of streams and in ponds	Significant freshwater input into lagoons may serve as indicator for humidity increase
FUNGI		
Glomus	Principal plant in the coastal plain that fix and support dunes	Increase in frequency in lagoon sediments may be indicative for the shallow lagoons and an proximity of the coast indicative for drier climate
Tetraploa	Sporadically in salt and brackish-water marshes	Salt and brackish-water marshes and mangroves
Hyphae	Numerous hyphae in organic rich sediments	Indicative of humid and warm climate, freshwater input during pluvial periods and transport by rivers
SCOLECODONTS	Salt marshes and beaches	Indicators of shallow water basins, the beaches, showing the coast proximity to the lagoons occurred when climate changes became drier
PALYNOFORAMINIFERS	Oceans and seas	Sea level rise (transgressions) caused by temperature increase

palynomorphs, resistant to destruction and important for palaeoenvironmental reconstructions have been recently reported (Jarsen & Elsik 1986, van Geel & Aptroot 2006).

Use of fungal palynomorphs for the elevated salinity environments of the coastal plains, spread inthe Quaternary, has not been sufficiently elaborated yet. The abundance and taxonomic variability of mycorrhizic *Glomus* and its importance for dune stabilization was shown by Cordazzo & Stümer (2007), who studied *Glomus* in the roots of *Panicum racemosum*, a species that fixes and supports dunes. Limaye *et al.* (2007) registered an increase in *Glomus* in the sediments, formed during the Late Glacial Period of the Pleistocene in India, related to active erosion processes under a dry and continental climate. Fungal palynomorphs of *Tetraploa* are common in the salt and brackish-water marshes of coastal plains (Medeanic *et al.* 2001, Limaye *et al.* 2007).

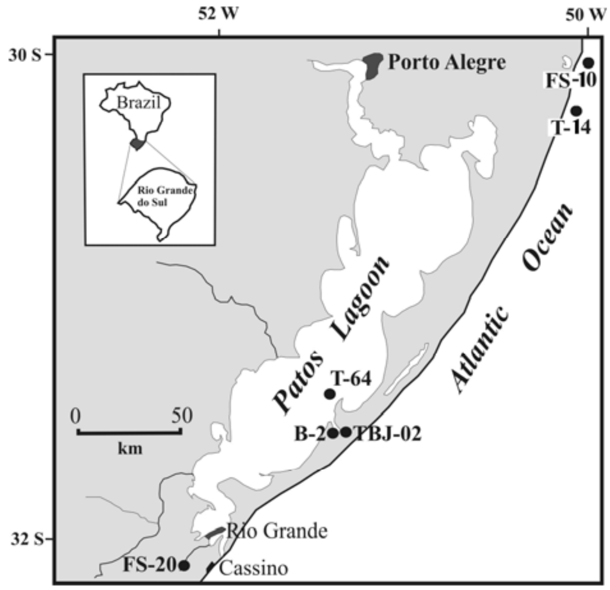

Figure 1. Map of the coastal plain of the Rio Grande do Sul State, Brazil, with the location of the core-drilling sites.

Scolecodonts are the jaws of polychaete annelids. They are fossilized due to their chitinous teeth and dwelling tubes. Representative amounts of scolecodonts are important indicators of sediment deposition near the shelf or near the beaches (Limaye *et al.* 2007). Silicoflagellate skeletons of Dictyocha are important marine indicator for the lagoon sediments subjected by the marine influence when temperatures were higher than in present (McCarthny & Loper 1989, Medeanic & Corrêa 2007).

For the reconstructions of palaeoclimate changes occurred in the different periods of the Holocene, based on palynomorphs, the absolute age data of some samples on ^{14}C were used (Table 2). Present day, using both absolute age data, and palynomorphs records, we can detect some periods of distinctive climatic changes.

Early Holocene

Some samples whose ages correspond to 9,620+/-160 and 9,400+/-140 yrs BP included palynomorphs, indicated on relatively humid and lower than present day temperatures. That time, freshwater marshes, sometimes subjected by sea-water entrance, were wide spread (Medeanic & Dillenburg 2001, Weschenfelder *et al.* 2008). Thin layers (30-40 cm) of peat were formed under such climatic conditions. Then, 8,620+/-170 yrs BP, a drier climate caused a decrease in the areas of freshwater marshes and an increase of xerophylous and halophylous herbaceous plants. At the same time, marine influence in the coast increased, which was revealed by marine palynomorphs (prasinophycean phycomata, cysts of dinoflagellates, and palynoforaminifers) appearance in the lagoon sediments.

Middle Holocene

Further results point to climatic and environmental changes in the coast during the Middle Holocene. Palynomorphs from one sample, dated as 7,840+/-140 yrs BP indicated a relatively humid climate and sea level rise, influenced on notable spreading of the salt-and-brackish-water marshes. Ahead of marine influence, freshwater marshes were inhabited by ferns, mesophylous and aquatic herbs. The obtained data delay with oscillate character of climate during the Middle Holocene. The period of time since 7,570+/-150 and 7,370+/-150 yrs BP was characterized by dry and hot climate, resulted in less dense vegetation cover, decrease in taxonomic variety of plants. In the coast, dunes were more spread, and lagoon were subjected by sea water entrance, ampli-tude of sea-level rise continuously grew (Medeanic *et al.* 2001, 2003, Weschenfelder *et al.* 2008). Maximum of sea water rise was detected from the samples dated as 5,500-6,000 and 4,940+/-80 yrs BP. There was a notable increase in marine algae palynomorphs and Dictyocha skeletons (Fig. 2). Frequency of freshwater algal palynomorphs (*Spirogyra*, *Pediastrum*, *Zygnema*, *Mougeotia*, *Pseudoschizaea*) was very low, indicating salinity increasing in paleolagoon in the maximum sea-level rise (Fig. 3). Predominance of *Botryococcus* colonies in the paleolagoon was evident. Hot and dry climate was the reason of relatively pure vegetation cover in the coastal plain – small frequency of pollen of aquatic vascular plants and arboreal pollen (Fig. 4). Increase in humidity caused more spreading of ferns, arboreal and herbaceous terrestrial and aquatic plants (Figs. 4-5). The final of marine transgression was a result of temperature lowering and climate drying. Sea level fall led to regressive stage.

Late Holocene

That time interval corresponds to regressive stage of the Holocene. We have not yet radiocarbon data on absolute age of sediments from the different depths of the core drillings. But palynomorphs data from the lagoon sediments indicate that oscillate climatic changes occurred after transgressive stage. Based on the evaluation of algal palynomorph taxa frequency and relation (%) between *Botryococcus*

Table II. The cores, absolute age of studied sediments and interpretations of climate, based on palynomorphs.

Cores	^{14}C dating, (yrs BP)	References	Paleoclimatic reconstructions
FS-10	9620+/-160	Medeanic & Dillenburg 2001	Relatively humid
B-2	9400+/-140	Weschenfelder *et al.* 2008	Relatively humid
FS-10	8620+/-120	Medeanic & Dillenburg 2001	Drier
FS-10	7840+/-140	Medeanic & Dillenburg 2001	More humid
T-14	7570+/-120	Medeanic *et al.* 2003	Relatively dry
TBJ-02	7370+/-150	Medeanic *et al.* 2001	Relatively dry
B-2	7370+/-150	Weschenfelder *et al.* 2008	Relatively dry
T-64	~5500-6000	Medeanic *et al.* 2001	Higher temperature and humidity
FS-20	4940+/-80	Clerot 2004	Higher temperature and humidity

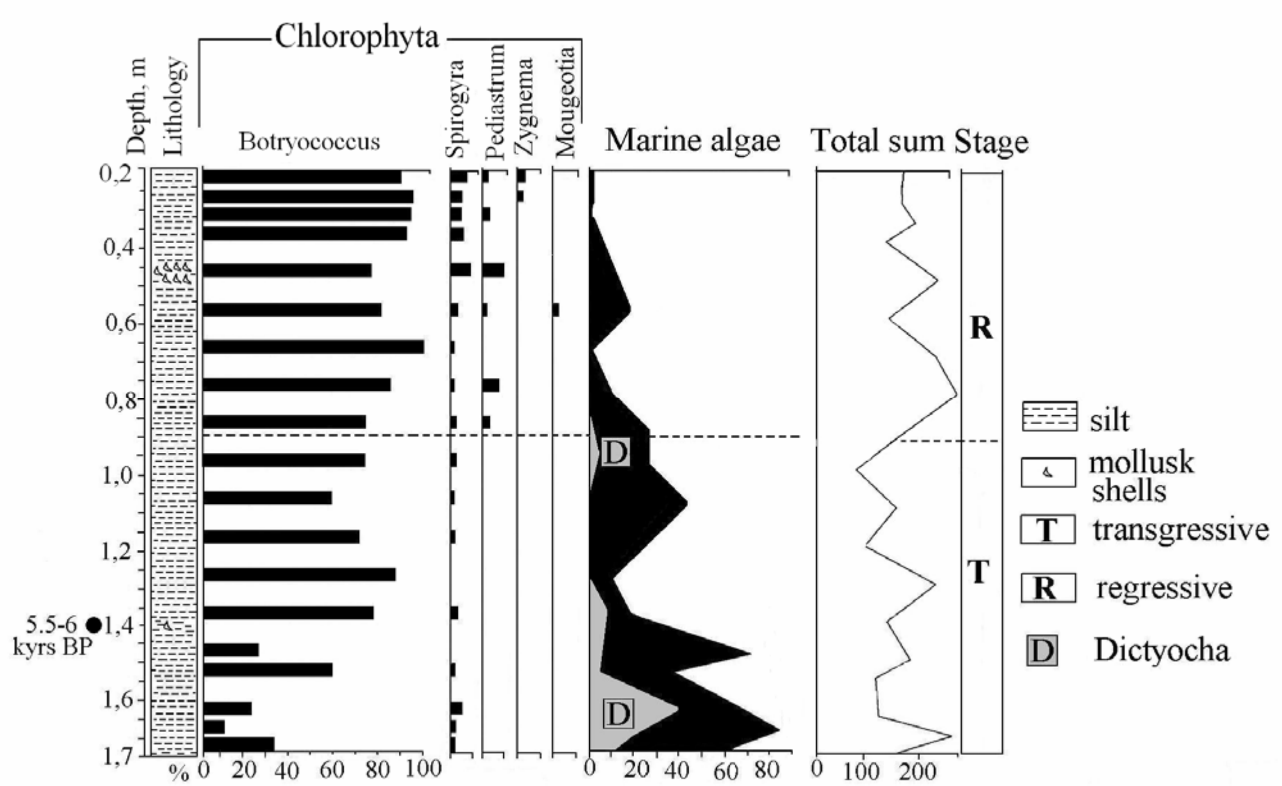

Figure 2. Percentage palynodiagram of algal palynomorphs from the samples of the core T-64 (adapted from Medeanic & Corrêa 2008).

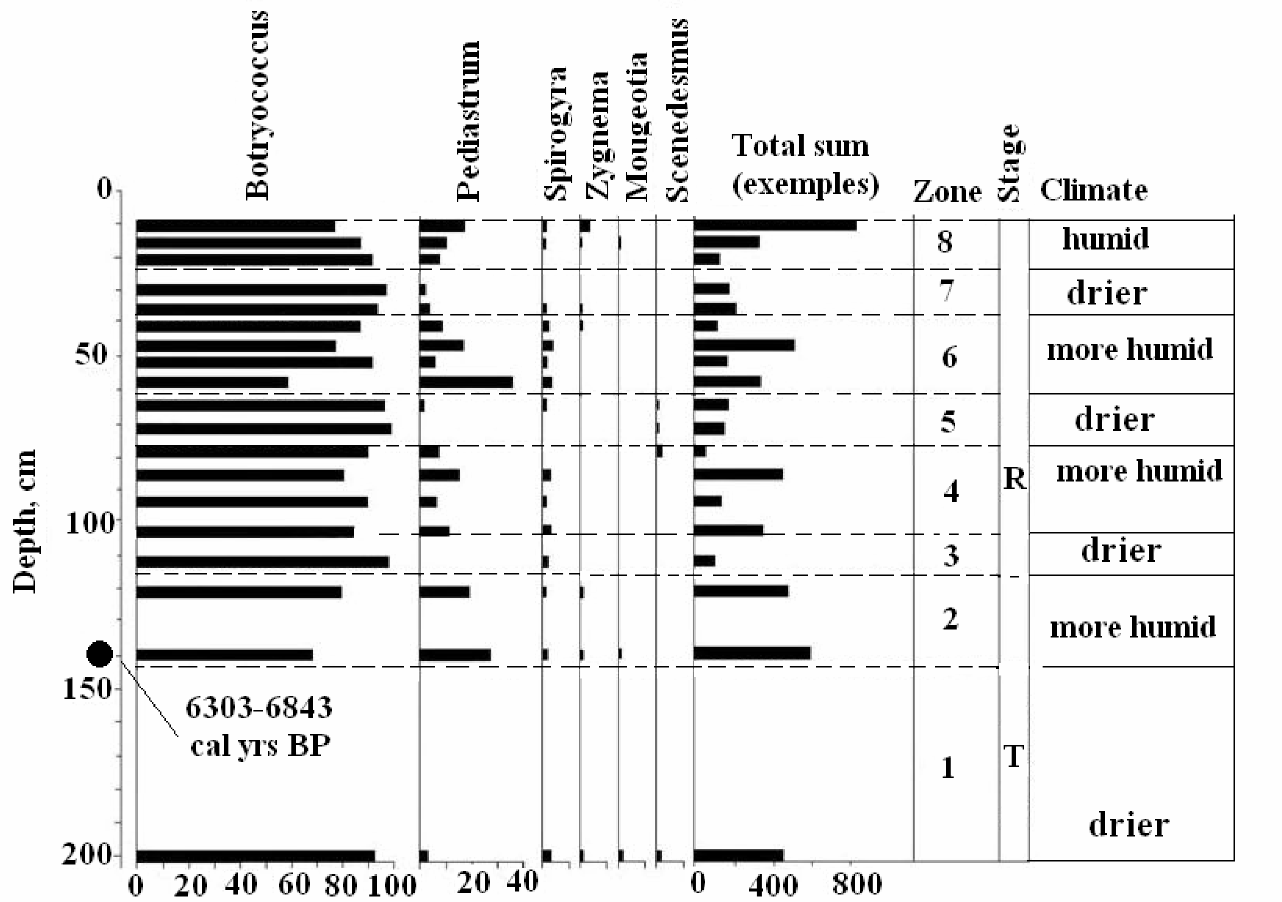

Figure 3. Percentage palynodiagram of algal palynomorphs of Chlorophyta from the samples of the core T-14 (adapted from Medeanic 2006).

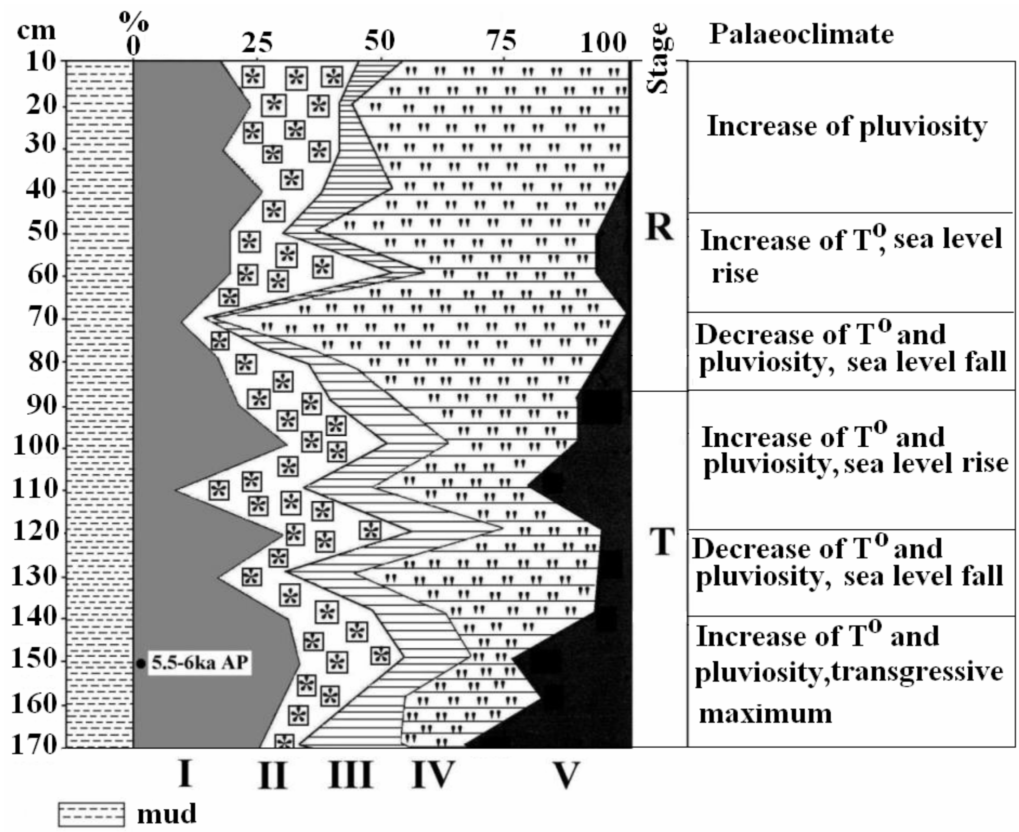

Figure 4. Generalized percentage palynodiagram from the samples of the core-drilling T-64: I – pollen and spores of terrestrial vascular plants, II – pollen and spores of aquatic plants, III – pollen of Poaceae, IV – palynomorphs of Chlorophyta, V – marine algal palynomorphs, T – transgressive stage, R – regressive stage.

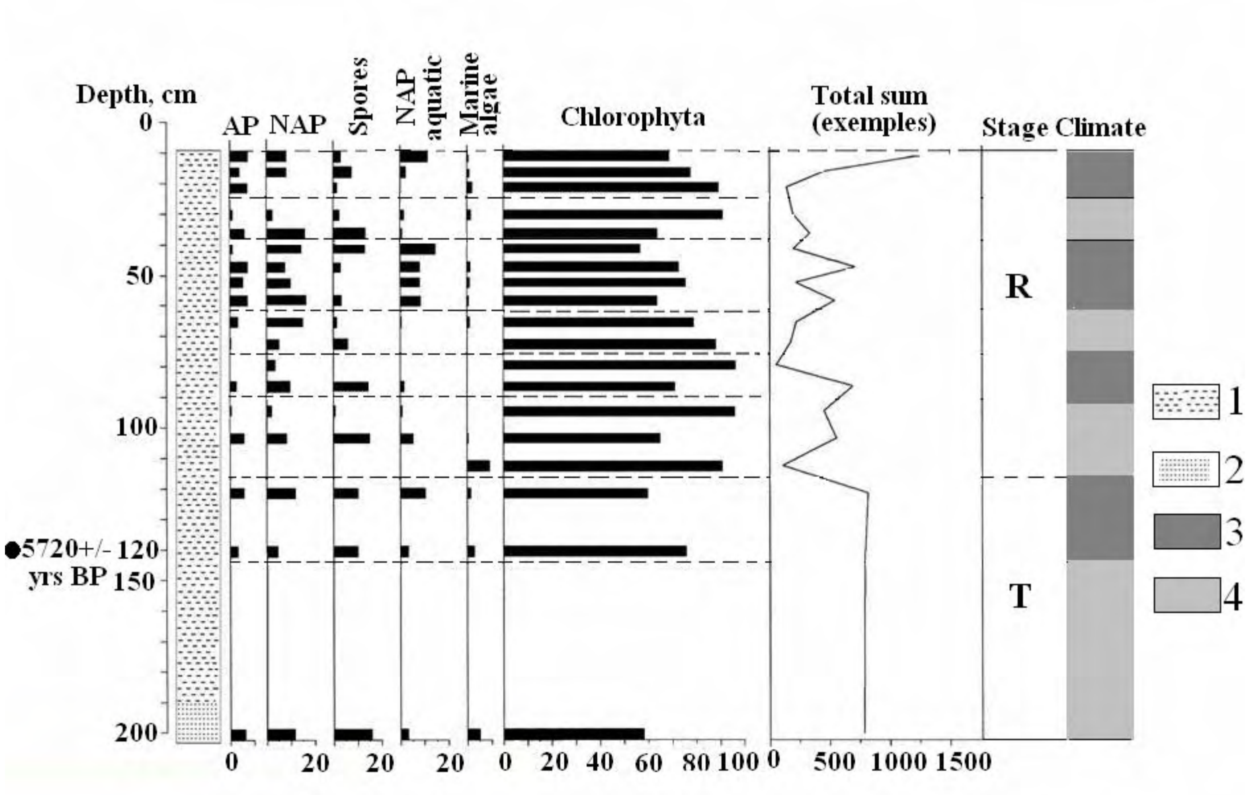

Figure 5. Percentage palynodiagram of palynomorphs counted from the samples of the core T-14: AP – arboreal pollen, NAP – non-arboreal pollen, T – transgressive stage, R – regressive stage, 1 – mud, 2 – sand, 3 – more humid climate, 4 – drier climate (adopted from Medeanic *et al.* 2003).

(indicative for drier climate) and *Pediastrum* (pointing to an increase in humidity) from lagoon sediments of the core drilling T-64, we concluded different sub/stages of climatic changes during regressive stage: drier-more humid-drier-more humid, drier and humid (Fig. 3). In the lagoon sediments formed in the periods of drier climate, a great number of scolecodonts and various fungal palynomorphs were recorded, indicating a lagoon shallowing and on the coast (beach) proximity.

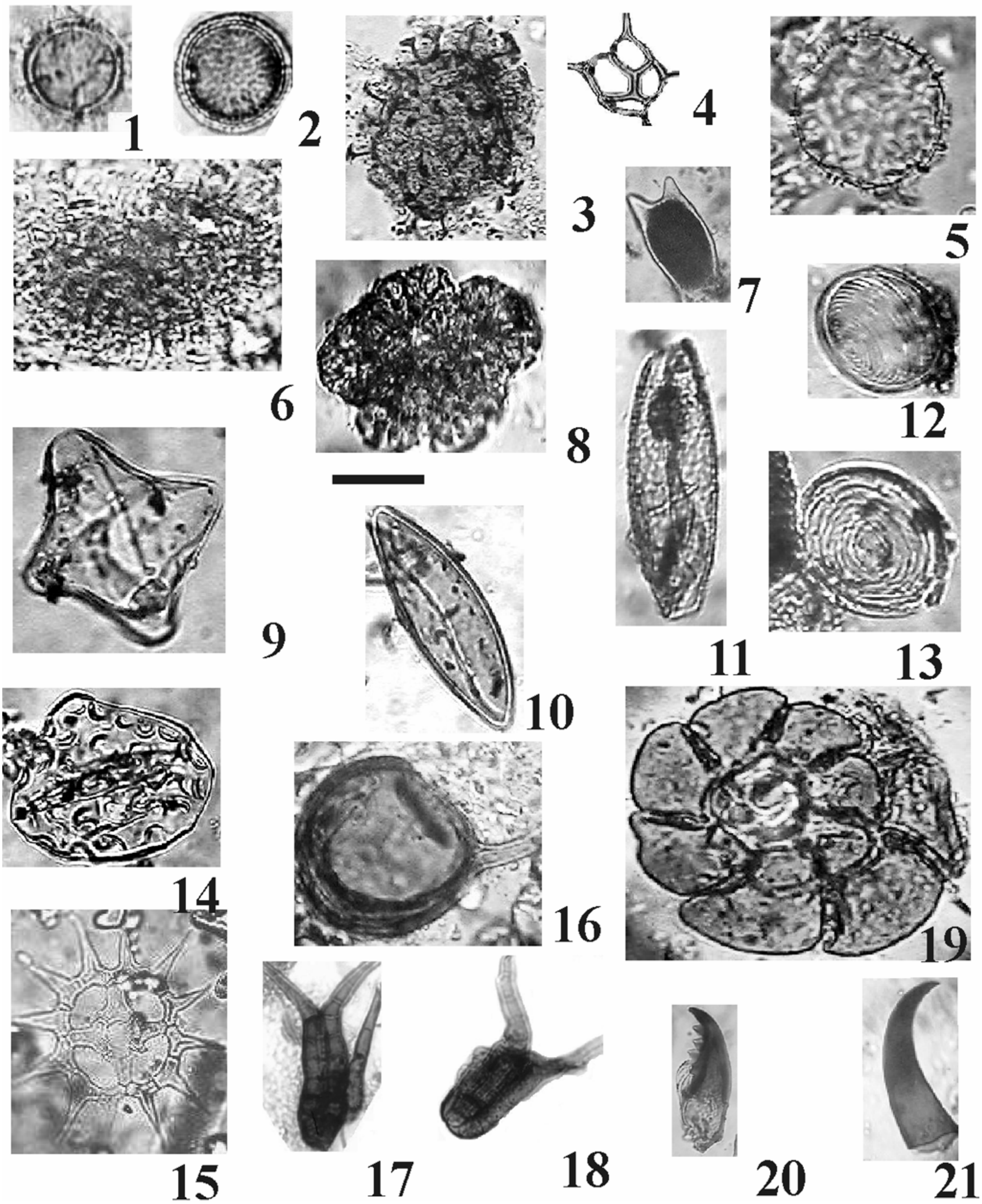

Plate captions: 1,2 – *Prasinophycean phycomata*, 3 – Spiniferites, 4 – *Dictyocha*, 5,6 – *Operculodinium*, 7 – dinoflagellate cyst undetermined., 8 – *Botryococcus*, 9 – *Mougeotia*, 10, 11 – *Spirogyra*, 12,13 – *Pseudoschizaea*, 14 – *Zygnema*, 15 – *Pediastrum*, 16 – *Glomus*, 17, 18 – *Tetraploa*, 19 – microforaminifera, 20,21 – scolecodonts. Scale: 10 µm.

Samples, corresponding to more humid period had more freshwater algal palynomorphs (*Zygnema*, *Mougeotia*, *Spirogyra*, *Pediastrum*, *Pseudoschizaea*), which were carried to paleolagoons by fluvial fresh-water flows (input) when it was heavy raining.

The same sequence of climatic changes based on analysis of increase-decrease frequencies of arboreal pollen (AP), pollen of aquatic herbs (NAP aquatic), and spores of ferns is shown in Figures 4 and 5. The end of the regressive stage (approximately last two thousand years) is characterized by notable increase in humidity, reflected in increasing in the lagoon sediments of freshwater algal palynomorphs and NAP aquatic. The more dense vegetation cover in dunes, salt-brackish water marshes, and arboreal and shrubs were reconstructed.

Conclusions

In this paper, we tried to show some time intervals of climatic changes occurred in the coastal plain of the Rio Grande do Sul state during the last 10 kyrs BP based on dated by ^{14}C samples and palynomorphs study from different core-drillings. Indicative value of some palynomorphs allowed paleoreconstructions of the relative climate changes, sea level oscillations, and coastal palaeoenvironmental changes.

Currently, we have a limited number of profiles conducted on the coastal plain of the Rio Grande do Sul and only a few data on radiocarbon absolute age. Therefore, our conclusions regarding climatic changes that occurred in this region during the last 10 kyrs BP are general and preliminary. Nevertheless, our obtained results clearly show that palynomorphs are important indicators of climate change and could be use to predict future scenarios based on the climatic change periodicity (more humid – drier, lower temperature – higher temperature) revealed in the present study.

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Representations in the Brazilian media of the impacts of climate change in the coastal zone

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Abstract. This study aims to examine texts which deal with climate change in the coastal zone, and looks specifically at the coverage of Brazilian daily newspapers with national and regional circulation. The paper begins by introducing the study with a selective review of recent literature on climate change and media, looking both at international and Brazilian research. The literature review also focus on the impacts of climate change in the coastal zone and its links with policy, particularly in Latin America. The theoretical basis of the research is presented - social construction of meaning - with the questions which guide the work and a summary of the methodology. The final sections show results, analysis and conclusions with particular comments on the frequency of the coverage at national and regional levels and a detailed look at elements of the news discourse in a specific case. The predominance of issues set by an international scientific and political agenda in the Brazilian media and relative absence of references to the coastal setting on the national coverage point to the need of an urgent review of priorities in the mass communication of scientific and environmental themes in Brazil.

Keywords: newspapers, sea-level rise, social construction

Resumo. Representações na mídia brasileira dos impactos das mudanças climáticas na zona costeira. Esta pesquisa busca examinar textos que tratam especificamente do tema mudanças climáticas em zonas costeiras, com interesse na cobertura de jornais diários brasileiros de circulação nacional e regional. Inicia-se com uma introdução do estudo através da revisão seletiva da literatura recente sobre mídia e mudanças climáticas, focando estudos no âmbito internacional e brasileiro. Em seguida são focados os impactos da mudança climática em zonas costeiras e sua ligação com políticas públicas, particularmente no caso da América Latina. A base teórica – construção social do significado – é apresentada a seguir, assim como as perguntas da pesquisa e um sumário da metodologia. As seções finais mostram resultados, análise e conclusões, especificamente comentários sobre a frequência da cobertura em níveis nacional e regional, bem como um tratamento detalhado de elementos do discurso empregado pela mídia em um caso particular. A predominância de tópicos na mídia brasileira que são determinados por uma agenda científica e política internacional, somada a relativa ausência de referências ao contexto costeiro na cobertura de jornais nacionais sugerem a necessidade urgente de revisão das prioridades na comunicação de massa de temas científicos e ambientais no Brasil.

Palavras-chave: jornais, aumento do nível do mar, construção social

Introduction

Climate change and media

Climate change began to receive widespread attention in the United States and United Kingdom media by the late 1980s, triggered by a series of events ranging from scientists making their views on the rapid global warming explicit for the first time, politicians reactions to the growing concern that humans were implicated in the global climate change and the creation of the United Nations Intergovernmental Panel on Climate Change, or IPCC (Carvalho & Burgess 2005, Boykoff & Roberts 2007). Since then, the coverage of climate change by the international English-speaking media has steadily increased (Boykoff 2008), although it has recently shown signs of a slight decrease (Revkin 2009). The trend of general increase in coverage is largely associated with either specific events (such as the release of Al Gore's film The

Inconvenient Truth, as well as his shared Nobel prize with the IPCC) or large scale disasters, such as the effects of Hurricane Katrina in the US (Boykoff & Roberts 2007, Boykoff & Roberts 2008). In spite of a tendency for improvement in terms of richer contextualisation and broader coverage of different aspects of the issue – for example, relatively fewer attention to "climate skeptics" and greater space for the political dimension of climate change - the overall quality of the coverage has been criticised (Carvalho 2007, Boykoff 2008).

Research has drawn attention to the how ideology and politics can determine the framing of news on climate change (Smith 2005, Carvalho 2007), specifically highlighting how supposedly objective scientific views can be given different meanings according to political interests. Carvalho (2007: 240) suggests a "politicised reading of *science reports* in the press" (italics as in the original), adding that "audiences could engage in a more active interpretation of representations of knowledge in the media and in a critical understanding of their implications". Boykoff & Boykoff (2007) examine specifically how the normative dimension of journalism has interfered with the communication of human contribution to climate change. The authors mention how political, economic and professional norms are interrelated, and show how journalistic (professional) norms are the main factor causing the failure by the media to communicate "central messages" about the anthropogenic causes of climate change, and conclude that this "occurs not only because of complex macro-political and economic reasons rooted in power relations, but also, in part, because of the micro-processes that undergird journalism" (Boykoff & Boykoff 2007).

As the Brazilian media is concerned, the coverage of climate change issues has shown an increase similar to that recorded in the English-speaking media, and the general pattern of peaks in coverage related to specific events was also identified (ANDI, 2009). However, research on the Brazilian media representations of climate change are scarce, as noted by the authors of the aforementioned study, which quotes the almost total lack of records in the Scielo database (ANDI, 2009). Likewise, in spite of looking at a broader search base in our own review of the Brazilian literature on the theme, we were able to find only relatively few studies (Lavezzo Filho & Nunes 2004, Costa & Lages 2008, Silva Junior & Bortotti 2009). Only by widening the scope are we able to find relevant, even if indirect, references on communication of scientific knowledge to the general public. For instance, the survey on public perception of science carried out by the Ministry of Science and Technology in 2006 (MCT 2007) showed that a sizeable portion of the Brazilian public is interested in scientific issues (41% of 2004 respondents). Furthermore, the survey also showed how the public considered journalists to be the most trustworthy sources of information (27%), well above scientists working at state universities (17%) (MCT 2007). These findings suggest that there is clearly potential public interest in a theme such as climate change in Brazil, and that coverage of the theme by the media seems to play an important role in how people construct the meaning of related issues - for example, impacts of climate change on coastal areas.

Climate change in the coastal zone – science and policy

Nicholls *et al.* (2007) draw attention to how the understanding of the implications of climate change on coasts has improved and summarise the findings in their assessment as what they called "important policy relevant-messages" (Table I). The report clearly stresses the high cost of the impacts of climate change, both when short-term events (e.g. floods) and long-term process (e.g. sea-level rise) are considered. It also highlights the need for policies which are able to anticipate and respond to events and processes at both time scales. The general aim of such synthesis, or "executive summary" as it is called, is to communicate scientific findings to the actors involved in the policy-making processes, above all those making the decisions. Therefore, by following how these "messages" (as they are referred to by the authors themselves) circulate amongst the general public it is possible to assess effectiveness of the communication of scientific knowledge and policy advice.

There is a well-developed body of research which investigates the vulnerability and adaptation of coastal communities to climate change (Allison *et al.* 2009). This literature highlights particularities of climate change impacts on human population in coastal settings. Firstly, poor people living in coastal zones show relatively higher exposure and sensitivity to impacts from climate change in comparison with well-off groups or those living inland – for example, as reviewed by Daw *et al.* (2009) in the case of small-scale fisherfolk.

Secondly, livelihoods based on coastal natural resources are affected by composite impacts of climate change and social and economic processes (Glavovic & Boonzaier 2007). For instance, small-scale fisheries are affected not only by the ecological outcomes of rainfall variability or

Table I. Policy issues related to the impacts of climate change in the coastal zone, according to the assessment by the IPCC Working Group II on “Coastal Systems and Low-lying Areas” (Nicholls *et al.* 2007: 317). Issues selected have “very high” confidence levels according to the IPCC: experts have 9 out of 10 chances of being correct in their predictions or judgements. Statements in the “policy issues” column are direct quotes from Nicholls *et al.* (2007), page 317.

Policy issues	Highlighted aspects
“Coasts are experiencing the adverse consequences of hazards related to climate and sea level.”	Costs and loss of lives due to extreme events such as storms and floods.
“Coasts will be exposed to increasing risks, including coastal erosion, over coming decades due to climate change and sea-level rise.”	Increase in floods and cyclones, coral mortality and loss of wetlands. Impacts on fisheries and sources of freshwater with “serious implications for the well-being of societies.”
“The impact of climate change on coasts is exacerbated by increased human-induced pressures.”	Growth in human population, particularly, the increase of settlements in coastal areas.

changes in sea-surface temperature, but also by the interaction of these physical processes with so-called "adaptive strategies" - for example, changes to watershed management, land use and economic development brought about by a move from fisheries to aquaculture (Badjeck *et al.* 2010). Studies in the field highlight the need for the integration of climate change in policies and management regimes applied to coastal areas, particularly in the cases where livelihoods of poorest people and ecological sustainability are at stake (Badjeck *et al.* 2010, McIlgorn *et al.* 2010).

Thus, impacts on the coastal zone are the result of the interaction of different multiple stressors - sources of undesirable change - climate change being only one of them. It is argued that policies may become a stressor in their own right if policy-making does not consider the complexity of the coastal zone (Bunce *et al.* 2010). According to this view, a fuller representation by the media of climate change affecting coastal areas would require a treatment of both climate-related impacts and social and economic development. The contextual-lisation of climate change by the media becomes crucial to its understanding as its impacts are compounded by processes such as diverse as ecosystem conservation, urbanisation, tourism and fisheries development (O’Brien & Leychenco 2000, Bunce *et al*. 2010).

Climate change and public policy in the coastal zone – the Latin American context

The most up-to-date national level Brazilian policy aimed at tackling climate change, the “National Action Plan” (Rosa 2009), is the result of an extensive consultative process carried out by the “Brazilian Forum of Climatic Change”. This was an initiative led by the Brazilian government including government officials, scientists, state companies from the energy sector and international NGOs (Rosa 2009: 45). The term “coast” is directly mentioned only once in the synthesis of the “action plan” provided by Rosa (2009), and there are no other indirect references to coastal or marine areas - the closest reference is a mention to “river banks”, yet specifically in the context of reforestation. Coastal zone figures in the “action plan” in the context of data generation - “Instalment of systems to collect data on the sea level on the Brazilian Coast” - under one of the three major components of the plan “Vulnerability and Transversal Actions” (Rosa 2009: 47). This is in clear contrast with the attention paid by the “action plan” to forests, with repeated quotes in several sections, focussing on the need to control deforestation as a means to curb Brazilian emissions of greenhouse gases (Rosa 2009).

The apparent lack of attention to coastal issues in a high level policy plan is not easily explained, as the relevance of climate change to coastal populations is well established in policy and academic circles (Nicholls *et al.* 2007, among others aforementioned).

In the case of Latin America, for example, governmental policy originally aimed at improving living conditions of coastal urban settlements has been found to have the opposite effect, increasing the vulnerability of human population. In a review of policies applied in Buenos Aires, Murgida & Natenzon (2009: 149) highlight a program aimed at providing housing “for [the] underprivileged population” which did not consider “scenarios related to climate change and variability, [neither] the flood [...] recurrence maps” for Buenos Aires. The authors conclude that this is an example of how “the lack of an integrated vision” between government, urban planners and other sectors may cause “maladaptation, as well as an [increase in] risk and new aspects of vulnerability”.

Similarly, Romero *et al.* (2009: 225) found that "[the] lack of urban planning and management are allowing [for careless] watershed urbanization", with particularly negative impact in the case of coastal cities with "complex topography", such as Valparaiso (Chile). The increased risk of floods and landslides in coastal areas caused by extreme weather events is frequently highlighted in the literature (Romero *et al.* 2009, Sant'Anna Neto & Roseghini 2009). For instance, findings from a study by Sant'Anna Neto & Roseghini (2009: 244) suggest that the seasonal pattern of rainfall in the northern coast of São Paulo (Brazil) "presents a great potential to cause perturbations and reach a greater number of victims", because rainfall tends to be more intense and concentrated in short periods of time when a large number of people to move temporarily into the region for the tourism season.

Summing up, the review of the literature shows that, firstly, there is indisputable evidence of how climate change can have direct and specific effects in the coastal zone. Secondly, research carried out in diverse contexts points to common problems related to the complex interaction between physical, social and economic processes in coastal areas. Finally, another concern shared by several studies is the need for improvement in public policies aimed at coastal development, which currently do not seem to effectively take climate change issues into account.

These considerations indicate how highly diverse factors may affect the ways in which the media represents climate change impacts on the coast. As a result, we argue that an attempt to understand this process of representation requires both an appraisal of inherent features of scientific journalism (and the media sector as whole) and the complex nature of environmental and political dimensions of climate change.

Material and methods

Theoretical framework - Media and representation

This research is based in a theoretical framework which understands risk as being socially constructed (Dake 1992, Beck 1992). By adopting this stance we assume that the perception of risk among social actors will depend on their background, the context in which they live, the access to sources of information and ability to articulate responses to phenomena, among other elements which directly or indirectly contribute to the process of social construction of meaning. It is important to note that such perspective acknowledges the material existence of the natural and human phenomena, *e.g.* storms and floods, is independent of what humans think about them. On the other hand, the meaning that these same storms and floods have to us, for example, as causes of death and material loss, is the result of the complex interplay between individual perception and social relationships (Johnson 1986).

Such considerations are relevant for this research precisely because they imply that the understanding of perception of phenomena is only possible if we look at the cultural aspects underlying it. In the specific case of this research it means that if we wish to examine how the media represents a complex set of phenomena such as climate change, we need to look at who are the actors involved - media, scientists, politicians – and what are the relationships between them and their connection to the phenomena in question (Beck 1992). It also implies that all actors in this process have the ability to interpret phenomena and, consequently, to interfere in the way they are given meaning. Therefore, the journalist is not seen as objective and impartial messenger, neither the public as passive receptor of news.

More specifically, we adopt the concept of "cultural circuit", which has been applied to studies of media representation of environmental issues (Burgess 1990), and particularly of climate change (Carvalho & Burgess 2005). In this model (Fig. 1), the production and circulation of texts is made possible through encoding and decoding processes, which are determined by specific contexts. Texts, understood as content in any form, are produced by the media (encoded according to diverse norms and criteria – visual, linguistic, professional, economic, institutional, etc.), and are then circulated in the "public sphere". The readers will then consume these texts, decoding them in the "private sphere" (Habermas 1989). In the following stage, readers not only decode the texts, but also provide feedback and input for another cycle of production.

The construction of meaning during the production stage is determined by a professional context in which technology and institutions play a major role. Meanwhile, in the consumption of texts meaning is constructed in a personal context, in which subjectivity and everyday actions prevail (Carvalho & Burgess 2005). The assumption of a reader who is able to actively select which and how issues are relevant, interpret these issues and transform their meaning is also central to our approach (Burgess *et al.* 1991). It has been shown how not only readers, but all actors constantly revise and contest the meaning of environmental issues and their portrayal in the media (Smith 2005).

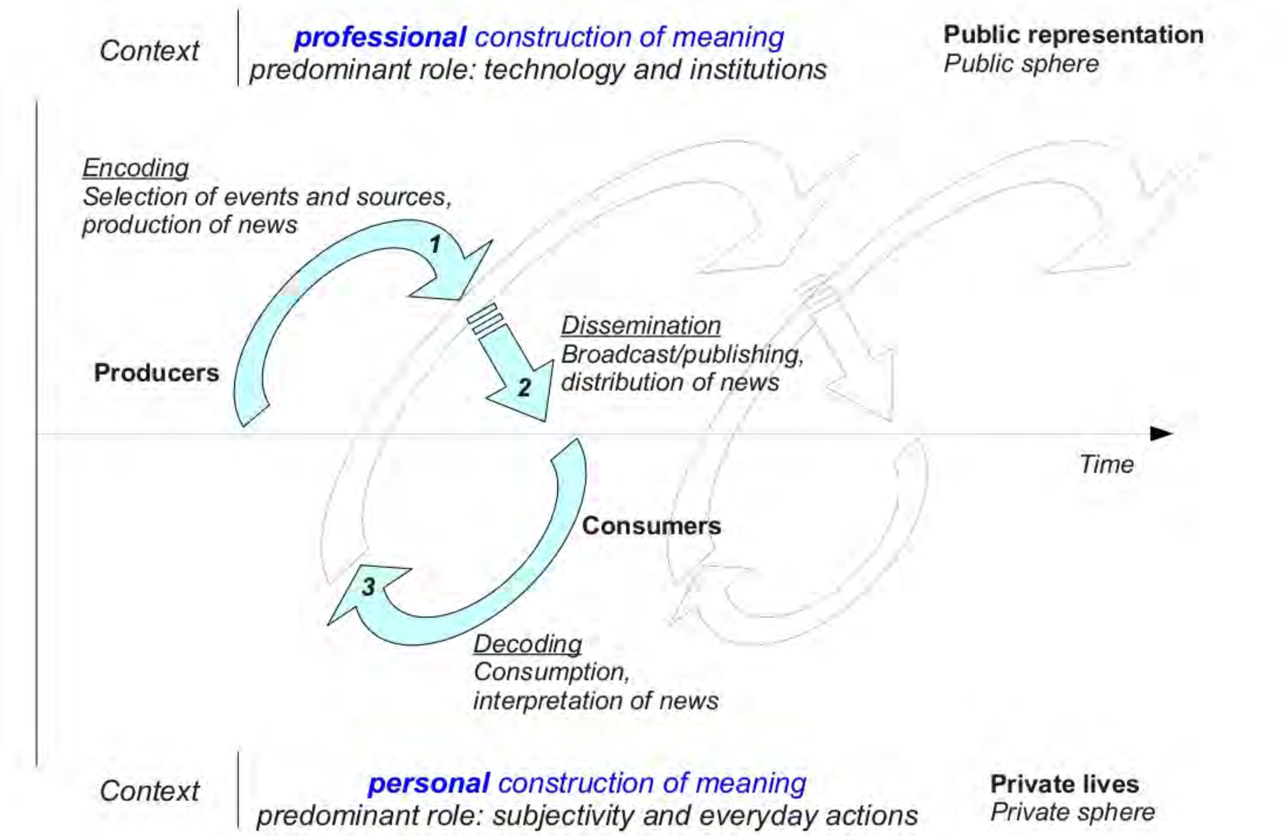

Figure 1. Analytical framework: "Circuits of culture" model, adapted from Carvalho and Burgess (2005). The news production cycle consists of three phases (numbered arrows in the diagram): news are produced (1) and distributed (2) in the public sphere. Then, news are consumed (3) in the private sphere and subsequent cycles are originated (light grey arrows).

Research questions and methodology

This research project is a component of a Brazilian network aimed at the multi and interdisciplinary study of climate change in the coastal zone ("Rede CLIMA – INCT para Mudanças Climáticas, Zonas Costeiras"). This project seeks to answer the following research questions: (1) how journalistic coverage contextualises the climate change theme, especially in terms of social and economic processes, (2) how different actors determine the framing of theme in the media, with special focus on the role of institutions and (3) how the media articulates the discourse on factors affecting vulnerability and adaptive measures which are particularly relevant in coastal zones (for example, urbanisation and integrated coastal management).

The research aims to examine the coverage of daily newspapers at three levels – local (defined by the towns in the estuarine area of the Patos Lagoon (Southern Brazil), state/regional (State of Rio Grande do Sul) and national – for a 12 month period (second semester of 2008 and first semester of 2009). Texts which deal specifically with climate change in the coastal zone have been selected and organised in a database. The texts will be explored with qualitative techniques and critical discourse analysis (Bazeley 2007, Wodak & Meyer 2006). At the time of writing the research is part of an ongoing project and its scope will be gradually expanded in following stages, when we expect to include other media, as well as extend the analysis to other periods. The choice of geographical context is due to the very nature of the research, which is integrated with another existing project (SACC-HD) in which we look at the perception of climate change and vulnerability among fisherfolk in the small-scale fisheries of the Patos Lagoon.

Results and discussion

As mentioned above, the findings obtained so far are the result of ongoing analysis and limited to part of the total database of articles. Nonetheless, it was possible to identify patterns in the general coverage which are in line with those shown in the literature. Moreover, we were also able to select a case of particular relevance to the understanding of how the media discourse is developed with respect to our specific research focus. Findings from both quantitative analysis and in-depth case study are presented and discussed in the following sections.

The analysis was developed in two stages, defined on the one hand by the geographic scope of the newspapers, and on the other hand by a specificity of the news coverage. To begin with, we analysed the coverage of climate change in its broadest sense, as done by the newspapers aimed at audiences in all Brazilian territory. Then, we narrow our focus to target the coverage of climate change issues only in the context of the coastal zone. Also, a newspaper primarily aimed at the southern Brazilian audiences is included. By presenting the analysis in the structure outlined above we intend to gradually introduce the theme to the reader: first, with a general view of how the Brazilian media has handled the climate change issue, then with a more localised and specific analysis. The inclusion of the newspaper with regional scope at the national level would lead the analysis of results in a different direction – it could be equally valid, but would not support the gradual interpretation aimed in this paper, and would not be helpful in terms of the comparison with other studies which look at national media coverage of climate change (e.g. ANDI 2009).

Frequency and level of the coverage

Firstly, we looked at texts containing the expression “mudança climática” (climate change) in the online editions of three of the Brazilian newspapers with largest readership and nationwide distribution – “A Folha de Sao Paulo”, “O Estado de Sao Paulo” e “O Globo” - during the first semester of 2009. The number of texts selected was as follows: “Folha”=279, “Estadao”=528 and “O Globo”=423. The frequency of texts throughout the period is shown in the figure 2. There is a relatively similar pattern in the coverage of different newspapers, with a few pronounced peaks. The increase in coverage seems to be related to specific events: in the end of January the surge in news was related to several events: the World Economic Forum in Davos, a meeting of the IPCC held in São José dos Campos and, above all, to the new climate change policy being implemented by the US under Barack Obama. In contrast, at end of March, the coverage peaked in response to a single event: the WWF campaign called “The Planet Hour” (“A Hora do Planeta”) in which major cities around the world switched off their lights to show support for energy saving policies and control of CO^2 emissions. Finally, in mid April, the US policies lead the news coverage again when a change in the status of CO^2 (which became to be regarded as pollutant) reinforces the move in policy towards more control of emissions.

These findings are corroborated by the trend observed in other studies, where the newspaper reinforces the move in policy towards more

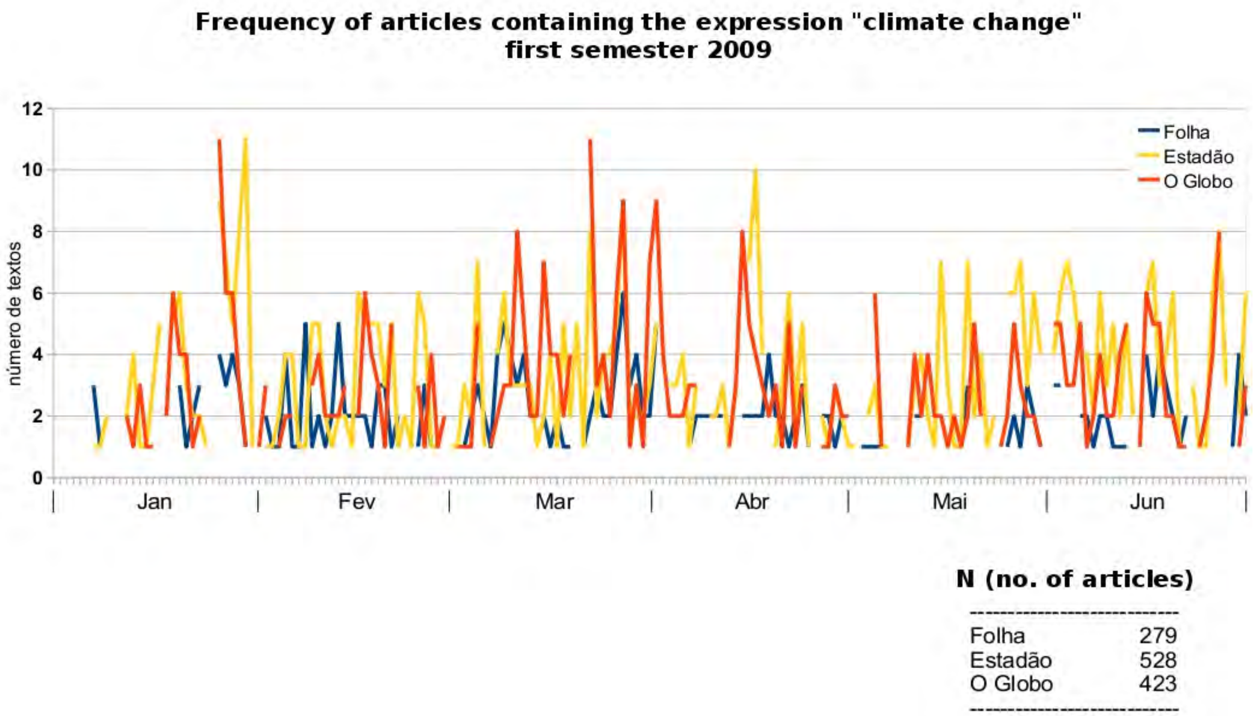

Figure 2. Frequency of articles containing the expression “climate change” first semester 2009. http://migre.me/38jIW

control of emissions.

These findings are corroborated by the trend observed in other studies, where the newspaper coverage of climate change is guided by specific events (Boykoff & Roberts 2007), and shows a particularly tendency by Brazilian newspapers to increase its coverage of the theme in response to international events. A very similar tendency of a national coverage largely dictated by an international agenda was observed in 2007 in the study organised by ANDI (2009) in Brazil. Accordingly, Billet (2010) mentions the "strong international focus" of the news addressing climate change in India between 2002 and 2007.

In the next stage of analysis we narrow our focus, adding the regional level of news coverage (represented by the newspaper "Zero Hora") and restricting the selection of texts to those containing simultaneously the terms "mudança climática" (climate change) and "costa" (coast). The resulting number of texts was as follows: "Folha"=14, "Estadao"=42, "O Globo"=22 and "ZH"=2. The frequency distribution of texts is shown in figure 3. A smaller number of texts was expected, but the extremely low count in the regional newspaper is somewhat surprising as its readership encompasses the whole state of Rio Grande do Sul and tends to provide national as well as regional news coverage, thus could have more closely followed the coverage given by national newspapers - in 2008 "Zero Hora" circulated approximately 180,000 copies/day, compared to 246,000 by "Estadao"; 281,000 by "O Globo" and 311,000 by "Folha, the largest circulation in Brazil (ANJ 2010).

It is worth mentioning that several terms with equivalent or closely related meaning were used in the search and selection of texts: for example, "aquecimento global" (global warming), "mudança global" (global change),"praia" (beach), "litoral" (litoral), etc. Despite the low quantity, the results from the combination "mudança climática" (climate change) and "costa" (coast) yielded the largest number of texts between all possible relevant term matches.

The paucity of articles dealing with climate change in coastal settings is remarkable when one considers the significance of climate-related risks in these areas (Nichols 2007). The texts in this subset follow the general pattern observed above and did not refer to the specific Brazilian coastal context. These findings help to put into perspective the relative absence of consideration for coastal processes in the national policies aimed at tackling climate change (Rosa 2009). The tendency in question also suggest that the mismatch between existing public policies and the needs of vulnerable coastal populations in Brazil an Latin America (Romero *et al.* 2009, Sant'Anna Neto & Roseghini 2009, Murgida & Natenzon 2009) is unlikely to be challenged by a mass media which responds to issues set by an agenda removed from local

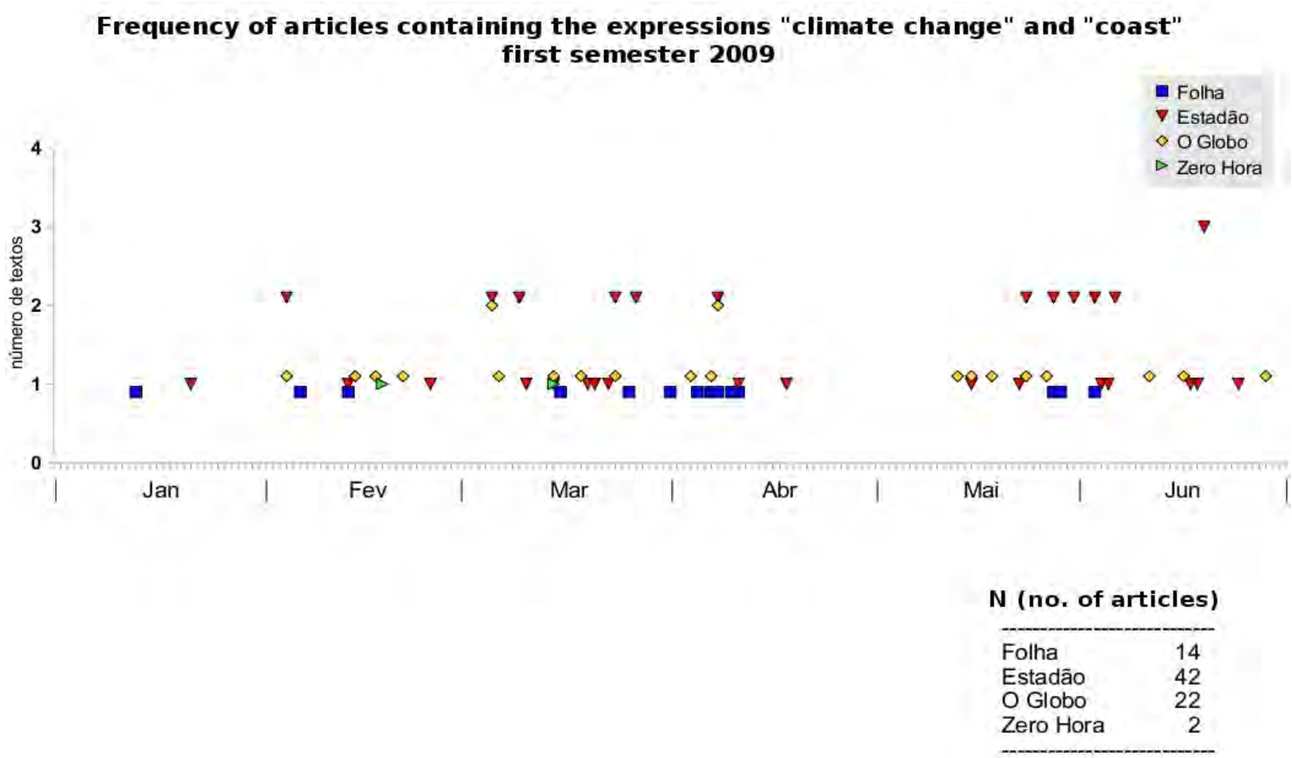

Figure 3. Frequency of articles containing the expression "climate change" and "coast" first semester 2009.

concerns. Our study indicates that not only the national newspaper coverage of climate-related impacts on the coast was arguably insufficient, but it was practically non-existent in regional newspapers. Where the debate outlined in the previous paragraph is concerned, one group of occurrences seemed particularly interesting, as it was the only occasion in which all four newspapers reported almost simultaneously on the theme of climate change in coastal zone. Indeed, on closer examination it proved to be a revealing case, which we present in detail below.

How (and why) we are told about sea level rise

Between 15 and 16 March 2009 the online editions of the three papers analysed reported on exactly the same story: a rise in sea level threatened to flood New York by 2100. The news originated in a scientific paper published online in the journal Nature Geoscience, on that exact same day (15 March 2009) (Yin *et al.* 2009). All three Brazilian papers only reproduced stories written originally by international news agencies (Reuters and EFE), with almost no differences in the content – with notable exception for the version presented by "Zero Hora" in which it says that the sea level "*might* increase from 36 to 51 cm", while the text in the "Folha" article reads "*will* increase".

The path taken by the news in this case is represented in figure 4. It also shows the main features determining the context in each step of news production and consumption (in italics). The blue arrows represent the steps followed by the text until the "final" reader. The grey arrows represent the possible feedback from the reader towards the beginning of a new cycle of news production, and potentially changing human behaviour and influencing phenomena. The grey cross at the centre of the diagram represents the potential interaction between different contexts. This representation of how news were produced is based on both empirical evidence and our intepretation, which is in turn related to the analytical framework followed in this research, as articulate in detail below.

Each step in figure 4 can be clearly identified based on direct analysis and/or inferences from the research paper and the news articles. Actors and the relationships depicted in the sequence of events throughout the production of the news follow from the analysis of the paper and articles: for example, the intermediary role of international news agencies is not assumed or extrapolated, it arises from the simple annotation of sources in the opening of each news article. On the other hand, the features of the context in each step are not presented in the texts themselves and are infered - though in all instances presenting objective aspects of each context. For example, the requirement of instru-ments for gathering of information about natural phenomena or the existence of deadlines and editing in newspapers production are well-known, concrete aspects of these settings.

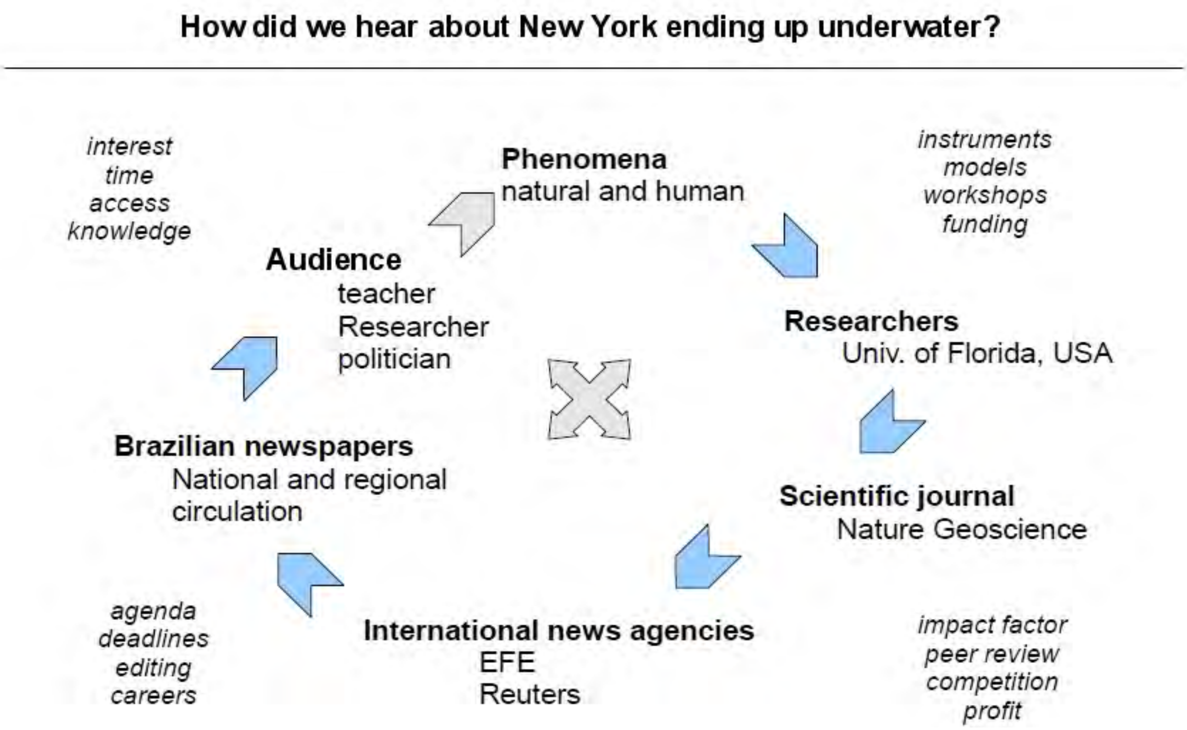

Figure 4. News circuit: stages of production and consumption of news in the story about sea level rise and flood threat to New York in 2100.

The contexts are obviously more complex than a handful of concepts can describe, and those shown in the diagram seek to add to the interpretation of the news cycle without reference to excessively technical or subjective descriptions which would detract from the analysis and add bias to the interpretation of results.

The cycle itself is related to a particular interpretation of news production, as indicated above in the section "Theoretical framework – media representation" (Material and Methods). Such interpretation follows from an understanding of society which assumes the existence of a private and a public sphere (Habermas 1989). As this study is concerned, each sphere is related to different but interconnected contexts of production and consumption of news; the production of news takes place initially in the public sphere, where professional, technological and institutional factors determine the context – shown in figure 4 as academic institutions, journals and news outlets. For instance, the role of the market-related aspects of the public sphere in determining the social construction of news has been focus of media studies for more than a decade – for a comprehensive review, see Gamson *et al.* (1992).

In the following stages, news are consumed in the private sphere, where personal and subjective factors are predominant in defining the context – in figure 4 represented by the individuals who make up the different groups of news readers – teachers, researchers, politicians, etc. These steps are not insulated from each other, quite the opposite, there are feedbacks and interferences, as well as individual actors which can stride both spheres - as noted, for example, by Doulton and Brown (2009) in the case of academic researchers and non-governmental actors which can be involved in several stages of the production and consumption of news. These connections cannot be fully appreciated at the level of analysis aimed at in this paper, neither can they be fully depicted in a single diagram. Nonetheless, we seek to ackowledge their existence, and draw attention to their potential role in the news cycle production by representing them as grey arrows in figure 4.

The latter aspect is particularly relevant to a critical perspective on how the media represents environmental issues. It connects direclty to what Carvalho and Burgess (2005) call "diachronic model" (see Fig. 1), a explanation of how news are produced and consumed which expressly aims to include changes to society through time. In that perspective, the so-called "circuits of culture" are not closed circuits, but a succession of interrelated cycles which allow us to understand how construction of news changes along with changes in society and culture. By adopting this view we may be able to unravel the mechanisms which lead to long-established patterns of news production, such as the focus on extreme climatic events (Boykoff & Roberts 2007), as well as explain sudden changes to the news agenda, as in the case of attractive news headlines offered by celebrities statements (Boykoff, 2009). The diachronic model of circuits of culture helps to clarify the roles of different actors and the existence of feedbacks along construction of news, as the interaction of research community and media and the consequent evolving focus on climate change thorugh 19 years of news coverage demonstrated by Burgess and Carvalho (2005).

Some aspects of this case are illustrative of how the social construction of meaning affects the communication of scientific findings, as well as their relevance for policy. Firstly, the focus on the impact of sea level rise in New York seems to render the news more attractive. The coverage in all three papers suggests that editors and/or journalists from independent news companies, thus irrespective of specific professional contexts, judged the same news to be relevant. As to what criteria they used, we can only speculate, but it might be related to the fact that the text stresses the risk of floods and extreme events, with views on possible disaster scenarios. The tendency to report on episodic events has been identified in the literature (Boykoff & Roberts, 2007), which also points out to the loss of context that the excessive focus on the "disaster" aspect can cause to the reporting of environmental news. Furthermore, these findings suggest that despite the existence of well-defined policy issues relating coasts and climate change in the Brazilian and Latin American context contex (see introduction), the media tend to ignore this connections in the representation of the theme. In this case, this is done by literally reproducing news related to a foreign context. A similar detachment between news and policy has been noted in other studies, which highlight how the media focus on narrow issues in detriment of broader discussion of social and policy-related topics (Hayes *et al.* 2007).

Secondly, the reproduction of content from international news agencies might be related to financial and institutional aspects of journalism which are reason for concern in the specific case of reporting environmental and scientific issues: these are not regarded as priority and often do not receive funds or editorial support, with few corporations interested to maintain specialised staff (Hannigan, 2006, Gamson *et al*. 1992). As a result, environmental news end up being covered with ready-made content which allows the news companies to save on resources and personnel. For these reasons, it is reasonable to argue that we are more likely to be informed about the impact of sea level rise in New York, as told by indirect sources, than to hear an account of how the Brazilian coast could be affected by climate change, told by a local journalists with the ability to provide rich context to the story.

Conclusions

Findings from this study show that Brazilian newspapers tend represent the climate change theme along similar lines used by the English-speaking press, that is, largely following high-profile events. The predominance of issues set by an international scientific and political agenda in the Brazilian media and relative absence of references to the coastal setting on the national coverage point to the need of a urgent review of priorities in the communication of scientific and environmental themes in Brazil. Moreover, as it has also been noted in other studies, the coverage of climate change in Brazilian newspapers is overwhelmingly concentrated in a few major vehicles of large circulation. The study by ANDI (2009) showed how in comprehensive sample of 50 newspapers only six – four general daily papers and two specialised in economic isssues, all with national circulation – published 37% of all news articles on climate change issues between 2005 and 2008 in Brazil. The authors repeated the study in 2008 and found that 48% of the coverage of climate-related news was done by those same newspapers (ANDI, 2009). These trends represent a considerable obstacle to the advancement of a coverage which reflects the existing knowledge of coastal processes and their relation to public policy. Science has been able to approach the impacts of climate change on coastal zones in a nuanced manner, acknowledging its complexity and generating knowledge potentially applicable to improving peoples lives in vulnerable areas. However, the mass media vehicles analysed seemed to represent the issues in a detached way, focussed on issues removed from Brazilian reality, overlooking both local problems and scientific expertise. The concetration on topics which must appeal to a broad national audience leaves little room for localised accounts of impacts, while a specialised agenda may limit the coverage, in the case of Brazilian newspapers, to economic issues. Such findings and interpretations reinforce the relevance of a critical perspective on the study of the representation of climate change impacts in the Brazilian media. Further, the coastal zone emerged as a clearly valid focus of this research effort, given the urgent need of concerted policies and accompanying communication aimed at increasing the chances of preventing disasters and implementing successful adaptive measures for coastal human populations.

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Differences between spatial patterns of climate variability and large marine ecosystems in the western South Atlantic

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Abstract. Despite their importance for environmental management, the response of Large Marine Ecosystems (LMEs) to climate changes is unlikely to be controlled by the ecological criteria used to define them. This is because productivity and trophic relations are endmembers of a chain effect that starts with physical processes not necessarily bounded by LMEs. Correlation fields were calculated for climate indices and sea surface temperature anomalies (SSTA) for the southwest Atlantic to identify interannual correlation patterns. Significant correlations indicate that the influence of El Niño/Southern Oscillation (ENSO) along the north and east coasts of Brazil is not coincident with the boundaries of LMEs. The antisymmetric (opposed signs) correlation pattern of the Tropical South Atlantic (TSA) observed in the South Brazil (SB) LME, during the warm PDO phase, may be related with the northeast-southeast SST dipole. It is possible that both the TSA and the Antarctic Oscillation Index (AAO) have distinct influences on the Brazilian LMEs depending on the geographic location and time scale. The PDO multidecadal and the ENSO interannual induced SSTA variability along the Brazilian coast exhibit a complex spatial dynamics against which ecosystem functioning should be tested to provide clues as to how the LMEs might respond to these climate forcings.

Keywords: Ecosystems, Tropical South Atlantic, climate indices, global changes

Resumo. Diferenças entre os padrões espaciais de variabilidade climática e dos grandes ecossistemas marinhos no oeste do Atlântico sul. A despeito de sua importância para o gerenciamento ambiental, é improvável que a resposta dos grandes ecossistemas marinhos (GEMs) às mudanças climáticas seja regida pelos critérios ecológicos usados em sua definição. Isto acontece porque a sua produtividade e relações tróficas são o resultado de uma cadeia de eventos que começa nos processos físicos que não seguem, necessariamente, os contornos dos GEMs. Campos de correlação foram calculados para índices climáticos e temperatura da superfície do mar (TSM) para o oeste do Atlântico sul para a identificação dos padrões interanuais. Correlações significativas indicam que a influência do El Niño Oscilação Sul (ENOS) ao longo da costa brasileira não é coincidente com os limites espaciais dos GEMs. Os padrões antisimétricos de correlação do índice do Atlântico Tropical Sul (ATS) no sul do Brasil durante a fase quente da Oscilação Decenal do Pacífico (ODP) pode estar relacionada com o dipolo de TSM. É possível que tanto o ATS quanto a Oscilação Antártica (OA) apresentem infuências distintas nos GEMs do leste e do sul do Brasil. A variabilidade interanual da TSM ao longo dos GEMs no Brasil, induzida tanto pela ODP quanto pelo ENOS, exibe uma dinâmica espacial complexa contra a qual o funcionamento dos ecossistemas devem ser testados.

Palavras-chave: Atlântico Tropical Sul, índices climáticos, mudanças globais

Introduction

Large Marine Ecosystems (LMEs) have been used as a framework for the assessment and management of marine resources and they are defined according to four ecological criteria: bathymetry, hydrography, productivity, and trophically related populations (Sherman 1991). It is assumed that ecosystem variability in LMEs can be captured by indicators grouped into five modules:

productivity, fish and fisheries, pollution and ecosystem health, socioeconomics and governance (Duda & Sherman 2002). Recent efforts to relate large scale climatic changes to ecological processes such as fisheries biomass yields in LMEs have indicated the presence of emergent trends induced by global warming (Sherman *et al.* 2009). It has been suggested that increasing sea surface temperature (SST) exceeding the levels expected from the warm phase of the Atlantic Multidecadal Oscillation affected the Icelandic Shelf, Norwegian Sea and Faroe Plateau, a region responsible for 5% of the global fisheries yields. The perceived increase in fisheries yields in these regions is a result of increased availability of zooplankton leading to improved feeding conditions of zooplanktivorous species in the Northeast Atlantic. Similarly, fisheries biomass yields are increasing in the proposed North Brazil (NB) and East Brazil (EB) LMEs (Fig. 1), where changes in production seem to be responding predominantly to overexploitation rather than climate warming (Sherman *et al.* 2009).

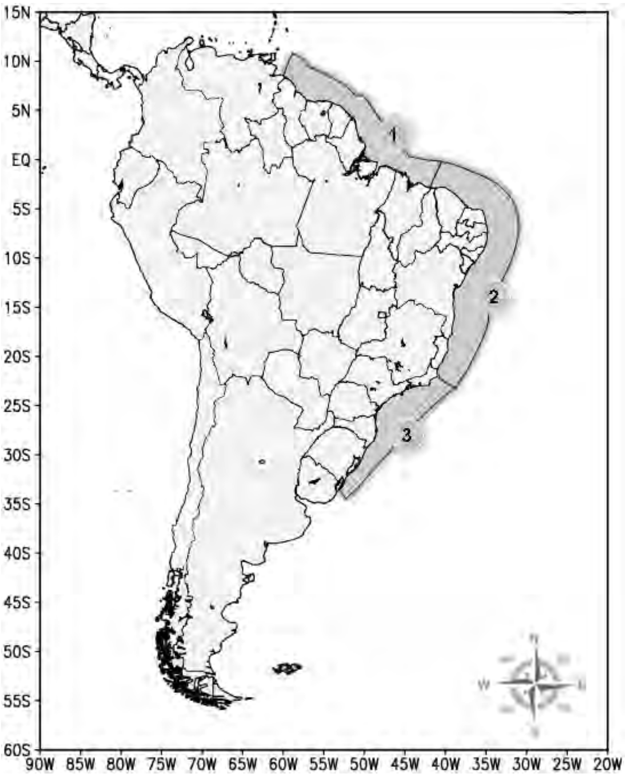

Figure 1. Map of South America showing the location of Large Marine Ecosystems in Brazil. 1) North Brazil LME, 2) East Brazil LME, 3) South Brazil LME.

Integrative research tackling the influence of large and mesoscale processes on biological systems of the western south Atlantic has gained momentum in the last years. Variations in mean SST, cloud cover and turbidity in Bahia State, eastern Brazil, induced by the 1997-98 ENSO caused partial mortality of octocorals and actiniarians, but had limited impact on scleractinian communities in coral reefs (Kelmo *et al.* 2003). ENSO is also known to have caused increased precipitation and reduced salinity of the Patos Lagoon estuary (southern Brazil), driving away euryhaline species (Garcia *et al.* 2001). Remote sensing data show that cold-core eddies form at the Brazil-Malvinas Confluence (BMC) region and rapidly separate from the mean flow with chlorophyll concentration in their cores higher than the surrounding waters (Garcia *et al.* 2004). The western boundary Brazil Current (BC) also produces warm core rings that can be expelled to the shelf (Souza & Robinson 2004). The interannual variability in the number of warm core rings shed in the BMC may be forced by the Antarctic Circumpolar Current (Lentini *et al.* 2002), which helps propagating Pacific ENSO signals to the Atlantic ocean (Peterson & White 1998).

Despite increasing evidences that point to the importance of large geographical areas as target units for ecosystem-based management (Belkin 2009), the response of these areas to climate changes is unlikely to be controlled by the ecological criteria used to define the LMEs. The reason for that is very simple, climate changes can act directly on physiology, behaviour, mortality and distribution, and indirectly on productivity, structure and composition of the ecosystem (Brander 2007). Productivity and trophic relations are endmembers of a chain effect that starts with physical processes not necessarily bounded by LMEs as they are defined today. The response of the tropical Atlantic to climate variability depends on atmospheric teleconnection mechanisms and on basin-scale SST gradients acting on different time scales (Lanzante 1996, Enfield & Mayer 1997, Alexander *et al.* 2002, Giannini *et al.* 2004, Hastenrath 2006). Mechanisms include the upper-tropospheric Rossby-wave train that extends from the equatorial eastern Pacific to the northern tropical Atlantic and the east-west displacement of the Walker circulation during El Niño years (Hastenrath 1976, Kayano *et al.* 1988). It is clear that the interplay of local dynamics and remote forcing, including the ENSO, is responsible for the observed SST anomalies over the tropical Atlantic (Nobre & Shukla 1996).

It is plausible to assume that if the spatial extent of SST anomalies can only partially affect a LME, the resulting changes in fisheries biomass yields or geographical distribution of species within it may not be statistically detectable. As a result, unbiased assessment of climate change impacts could be hampered and national governments would face too many uncertainties regarding the effectiveness of response policy measures. Also, managers responsible for mitigation programmes and action plans aimed at dealing with climate change impacts on marine and coastal ecosystems may find it difficult to envisage the necessary site-specific management strategies for multiple stressors (Higgason & Brown 2009). This is an important issue because the reduction in carrying capacity can be coupled with density-dependence effects on biomass changes of small pelagic fish species, such as observed with the Japanese sardine (Yatsu *et al.* 2008). As large-scale climatic-induced regime shifts are modulated by local physical conditions, this will most likely impose time-lagged changes on biological production at lower trophic levels (*e. g.* mesozooplankton). Recen-tly, Gigliotti *et al*. (2010) showed that the interannual variability of egg concentration of the Brazilian sardine can be related to the expansion and contraction of the spawning habitat. The Brazilian sardine is capable of exploring suitable spawning sites provided by the entrainment of the colder and less saline South Atlantic Central Water (SACW) onto the shelf due to the combined effect of coastal wind-driven and meander induced upwelling.

The purpose of this paper is to present some exploratory results that point to important differences between the spatial patterns of correlation of climate indices and SST anomalies (SSTA), and the geographic arrangement of LMEs for Brazil (North Brazil, East Brazil, and South Brazil Shelf), as recently discussed in Sherman *et al.* (2009). The consequences of such differences to the study of the impacts of climate variability in these LMEs are discussed.

Materials and Methods

Climate indices calculated as SST anomaly averages were obtained for three different areas: Niño 3 limited at 5° S, 5° N and 150° W, 90° W; Tropical North Atlantic (TNA) bounded at 5.5° N, 23.5° N and 15° W 57.5° W; and Tropical South Atlantic (TSA) at 0°, 20° S and 10° E 30° W (Fig. 2). These indices are the same used in other studies of tropical Atlantic climate variability (Enfield *et al.* 1999, Kayano *et al.* 2009) and are available at http://www.esrl.noaa.gov/psd/. The SST data used in this work are the monthly gridded series from 1948 to 2008, with a spatial resolution of 2° in latitude and longitude, derived from the version 3 of the reconstructed SST data set, described by Smith *et al.* (2008). These data can be freely downloaded from http://migre.me/3Hy49. The Antarctic Oscillation Index (AAO), also known as the Southern Hemisphere Annular Mode (Kidson 1988, Thompson & Wallace 2000) is calculated by projecting the monthly mean 700 hPa geopotential height (normalized) anomalies poleward of 20°S onto the leading Empirical Orthogonal Function (EOF) mode of these anomalies from 1979 to 2000. The AAO describes a mass seesaw between the southern mid and high latitudes, with positive (negative) values representing above (below) normal geopotential height in the midlatitudes and below (above) normal geopotential height in the high latitudes. The monthly AAO dataset corresponds to the period from 1979 to 2007, available at http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/aao/aao.shtml.

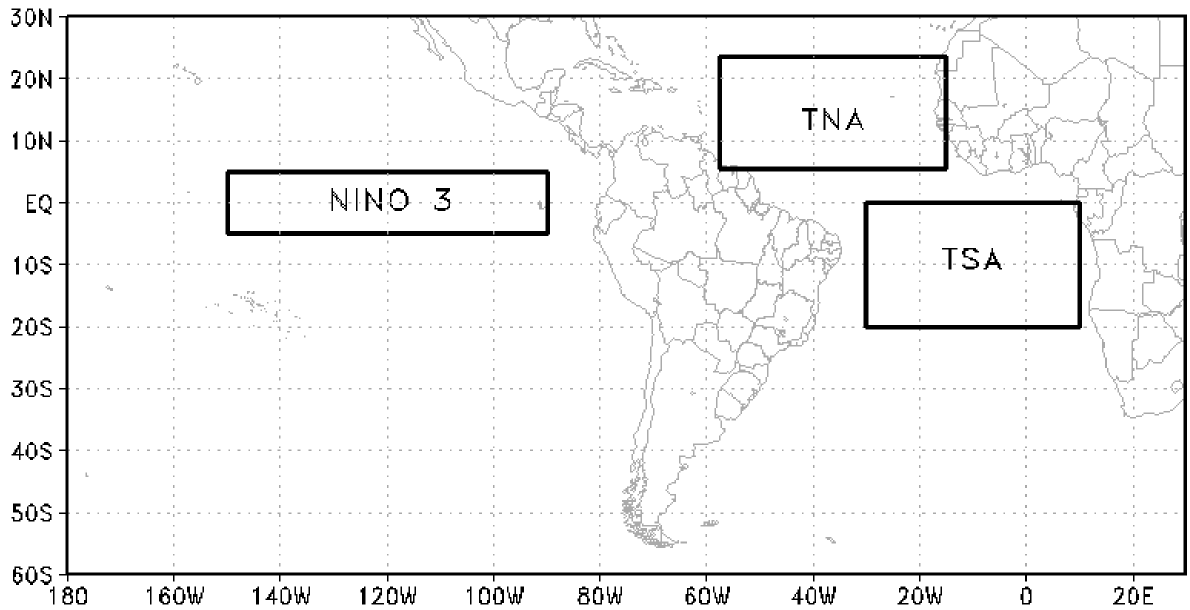

Figure 2. Location of areas from which the climate indices have been calculated.

In order to determine the spatial patterns of interannual SSTA variability along the Brazilian coast associated with global climate change, correlations between Niño 3, TNA, TSA and AAO indices and the SST anomaly field were calculated for the area between 10ºN to 40ºS and 62ºW to 26ºW. The influence of the Pacific Decadal Oscillation (PDO) shift on correlations was investigated by dividing the complete time series (1948 to 2008) in the cold PDO phase from 1948 to 1976, and the warm PDO phase from 1977 to 2008 (Mantua *et al.* 1997). Correlations were carried out for each grid point in the study area using linearly detrended, standardized and filtered data. Filtering procedure made use of a Morlet wavelet as a bandpass filter (Torrence & Compo 1998) to retain only the interannual variability between 2 and 7 years. The cross correlation time lags used in the analyses apply to all grid points and were selected based on the higher significance value obtained for each climate index. The statistical significance of all correlations has been assessed by Student's t-test at a 95% confidence level and only significant correlations are presented in the results section. The number of degrees of freedom (DOF) was determined by dividing the total time length of the series by the time lag needed to achieve decorrelation time closest to zero (Servain *et al.* 2000, Kayano *et al.* 2009). Only the lower values for the number of DOFs were adopted, so that the test is the most severe.

Results

For the sake of simplicity, all correlations between the climate indices and SSTAs along the Brazilian coast will be referred to only in terms of the indices used in each case. Maximum positive correlations of 0.7 with the Niño 3 are found along the eastern coast and offshore the northern coast of Brazil and to the north of the equator after a time lag of eight months (Fig. 3). This time lag has been also reported by Lanzante (1996) and indicates that under an El Niño (La Niña) the surface waters in these areas of the tropical Atlantic are anomalously warmed (cooled) eight months later. Possibly, the most striking aspect of the correlation fields is the marked spatial differences between the cold and warm PDO phases, namely the lack of positive correlation in the South Brazil (SB) LME during the warm PDO. Positive correlations with values up to 0.6 appear at the SB LME and up to 0.7 offshore for the cold phase only. It is also important to note that during the warm PDO, correlations in the EB LME are mostly located in its southern half, characterized by high (up to 0.7) values. This suggests a separation between the two halves of the EB LME, in terms of the decadal SSTA variability. It is worth noting that to the north of the equator correlations are significantly lower for the warm phase of the PDO than for the cold phase.

The TNA achieves higher positive correlations after one month lag but has a limited impact on the SSTA along the Brazilian coast (Fig. 3). During the cold phase of the PDO the north Brazil coast experienced the highest correlations, but these are greatly reduced moving offshore in the following warm phase. In fact, there is no significant correlation for the TNA along the north Brazilian coast during the warm phase. On the other hand, significant correlation of 0.5, restricted to a small area in the eastern coast in the cold phase, evolves into a wide northwest-southeast correlation band. This extends towards the subtropical portion of the central south Atlantic in the subsequent warm phase. So, for the warm PDO, an anomalous warmed (cooled) TNA relates to an anomalous warmed (cooled) subtropical South Atlantic.

Not surprisingly, the TSA achieves the highest correlation (with zero lag) in the northern and eastern portions of Brazilian coast, with the latter being more developed during the warm PDO phase (Fig. 3). This appears to be the result of the proximity with the area of the tropical Atlantic where the TSA is calculated. Furthermore, the positive correlation pattern also resembles the SST equatorial mode previously detected by Zebiak (1993) and Wagner & da Silva (1994). These authors showed that a significant part of the observed SST interannual variability in the tropical Atlantic is related to an internal Atlantic equatorial mode similar to the ENSO in the Pacific. A new feature, however, emerges for the warm phase characterized by negative correlation values as high as -0.6 along the southern limit of the SB LME. For the warm PDO phase, anomalously warm (cold) surface waters in the TSA relate to cold (warm) than normal surface waters in the South Atlantic to the south of 35°S. It is worth noting the lack of significant correlations in the area under the influence of the South Atlantic Convergence Zone(SACZ), similar to the observed pattern for the Niño 3 and TNA indices. The SACZ is an elongated convective band that originates in the Amazon basin extending to the southeastern Atlantic Ocean, responsible for extreme precipitation events and strongly influenced by warm ENSO events that favors its persistence over de Atlantic (Carvalho *et al.* 2004).

It takes six months for the AAO to develop the highest positive correlations along the SB LME

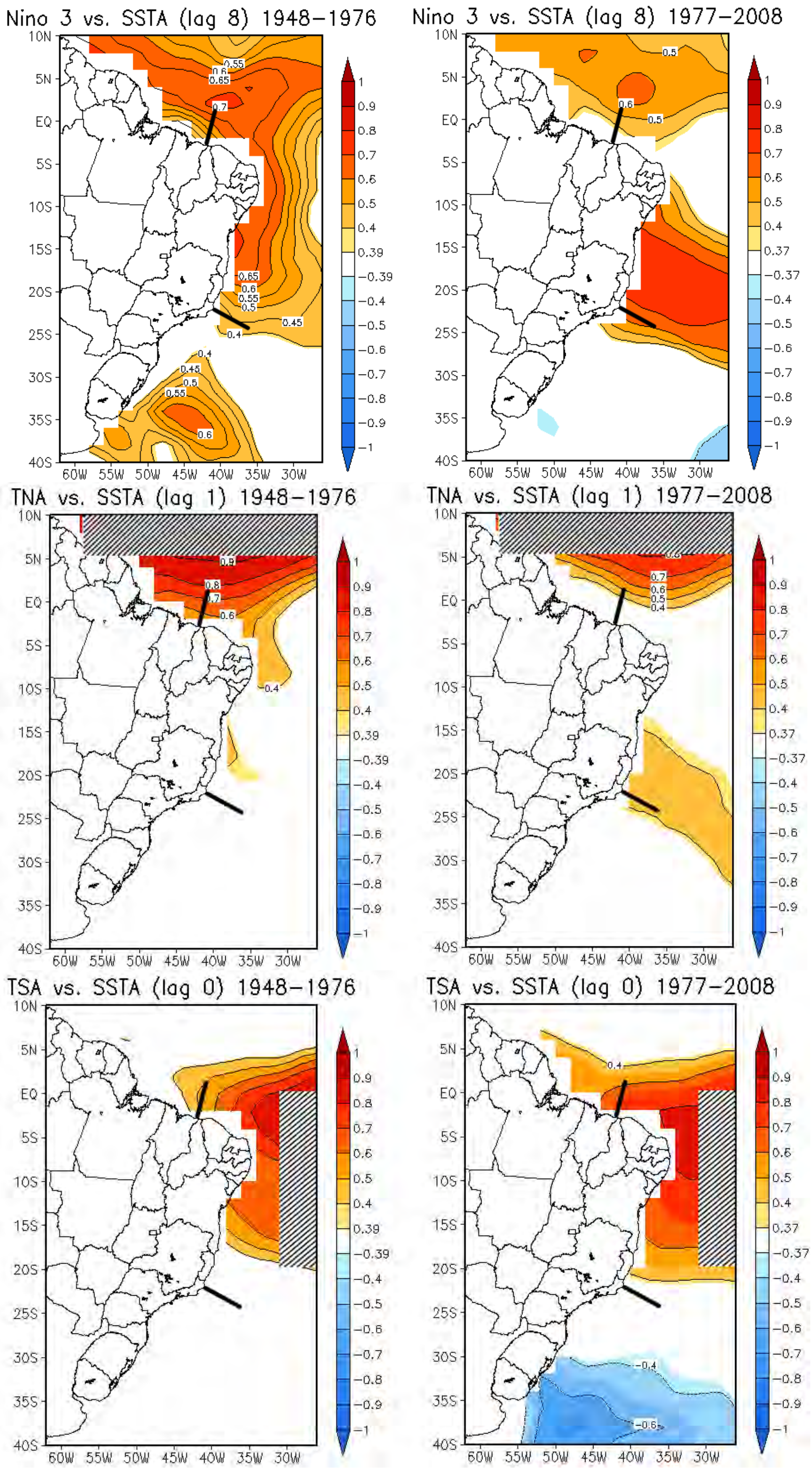

Figure 3. Significant correlation maps for Niño 3, TNA and TSA during the cold (left) and warm (right) PDO phase and their respective time lags. Hatched rectangles indicate areas of spurious correlation. Black straight lines correspond to the limits between LMEs in Brazil and were added for reference. Color bar is in (nondimensional) units of correlation.

and two years (24 months) to develop negative correlations along the NB and EB LMEs, as well as positive correlations restricted to the southern coast (Fig. 4). The most relevant aspect of these correlations is that this is the only index to present some relation with the interannual variability of SSTA within the SACZ region. The fact that significant correlations also developed with a 24 months delay with inverted signals in tropical and southern Atlantic deserves further attention. This aspect is analyzed through the sequential lagged correlation maps from lag 0 to 24 months (Fig. 4). Significant positive correlations appear offshore the southern coast between 25°S and 30°S at lag 1 month. Gradually, these correlations intensify and occupy a large area between 25°S and 35°S from lag 1 to 9 months. Significant negative correlations develop along the NB LME by lag 9 months. As these negative correlations intensify, significant (negative) correlations start to develop between 15° S and 20° S in the South Atlantic, and the positive correlation center between 25° S and 40° S splits into two centers by lag 17 months. With time, all correlations intensify, with the strongest values being settled by lag 24 months. This pattern shows, indeed, three main centers with the largest magnitude of correlation: two negative centers, one along the NB LME and another along the EB LME, and one positive center along the SB LME.

Discussion

There are striking differences between the correlation fields for Niño 3 and the proposed separation of LMEs along the Brazilian coast. This is also the case when the correlation fields for the cold and warm PDO phases are projected onto these LMEs. We have found that the time lag necessary for maximum correlations to be reached is the same (eight months) for both PDO phases, suggesting that the mechanisms connecting the Pacific and the Atlantic Ocean are comparable. During the cold PDO phase the boundary between the NB and the EB LMEs intersects a large region where SSTAs are highly correlated with the tropical Pacific variability (Fig. 3). It is striking, however, the coincidence between the significant correlations and the southern limit of the EB LME. High correlations between Niño 3 and SSTA cover the SB LME only partially and are mostly centered offshore (at 35°S, 45°W). This contrasts with our results for the NB and EB LMEs, where high correlations are found close to the coastline. This gives a strong indication that marine organisms living on the continental shelf of the SB LME, which are sensitive to SSTAs, may take longer to react the impact of ENSO events. We do know, however, that ENSO induced increase in precipitation in the Patos Lagoon estuary has a negative impact on euryhaline species (Garcia *et al.* 2001). Looking at the warm PDO phase, the EB LME includes areas with high and medium positive correlations and also a large area where no significant correlation was detected. This means that trophically related populations in the EB LME may not respond consistently to a remote climatic forcing such as the El Niño because environmental conditions expressed as SSTAs co-vary differently inside this region. This spatial discontinuity of correlations within the EB LME can pose some threat on pelagic species that rely on the thermal structure of the west tropical Atlantic, such as the albacore *Thunnus alalunga* during their reproductive phase (Frédou *et al.* 2007). Two other emblematic examples of the spatial and temporal effects of climate on marine pelagic ecosystems are provided by Stenseth *et al*. (2002), the Peruvian anchovy crash in 1972 and the zonal displacement of the Pacific skipjack tuna following the eastward displacement of the warm pool during ENSO events.

A further complicating factor is that ecological processes sensitive to long term (e.g. decadal) environmental changes are likely to be submitted to different regimes (see North *et al.* 2009) within the EB LME. The same complicating factor is even more evident in the South Brazil (SB) LME, where high positive correlation with El Niño has been detected during the PDO cold phase, but no signify-cant relation was found in the subsequent warm phase (Fig. 3). So, the PDO-related multi-decadal and ENSO-related interannual SSTA variability along the Brazilian coast exhibit a complex dynamics against which ecosystem functioning should be tested to provide clues as to how NB, EB and SB LMEs might respond to these climate forcings. Besides, if one considers the hypothesis that the PDO can be represented as a red noise process, then extreme values or rapid shifts might occur when fortuitous random phasing combine contributions of different frequencies (Overland *et al.* 2010).

The TNA and TSA indices are long known as indicators of the principal modes of Tropical Atlantic Variability (TAV), namely meridional SSTA gradients, which are important for the climate of the tropical Atlantic and the surrounding land masses (Enfield *et al.* 1999). The reason to include these indices in our analyses is to portray a balanced view of the inter-basin and within-basin influence on the SSTA of the Brazilian LMEs. The extent to which the TNA and TSA interact with SSTA along the Brazilian LME can be explored in the correlation maps of Fig. 3. These maps show a scenario where correlations with TNA are limited to the southern half of the EB LME during the warm PDO phase, with a single correlation area between 15° and 25° S, and points to a possible indirect influence via ENSO teleconnection over the region. In fact, the TNA itself is forced by the ENSO and is likely to be of marginal importance to the NB and EB LME if compared to the meridional propagations of SSTAs in the tropical Atlantic (Andreoli & Kayano 2004). It is worth mentioning the significant differences between cold and warm PDO correlations for the TNA. This is a recurrent feature that highlights the importance of decadal variability in shaping spatial patterns of LME vulnerability to climate change.

Interpretations regarding the TSA should be made with caution due to the proximity of the EB LME with the region from which the index has been calculated. However, the antisymmetric (opposed signs) correlation pattern observed in the SB LME, during the warm PDO phase, may be related with the northeast-southeast SST dipole suggested by Grodsky & Carton (2006). It is beyond the scope of the present work to discuss the applicability of the term dipole but our results point to a basin scale interannual relation between the SB LME SSTA and the so-called TAV. It is important to highlight that not only TAV may have an impact in SB LME but it strengthened after 1977, since it was absent during the PDO cold phase. Again, the negative correlations of TSA found only for the southern half of the SB

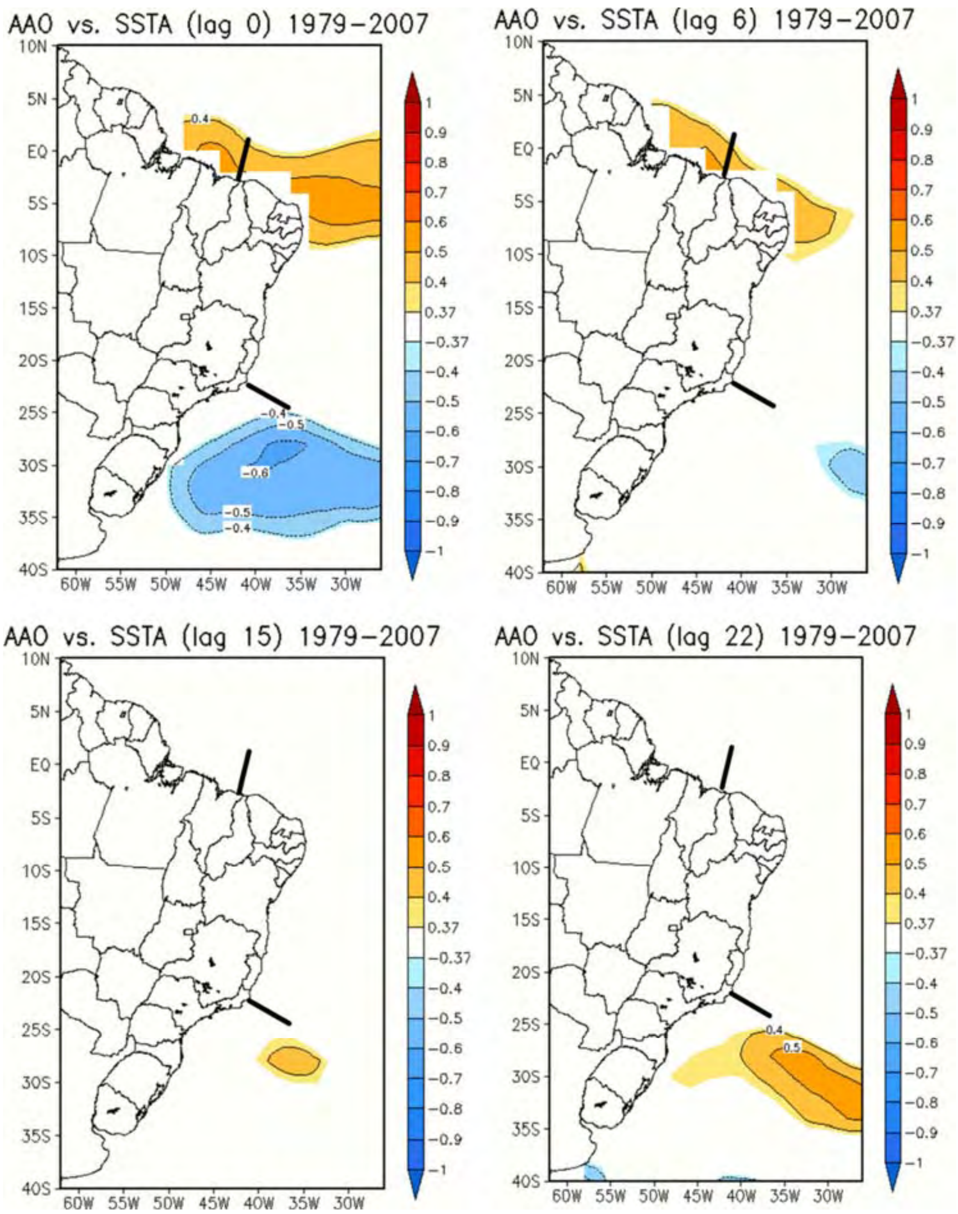

Figure 4. Significant correlation maps for AAO (warm PDO phase only) indicating the time and space evolution of correlation fields along four time lags (from zero to 22 months). Black lines correspond to the limits between LMEs in Brazil and were added for reference. Color bar is in (nondimensional) units of correlation.

LME suggest that possible random phasing with remote forcing of SSTA is likely to produce mixed effects in this LME.

The leading EOF of monthly sea surface height anomalies (SSHA) shown by Grodsky and Carton (2006), indicates a region of shallow thermocline in the southwest Atlantic between 25° and 35° S coincident with negative SST EOF scores. They interpreted the westward 10 cm interannual SSHAs as Rossby waves produced by thermocline anomalies due to local and equatorial air-sea interactions. These waves would propagate along the Agulhas Eddy Corridor (AEC). The region of shallow thermocline is coincident with a field of negative correlations with the AAO without time lag that dominates the northern half of the SB LME (Figure 4). This means that positive AAO indices are correlated with cold of SSTAs and stronger westerly circumpolar flow (positive mid-latitude pressure anomalies) as previously indicated by Thompson and Wallace (2000). Coupled ocean-atmosphere model results suggest that much of the variability of the south Atlantic poleward of 30° S has a direct relation with the Southern Hemisphere Annular Mode (hence, the AAO; Hall & Visbeck, 2002). Positive AAO is related with increased poleward ocean heat transport at 30° S and a reduction at 50° S, with associated 0.05° C increase in SSTA in the subtropics. The importance of AAO as a source of large-scale interannual variability in the tropical and Southern Atlantic Ocean can be also inferred from positive correlation centers along the northern and eastern coast and positive correlations observed between 25° S and 35° S, 15 and 22 months ahead of the AAO for the warm PDO phase (Figure 4). Whether this is a result of enhanced Ekman drift and convergence of heat it is not possible to ascertain, but the observed correlations indicate that the AAO exerts a strong influence on the environmental conditions along the LMEs.

It is possible that both TSA and AAO have an influence on the EB and SB LME acting in different ways depending on the geographic location and time scale. This influence seems to be particularly conspicuous during the warm PDO phase. In this preliminary report, we can only be speculative, but this is not to say that there are no evidences for the influence of the spatial scale. Indeed, it is quite the opposite, looking at the interplays among population dynamics, climate change and fisheries throughout the Atlantic, it is seen that at the basin scale patterns of variations are spatially structured (Rouyer *et al.* 2008).

The current knowledge on coupled ocean-atmosphere dynamics tells us that LMEs are tied together by wind stress forcing, Ekman drift and heat transport. All of these are important agents that control the pelagic food-web structure, including primary productivity, mesozooplankton biomass and the position of spawning habitats of pelagic fishes (Kiorboe 2008). Changes in surface currents, wind stress and heat flux can have an impact on the long-term dynamics of zooplankton functional groups, leading to regime shifts in the ecosystem functioning from bottom-up to top-down control (Molinero *et al.* 2008). If monitoring and management of LMEs are to become an effective means to respond to climatic impacts on marine biodiversity and productivity, then the physical linkages between ocean-atmosphere dynamics and the pelagic ecosystem on a regional and basin scale have to be explicitly considered.

Conclusions

The above results are preliminary findings that aim at exploring the spatial patterns of correlation between climate indices and the SSTA along the Brazilian LMEs at the interannual time scale. Significant correlations indicate that there is a separation between the north and east Brazil coasts located halfway between the boundaries of the EB LME. The SSTAs in the SACZ region showed no significant correlation with Niño 3, TNA and TSA, but are correlated with the AAO during the warm PDO phase. Possibly, the most evident pattern that surfaced from the results is the influence of the PDO phase shift causing dramatic changes in the spatial distribution of correlations. The correlation patterns for the TSA and AAO seem to have a better fit with Brazilian LME during the warm PDO phase (1977-2007). During this phase of the PDO, while the largest magnitude correlations are found in the EB and SB LME for the TSA, they are centered in the three LME areas for the AAO. It is, strongly recommended the combined use of coupled ocean-climate and ecological models as a means to elaborate the possible mechanisms linking climate change and the functioning of LMEs in Brazil. The assumption that LMEs delimited along the Brazilian coast coherently respond to global climate changes, and that these can be used to monitor their impacts should be taken with caution. It is clear that, as far as their dependence on SSTA is concerned, productivity and trophic relations in each of the Brazilian LMEs are likely to generate mixed responses at the ecosystem level. This would, in turn, induce policy makers to react to a confounded scenario of environmental change.

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An essay on the potential effects of climate change on fisheries in Patos Lagoon, Brazil

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Abstract. Important artisanal fisheries depend on the Patos Lagoon estuarine resources (southern Brazil). About 3,500 fishermen work in this region. Some resources, notably pink shrimp, white-mouth croaker and grey-mullet are estuarine-dependent species as their life cycles depend on a brackish water environment. The ENSO cycle and climate changes may impact the estuary. In this essay, we sought to qualitatively analyze these environmental changes impact on estuarine secondary production and fisheries. We ponder the currently available knowledge about the species and regional climate models which show a maximum 2ºC increase in the next 30 years, with rainfall rates showing little change. However, the lagoon outflow should increase due to changes on the hydrographic basin, which would increase the limnic and decrease the saline influence in the estuary. This scenario may impact the biology and dynamics of estuarine-dependent species and their fisheries, because temperature influences metabolism, which affects the growth of individuals. Larvae natural mortality may increase due to metabolic stress, although increased growth rates may also reduce the vulnerability period of young to predation. A decrease in the species maximum size is also expected, as well as a shift in biomass peaks and changes in the fishing calendar.

Keywords: temperature and rainfall increase, estuarine fishery resources, climate impacts

Resumo. Um ensaio sobre os efeitos potenciais das alterações climáticas sobre a pesca na Lagoa dos Patos, Brasil. Importantes pescarias artesanais dependem dos recursos estuarinos da Lagoa dos Patos (sul do Brasil). Estima-se que 3.500 pescadores trabalhem na região. Alguns recursos (camarão-rosa, corvina, tainha) são estuarino-dependentes, tendo seus ciclos de vida ligados ao ambiente salobro. Este ensaio analisa qualitativamente os impactos que as mudanças climáticas terão sobre a produção secundária e a pesca estuarina. Considerou-se os conhecimentos disponíveis sobre a biologia e dinâmica das espécies envolvidas e os modelos climáticos. Estes apontam um aumento máximo de 2ºC na região nos próximos 30 anos, com pouca mudança na precipitação. Entretanto, a vazão da lagoa deve aumentar, devido às mudanças antrópicas na bacia da Lagoa dos Patos, aumentando a influência límnica e reduzindo a influência salina no estuário. Nesse cenário, esperam-se impactos na biologia, dinâmica e pesca das espécies estuarino-dependentes, pois a temperatura influencia o metabolismo, afetando o crescimento individual. A mortalidade natural larval aumentaria, devido ao estresse metabólico, mas o aumento das taxas de crescimento reduziria o período de vulnerabilidade juvenil à predação, diminuindo a mortalidade natural. É esperada uma diminuição no tamanho máximo das espécies, assim como um deslocamento dos picos de biomassa e mudanças no calendário de pesca.

Palavras-chave: aumento de temperatura e chuva, recursos pesqueiros estuarinos, impactos climáticos

Introduction

Until the Industrial Revolution (early nineteenth century), anthropogenic actions (e.g., deforestation, the regional extinction of species, destruction of the natural landscape) had only regional or perhaps even continental impacts. After the Industrial Revolution, however, the impacts of human activities became global (based on the premise that climate changes are the result of anthropogenic actions and that they are related to the carbon concentration in the atmosphere) (IPCC 2007).

The Industrial Revolution marks the beginning of the use of fossil fuels, resulting in the production of greenhouse gases such as carbon dioxide (IPCC 2007). These gases increase the retention of heat in the atmosphere, causing global warming and climate change on the planet (Mitchell 1989, Cline 1991). At present, there is a great deal of emphasis within the academic community on continuing studies on the consequences of global warming, how it may be prevented and on the adoption of mitigation measures.

The delay of many countries in adopting measures to reduce greenhouse gas emissions have resulted in steady and rapid increase in levels of carbon in the atmosphere, such that the current concentration is the highest in the last 450,000 years (King 2007).

The carbon absorption capacity of the oceans, which are the largest absorbers of carbon dioxide on the planet, seems to have reached its limit and has decreased over recent years (Khatiwala *et al.* 2009). This means that more greenhouse gases will remain in the atmosphere and will continue to drive climate change.

According to Solomon *et al.* (2009), many of the effects of climate change are already irreversible (King 2007) because of the high degree of inertia of the oceans and other climate control systems, which respond slowly to environmental changes (Caldeira *et al.* 2003). If emissions were reduced to zero today, the temperature of the planet would still continue to rise for over a thousand years (Solomon *et al.* 2009).

Thus, reversing the climate change process and returning the planet to a pre-Industrial Revolution climate appears to be an almost impossible task. Because of this, it will be necessary to make adjustments to the new climate of the planet by undertaking measures to minimize further impacts on mankind.

The analysis of likely future climate change scenarios and characterization of their biotic impact can support this adaptation.

The study presented in this essay is a qualitative analysis of the influences of climate change in the Patos Lagoon estuary and the biological response of some fish species there. It is based on the best information that is currently available without making a distinction between natural and anthropogenic effects. The synergistic effects of living beings and their adaptive capabilities are also disregarded.

Patos Lagoon

Patos Lagoon (Fig. 1), which is located in the coastal plain of Rio Grande do Sul, is 250 km long and has an average width of 40 km, covering a total area of approximately 10,360 km^2. This makes it the largest coastal lagoon of the choked type in the world. It can be classified as a shallow lagoon having an average depth of 5 m. The topography of the main lagoon body is characterized by major natural and artificial channels (8 - 9 m), wide adjacent areas (<5 m) and marginal shallower embayment areas (Seeliger *et al.* 1998).

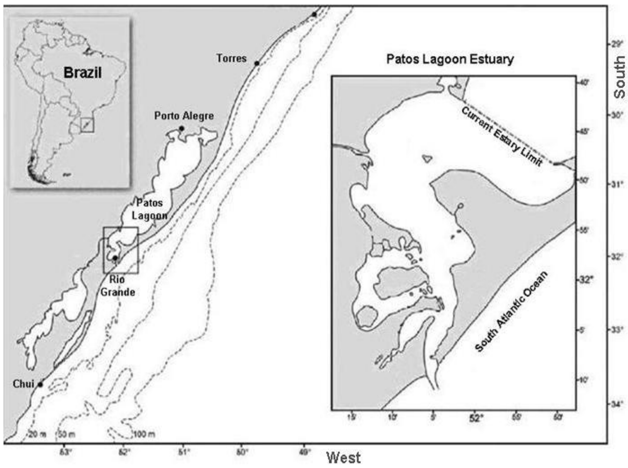

Figure 1. Coastal plain of Rio Grande do Sul state in southern Brazil showing in detail the Patos Lagoon Estuary.

The Patos Lagoon estuary occupies approximately 10% of the total area of the lagoon and is characterized by large regions of banks (80%), where the depth varies between 1 and 5 m. The connection of the estuary with the Atlantic Ocean occurs through a narrow entrance (750 m wide) with an access canal that has an average depth of 15 m and a maximum depth of 20 m. This canal acts as a filtering buffer, confining much of the tidal influence to the tapered portion of the estuary and strongly attenuating its amplitude (Möller *et al.* 2009).

The limit for inland penetration of salt water is up to 60 km from the mouth of the estuary and is related to wind conditions and river discharge, which results in seasonal variability. The annual average salinity of the estuary is 13, with values at a particular time ranging from 0-34. The strongest longitudinal salinity gradient is always observed to the north of the channel entrance. Lateral gradients are observed where the cross-sectional area increases, and vertical gradients can vary from the saline wedge to the well-mixed type (Fernandes *et al.* 2005).

Why the Patos Lagoon Estuary?

This estuary in southern Brazil was used for this study because it is an area that has been studied by the University of Rio Grande (FURG) in detail since the 1970s (Seeliger *et al.* 1998). It is also a region with a high degree of socio-environmental importance in the Southwest Atlantic (Seeliger *et al.* 1998) as a fishing ground for artisanal fisheries, as a nursery area for larvae and juveniles of many species (Chao *et al.* 1985, Haimovici *et al.* 2006) and because of its agro-industrial, tourist and port activities (Seeliger *et al.* 1998).

Rice production in the region reached more than eight million tons in 2008 (Instituto Riograndense de Arroz 2009). The port of Rio Grande (the only seaport in the state) processed more than 21.5 million tons of cargo in 2003 and served as a port for almost three thousand ships (Superintendência do Porto de Rio Grande 2009).

The artisanal fishermen community in the region, which depends on these resources, fluctuates around approximately 3,500 people who are directly involved in fishing (Haimovici *et al.* 2006), highlighting the socio-economic importance of the region.

Materials and Methods

Climate Models

For future climate projections, we used the future scenarios A2 (pessimistic) and B2 (optimistic) of the Intergovernmental Panel for Climate Change (IPCC 2007). The A2 scenario describes a very heterogeneous world that is characterized by a high degree of self-sustenance with the identities of local populations being preserved. Birth rates in this scenario continue to be higher than mortality rates, resulting in continuous population growth. Economic development is regionally oriented, and economic growth and technological changes are more fragmented and slower than in other scenarios.

The B2 scenario describes a world with an emphasis on local solutions for economic, social and environmental sustainability. It is a world with a continuously growing global population, though at a rate lower than in the A2 scenario, and with intermediate levels of economic development. Technological change will be less rapid and more diverse than in scenarios B1 and A1. This scenario is also more oriented towards environmental protection and social equality focused on both local and regional processes.

From these scenarios, the National Institute for Space Research (INPE) created thirty-year future climate models (2010 to 2040), aimed at understanding expected changes in rainfall and local air temperature (Marengo 2007).

Time Series

In this study, the following time series were used: rainfall and river flow of the main rivers contributing to the Patos Lagoon basin (Costa *et al.* in press) (Fig. 2) rainfall (Steinmetz 2007, Costa *et al.* in press) (Fig. 3) and air temperature in the city of Pelotas, which is located in the margin of the estuary region (Steinmetz *et al.* 2007) (Fig. 4).

Fishing Resources

Among the 28 species that are exploited through fishing in this region, five have historically been the most important: pink shrimp (*Farfantepenaeus paulensis*), corvina/whitemouth croaker (*Micropogonias furnieri*) miragaia/black drum (*Pogonias cromis*), tainha/grey-mullet (*Mugil platanus*) and bagre/white sea catfish (*Genidens barbus*). However, according to the present profile of artisanal fishing, only three species (pink shrimp, whitemouth croaker and grey-mullet) were selected for the study because the black drum and catfish have been heavily over-exploited and their catches are no longer significant (Haimovici *et al.* 2006).
Together, the three species represent more than 30% of the landings and nearly 45% of the revenue from fishing in this region (Haimovici *et al.* 2006, Castello *et al.* 2009). Thus, it is possible to characterize them as the most important socio-economic resources of the estuary. As such, it can be assumed that characterizing the impacts on these three fisheries is equivalent to characterizing the impacts on the entire estuarine fishing in the region.

The reproductive peak of the whitemouth croaker takes place from September to October, with spawning occurring at the mouth of the estuary. The eggs and larvae of this species penetrate the estuary by being passively transported by the current, particularly in late spring and early summer, and come to occupy the shallower marginal areas. As their development progresses, the croakers will move to the deeper areas of the estuary, and they will return to the sea upon reaching adulthood (Castello 1985, Oliveira & Bemvenuti 2006).

The grey-mullet also spawns in the open sea between the coasts of the neighbour states of Rio Grande do Sul and Santa Catarina in the late fall and early winter. Juveniles then migrate to shallower waters and enter the estuaries, particularly during the spring. Upon reaching maturity, they return to the ocean in shoals, generating the so-called “mullet race” (Oliveira & Bemvenuti 2006).

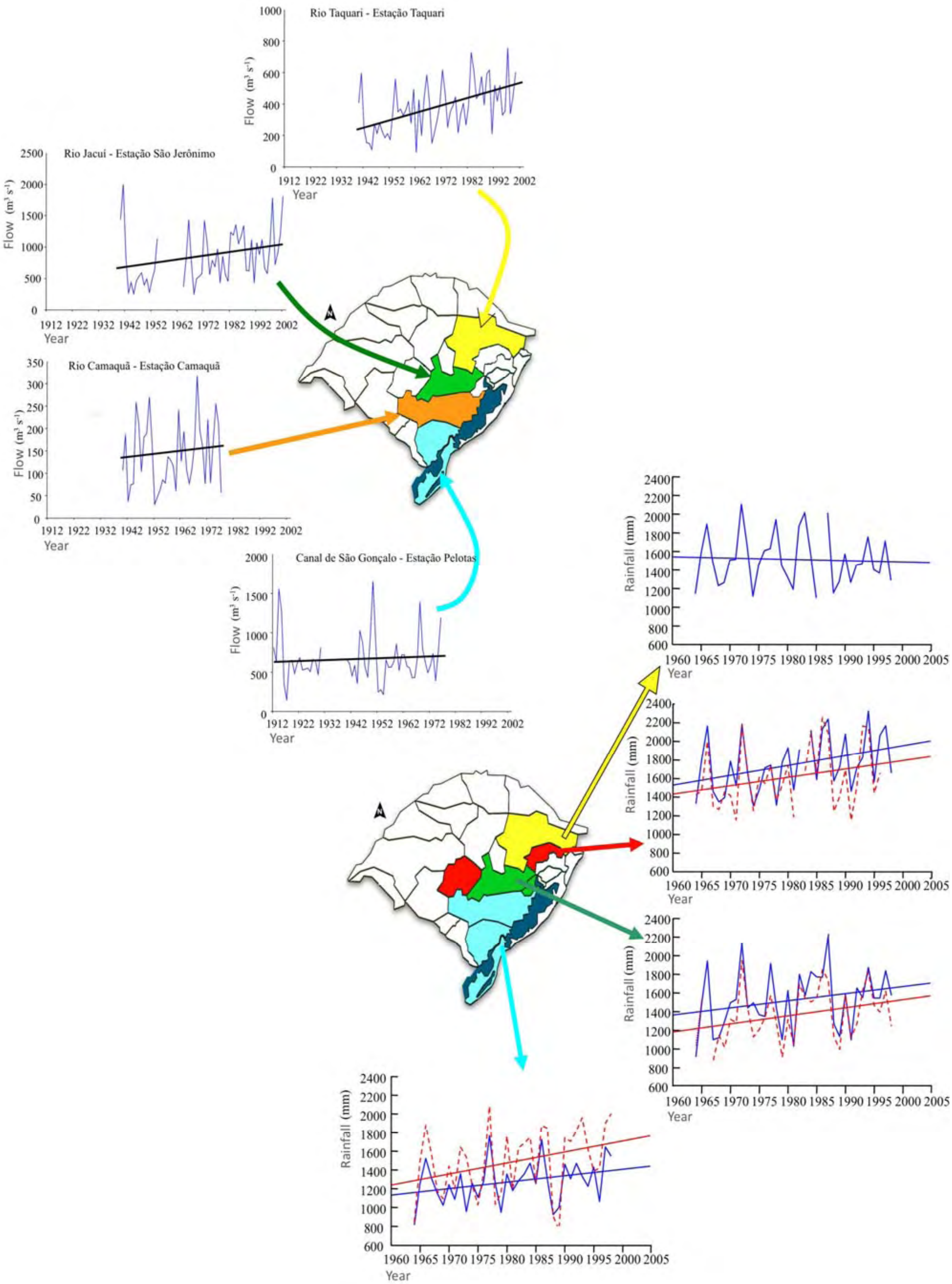

Figure 2. Rainfall time series (right) in the drainage basin and flow (left) of the main rivers contributing to Patos Lagoon. The study period is 40 years (1960 to 2000) for the rainfall series and 90 years (1912 to 2002) for the river flow series. (Costa *et al.* in press).

Pink shrimp breed in the spring on the shelf at the coastal front of Santa Catarina. The larvae migrate in a passive manner into the Patos Lagoon estuary in the form of megalopae (D'Incao 1991). They will remain there for three to four months in the shallower embayment areas of the estuary until they reach the juvenile or pre-adult stage, at which point they will return to sea in autumn-winter (Ribeiro *et al.* 2004).

Combining the INPE predictions and the time series, we chose to create a future climate scenario for the next 30 years.

A conceptual model was developed based on the main stages of the life cycle of a cohort (Fig. 5). From this, we identified the stages and parameters of the life cycle that could be altered by climate change.

In Figure 5, the rectangles represent the biomass (B) of a cohort at each time point (T). At each time transition, there is an effect of growth (G), natural mortality (M) and, after a certain age, fishing mortality (F). The sub-index 1 represents larvae and juveniles, 2 represent the recruits, and 3 represents the sexually mature (breeders). Tr and Lr identify the age and size at the time of recruitment, respectively. Analogously, Tc and Lc identify age and size at the time of the first catch, respectively. Age and length at first maturation, which is the time of first breeding, are designated by Tm and Lm. Closely connected to this whole process, there is migration between the mating, breeding and feeding sites.

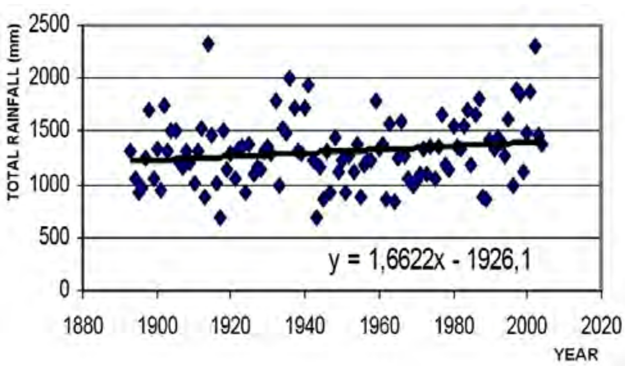

Figure 3. Rainfall time series for the city of Pelotas (city marginal to the estuary) during the period from 1880 to 2002. The line shows a variation of 184 mm in 111 years (Steinmetz *et al.* 2007b).

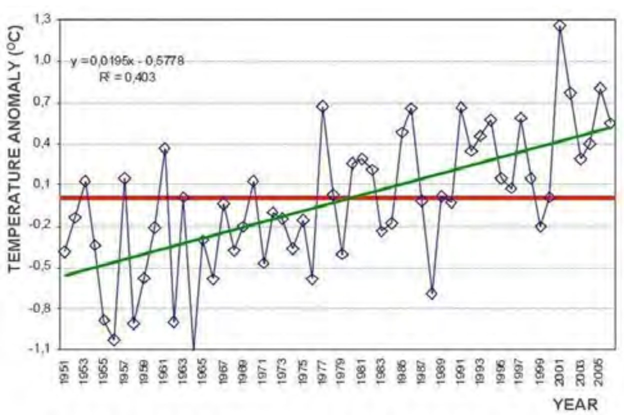

Figure 4. Air temperature anomaly time series for the city of Pelotas (from the portion of the city marginal to the estuary) during the period from 1951 to 2006 (Steinmetz 2007).

To carry out this study, we used the following premises:

- All of the determinants that affect climate, and estuarine characteristics and processes and/or the biology of fishing resources were considered without distinguishing between natural and anthropogenic forces.
- The adaptive capacities of species were not considered.
- The 30-year scenario was chosen as the most prudent because future knowledge shall come into play if predictions are made for longer periods.

Results and Discussion

Future Scenario

Precipitation and salinity

The INPE climate models (Marengo, 2007) do not indicate rainfall anomalies for this region, i.e., climate change will not affect rainfall in the drainage basin of Patos Lagoon in the next thirty years independent of the analyzed scenario (A2 or B2). However, the spatial and temporal resolution of these climate models is low and large-scale and does not take into consideration local characteristics of each region.

During the discussions of the First Brazilian Workshop on Climate Change in Coastal Zones (held in Rio Grande/RS; 13-16/09/2009), the need to increase our knowledge on the specifics of how climate change is occurring was remarked. This would attend the purpose of producing models that are better predictors of climate change in the future (Rede Clima 2009).

In contrast with the INPE models, the flow time series of the major rivers contributing to the Patos Lagoon (Fig. 2) shows a clear upward trend. The Taquari River nearly tripled its flow over the past 65 years; the flow of the Jacuí almost doubled; the Camaquã had a smaller increase of about 20%; and the contribution of the Mirim Lagoon remained almost stable with a slight increase. This means that there is an increasing amount of fresh water reaching the estuary.

This increase in outflow is associated with rising rates of rainfall in the drainage areas of these rivers (Fig. 2). At the same time there is a superimposed decadal cycle. Costa *et al.* (in press), for a shorter time period, found a much higher increase in rainfall rates (up to 40% in 40 years) when compared with the data from Pelotas.

Toldo *et al.* (2006) points to an increase in sedimentation rate in Patos Lagoon in the last 150 years, i.e., before and after the agricultural colonization of the banks of its hydrographic basin. Soil impermeabilization (due to building cities and roads), destruction or reduction of riparian vegetation and agriculture all decrease the rates of water penetration into the soil, causing more water (and therefore more sediment) to be carried to Patos Lagoon. This process, along with increased rainfall in the drainage areas of the rivers basins, may explain the increased outflow of contributing rivers.

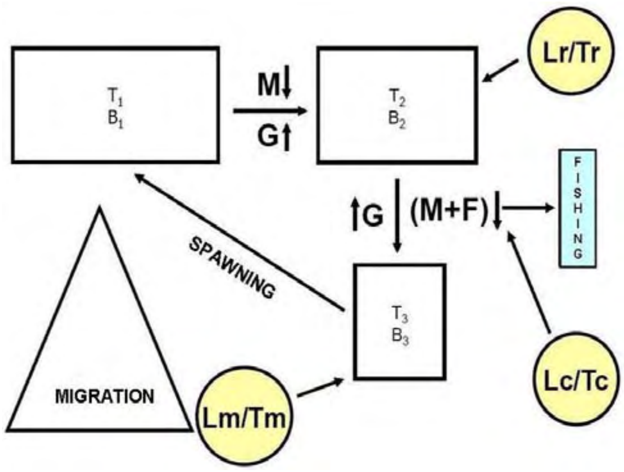

Figure 5. Conceptual model of the evolution of a cohort.

This scenario may be relieved by the high rates of evaporation in the Patos Lagoon, estimated to be approximately 600 m^3/s (Hirata & Möller 2006). As evaporation is directly proportional to temperature, increased heat in the region should increase evaporation rates, reducing the amount of water available.

Assuming that freshwater input will increase (in a linear fashion or in a decadal cycle) in the system despite the evaporation rates, more fresh water will be carried to the estuary over the next 30 years resulting in ‘limnification’, therefore, decreasing the size of the estuary (Costa *et al.* in press).

The ‘limnification’ process increases the fresh water in the estuary, reducing the salinity in its entire area of influence. Therefore, the position of zero salinity which determines the upper limit of the estuary, should move towards the sea, reducing the area of influence of the salt and the brackish water that is present in the southern region of Patos Lagoon (Costa *et al.* in press). Still, it is expected that this process shall be intensified when increasing the length of the rocky man-made pair of jetties located in the mouth of the estuary (Fernandes *et al.* 2005).

An increase of the outflow of the estuary is also expected because there is an increase in the volume of displaced water into the lagoon. In parallel, the speed at which the water exits through the rocky jetties should increase, resulting both from the volume of the outflow and renovation work that is done on them (Fernandes *et al.* 2005).

Temperature

Air temperature is expected to rise in the region. The INPE model points to an elevation of between one and three degrees Celsius, depending on the season and model that is analyzed. Although there are no historical data on water temperature in the lagoon and estuary, the low average depth and residence time of the water there indicate that it will follow the trends that have been verified for the air (i.e. increasing temperature).

The time series (Fig. 4) shows an upward trend in temperatures in the region, reinforcing the conditions outlined in these models.

Estuary of Patos Lagoon - 30 years

In light of the data presented above, it can be predicted that, in 2040, the estuary would be smaller, less salty and warmer, with stronger outflow and weaker inflow currents at the mouth of the estuary.

Response of fish stocks

Over time, the evolution of a fish cohort that is not fished behaves according to the conceptual model in figure 6. The number of individuals in the cohort is maximal at time zero, i.e., immediately after larval eclosion. As these individuals grow, the cohort biomass increases, while mortality reduces the number of individuals. The cohort biomass peak occurs when the natural mortality removes a large enough number of individuals that the growth of the survivors can no longer compensate the biomass of the cohort. This point occurs at the intersection of the curves for number and weight of individuals (Fig. 6).

When fishing is added to the model (Fig. 7), the curve representing the number of individuals declines even more due to increased mortality from death by fishing. The biomass and numbers of a cohort decrease with the increase in fishing mortality.

Estuary Reduction and Limnic Influence

The reduction in the estuary area should result in an increase in inter-and intra-specific competition among brackish water species, for both space and food. If we start with the premise that the number of individuals should not decline (at least at first instance), the population density in shallow areas with conditions of suitable salinity and vegetation will be higher. This means that embayment areas, with seagrass meadows, which are conducive to the proliferation of fish and crustaceans (Seeliger *et al.* 1998), should bear a greater density of consumers.

It is thus likely that the available food, which previously supported a lower density of individuals in areas with brackisk waters, will be competed for more severely. This situation can create stress in the populations, increasing mortality of the estuarine-dependent species. On the other hand, grey-mullet, which lives and growths in the fresh water area, will probably be affected during recruitment time.

While studying the effects of 'El Niño' on the estuary, Garcia & Vieira (2001) noticed that the phenomenon caused a local reduction in salinity due to high rainfall in the lagoon drainage basin. He also found that freshwater species, particularly *Parapimelodus nigribarbis*, *Astyanax eigenmaniorum* and *Oligosarcus jenynsii*, had subsequently become more frequent in the estuary.

These species will also compete for space and food with the estuarine-dependent species, and may, especially in the case of the carnivore *O. jenynsii*, represent one more predator of larvae and juveniles in the region.

The influence of 'limnification' can cause changes in the dynamic movements of estuarine-dependent species. 'El Niño' events reduce the recruitment of juvenile grey-mullets, negatively affecting the next growing season (Vieira *et al.* 2008) and the reproductive migration ("mullet race").

However, the variation in salinity should not affect the biology of the species, since the fluctuation of salinity in the estuary is common, ranging from marine to limnic conditions (Seeliger *et al.* 1998). These changes are, however, ephemeral, while the changes that will occur due to climate change are expected to be of a more constant nature.

Thus, with the reduction of the estuary size and the influence of 'limnification', increased mortality of the estuarine-dependent species and changes in migration and population dynamics are expected, reducing the available population for fishing.

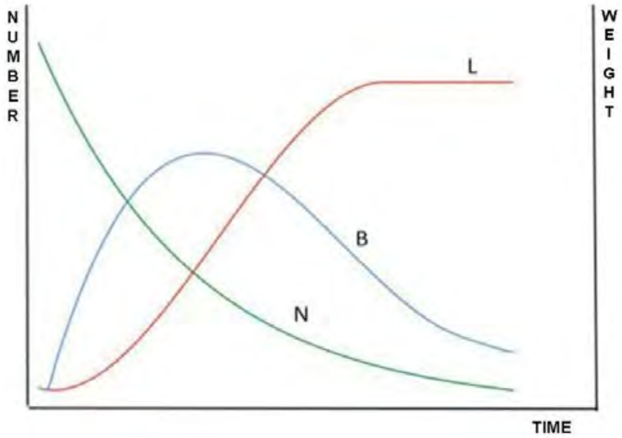

Figure 6. Model of a "virgin" cohort. The curve L represents the weight of individual species. Curve B represents the biomass curve, and N is the total number of individuals.

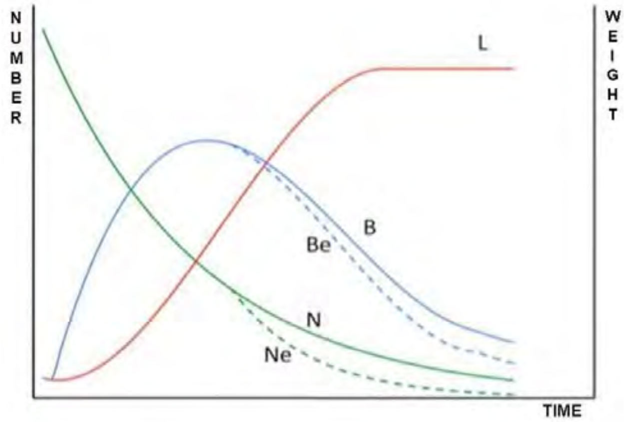

Figure 7. Model of an exploited cohort. Curve L represents the size of individual species, B the biomass, Be the biomass with exploitation, N the number of individuals and Ne the number of individuals with exploitation.

Increased temperature

Temperature is determinant to metabolism in fish, in a manner that the second is proportional to the first and that affects the rate of growth at all life stages. Because the Patos Lagoon is shallow (average depth of 5 m), variations in air temperature are quickly transmitted to the water column.

Krummenauer *et al.* (2006) pointed out to the low water temperature of the estuary in the autumn-winter period as a limiting factor for the cultivation of pink shrimp throughout the year. Therefore, a higher temperature could extend the growing season for shrimp and increase their growth rate.

Okamoto *et al.* (2006) discussed the advantages of higher temperatures on the development of juvenile grey-mullet. At a higher temperature, the feed-to-weight gain ratio increases (i.e., the same amount of food generates a greater amount of body mass). Higher growth and fattening rates with higher temperatures are also observed.

This rapid growth should affect the age of first maturity and result in an earlier start for reproduction in the species. Thus, the maximum length of the species (L_∞) should decrease (Beverton & Holt 1957, Weatherley 1972).

With individuals growing faster, the biomass peak of the species should shift, occurring earlier in the year. However, as the L_∞ should decrease, the peak of biomass should follow this trend, decreasing as well.

With higher growth rates, larvae will quickly pass through the periods of greater vulnerability, being exposed to "windows" of predation for less time. This should cause a decrease of the natural mortality rate, allowing more individuals to reach youth.

However, increased temperature can also cause metabolic stress on larvae, causing an increase in their natural mortality. Okamoto *et al.* (2006) found 5% higher mortality rates at higher temperatures compared with lower temperatures.

Yet, metabolic stress is a response to temperature stress, or a sudden change in temperature. Climate change results in small, incremental changes in warming rates of less than one degree Celsius every ten years. Therefore, there is the possibility that physiological adaptations may arise to circumvent the effects of temperature change on metabolism.

With accelerated growth rates and likely changes in the timing of migrations, the fishing calendar for the main species in the estuary may change. Haimovici *et al.* (2006) have, in fact, previously reported changes in this calendar (Fig. 8).

It is worth noting that there was a decrease in the peak of production, and an increase in the overall time of harvesting. There were changes of some harvested species, for example, catfish, between the periods from September-November (spring) to June-September (winter).

These changes are not unambiguously a result of climate change. They may be associated with specialization and adaptation of fishermen to different patterns of abundance caused by over-fishing (Kalikoski & Vasconcellos 2007). However, because of changes in travel patterns and population dynamics, we cannot dismiss the possibility of changes occurring as a result of climate change. Temperature and salinity are known factors for triggering migrations into or outward the estuary; therefore, an increase in temperature and a decrease in salinity may affect the timing of migration of estuarine dependent species (Pitcher 1993).

Currents at the Mouth of the Estuary

The larvae, post-larval individuals and juveniles of the three main fishery resources enter passively into the estuary, carried out by currents (Möller *et al.* 2009, Vieira *et al.* 2008, Garcia & Vieira 2001). Thus, the balance between the inflow and outflow currents of the estuary is of paramount importance for successful migration to occur.

Möller *et al.* (2009) have discussed the effects of rainfall anomalies (and consequently, the acceleration of the output current of the estuary) on the harvest of shrimp in the estuary and found an inverse relationship in which more rain resulted in less shrimp in the following harvest.

Vieira *et al.* (2008) performed a similar analysis for the grey-mullet, concluding that, with increased rainfall intensity and outflow current, juvenile recruitment would be hampered, reducing amounts of both current and future catches.

Thus, the increase in the speed of outflow currents constitutes the largest impact on these fisheries, hindering the entry of larvae and post-larvae into the estuary and affecting the life cycles of these species.

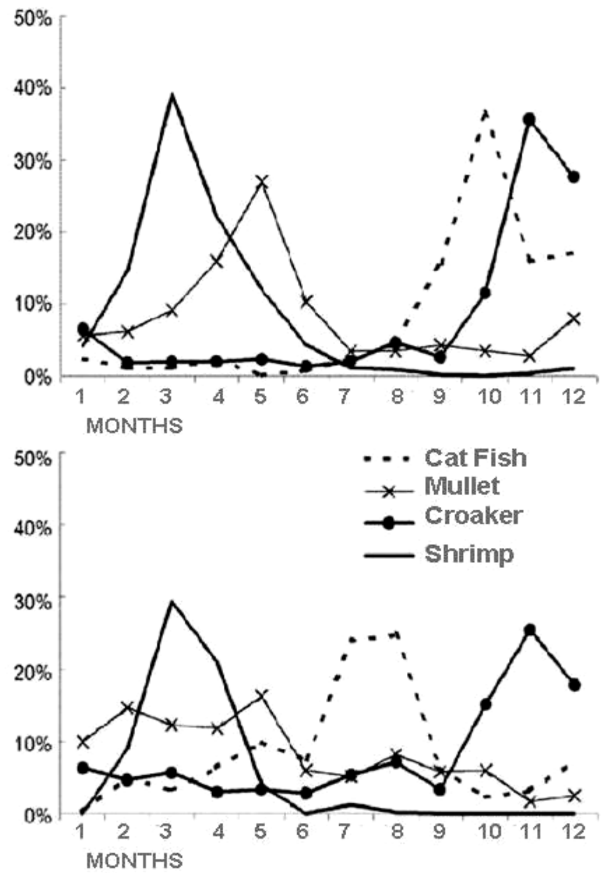

Figure 8. Calendar of artisanal fisheries in the 1960s (above) and 1990s (below). The lines represent the proportion of the total catch in each month (Haimovici *et al.* 2006).

Sedimentation rates

Toldo *et al.* (2006) have demonstrated that the sedimentation rate of the Patos Lagoon had increased from 5-11 times over the past 150 years. Suspended material that is transported by water increases the turbidity of the water column, reducing light penetration and, thus, impairing primary production, which is generally already at a low level in estuaries (Barnes 1974).

Visual predation by fish, such as the whitemouth croaker, is also affected by increased turbidity (Figueiredo & Vieira 2005). Turbidity reduces the visual field and acuity, thus undermining a visual strategy of predation. This may alter their food intake and consequently, their growth rates.

Marshes and submerged grasslands

Submerged marshes and seagrasses are the nurseries of the main fish stocks in the estuary. They provide shelter from predators, which have difficulty traveling in these densely vegetated environments.

These regions are also providers of food because they trap organic matter that is carried out by currents and retain the debris that is generated locally. They also house a whole community of benthos and plankton and even bacterial biofilms on the vegetation, which serve as food for larvae and juveniles.

Just as these environments trap organic matter, they also cause the retention of sediments. With the increase in the amount of suspended matter, sedimentation rates at these sites should also increase.

Thus, silting of seagrass meadows and marshes can occur, reducing the footprint of these highly productive areas. Copertino (2010) shows that climate change may impact the estuarine seagrass fields, reducing its area. Therefore, the “nursery” area would also be reduced, increasing mortality of the species that depend on it.

In contrast, scavenging species such as pink shrimp and grey-mullets would benefit from this condition. The nutrition of these species comes from two sources, allochthonous and autochthonous. With more material being trapped, the allochthonous amount that is available increases, so there is more food for scavengers. This could result in increased growth rates and decreased natural mortality for these species, representing a trend in the opposite direction to the previous case.

Conclusion

Climate change will have both positive and negative impacts on fish stocks in the Patos Lagoon estuary.

For the next 30 years, the main factor affecting fisheries in this region should be the acceleration of the outflow current at the mouth of the lagoon. This current will be intensified, both by climate changes and by anthropogenic actions from the occupation of the banks of the Lagoon and from work on the pair of jetties located in the mouth of the estuary.

With decreases in the age of recruitment, catch and first maturity, changes are also expected to occur in population structure and dynamics. There is also expected to be a reduction in the maximum size of specimens (L_∞) and their life expectancy. An advance in the timing and a reduction in the size of the biomass peak are also expected (Fig. 9), as are changes in migration patterns.

Importantly, no single factor can be considered totally positive or negative. Many of the effects are beneficial when analyzed from one perspective and detrimental when analyzed from others. The best example is the increase in turbidity that should affect the predatory strategy of the whitemouth croaker but will introduce more food into the system for the grey-mullet. Future, more complex models and new data may increase our level of understanding of climate change effects.

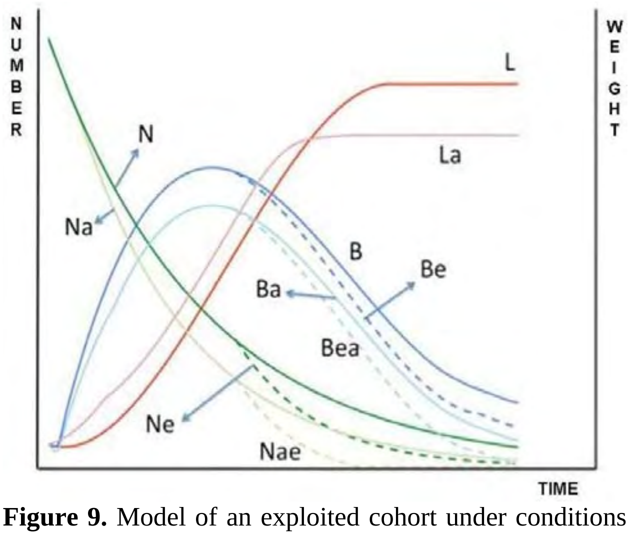

Figure 9. Model of an exploited cohort under conditions of climate change. The curve L represents the size of individual species, La the individual size with climate changes, B the biomass, Be the biomass with exploitation, Ba the biomass with climate changes, Bea the exploited biomass with climate change, N the number of individuals, Ne the number of individuals with exploitation, Na the number of individuals with climate changes and Nae the number of individuals with exploitation and climate change.

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Long-term mean sea level measurements along the Brazilian coast: a preliminary assessment

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Abstract. The main objective of this work is to present a brief historic review focused on sea level measurements along the Brazilian coast. Furthermore, it aims to describe the protocols as well as the state-of-the-art and future challenges regarding the mean sea level (MSL) estimates along the Brazilian coast. The Brazilian initiative of measuring the sea level can be grouped into two distinct periods. The first period basically involved the setup and maintenance of tide gauges, focusing on obtaining information for navigation and harbor applications, elaboration of nautical charts and altimetric surveys, which did not require accurate estimates. The second phase, from the 1990s to date, is marked by an improvement in the establishment of reference levels (either local or the Vertical Datum) and the creation of PTNG (permanent tide network for geodesy) along with more precise and accurate estimates using continuous GPS (CGPS), gravimeters and altimetry. In conclusion, it is believed that continuation of current efforts to improve MSL measurements, implementation and maintenance of a geocentric datum, use of altimetric information and incorporation of geodesic measures as well as crustal movements control, are technical approaches that allow for the development of long time-series data appropriate for application in studies regarding effects of climate change on MSL.

Keywords: Mean sea level, mean sea level measurement, tide, Brazilian coast, tide gauge

Resumo. Medições a longo prazo do nível média do mar ao longo da costa Brasileira: uma avaliação preliminar. O objetivo deste trabalho é apresentar uma breve revisão histórica focada nas medições do nível do mar ao longo da costa brasileira, além de descrever os protocolos, o estado-da-arte e os desafios futuros em relação a estimativa do nível médio do mar (NMM) ao longo da costa brasileira. A iniciativa brasileira de medição do nível do mar pode ser agrupada em dois períodos distintos. O primeiro período, envolvendo basicamente a instalação e manutenção dos medidores de maré, com foco na obtenção de informações para navegação e atividades portuárias, elaboração de cartas náuticas e levantamentos altimétricos, que não requerem estimativas precisas. A segunda fase, a partir da década de 1990 até à data atual é marcado por uma melhoria no estabelecimento dos níveis de referência (local ou Datum vertical) e a criação da RMPG (rede maregráfica permanente para geodésia), juntamente com estimativas mais precisas e exatas usando medidas contínuas de GPS (CGPS), gravímetros e altimetria. Conclui-se, então, que a continuidade dos esforços atuais voltados para a melhoria das medições do NMM, isto é, a implementação e manutenção de um datum geocêntrico, o uso de informações altimétricas e a incorporação de medidas geodésicas, bem como o controle de movimentos da crosta terrestre, se constituem em abordagens técnicas necessárias que permitirão o desenvolvimento de longas séries temporais de dados adequadas para aplicação em estudos sobre os efeitos das alterações climáticas no NMM.

Palavras-chave: Nível médio do mar, medida de nível médio do mar, maré, costa brasileira, marégrafo.

Introduction

The mean sea level (MSL) is defined as the average of the daily oscillating processes of rise and fall of tides and all the disturbing processes associated with the meteorological effects and seasonal cycles (Pugh 2004). Understanding the factors that influence MSL are important owing to the impact an eventual rise or fall of sea level may have on human activities, especially on continental borders. To evaluate MSL, a multidisciplinary approach comprising several oceanic and atmospheric processes of different spatial and temporal scales like termohaline processes, currents, long waves, meteorology, atmospheric pressure, wind curl, evaporation, precipitation, river discharge, crustal movements, tides, glaciology and eustatic changes, is required (Lisitzin 1974). Any possible change in one or more of these processes has the ability to deform the marine surface and thus, change the sea level (Dalazoana 2005).

According to the 4º Report of Assessment of the Intergovernmental Panel on Climate Change (IPCC 2007), the main processes affecting the oceans in a scenario of global warming are seawater thermal expansion and melting of ice caps. According to the report, the MSL derived from tide gauge records on a global scale during the last century points toward a gradual rise in sea level, and the projections for the current century indicate an average elevation of approximately 1.7 mm year^{-1}. Despite being one of the main causes of MSL elevation, thermal expansion of oceans is too complicated to be measured. Different features respond in different ways to thermal expansion in an eventual warming. For example, when tropical sea surface water is heated, it will expand more easily than the deep cold waters (Pugh 2004). According to Houghton (2004), if the first 100 m of the ocean, with an average original temperature of 25ºC, show a temperature increase of 1°C, then the local depth will increase by 3 cm. However, the first 100 m of the ocean include the mixing layer, a stratum susceptible to atmospheric changes, which makes it difficult to estimate thermal expansion. Thus, to calculate the increase in MSL, it is necessary to use oceanic-atmospheric coupled models. Some results from these models show a gradual increase in ocean volume as a consequence of the observed increase in atmospheric temperature since the last century (Pugh 2004). The sea level rose at a rate of approximately 0.3-0.7 mm year^{-1} in the last century (IPCC 2007), and has increased from 0.6 to 1.1 mm year^{-1} during the last decade.

Accurate measurement of sea level to the order of millimeters is a challenging task, mainly due to the technological dependence of instruments and techniques used over the years. There are two methods for measuring sea level: direct and indirect. Direct measurement is performed *in situ* using metric ruler, tide gauges, reference levels, etc. In contrast, indirect measurement involves the estimation of sea level from altimetry using satellites.

In Brazil, the first measurements of sea level using tide gauges started toward the end of the 19th and the beginning of the 20th century, under the responsibility of the Navigation and Hydrographic Bureau (DHN). These estimates were reserved for use on harbor applications to obtain tidal components, and/or for the elaboration of nautical charts. Majority of the *in situ* measurements lasted for no longer than a lunar month, covering one spring and neap tide.

The main objective of this work is to present a brief historic review focused on the sea level along the Brazilian coast. In addition, it is intended to describe the protocols as well as the state-of-the-art and future challenges regarding MSL estimates along the Brazilian coast. It is important to point out that this work is focused on the long-term absolute sea level measurements, and not on the relative sea level within the scale of decades, which is used in engineering surveys with local application.

Materials and Methods

Equipment and protocols for measuring MSL

Sea level mensuration can be carried out directly and indirectly. The method is considered to be direct when the equipment is installed *in situ*, like the tide stakes and tide gauges. As these methods are relatively cheap, easy to handle and do not require sophisticated technology, they were initially used to assess the MSL. Indirect method of sea level measurement makes use of altimetry satellite estimates and represents a new technology (in use since the 1990s) as well as a more accurate technique than the direct estimates. Nevertheless, both the methods have their advantages and disadvantages, and the readers are referred to the reports by UNESCO (1985, 1994, 2002, 2006) for further information.

In Brazil, direct estimates are generally used to measure sea level. Nowadays, the two most common and recommended tide gauges are the float tide gauge and the radar tide gauge. The float tide gauge is basically a weight floating inside a tube immersed partially in water. The tube prevents the float from moving under the action of winds and waves for short periods. The float keeps itself linked to a cable and one pulley. When the cable is displaced on the pulley, an encoder transforms this movement into a measurement of sea level oscillation. Despite the equipment being simple to install and widely used, it is susceptible to many errors, such as sedimentation in the installation site, biological encrustations and crustal movements. The radar tide gauge is a new technology recently applied in Brazil. The main advantage of this system is its installation (it is located outside the water) and thus, is not susceptible to temperature and density oscillations. It measures the distance between the air–sea interface and the equipment through an acoustic signal. However, a major disadvantage of this system is the energy demand in case of use in long-term research.

Protocols for measuring MSL using tide gauges

Since tide gauges are being currently used in Brazil to measure MSL, we will further discuss the protocols associated with this technique.

The choice of system to measure sea level depends mostly on the purpose for which the data is to be used. Aspects such as costs, accuracy, location and duration of measurements must be taken into account to make the best decision possible. For example, harbor operations demand an accuracy of about 0.1 m (Pugh 2004). Hence, there is no need of the equipment to be sophisticated and a low cost tide gauge may be used accordingly.

Scientific studies focusing on MSL, on the other hand, require a more accurate estimate of about 0.01 m. In this case, the installation must have an adequate number of reference levels (RRNNs) to monitor possible changes in the ruler(s) position, to carry out a topographic–geodesic monitoring of the reference levels and tide gauges, besides a digital data record (Fig. 1). These items will be discussed later.

Nevertheless, once the choice is made, it is essential to follow its basic recommendations accordingly to obtain a valid and useful measurement.

The use of metric ruler is the simplest way to measure sea level. Despite being quite susceptible to positioning mistakes, it is still used as a calibration reference to verify and/or correct eventual vertical displacements of already installed tide gauges.

Tide gauges are relatively simple to install, widely known and do not require sophisticated technology to operate. However, there are many errors and some disadvantages associated with them. For example, they are for local use (i.e., the information is restricted to the point being sampled), are subject to operational errors (e.g., biological incrustation), crustal movements, meteorological factors, geographic positioning of the levels' references, etc.

There are many types of tide gauges. They can be classified, for example, according to the physics employed to obtain the information. The readers can refer to UNESCO (2002) for a complete list of tide gauges and their operating systems. To ensure accuracy of results, all of them commonly follow the same basic installation requirements. Any measurements of height should have a reference level relative to that plane. A reference plane is well defined locally on a stable surface, free of any influence of vertical and horizontal movements,

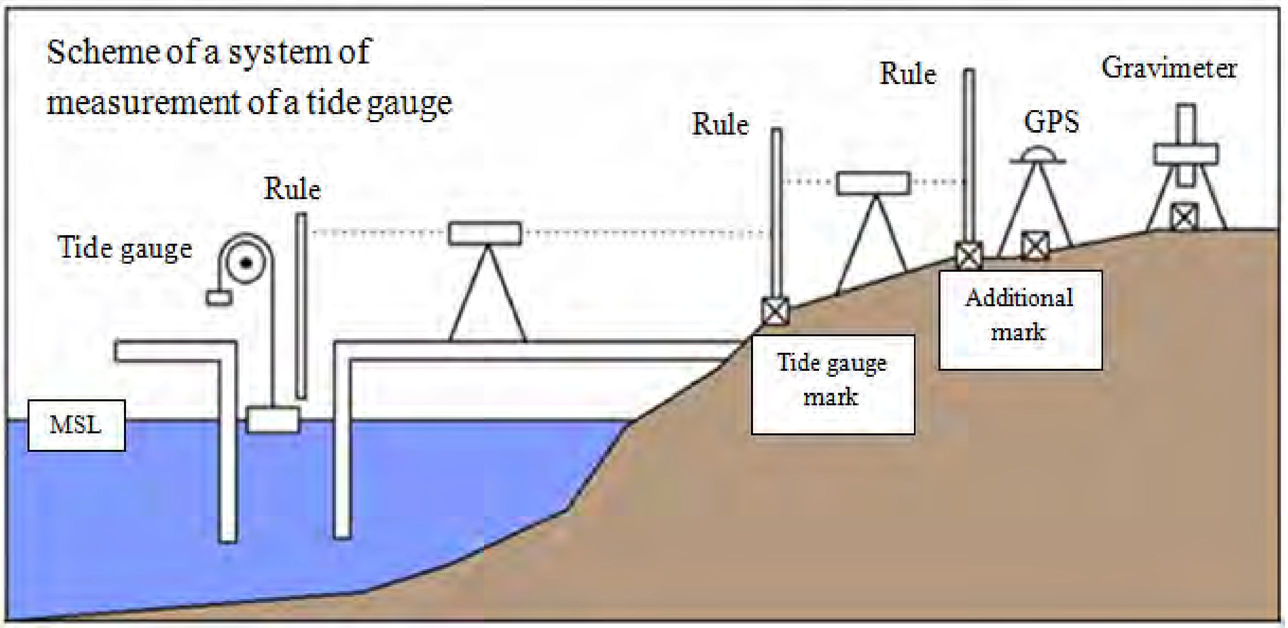

Figure 1. Scheme of the system of measurement using a tide gauge. Adapted from UNESCO (2002).

erosion, sedimentation, weathering, etc. Usually, a rock is used as a stable surface. When greater accuracy is required, or even for safety reasons in case one or more of them are destroyed, it is strongly recommended to use more than one reference plane (three, at least; UNESCO 1985). These local RRNNs are called Local Fixed Datum. Having more than one reference level guarantees the long term stability of a sea level time-series. In Brazil, the majority of tide gauges in operation are located in the harbor zones that are currently expanding their installation areas, and hence, it is quite possible to have some of the RRNNs destroyed during this process. The main disadvantage of this system (having multiple RRNNs) is that it is susceptible to crustal movements that may cause errors to the order of millimeters. Such errors must be removed using continuous GPS (CGPS) and gravimeter information if the data is to be used in studies regarding MSL variation due to climate change. CGPS is a GPS that records information continuously so that one can infer horizontal and vertical crustal movements.

The local datum RRNN should also be referenced to the Vertical Datum. The Vertical Datum can be defined as a standard mark to which any height measurement over the national territory is referenced.

According to UNESCO (1985), the local-depth tide gauge installation site should be at least 2 m below the surface in a low-tide regime. Estuaries, promontories, straits, and low-tide impoundment zones should, if possible, be avoided. Besides the RRNNs, the tide gauges should also have their own reference surface level, the so-called zero tide gauge (ZTG). The ZTG is a horizontal surface that indicates the mark zero. This mark can be any point located below the equipment. Table I summarizes the basic procedures that must be taken into account when a sea level measurement system based on tide gauges is set up. The readers are referred to the reports by UNESCO (1985, 1994, 2002) for more detailed information.

Results

The Brazilian initiative of measuring MSL

The first sea level measurements date back to the beginning of the last century, between 1910 and 1920, under the responsibility of DHN and INPH (National Institute of Hydrologic Research). Initially, the focus was toward navigation and harbor applications, elaboration of nautical charts and altimetric surveys (Neves 2005). After the creation of Portobras (Brazilian Harbor, or 'Portos Brasileiros'), the INPH became responsible for the installation and maintenance of all the equipment installed in harbors.

Over the decades, a total of 281 sites throughout the Brazilian coast, and a few offshore ones, were sampled (Fig. 2). Most of the sampling did not last for more than a month and were carried out during the 1970s. As described earlier, the data were used on specific applications, mainly harbor activities, and determination of tide components and amplitude.

Almost simultaneously, another set of information about the MSL was used to establish the Brazil Vertical Datum. Between 1919 and 1920, the extinct Brazilian General Chart Commission operated a tide gauge in the city of Torres in the Rio Grande do Sul state.

Despite the fact that such information no longer exists, those observations were referenced to a geodetic mark of the Geographic Service Board (or

Table I. Basic procedures to be considered when a tide-gauge sea level measurement scheme is set up. Adapted from UNESCO (1985, 1994, 2002).

Characteristic	Description
Installation	Locals of strong erosion, sedimentation, and hydrodynamics must be avoided
Reference levels	At least 3, arranged radially
Rules	Should be used for calibration and operational control purpose
Vertical Datum	All the RRNNs should be referenced to the Datum
CGPS	The equipment should be used for continuous monitoring of tide gauges' positions
Topographic–gravimetric control	It should be used to monitor the gravitational field of the installation site
Data records	Must be digital
Sampling	At least hourly, although high-frequency sampling is recommended
Physical protection	Built around the tide gauge to prevent damages
Accuracy	Minimum 0.01 m (Scientific studies)

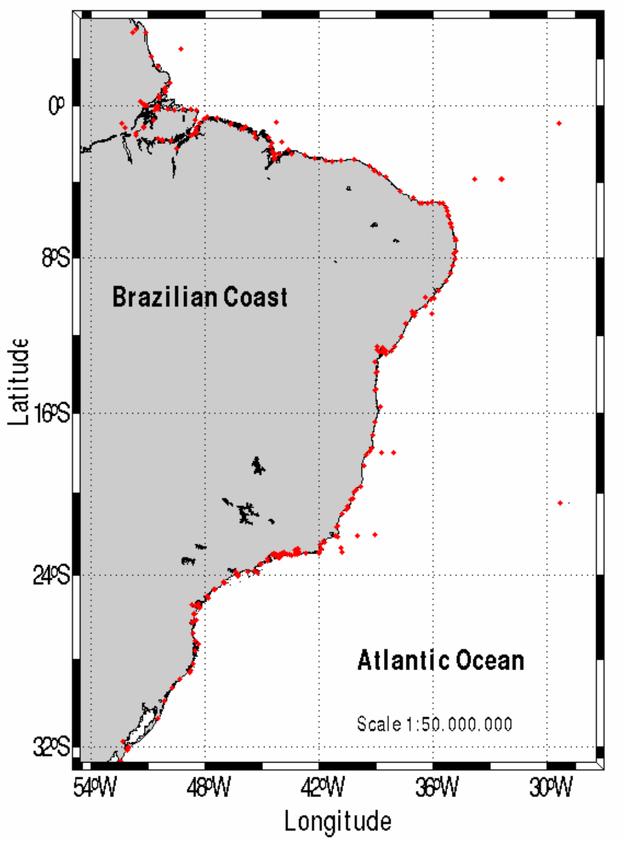

Figure 2. Geographic distribution of sites where tide-gauges measurements were carried out during the last century (red dots). Adapted from FEMAR (2000).

'Diretoria do Serviço Geográfico – DSG'), which was included in a new research leveling line between the city of Criciuma (Santa Catarina state) and Torres. As a result, a provisory Vertical Datum, called Torres Datum, was established. The determination of Vertical Datum had already attracted the attention of the Brazilian Geodesy System (SGB). Consequently, the Altimetry High Precision Net (or 'Rede Altimétrica de Alta Precisão – RAAP'), created in 1945, opted to establish the Datum of Torres, which marks the origin of all altimetric measurements. Thereafter, the Geographic National Council (presently, Brazilian Statistic and Geography Institute – IBGE) began proceedings to connect the RAAP datum with the several tide gauges spread along the Brazilian coast. In 1952, the first geographic readjustment of the Datum of Torres was established. By that time, more than 5000 RRNNs had been set near the Brazilian tide gauges. In 1959, the last readjustment of the Datum took place when it was moved definitely to the city of Imbituba (Santa Catarina state). The new Vertical Datum – Imbituba Datum – was carried out by the Inter-American Geodetic Survey after 9 years of observations, extending from 1949 to 1957. According to Franco (1988), the minimum recommended duration is 19 years. In the following decades (especially after 1970), there was a northward and mainland expansion regarding the establishment of RRNNs referenced to the Datum of Imbituba.

By the year 1960, a number of important tide-gauge stations with long data set records began to be deactivated. Recognizing the importance of having continuous and detailed records of sea level, in 1976, the IBGE considered the possibility of reactivating the tide gauge stations that were previously under the responsibility of IAGS. Between 1980 and 1986, the IBGE realized some re-evaluation of the Imbituba Datum. In 1993, the IBGE began to monitor sea level using tide gauges. This was done experimentally at the 'Estação Maregráfica Experimental de Copacabana', and lasted for one year when the gauge was destroyed by a storm surge. After a year of observation, it was concluded that sea level variation could be biased owing to instrumental deviation and vertical motions of the RRNNs.

In 1994, the IBGE took over the conventional tide gauge located at Porto de Imbetiba in the city of Macaé (Rio de Janeiro state) from Petrobras. Based on previous experience, IBGE upgraded the station, that is, employed measurement redundancy by operating two tide gauges with distinct principles of functioning, to avoid lack of information due to instrument failure. In addition, by upgrading the method of data storage, it was possible to make the information available in real time. As a result, the Macaé station has become a pilot station for the future Permanent Tide Network for Geodesy (PTNG) (or 'Rede Maregráfica Permanente para Geodésia – RMPG').

The PTNG was created in 1997 with a clear picture regarding the location of tide gauges. The locations chosen were in the following cities: Imbituba (Santa Catarina), Macaé (Rio de Janeiro), Salvador (Bahia), Fortaleza (Ceará), and Santana (Pará). The network became operational effectively from 2001, after the installation of digital equipment in Macaé and Imbituba.

The main goal of this network is to provide information to correlate the Datum of Imbituba with other sea level (tidal) references. The demand for such information was made clear in a study carried out by Alencar (1990). In his study, the author compared the local MSL with that referenced to the Datum of Imbituba (Table II).

Table II. MSL discrepancies between that measured locally and the reference level transported mechanically by geometric operations from Imbituba (SC). Adapted from Alencar (1990).

Tide gauge stations	Gap
Torres (Rio Grande do Sul)	+0.0584
Itajaí (Santa Catarina)	+0.1399
Paranaguá (Paraná)	+0.0010
Rio de Janeiro (Rio de Janeiro)	+0.1237
Vitória (Espírito Santo)	+0.2840
Fortaleza (Ceará)	+0.2923
Belém (Pará)	+0.8808

Positive values indicate that the local MSL is above the MSL referenced to Imbituba. According to Alencar (1990), the differences were accounted for by the errors in measuring sea level locally as well as by the instrumental, operational and gravimetric errors associated with the procedure of transporting the reference from Imbituba. Other causes may be due to meteorological and oceanographic factors, such as sea-surface temperature and salinity, and the lack of accurate information about MSL.

To achieve the main PTNG goal, it is necessary to repeat the leveling operations between stations using gravimetric information, and control the horizontal and vertical movements using CGPS estimates. These procedures will allow for a meticulous determination of the tide-gauge RRNN altitude as well as help in identifying the crustal movements, because any movement introduces error in the MSL estimates.

The PTNG is also a part of the SIRGAS Project (Reference System to the Americas (‘Sistema de Referência para as Américas’), a study that began in 1993. The project aims to define a unique reference system for the whole of South America, to establish and maintain a reference network among the South American countries, as well as to define a geocentric Datum. The readers can refer to SIRGAS (1997) for more details about the project.

Until 1993, every measurement assigned to the Datum and to the RRNN were (and most, or all, of them still are) topocentric. According to Freitas *et al.* (2002), the geocentric positions of the tide gauges serve as an initial condition to associate the MSL with global geoids. Thus, the contribution of SIRGAS to the studies on MSL comprises producing accurate positioning of the tide gauges and RRNNs, and their respective referencing to the new geocentric Vertical Datum.

The MSL topography, defined as the distance between the MSL and the geoid, should always be used to correct the tide gauge observations (Luz *et al.* 2008). The MSL topography results from the almost continuous action of many meteorological and oceanographic factors active on the sea surface, mainly on the shallow coastal regions. Thus, it is necessary for each tide gauge station to determine a specific value for the MSL topography, which was not possible until after 1995, making it difficult to correlate the MSL of the Vertical Datum region with that measured by the tide gauge stations along the coast. The technology that enables accurate estimates of MSL topography is altimetry satellite. The altimetry information was available since after the launch of a Franco-American mission carrying the TOPEX/Poseidon (T/P) sensor in 1992 (Dunbar & Hardin 1992). In 2005, the T/P mission finished its operations, when it was substituted by the Jason-1 satellite, launched in 2001. Despite the importance of the altimetry satellite in determining MSL topography, the estimates along the coastal regions are subject to some atmospheric and geophysical corrections of low accuracy. Nevertheless, Bosch & Savcenko (2007) used T/P and Jason-1 observations between 2002 and 2005 to estimate MSL topography in global coastal areas, using one-dimensional spectral filtering. Luz *et al.* (2008) applied the same methodology to the south-southeast Brazilian coast, with the purpose of solving the problem of integrating the RMPG results with the RRNNs. The results obtained showed some problems in estimating the MSL topography, mainly due to the spatial extension of the filter used to make the satellite and geoid model estimates compatible. However, the authors suggested a further study using the EGM-2008 (Earth Gravitational Model – US – National Geospatial-Intelligence Agency – NGA) model, which allows for a better spatial resolution of the geoid model in shallow waters. Matching deep-water sea level estimates and in situ tide gauge measurements, obtained along the satellite tracks, is also one of the objectives of the PTNG.

Present state of sea level measurements along the Brazilian coast

During the last century, some effort has been made to collect sea level information along the Brazilian coast. This aspect has been briefly reviewed in the previous section. Unfortunately, the majority (if not all) of the tide gauges, once active, are either not operational or have been destroyed. An exception is the Cananéia station, where the time-series is more than 50 years long. According to Pirazzoli (1986), who analyzed the data of long-term variations of MSL measurement from a data set available in the Permanente Mean Sea Level Institute (PMSLI), the rate of variation of the MSL followed a period of 20 years. Hence, the studies on long-term tendency should have at least 50 years of data.

Presently, according to their own needs for such information, universities, private institutions (industries), and public institutions or agencies (e.g., IBGE, INPE – Space Research National Institute, CHM – Navy Hydrographic Center) are (or are starting to) conducting long-term in situ sea level measurements. As a result, the effort of measuring sea level seems to be pulverized and uncoordinated, and it is not uncommon to observe gaps or discontinuity in the sea level time-series. Table III presents the active or planned (yet to install) tide gauges along the Brazilian coast and oceanic islands, and Figure 3 shows their spatial distribution. It is important to point out that a majority of the already-active stations shown in Figure 3 have not been planned for sea level change studies owing to climate change.

Table III. GLOSS-Brazil stations (Global Sea Level Observing System). Adapted from CHN (2009). Stations marked by * are part of the PTNG program.

Station	Responsible	Situation	Expected situation in 2010	Observations
Rio Grande (Rio Grande do Sul)	FURG-CHM	To be installed	Yet to be installed	Radar tide gauge
*Imbituba (Santa Catarina)	IBGE	Operating	Operational	Pressure tide gauge since 2001, CGPS from Dec 2006
Cananéia (Santa Catarina)	IOUSP	Operating	Operational	Radar tide gauge
Ilha Fiscal (Rio de Janeiro)	CHM	Operating	Operational	Radar tide gauge, conventional tide gauge (backup)
*Macaé (Rio de Janeiro)	IBGE	Operating	Operational	Pressure tide gauge, since July 2001, no CGPS station
Barra do Riacho (Espírito Santo) / Transfering to Vitória (Espírito Santo)	PORTOCEL/ VALE	Under test	Operational	Pressure tide gauge
*Salvador (Bahia)	IBGE (CHM)	Operating (under evaluation)	Operational	Radar tide gauge since Apr 2008; CGPS from Apr 2007; data transmitting in real time through satellite
*Fortaleza (Ceará)	IBGE	Operating (under evaluation)	Operational	Radar tide gauge since Apr 2008; CGPS from Oct 2008; data transmitting in real time through satellite
Ponta da Madeira (Maranhão)	Vale	Operating	Operational near real-time automatic data transmission	Conventional tide gauge, radar to be installed
Ilha da Trindade (Espírito Santo)	INPE-CHM	To be installed	Under evaluation	Radar tide gauge to be installed in 2010
Fernando de Noronha (Pernambuco)	INPE-CHM	To be installed	Under evaluation	Radar tide gauge to be installed in 2010
Arquipélago de São Pedro e São Paulo (Rio Grande do Norte)	INPE-CHM	Installed in 2008 (under test)	Operational	Radar tide gauge; data transmitting in real-time through satellite
*Santana (Pará)	IBGE	Operating	Operational	Radar tide gauge since Dec 2007; CGPS from July 2008

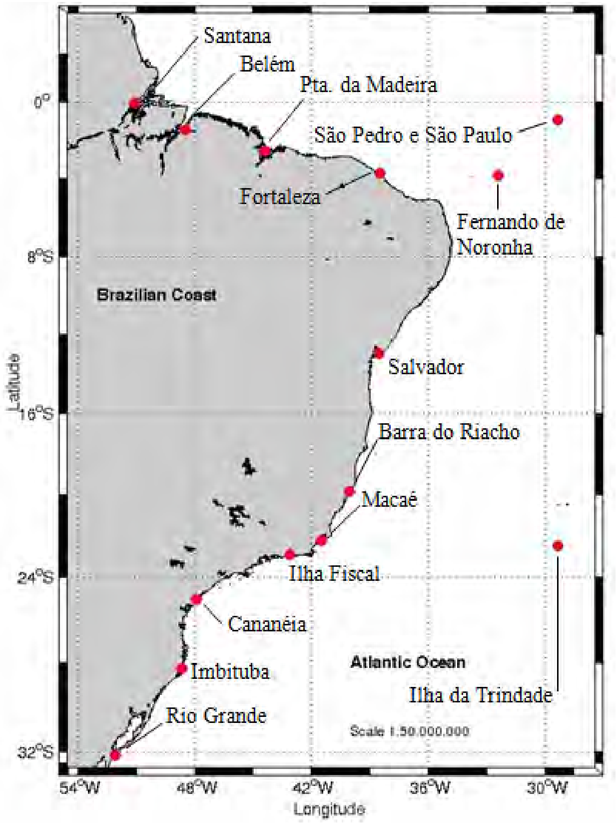

Figure 3. Location of the tide gauge stations along the Brazilian coast (red dots) included in the GLOSS-Brazil Program.

Discussion

In the Brazilian context of sea level measurements, two distinct periods can be established. The first basically comprised the setup and maintenance of tide gauges, focusing on obtaining information for harbor purposes, which did not require accurate estimates. This period ended by the late 1980s. The second phase that spans to date is marked by an improvement in the establishment of reference levels (either local or Vertical Datum) and the creation of PTNG for more precise and accurate estimates using CGPS, gravimeters and altimetry.

Although there are many tide gauge stations distributed along the Brazilian coast, a majority of them do not have an associated time-series of more than 10 years. Time-series longer than 30 years are restricted to the stations of Cananéia (São Paulo state) and Ilha Fiscal (Rio de Janeiro state). From the 1990s, these stations started implementing a topographic–geodesic control and installed digital equipment like the CGPS, covering a relatively short period of accurate data compared with the period when tide gauges were operational. The available time-series is shorter than that stipulated to study the impact of climate change on MSL. Douglas (1991) and Pirazzoli (1986) affirmed that the time-series should be of at least 50 years duration, to draw any specific conclusion regarding the sea level change.

Despite the results obtained by Douglas (1991), there have been some studies focused on evaluating the tendency of MSL along the Brazilian coast. França (1995) used tide gauge information from 1950 to 1990 from some Brazilians stations (Belém-Pará, Salinópolis- Pará,, Fortaleza-Ceará, Recife-Pernambuco, Salvador-Bahia, Canavieiras-Bahia, Rio de Janeiro-Rio de Janeiro, Ubatuba-São Paulo, Cananéia-Santa Catarina, and Imbituba-Santa Catarina) to verify the trend of MSL elevations. He found the tendency of elevation to be approximately 4 mm year^{-1} or about 50 cm century^{-1}.

Furthermore, the work carried out by Aubrey *et al.* (1988) also used the information from tide gauges to estimate MSL oscillations on the Brazilian coast, and concluded that the national tendency is of elevation. Both studies represent the first attempt to estimate the MSL changes along the coast. However, as stated previously, the information used in these studies had neither topographic–geodesic control nor correction from CGPS to eliminate the possible vertical and horizontal displacements of the crust.

Two problems can be associated with the current implemented system of using tide gauges for measuring sea level based on climate changes. The first problem is the use of different tide gauges along the coast (distinct physical principles of measurement); they might have different sampling rate and/or methods of digital record. Furthermore, the use of CGPS and gravimeter, the errors associated with the leveling using different techniques and the incompatibility of data from different types of equipment (cannot be used statistically) also pose a problem. Neves (2005) reported that to maintain a long-term MSL measurement, a rigorous assessment of the internal monitoring network, identification of the operation and its responsibilities, and a solid organization to maintain the network operation to continue data assimilation along the years are necessary.

The second problem is related to the maintenance of the station (which demands long-term financial support to maintain the functioning of the network), the control and processing of the data collected and its availability to the general public. These two aspects may be the cause of gaps in the historic time-series and the lack of sufficiently long sea level time-series to be used in studies regarding the impact of climate change on MSL.

Despite the efforts made by IBGE, CHN and other universities since the 1990's to obtain sea level data, Brazil is still in the early stages of developing a safe, precise, accurate and long-term sea-level time-series according to the standard protocols. An important initiative to create a realistic network for monitoring MSL is the Fluminense Tide Gauge Network (or 'Rede Maregráfica Fluminense – RMFlu'). This network was created in 1995 to control and support MSL measurements in Rio de Janeiro state. Currently, several organizations and institutions, like COPPE/UFRJ (Federal University of Rio de Janeiro), IBGE, Petrobras, DHN, CHM, IEAPM (Marine Research Institution Almirante Paulo Moreira) and Electronuclear S.A., constitute the RMFlu.

Nevertheless, the most recent and complete collection of MSL information and observations is included in the GLOSS-Brazil Program and PTMG project. According to the Marine Hydrographic Center (CHM-DHN), currently, only the tide gauge station of Imbituba (since December 2006), Cananéia (since January 2006), Salvador (since April 2007) and Fortaleza (since October 2008) have the CGPS installed and none of the GLOSS-Brazil stations have a gravimeter installed (Table III). In addition, they are mostly of the conventional (float) and pressure type. However, some stations like the stations of Ilha Fiscal, Cananéia, Vitória, Salvador, and Fortaleza, use the radar technology. Only two of the sites shown in Figure 3, Salvador and Fortaleza, have their measurements available online (data can be accessed on www.vliz.be/gauges). Most of the other stations have their information supposedly continuously uploaded (gaps in the records are common) to the international data centers like UHSLC (University of Hawaii Sea Level Center) and PSMSL. Finally, the application of altimetry technology on coastal regions is fundamental to studies regarding MSL changes since a geocentric Datum has to be used as the reference for MSL measurement.

Conclusion

Owing to the inconsistency of the local data distributed along the coast in relation to the Brazilian Vertical Datum, most of the tide gauge measurements carried out along the coast are not strictly accurate. This is because of the absence of accurate MSL topography estimates in shallow water regions. In addition, the fact that most of the MSL time-series do not have CGPS and gravimeter measurements (only recently, some stations have installed a CGPS) and the absence of a central organ responsible for managing the implementation, control and maintenance of the tide gauges, contribute to the current scenario where Brazil is still not able to precisely inform the impact of global warming on MSL. Hence, it can be concluded from the present work that these two aspects are the primordial issues that should be addressed. Nevertheless, it is believed that the continuity of the current efforts to improve MSL measurements, the implementation and maintenance of a geocentric Datum, the use of altimetric information, the incorporation of geodesic measures, as well as the control of crustal movements are approaches that allow for the development of long time-series data that can be applied to studies on the effects of climate changes on MSL.

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Vulnerability and impacts related to the rising sea level in the Metropolitan Center of Recife, Northeast Brazil

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Abstract. The Metropolitan Center of Recife figures as one of the most vulnerable regions to a rise in sea level along the Brazilian coast, due to its physical characteristics and to various problems related to flooding and coastal erosion. The analysis of potential flood zones and vulnerability assessments was based on an empirical approach, considering the estimates made by the IPCC on sea level rise and extreme scenarios of astronomical ride, storm surge and run up for the region. The results indicate that for a 0.5 m (optimistic scenario) rise in sea level, at least 39.32 km^2 of the area of the municipalities would become potential flood zones. In a scenario of critical sea level rise (1 m), this figure would increase to 53.69 km^2. Analysis of the entire coast indicates that 81.8% of urban constructions situated less than 30 m from de shoreline and located 5 m below ground level would be severely affected by changes in sea level. Currently 45.7% of the coast is considered a high vulnerability area. In view of the severe losses predicted by the simulated scenarios, response strategies identifying the most appropriate adaptation options must be developed.

Key words: coastal flooding risk, sea level rise, Northeast Brazil

Resumo: Vulnerabilidade e impactos relacionados a subida do nível do mar no centro metropolitano do Recife, nordeste do Brasil. O Centro Metropolitano do Recife figura como uma das cidades mais vulneráveis ao aumento do nível do mar do litoral brasileiro, devido às suas características físicas e aos diversos problemas referentes a inundações e erosão costeira. A análise das zonas potencialmente inundáveis e da vulnerabilidade costeira foi baseada numa abordagem empírica, considerando as estimativas realizadas pelo IPCC sobre a elevação do nível do mar e os cenários extremos de maré astronômica, ressaca e run up. Os resultados indicam que diante de um aumento do nível do mar da ordem de 0,5 m (cenário otimista), é esperado que, pelo menos 39,32 km^2 da área dos municípios analisados constituam zonas potencialmente inundadas. Num cenário crítico de elevação do nível do mar (1 m), este valor aumentaria para 53,69 km^2. A análise da costa como um todo indica que os 81,8% das construções urbanas, que estão a menos de 30 m da linha de costa e em terrenos abaixo de 5 m, deverão ser rapidamente atingidos pela mudança no nível do mar atual e que o litoral possui 45,7% de sua extensão sob zona de alta vulnerabilidade. Frente aos cenários simulados, aponta-se a necessidade de um planejamento público para mitigação dos futuros impactos.

Palavras-chave: risco a inundações costeiras, elevação do nível do mar, nordeste do Brasil

Introduction

The last report of the Intergovernmental Panel on Climate Change concluded that the planet climate is unmistakably experiencing rapid heating and this is partially due to human activities (IPCC, 2007). According to this and other recent studies (Neves & Muehe 1995, Thieler & Hammar-Klose 1999, Alfredini *et al.* 2008, Snoussi *et al.* 2008, Vargas *et al.* 2008), the rising sea level scenarios for near future are of great concern. The acceleration of the rate in which the sea level rises not only raises the possibility of intensified impacts – such as coastal erosion, habitat losses and saline intrusion in coastal aquifers and rives – but could also result in complete suppression of sandy beaches and wetlands (Snoussi *et al.* 2007).

Such an impact, although felt globally, depends on local peculiarities; therefore, happens unevenly across countries, regions, communities and individuals as the result of different levels of exposure and vulnerability (Clark *et al.* 1998). Moreover, adapting coastal regions represent a larger challenge to developing countries than it does to developed ones, because of economic limitations. As an option for minimizing such effects, vulnerability and impact assessment provides a starting point for guidance in decision making for effective measures that envision impact reduction and reestablishment of initial conditions.

In Brazil, sea level trends for different places are sparing. For Recife, specifically, Harari *et al.* (2008) pointed a sea level rise of about 5.6 mm.year^{-1}. In spite of this gap, some studies have been dedicated to the coastal predictions in front of future sea level sceneries, as Alfredini *et al.* (2008), which describes islands and coastal urban areas as the most vulnerable to flooding in medium and long terms. Another study, made by Marengo *et al.* (2007) in national scale, pointed Pernambuco as one of the most affected states by the increasing on the sea level, at this moment and potentially. The same conclusion is showed by two another studies: Neves *et al.* (2007) and Naccarati (2008). According to these authors, both, natural and occupation characteristics contribute for the vulnerability of the area.

The Metropolitan Center of Recife combines low topography, intense urbanization, high demographic density, and elevated ecological, tourist and economic values (Araújo *et al.* 2009). Furthermore, it presents several conflicts in coastal land and shoreline usage, which is one of the reasons it became one of the first regions in Brazil to be the subject of integrated studies on the problems of coastal erosion, with the collaboration of several spheres of public power (FINEP/UFPE, 2008).

Within this context, the goal of this paper is to present possible scenarios for Metropolitan Center of Recife, prompted by the rise in the average sea level trend forecasted by the IPCC emission scenarios. The aim is to foresee scenarios that will raise awareness in the decision makers, as well as to point out possible strategies for minimization of potential impacts of the rise in sea level in this region.

Methodology

Description of study area

The Metropolitan Center of Recife, which covers the cities of Paulista, Olinda, Recife and Jaboatão dos Guararapes, is located on the coast of the state of Pernambuco (Fig. 1) and extends over a sedimentary plain, with an average altitude of 4 m. The region presents Tropical Atlantic climate with an average annual temperature of 27oC and annual pluviosity of around 2000 mm unequally distributed between dry and rainy periods. The wind regime is governed by the general atmospheric pressure distribution pattern of the South Atlantic Ocean, with predominance of SE winds.

The tides registered in the region are all semi-diurnal and classified as mesotidal in terms of amplitude. The largest and smallest swells occur in the months of September and January, respectively, with significant wave periods between 5.1 and 6.8 seconds. The significant wave height varies between each location, with values of 0.29/0.27 for Paulista; 0.6/0.61 for Olinda; 0.97/0.66 for Recife and 0.61/0.44 for Jaboatão dos Guararapes (FINEP/ UFPE, 2008).

The main ecosystems in this region are mangroves, fragments of Atlantic Forest, coral reefs, and restinga. The hydrographic system is well drained, with several rivers, streams and lakes. The Capibaribe River is the main watercourse.

Establishing Potential Flood Zones

The methodological steps proposed by Hoozemans *et al.* (1993), Snoussi *et al.* (2007) and Vargas *et al.* (2008) were followed, with determination of the resulting flood levels by the sum of the factors involved in the sea level rise. Therefore, the contributions of the following extreme water level-induced phenomena were simulated: maximum high water line in the last 20 years; sea level rise due to storm surge (meteorological tide plus wave run up) (FINEP/UFPE, 2008); projected sea level rise for the

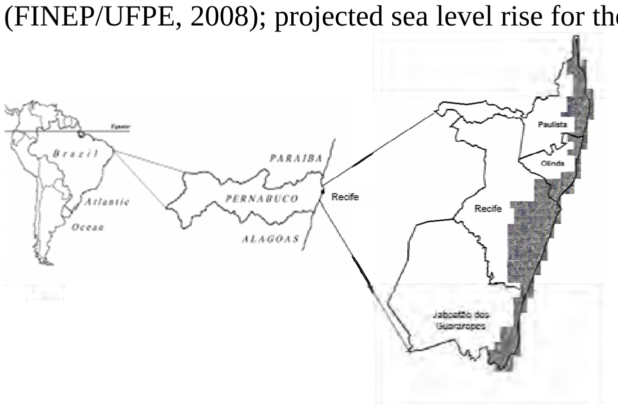

Figure 1. Location of the studied coastal area in the Metropolitan Center of Recife, Northeast Brazil.

next century (IPCC, 2007), which can be optimistic (+0.5 m by 2100, or about 5 mm·year^{-1}) or critical (+ 1.0 m by 2100, about 10 mm·year^{-1}). These scenarios were adapted from the IPCC Emission Scenarios (B1 and A2), considering that the sea level rise for the next century may be up to roughly twice the maximum projection found in this report (Rohling *et al.* 2008). Equations (I) and (II) express the empirical approach used to determine the flood levels in coastal and estuary areas, respectively.

NI = PM + MM + SLR (Eq. I)

NI = PM + SLR (Eq. II)

where NI – Flood Level; PM – maximum high tide water level; MM –Meteorological Tide (including wave run up); SLR – Sea Level Rise.

For delimitation of potential flood zones, a Geographic Information System (GIS) was used. Rectified aerial photography in a 1:2000 scale (Pernambuco, 1974) was processed in order to digitalize the flood level lines. The entire territorial portion below such levels, therefore, would potentially be flooded in similar conditions to the ones in the above modeled scenarios.

The rectified aerial photography employs the average sea level in Imbituba, South Brazil, established by the Brazilian Institute of Geography and Statistics (IBGE). According to Neves & Muehe (1995), it is located 1.106 m above the datum used by the Hydrography and Navigation Board (DHN). The values considered and the resulting levels are in Table I.

Attribution of Degrees of Vulnerability to the Shoreline

Bearing in mind that sandy beaches serve as a buffer, reducing the energy that the oceans impose to the shore, one can say that the closer the first man-made structures are to the shoreline, the higher their degree of vulnerability to the impacts of erosion and floods (Lathrop Jr. & Love, 2007). Accordingly, the degree of vulnerability was assigned based on the current capacity of the beaches of the Metropolitan Center of Recife to protect inland resources, be they economic, ecological or of cultural values.

To calculate the average distance between the maximum high water line and the closest infrastructure, a spatial analysis module available in a GIS environment was used. The line of first man-made structures was taken from UNIBASE (2002) – a cartographic base on a 1:1.000 scale – and the shoreline was obtained in situ using geodesic GPS equipment. The marker used was the High Water Line, or HWL.

Once the distances were calculated, limit values were established for each degree of vulnerability (Table II). In order to fulfill the safety conditions, beaches should not only present a backshore, but this sector should also be at least 30 m wide (FINEP/UFPE, 2008). This value was established through an estimation of the results obtained by Pajak & Leatherman (2002) and Costa *et al.* (2008) on the variation of the HWL position through time.

Analysis of the Coastal Resources at Risk

In a GIS environment, a layer containing the potential flood zones was superimposed to the layer containing occupation information. The resources at risk were divided into the following categories: wetland (mangrove and flooded areas), unoccupied land, beaches, buildings with over three floors, buildings with less than three floors and historical/cultural patrimony.

Table I. Values considered for the estimation of the levels in risk of flooding.

Scenario	Maximum high tide water level (m)	Storm surge effect	SLR (m)	Flood level (m)
Optimistic	2.7 (– 1.106)	1.0	0.5	3.1
Critical	2.7 (– 1.106)	1.0	1.0	3.6

Table II. Criteria used in the determination of the Degree of Vulnerability.

Backshore width (m)	Degree of vulnerability	Maintenance priority
Null*	Conditional	Constant maintenance
>30	Low	Moderate
<30	High	Maximum

* The high water line coincides with the first man-made structures, since there is no backshore and the shoreline was artificialized and immobilized.

Results

Establishing Potential Flood Zones

Jaboatão dos Guararapes presents the largest area among the studied cities, with 256 km^2. The area considered in this analysis was 15.45 km^2. The potential flood zone is shown in the following figure as polygons for the benign and critical scenarios (Fig. 2). The most important changes in both scenarios are seen in the areas surrounding the Pirapama-Jaboatão Estuarine Complex and also on the coastal strip positioned further south, on the Barra de Jangadas beach. Attention is drawn to Paiva Beach (Praia do Paiva), a sandy spit extremely vulnerable to the possibility of a rise in sea level. Of the 0.97 km^2 that form the extremity of the sandy spit, 0.30 km² would be left above water in a scenario with a 0.5 m sea level rise. In a critical scenario – 1m rise in the sea level – only about 0.15 km² of the initial area would be left.

It is worth while to observe that throughout practically the entire coast – except the portion in front of the Candeias beach, protected by a breakwater, and a small section of the Barra de Jangadas beach – the beach system is no longer an efficient means of coastal protection since one or more sectors have been suppressed. Nonetheless, there is still an estimated sandy beach loss of at least 13.71 m² as a result of coastal erosion

Recife is the city with lowest altitude among the ones studied here, with an average of only 4 m above sea level. As a result, in a scenario of a 0.5 m

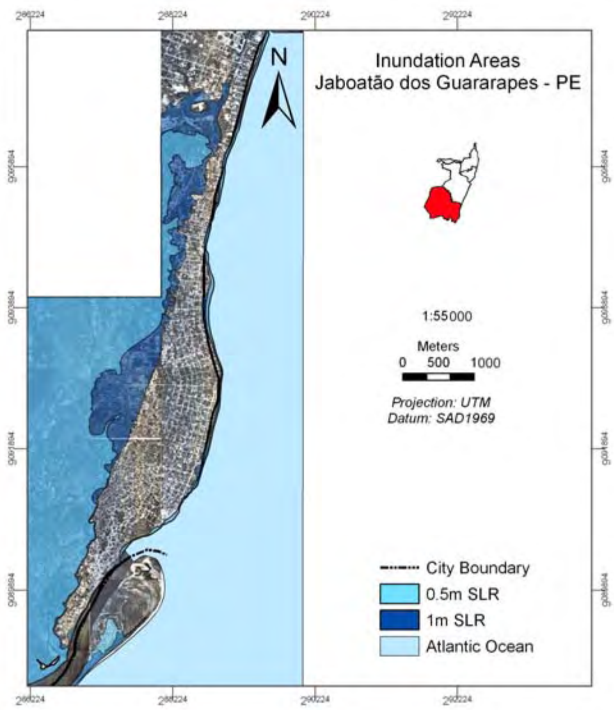

Figure 2. Potential flood zones in Jaboatão dos Guararapes.

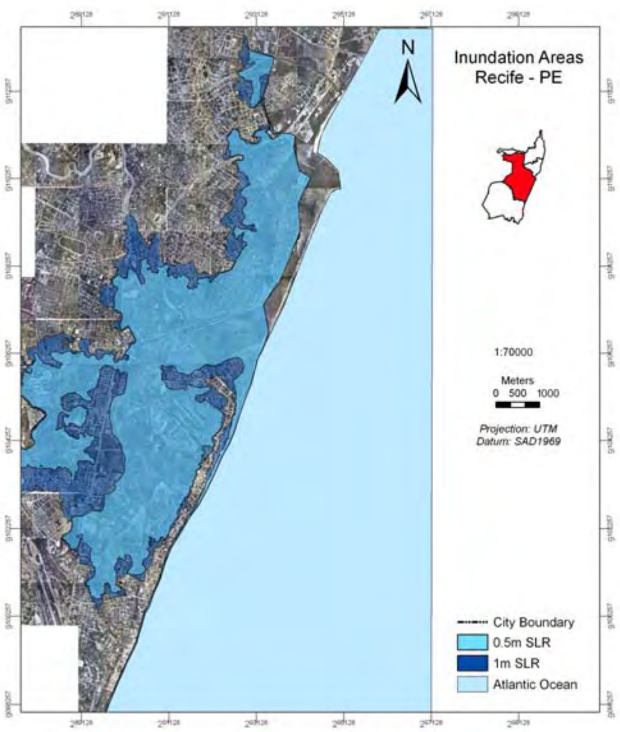

Figure 3. Potential Flood Zones in Recife.

sea level rise, it is estimated that the flooded area would amount to about 25.38 km^2; while in the critical scenario, with a 1 m rise in sea level, it would be approximately 33.71 km^2 (Fig. 3).

The city of Olinda is located on the highest average altitude among the cities studied, at roughly 16 m above sea level. Consequently, the forecast is that the most affected areas would be those situated near the city boundary with Recife, in the lowlands, bathed by the Pina Basin (Fig. 4).

According to the flood levels isolines analysis of the Del Chifre beach, better known as the Olinda isthmus, and considering a progressive flood of the spit, due to a rise in the level of flooding, there is a possibility that this sandy spit may develop insular characteristics, with an estimated area between 0.076 km^2 (optimistic scenario) and 0.069 km^2 (critical scenario). In light of the predictions for the other cities of the Metropolitan Center of Recife, this coastal strip does not present itself as an area highly prone to flooding. However, the coast of Olinda presents a severe and historical erosive process, with a noteworthy part of its extension (around 59%) impermeabilized by coast defense projects, which hinder the limited capacity of its beaches to act as protection zones for resources located inland.

The city of Paulista presents the most extensive coast among the cities in this study. It is limited to the North and to the South by the Timbó and Paratibe River estuaries, respectively. With a total area of 94 km^2, approximately 26.53 km^2 were analyzed (coastal and estuarine areas). The potential flood zones in the city are shown in figure 5.

Vulnerability Analysis

Generally speaking, the beaches of the Metropolitan Center of Recife would be severely affected in case of a sea level rise. An analysis of the entire coast indicates that 81.8% of urban constructions are less than 30 m from the shoreline. Comparatively, only small portions of the coast present a beach system little affected by adjacent development. Jaboatão dos Guararapes stands out in this sense, presenting 36% of its coastline with low variability. Olinda presents the most critical scenario, where 59% of the coast no longer has recreational beaches and the integrity of the urban development depends exclusively on coastal protection projects (Fig. 6).

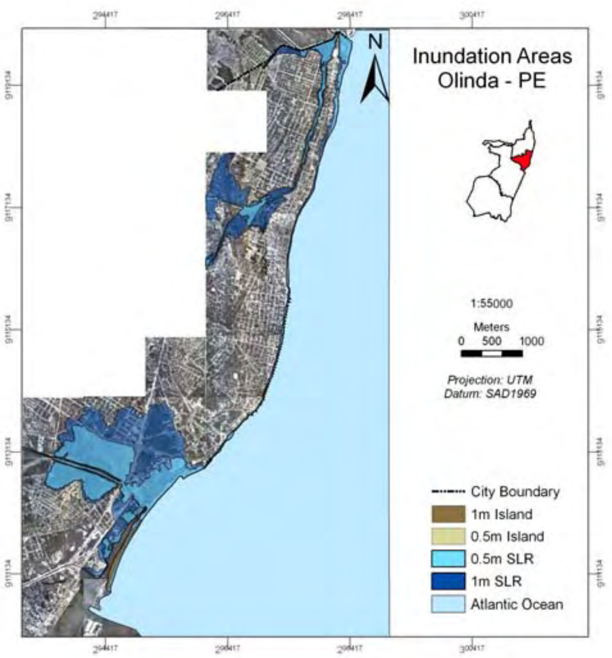

Figure 4. Potential flood zones in Olinda.

Analysis of Resources at Risk

Types of land use and the area (in m^2) of the affected resources in the cities studied are represented in figure 7.

For the city of Jaboatão dos Guararapes, in an optimistic scenario, the relatively pristine areas – unoccupied and beach areas – would suffer the greatest impact. On the other hand, in a critical scenario, the areas with buildings of cultural and historical interest would amount to 57% of the affected resources, exceeding the sum of vulnerable beach and unoccupied areas.

In the case of an overwash, there could be damage to historical and cultural patrimony such as an important culture and leisure center (SESC) and the Nossa Senhora da Piedade Church, both located on the Piedade Beach. This patrimony is vulnerable in both scenarios, optimistic and critical.

In Recife, the large area with buildings with less than three levels is highly vulnerable to a sea

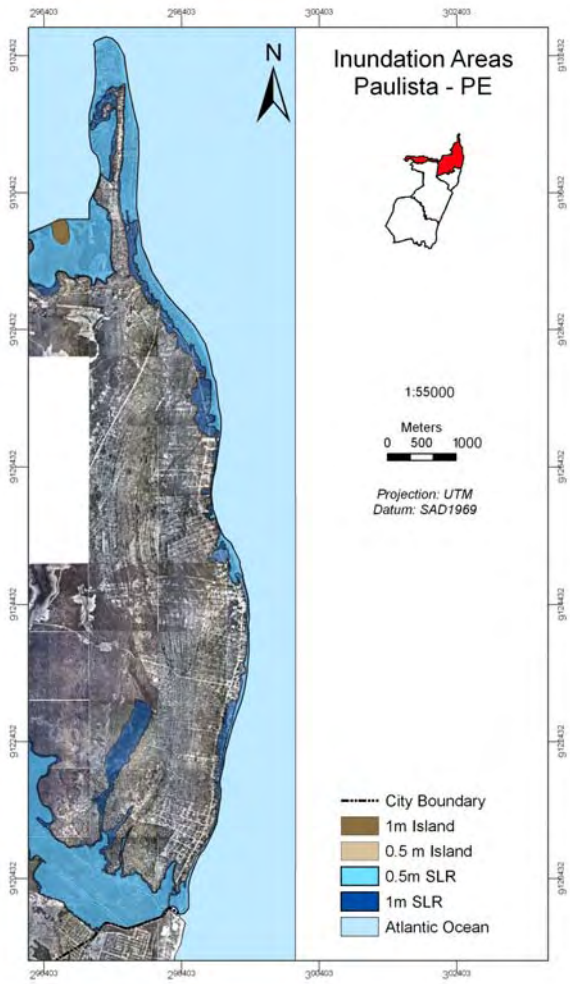

Figure 5. Potential flood zones in Paulista.

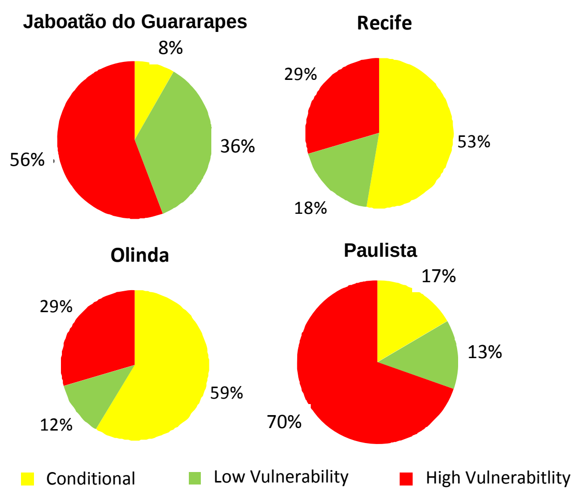

Figure 6. Areas with high, low and conditional vulnerability percentages.

level increase. From a historical-cultural perspective, we highlight the potential flooding of part of a green area of 33,000 m^2 set apart for leisure and a cultural center in the Boa Viagem neighborhood (Dona Lindu Park). In the optimistic and critical scenarios, the impacted areas would be of approximately 3,100 m^2 and 13,200 m^2 in area, respectively.

In terms of coastal resources endangered by flooding in Olinda, in an optimistic scenario of sea level increase, it was mostly the smaller constructions that were found to be at risk. In a critical scenario, though, taller buildings (>3 stories) are included in the vulnerable area.

Among the vulnerable areas of Paulista, Maria Farinha Headland demands attention since it is an area of great ecological and economic importance. From a historical and cultural perspective, Pau Amarelo Fort and a water park relevant for the tourism industry near the Maria Farinha Beach represent potentially impacted patrimonies.

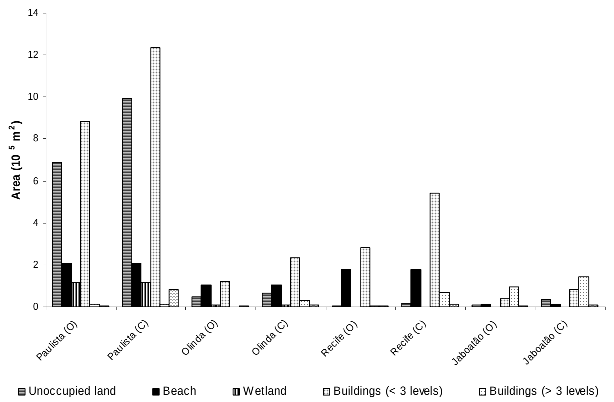

Figure 7. Resources at risk in each city for both scenarios: optimistic and critical.

Discussion

The present analysis was restricted to coastal and estuarine areas, which are the most affected by an increase in the sea level. For this reason it should be made clear that the numbers and debate here presented are underestimated and that the potential flood zones in the studied area are even greater, bearing in mind the low altitude of the terrain and vast drainage network that bathes the region and branches out to other estuarine areas.

In terms of environmental impact, we emphasize that important ecological losses may occur not only along the estuary – a rich and important ecosystem – but also to the south portion, beyond the area studied, to the Paiva Beach. This site, as previously mentioned, is a restinga rich in flowers and with typical morphological aspects, with ecological potential that justifies better protection of this ecosystem (Sacramento *et al.* 2007).

On the coast of Jaboatão dos Guararapes, the loss of beaches and damage to constructions by the shoreline, due to its exposure to the energy of the ocean, are common. For this reason, there are currently ten coastal defense construction sites along the shore, among them seawalls, groins, revetments and breakwaters (FINEP/UFPE, 2008). As mentioned previously, the shoreline of the city presents a high degree of verticalization, which increases the magnitude of the impact caused by coastal flooding.

For Recife, among the areas prone to flooding in both scenarios, attention is drawn to Recife Antigo (Old Recife). It represents an important economic and administrative center of the city with great historical and cultural value since it is the origin of the city of Recife. It is currently of great significance for cultural and artistic activities.

Attention should also be given to the fact that the largest estuarine complex in the studied area is located in the city and includes the Pina Basin, the Capibaribe and Beberibe Rivers. The Port of Recife is also located in the city. This Port, along with the Port of Suape, handles all cargo movements in the State of Pernambuco. The region has suffered flooding since the beginning of its occupation, but the intensification of the phenomenon makes an increase in the silting rate a possibility throughout the port area. This would increase the demand for dredging and would potentially be detrimental to port operations.

Although the potential flood area is narrow in the coastal strip, the intensification of the erosive process is notable, considering that there are buildings located very close to the beach, leaving little room for morphodynamic processes. As in Jaboatão dos Guararapes, the Recife shoreline presents a high degree of verticalization, to such an extent that the small area of land lost, or endangered by erosion, would imply in large economic losses and social disorganization. Additional disturbance could be implied by the fact that countless inhabitants use water extracted from the water table using wells, which could become unfeasible because of saline intrusion.

In the sandy coastal regions, it is now well-established that sea-level rise leads, in average, to erosion and consequent recession of the shoreline (Snoussi & Niazi 2007). Sea-level rise is the main cause of shoreline retreat in coastal areas under dynamic equilibrium, i.e., where the natural sand supply allows the potential and the effective littoral drift to be equal. However, on sandy shores, where this supply has been strongly reduced (as already discussed), the main cause of shoreline retreat is sediment deficiency, Ferreira *et al.* (2008). In this case, which is similar to the study area, this deficiency plays a larger role in erosion than the accelerated sea-level rise and coastal morphology and size will be mainly dependent on the direct result of human actions.

In Olinda, the flood problems are a historical inconvenience for the population. Floods are annual events in some of the main neighborhoods of the city, and are among the most distinguished environmental impacts, causing loss and disarray to the population. Some areas in this location are flooded from time to time, which damages road structures, makes the circulation of vehicles and people impractical, jeopardizes commerce and causes public health issues (Melo 2003). Anthropic causes are added to the geographic features and contribute to the intensification of the problem, such as the illegitimate occupation of freshwater swamp forests, illegal landfills in mangroves, criminal disposal of solid waste and the nonexistence of an efficient draining network.

The city, due to its historical erosion and flood problems, has a large range of coastal defense structures in place, which may provide efficient protection from the sea level rise (Neves & Muehe 1995). Presently, these structures, in addition to countless sections with hydraulic landfills, put the coastal streets in flood zones above sea level, reducing the area vulnerable to flood effects. In Paulista we can highlight the potential flooding of an area relevant from an ecological and economical point of view, the Maria Farinha Headland. On this site there is a complex estuarine system of elevated scenic attributes that have contributed to recent development of the tourism industry with the installation of marinas, hotels, inns and water park.

Generally, and in what is referred to as vulnerability assessment, the studies developed by FINEP/UFPE (2008), considering only the current erosion rate and the rate at which construction presses closer to the beach, indicate that the width of the beach tends to decrease with the passage of time. This analysis demonstrates that in most of the coastline analyzed, a significant part of the vulnerability may be related to the accelerated occupation of areas immediately inland. With the predicted sea level rise, a higher demand for shoreline protection structures is expected throughout the metropolitan coast of Recife.

Regarding the methodology adopted, the use of GIS is justified by the fact that the spatial component of climate risk is critical for building knowledge on climate risk, potential management options and challenges in local level. A range of methods is available for exploring climate risk across a landscape, however, as with any scientific assessment process, the appropriate methodology depends on the needs of stakeholders as well as potential constraints placed upon a project such as funding, time, data access and expertise (Preston *et al.* 2009).

Based on worldwide experience in policy creation, on data and recommendations of the MAI-PE Project (FINEP/UFPE 2008), and on the results given in this paper, the implementation of public policies for the protection of coastal and flood zones are suggested in two fronts: (I) expansion and consolidation of scientific knowledge of the phenomenon, since the effects of the change in the relative sea level will differ according to local characteristics; and (II) management and establishment of adaptive measures to minimize its impact. These fronts complement the suggestion of Jallow *et al.* (1996), which present the following means to deal with the problem of coastal vulnerability to the sea level rise: urban growth planning, public awareness, wetland preservation and mitigation, and coastal zone management.

Conclusion

The Metropolitan Center of Recife, due to its physical characteristics and its current erosion and flood problems, presents itself as a region highly vulnerable to an increase in sea level. Additionally, it has unfavorable social charac-teristics for responses to flooding, including high demographic density and intensified vertical growth on the coast, as well as occupation of riverside are-as. The impact associated with the relative sea level rise may intensify if relief measures are not taken.

These results comprise first an approach to the impacts caused by the combined projected changes in coastal areas in the Metropolitan Center of Recife. Since the response prediction and scenario anticipation for these areas are highly complex tasks, it is essential to obtain more funding from research foundations, institutions responsible for development of human resources and from those in charge of public policies in order to perform further research on the matter. The bigger the knowledge base and the better the prediction of the impacts resulting from climatic change, the better the plans for economic, social and environmental risk prevention will be.

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The authors wish to thank the agency Financiadora de Estudos e Projetos (FINEP/MCT) and the Recife, Jaboatão dos Guararapes, Olinda and

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Temporal changes in the seaweed flora in Southern Brazil and its potential causes

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Abstract. The anthropogenic activities in recent centuries have led to atmospheric changes that directly influence the climate, resulting in global warming. Coastal ecosystems are subjected to global threats by their sensitivity to chemical and physical characteristics of seawater and seaweed communities are considered good indicators of environmental changes. This study aimed to evaluate changes in the seaweed flora at Ribanceira Beach (Santa Catarina state, Southern Brazil) by comparing recent to past data (30 years apart), motivated by the possible effects of climate change in this subtropical region, dominated by warm-temperate coastal waters. Significant differences between the past and the current flora were observed. The absence of 17 taxa, observed in the past, and the presence of 16 taxa not reported before in the area are discussed under the perspective of possible global warming effects.

Key words: coastal ecosystems, climate change, macroalgal flora, Southern Brazil

Resumo: Mudanças temporais na flora de macroalgas no Sul do Brasil e suas causas potenciais. A ação antrópica nos últimos séculos vem provocando alterações atmosféricas que influenciam diretamente o clima, resultando no aquecimento global. Os ecossistemas costeiros estão sujeitos a ameaças globais pela sua sensibilidade a alterações químicas e físicas da água marinha, e as macroalgas são consideradas boas indicadoras de mudanças ambientais. Este trabalho teve como objetivo detectar mudanças na flora macroalgal da Praia da Ribanceira (Santa Catarina, Sul do Brasil) através da comparação de resultados de um inventário recente com um estudo passado, motivados pelos possíveis efeitos das mudanças climáticas nesta região sub-tropical, dominada por águas costeiras temperada quente. Diferenças significativas entre a flora atual e de três décadas atrás foram observadas. A ausência de 17 táxons, observados no passado, e a presença de 16 táxons não reportados para área no levantamento anterior são discutidas sob a perspectiva de possíveis efeitos do aquecimento global.

Palavras-chave: ecossistemas costeiros, mudanças climáticas, flora macroalgal, Brasil, Região Sul

Introduction

The planet has been affected by accelerated processes of global changes in such a way that probably no area, worldwide, remains completely unaffected by human influence (Halpern *et al.* 2008). Coastal ecosystems are one of the most vulnerable natural environments. Although not well understood, but traditionally used for providing goods and services, coastal ecosystems have been broadly threatened by anthropogenic impacts and will very likely be severely affected by climate changes (Vitousek *et al.* 1997, Orfanidis *et al.* 2001).

Some evidences are showing that global warming are progressing at a faster rate than previously recorded by IPCC third assessment report (IPCC, 2007), be responsible by recent variation in the species composition and distribution in marine environments (e.g. Stachowicz *et al.* 2002, Dijkstra *et al.* 2010). On the other hand, despite of the temperature increase be one of the most debated global climate change effect, directly or indirectly related factors must be considered. Additionally, the synergistic action of other physical, chemical and biological factors should be evaluated (Russel *et al.* 2009). Anthropogenic drivers associated to global climate change are distributed widely and are another important component of global synergistic impact (Halpern *et al.* 2008). Macroalgae, being stationary organisms, can be useful bioindicators to detect environmental changes of various kinds. Therefore, monitoring macroalgae distribution in space and time may help to anticipate effects of global changes on the biota and guide policies towards environmental conservation and planning of mitigation initiatives.

Changes in distribution patterns of macro-algae attributed to pollution have been documented only in two restricted areas along the Brazilian coast (Oliveira & Berchez 1978, Oliveira & Qi 2003, Taouil & Yoneshigue-Valentin 2002). However, an important constraint to detect changes in distribution patterns along time is related to the non-existence of previous reliable floristic surveys of seaweed floras. The publications mentioned above dealt with temporal changes on polluted tropical bays on the South East Brazilian coast and cannot be attributed to climate changes alone. In 1978, the seaweed flora of Imbituba, (Santa Catarina State, South Brazil) was surveyed motivated by the establishment of a carbon-chemistry industrial complex, in order to document the pre-impact situation (Citadini-Zanette *et al.* 1979). However, the company was declared bankruptcy shortly after opening and the power plant was not established. Despite the increased urbanisation and population increment observed along most of the Brazilian coast, the referred area was kept with similar pattern of urban occupation observed 30 years before (IBGE 2005). Here we report the results of a recent survey in the same area, to look for eventual changes in the seaweed flora after 30 years. This new survey meets further justification since the macroalgal flora reported for Santa Catarina is considered warm-temperate and transitional to the more tropical northern flora (Horta *et al.* 2001) and, therefore, more prone to yield clues to spot floristic differences due to environmental changes, eventually related with global warming process and anthropogenic ecological footprint.

Material and Methods

Macroalgal specimens were collected at Ribanceira Beach, Imbituba (Santa Catarina, Brazil). Samplings were made on two rocky shores (28°14' S/ 48°40' W; 28°11' S /48°39' W), which were selected in order to cover the same area surveyed by Citadini-Zanette *et al.* (1979). Our floristic list was based on collections made in August (winter) and June (late autumn) of 2007, and March (late summer) and September (early spring) of 2008. On each site, one 10 cm broad transect was placed perpendicularly to the water line and algae was scraped from the rocky substrate from the supra to the sublittoral fringe.

Specimens were collected during periods of low water spring tides, sorted and preserved in formaline:seawater 4%. After identification, vouchers were deposited at the Herbário Raulino Reitz (CRI, UNESC). Abiotic parameters were measured at surface water at each sampling period. Salinity was measured with a portable refractometer (RTS-101 ATC, Meditec, Brazil), pH with a portable pH-meter (pH 1800, Instrutherm, Brazil) and water temperature with a digital thermometer (HT-210, Instrutherm, Brazil).

The floristic similarity between this study and the previous one (Citadini-Zanette *et al.* 1979) was evaluated through similarity index of Sorensen ($S = [2C/(A + B)]\times 100$, in which C is the number of common species in both surveys , A is the total number of species and B is the total number of species in the work B, (Cullen *et al.* 2003). Comparison between both surveys consider that Citadini-Zanette *et al.* (1979) carried their survey out in the spring with similar methodology and general area. The Feldmann (1937) and Cheney (1977) indexes were utilized as an attempt to characterize the biogeographic affinities of the floras on the two sampling moments.

Results

Salinity varied from 35 to 39 ppt, pH from 7.20 to 7.37 and water temperature from 18.7 to 29.5 °C (Tab. I). The non expected low pH values may be due to the dynamics of oceanic CO_2 uptake on surface water determined by the rate of downward transport of CO_2 from the surface to bottom (Siegenthaler & Sarmiento1993) or to the runoff of residual waters from neighboring industries or urbanized areas. This hypothesis are reinforced by the works of Feely *et al.* (2010) that, working in estuary complex in the U.S. Pacific Northwest, estimate that part of the acidification observed results from remineralization of organic matter due to natural or anthropogenically stimulated respiration processes. Therefore, even considering that referred data are punctual and that pH is a very sensitive parameter, the observed values can be resulted from processes related to urbanization and pollution.

A total of 62 infrageneric taxa (Tab. II) was found, being nine Phaeophyceae (14.5%), 14 Chlorophyta (22.5%) and 39 Rhodophyta (63%). Among those, 43 species were found in the spring of 2008, 32 in the summer, 28 in the autumn and 50 in the winter (Tab. II, Fig. 1). Besides that, *Arthrocardia flabellata*, *A. gardneri*, *Crytopleura ramosa*,

Table I. Seasonal variation of the chemical and physical water parameters.

	Summer	Autumn	Winter	Spring
Water temp (°C)	25.8	29.5	18.7	24.7
Salinity (ppt)	39.0	35.0	36.0	35.0
pH	7.20	7.30	7.37	7.33

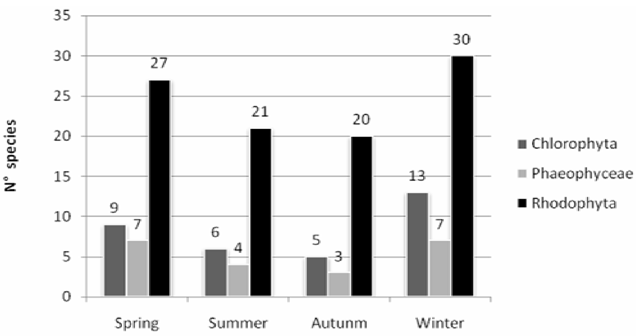

Figure 1. Seasonal distribution in number of species of Chlorophyta, Phaeophyceae and Rhodophyta, found at Ribanceira Beach, Imbituba, SC.

Gelidium floridanum, *Codium decorticatum*, *Ulva fasciata*, *U. lactuca*, *Cladophora prolifera*, *Chondracanthus teedi*, and *C. elegans* were the most frequent species in all seasons.

Among the Chlorophyta, the Cladophoraceae (six species) and the Ulvaceae (five species) were the more diversified, while among the Rhodophyta the families with higher diversity were Corallinaceae, with six species, followed by Gelidiaceae, Ceramiaceae and Rhodomelaceae with four species each. Within the Phaeophyceae, Scytosiphonaceae (three species), Acinetosporaceae (two species) and the other families with only one species each. Most of the species belonged to the filamentous morphological-functional group which are more likely to colonize physically disturbed environments, such as intertidal zones of rocky shores exposed to waves (Littler & Littler 1980).

The predominance in number of Rhodophyta species over Phaeophyceae and Chlorophyta is a common pattern for Santa Catarina region, as well as for other areas along Brazilian coast (Horta *et al.* 2001). However, looking at the physiognomy of the sampled area, the scenario was greenish since Chlorophyta, represented mainly by *Ulva* spp. and *Cladophora* spp., dominated over the red and brown seaweeds.

Species richness was higher in the coldest period, when water temperature was 18.7 °C, which is in agreement with Yoneshigue-Valentin & Valentin (1992) for an upwelling region in Rio de Janeiro state. However, one should consider that the highest species richness in winter may be due not to temperature, *per se*, but to other factors such as nutrient enrichment, what remains to be studied. The coastal upwelling around Cape of Santa Marta Grande occurs mainly in spring and summer, when northeast winds prevail, which facilitate the penetration of South Atlantic Central Water (ACAS) onto the local continental shelf (Pereira *et al.* 2008).The similarity followed by ANOSIM analyses shows a significant difference (ANOSIN p< 0,05) between our sample and the flora presented by Citadini-Zanette *et al.* (1979), indicating a change in species composition between the two surveys. Results from our analysis showed that the recent spring flora was more similar to summer, autumn and winter flora, surveyed in 2008 (similarities between 73,9 and 69,5), than to the old spring data (similarities between 64, and 51,2; Tab. III).

Yoneshigue-Valentin & Valentin (1992) documented a change in species richness along the year in areas subjected to upwelling north of Rio de Janeiro, which was attributed to temperature. However, in other instances, the distinction between the effects of temperature and other parameters, such as pollution, as causing factors of floristic changes is not clear. Stressful conditions due to the seasonal variation of different parameters seem to reduce species richness and favor the dominance of opportunist algae.

Comparing the total number of species found by Citadini-Zanette *et al.* (1979) in the spring and the present survey at the same season, a total of 27 taxa previously listed were not found in the study area. From these, 16 taxa were Rhodophyta, four Phaeophyceae and seven Chlorophyta. On the other hand, we observed the appearance of 15 taxa that were not present before: 11 Rhodophyta, one Phaeophyceae and three Chlorophyta. Feldmann and Cheney indices for 1978 show values typical of warm temperate environment (3.9 and 5.1, respectively). Higher values (5.0 and 6.14, respectively) were observed in spring of 2008, characterizing a tropical environment. The same results were found when considering general data of 2008 (4.5 and 6.125 respectively). Horta *et al.* (2001) evaluating the distribution pattern of the flora along the Brazilian coast, characterized the southern coast as belonging to a warm temperate province. Considering that temperature is traditionally considered the main controlling factor of seaweed distribution, the “tropicalization” of the values observed for Ribanceira beach, compared to the past, could be an indication of global warming. By analysing surface air and sea surface temperature trends in Southern Brazil, Marengo & Camargo (2007) highlighted that the frequency of warmer

Table II. Macroalgal species recorded at the Ribanceira Beach, Santa Catarina, during the periods 2007/2008 and Spring 1978 (Citadini-Zanette et al. 1979). Numbers I, II, III, IV refers to the sampling sites surveyed by Citadini-Zanette *et al*. (1979). 1 = presence and 0 = absence.

Species	**2007/2008 Present study**				**Spring 1978 (Citadini-Zanette *et al*. 1979)**			
	Sp	Su	Au	Wi	Site I	Site II	Site III	Site IV
Bryopsis pennata J. V. Lamour.	1	0	0	1	1	1	1	1
Bryopsis plumosa (Huds.) C. Agardh	0	0	0	1	0	0	1	0
Chaetomorpha antennina (Bory) Kütz.	0	0	0	1	1	1	1	1
Cladophora prolifera (Roth) Kütz.	1	1	1	1	1	0	1	0
Cladophora montagneana Kütz.	0	0	0	0	1	1	1	1
Cladophora sp.1	0	0	0	1	0	0	0	0
Cladophora sp.2	1	1	0	1	0	0	0	0
Cladophora vagabunda (L.) C. Hoek	0	1	0	1	1	1	1	1
Cladophoropsis membranacea (C. Agardh) Borgesen	1	0	1	1	0	0	0	0
Codium decorticatum (Woodw.) M. Howe	1	1	1	1	1	1	1	1
Codium intertextum Collins & Herv.	0	0	0	0	0	0	0	1
Codium taylorii P.C. Silva	1	0	0	1	0	0	0	0
Rhizoclonium riparium (Roth) Kütz. ex Harv.	0	0	0	0	1	1	0	0
Ulva compressa L.	1	0	0	0	0	0	0	0
Ulva fasciata Delile	1	1	1	1	1	1	1	1
Ulva lactuta L.	1	1	1	1	1	1	1	1
Ulva linza L.	0	0	0	1	1	1	1	1
Bachelotia antillarum (Grunow) Gerloff	0	0	0	0	1	0	0	0
Chnoospora minima (K. Hering) Papenf.	0	0	0	0	0	1	0	0
Colpomenia sinuosa (Roth) Derbès & Solier	1	0	0	1	1	1	1	1
Feldmannia irregularis (Kütz.) Hamel	0	1	0	1	1	0	0	0
Hincksia mitchelliae (Harv.) P.C. Silva	1	0	1	0	1	0	0	0
Levringia brasiliensis (Mont.) A.B. Joly	1	1	1	1	1	1	1	0
Padina gymnospora (Kütz.) Sond.	1	1	0	1	1	0	0	0
Petalonia fascia (O.F. Müll.) Kuntze	1	0	0	1	1	0	1	1
Rosenvingea sanctae-crucis Borgesen	1	0	0	1	0	0	0	0
Sargassum cymosum C. Agardh	1	1	1	1	1	1	1	1
Scytosiphon lomentaria (Lyngb.) Link nom.cons.	0	0	0	0	0	0	0	1
Rhodothamniella codicola Borgesen	0	0	0	1	0	1	0	0
Acrochaetium globosum Borgensen	0	0	0	0	1	0	0	0
Acrochaetium microscopium (Nägeli ex Kütz.) Nägeli	0	0	0	0	1	0	0	0
Aglaothamnion felliponei (M. Howe) N. Aponte, D. L.Ballant. & J. N. Norris	0	0	1	0	1	0	0	0
Aglaothamnion uruguayense (W.R. Taylor) N. Aponte, D. L.Ballant. & J. N. Norris	1	1	0	0	1	1	1	1
Arthrocardia flabellata (Kütz.) Manza	1	1	1	1	1	0	0	0
Arthrocardia gardneri Manza	1	1	1	1	1	1	1	1
Bangia fuscopurpurea (Dillw.) Lyngb.	0	0	0	0	1	1	1	0
Bostrychia tenella (J.V.Lamour.) J. Agardh	0	0	0	0	0	1	0	0
Bryocladia thyrsigera (J. Agardh) F. Schmitz in Falkenb	0	0	0	1	0	0	0	0

Callithamnion corymbosum (Sm.) Lyngb.	1	1	0	1	0	0	0	0
Centroceras clavulatum (C. Agardh in Kunth) Mont. in Durieu de Maisonneuve	1	1	0	1	1	1	1	1
Ceramium brevizonatum var. *caraibicum* H.E. Petersen	0	0	0	0	0	1	0	1
Ceramium dawsonii A.B. Joly	0	0	0	0	0	1	0	0
Ceramuim tenerrimum (G. Martens) Okamura	1	0	1	0	0	0	0	0
Champia parvula (C. Agardh) Harv.	1	0	1	1	0	0	0	0
Cheilosporum sagittatum (J. Ellis & Sol.) Aresch.	0	0	0	1	0	1	1	1
Chondracanthus acicularis (Roth) Fredericq	1	0	0	1	1	1	1	1
Chondracanthus elegans (Grev. in J. St.-Hil.) Guiry	1	1	1	1	0	1	1	1
Chondracanthus teedei (Mertens ex Roth) Kütz.	1	1	1	1	1	1	0	0
Corallina officinalis L.	1	0	0	1	0	0	0	1
Crytopleura ramosa (Hudson) Kylin ex L. Newton	1	1	1	1	1	1	1	1
Erythrotrichia carnea (Dillwyn) J. Agardh	0	1	0	1	0	0	0	0
Gelidium crinale (Turner) Gaillon	0	0	1	1	0	1	1	1
Gelidium floridanum W.R. Taylor	1	1	1	1	1	1	1	1
Gelidium pusilum (Stackh.) Le Jolis	1	0	0	0	0	1	1	1
Gracilaria cf. *tepocensis* (E.Y. Dawson) E.Y. Dawson	0	0	0	1	0	1	0	0
Grateloupia cuneifolia J. Agardh	1	1	1	1	1	0	0	0
Grateloupia filiformis Kützing	0	1	0	1	0	0	1	1
Gymnogongrus griffithsiae (Turner) Mart.	0	1	0	1	1	1	1	1
Herposiphonia secunda (C. Agardh) Ambronn	0	0	0	0	0	1	0	0
Hypnea musciformis (Wulfen in Jacquin) J.V. Lamour.	1	1	1	1	1	1	1	1
Hypnea spinella (C. Agardh) Kützing	1	1	0	1	0	0	0	0
Jania adhaerens J.V. Lamour.	1	0	0	0	1	0	0	0
Jania cappillacea Harv.	0	0	0	0	0	0	1	1
Jania crassa J.V. Lamour.	1	1	1	1	1	1	1	1
Laurencia sp.	0	0	0	0	1	1	0	0
Nemalion helminthoides (Velley in With.) Batters	1	0	1	0	1	1	1	0
Neosiphonia ferulacea (Suhr ex J. Agardh) S.M. Guim. & M.T. Fujii	0	0	1	0	0	0	0	0
Neosiphonia tepida (Hollenb.) S.M. Guim. & M.T. Fujii	1	0	1	1	0	1	0	0
Peyssonnelia capensis Mont.	0	0	0	0	1	1	0	0
Plocamium brasiliense (Grev. in J. St. -Hil.) M. Howe & W.R. Taylor	1	1	1	1	1	0	1	0
Polysiphonia decussata Hollenb.	0	0	0	0	0	0	0	1
Polysiphonia scopulorum Harv.	0	0	0	0	1	1	1	0
Polysiphonia subtilissima Mont.	0	0	0	1	0	0	0	0
Porphyra acanthophora E. C. Oliveira & Coll var. *acanthopora*	1	0	1	0	0	0	0	0
Porphyra pujalsiae Coll & E.C. Oliveira	0	0	0	1	0	0	0	0
Pterocladiella capillacea (S.G. Gmel.) Santel. & Hommers	1	1	0	1	1	0	1	1
Pterosiphonia parasitica var. *australis* A.B. Joly & Cord.-Mar	1	1	1	1	1	1	1	1
Pterosiphonia pennata (C. Agardh) Falkenb.	1	1	0	1	0	0	0	0
Sphacelaria tribuloides Menegh	1	1	1	0	0	0	0	0

Table III. Sorensen similarity matrix results, with comparison among the recent sampling periods and the four sites surveyed by Citadini-Zanette *et al.* (1979).

	Spring	Summer	Autumn	Winter	SiteI	SiteII	SiteIII	SiteIV
Spring								
Summer	71,23							
Autumn	69,56	62,07						
Winter	73,91	71,60	54,55					
SiteI	64,29	63,01	55,07	60,87				
SiteII	51,22	47,89	47,76	57,78	68,29			
SiteIII	59,74	60,61	51,61	65,88	72,73	74,67		
SiteIV	53,33	53,12	40	60,24	58,67	68,49	82,35	

days increased during both summer and winter, especially during the last two decades. Additionally, Wainer & Venegas (2002) described a possible displacement of the Brazilian/ Malvinas convergence to the south, resulting in a possible water warming in the referred region during next decades. Our results may represent some precocious signs of such reported warming. However, the variation of other parameters, such as eutrophization and pollution, or even their synergistic effect (Russel *et al.* 2009), besides species introduction, cannot be ruled out. Of course, on this kind of investigation, differences in presence-absence of species along time may be due to taxonomic problems, or details in sampling methodology.

However, in this case we were dealing mostly with conspicuous and easily identified taxa what makes our comparison more acceptable. The relative reduction in the number of Phaeophyceae species is an indication of impacts related to pollution. This is also supported by an increase of the Chlorophyta in comparison with other groups as documented by several authors (e.g. Reis & Yoneshigue-Valentin 1996; Oliveira & Qi 2003, Taouil & Yoneshigue-Valentin 2002, Lehmkuhl-Bouzon 2005). Conversely, the absence of *Scytosiphon lomentaria*, a species that need temperatures below 20 ºC to induce macrothallus formation (Lüning 1980, Orfanidis *et al.* 1996) may also indicate a warming process.

The appearance of taxa not present before, such as *Rosenvingea sanctae-crucis*, *Champia parvula*, *Erythrotrichia carnea*, *Callithamnion corymbosum*, *Sphacelaria tribuloides* may be related to biogeographic issues (Oliveira *et al.* 2001). The presence of *C. parvula*, although not recorded by Citadini-Zanette *et al.* (1979), was reported earlier in the area by Cordeiro-Marino in 1966 (Cordeiro-Marino 1978). Considering that *R. sanctae-crucis* is considered a tropical species, recorded to the Brazilian northeastern coast (Oliveira *et al.* 1983), the extension of its distribution to higher latitudes may also be an indication of global warming what remains to be tested. One may hypothesize that the reported changes are responses to climatic change, considering that temperature alterations also alter the pattern of geographic distribution of species. However, among the species not recorded by Citadini-Zanette *et al.* (1979), stands out species of *Cladophora*, *Chaetomorpha* and *Ulva* (Tab. II), genera that includes typically opportunistic species, evidencing that we cannot discard the interaction of factors related to the eventual increases of the anthropogenic ecological footprint. The human activities can change the seawater quality due the effluent discharge favoring species opportunists (Orfanidis *et al.* 2001) or even be responsible by the arrival of newcomer species through their transport via ships hull fouling (Mineur *et al.* 2007).

A decrease of species richness and an elevation of the indices of Feldmann and Cheney was observed after the discharge of thermal effluent from a nuclear plant in the Bay of Ilha Grande, Rio de Janeiro state, resulting from the effects of temperature increase on the seaweed flora (Széchy & Nassar 2005). Schield *et al.* (2004) observed that a 3.5 ^{o}C rise in seawater temperature, induced also by the thermal outfall of a power-generating station, resulted in significant community changes in 150 species of algae and invertebrates relative to adjacent control areas. However, they did not evidence clear tendencies toward warmer-water species with southern geographic affinities replacing colder water species with northern affinities. These authors reinforce that responses of these benthic communities to ocean warming were strongly coupled to direct effects of temperature on some key taxa, as habitat-forming subtidal kelps, and indirect effects operating through ecological interactions between herbivores and primary producers.

In spite of the uncertainties about the causal factors that produced the differences in the algal community composition, the observed changes are real. The interaction of factors such as temperature increase, variation in salinity, nutrient availability and pollution, acting *per se*, and interacting in a complex fashion, will certainly have a broad impact on seaweed floras and biodiversity, and should be evaluated with an experimental approach. Further, if we consider ocean acidification and the increase in the intensity and frequency of storms, biodiversity losses can be very high in the coming years. This scenario reinforces the need for constant monitoring and decision making with regard to coastal management, to mitigate environmental impacts derived from human activities.

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RIO GRANDE DECLARATION

1st BRAZILIAN WORKSHOP ON CLIMATE CHANGES IN COASTAL ZONES: CURRENT KNOWLEDGE AND RECOMMENDATIONS

UNIVERSIDADE FEDERAL DE RIO GRANDE (FURG)
Rio Grande, RS, Brazil
13 – 16 September 2009

The impacts of Global Climate Change on the environment and society represent the biggest challenge for human civilization in the twenty-first century. Scientists around the world are working intensely to understand the climatic processes involved and the possible consequences of climate change at global, regional and local levels. Governments of different countries have initiated studies of vulnerability to climate change and adopted mitigation and adaptation measures to face this new reality.

The establishment of the Brazilian Research Network on Global Climate Change (***Rede CLIMA***) and the implementation of the National Institute of Science and Technology (INCT) for Climate Change, were important initiatives to adequately address these issues in Brazil; since these organizations involve scientists of different disciplines. One of the main objectives of ***Rede CLIMA*** is to significantly increase the knowledge on the impact of climate change and to identify key vulnerabilities in different Brazilian sectors and systems. Coastal Zones stand out as an important system due to its environmental and societal significance.

Large cities and populations are concentrated near rivers and in low altitude regions (fertile valleys) within 100 km of the coastline, and population density of the coastal zone is likely to more than double by 2050. Impacts of climate change and urban development will triple the number of people exposed to coastal flooding by 2070. Goods and services from coastal ecosystems valued by society represent about 33 trillion dollars globally. Coastal zones are therefore, among the most vulnerable areas to global climate change impacts, since they will be directly affected by the increase in the average sea level, exposure to extreme storms, changes in discharge regimes of rivers, elevation of sea surface temperature, ocean acidification and other events. However, potential impacts of climate change, both physical and biological, will vary considerably among coastal regions, according to their natural characteristics and the degree of environmental degradation. Therefore, understanding the impacts of global climate change in every region is essential for strategic planning and decision-making by the government and the Brazilian society.

During the "First Brazilian Workshop on Climate Changes in Coastal Zones" in Rio Grande (RS), scientists from around the country assessed the current state of knowledge on impacts of climate change on Brazilian coastal zones and discussed procedures to standardize protocols and strategies for networking observational studies. About 200 university professors, graduate and post-graduate students attended the event. Among these, thirty-five were invited speakers from ***Rede CLIMA*** and the National Institute of Science and Technology (INCT) for Climate Change. Thirty-eight research papers (among oral and panels) were presented, representing 121 authors from different Brazilian institutions and regions. Based on the current state of knowledge and the discussions held during the workshop, the participants believe that it is still possible to save the coastal ecosystem and its environmental assets (ecological, social and economic) against scenarios of climate change, although urgency and determination are required to achieve this task.

In order to adequately assess and monitor the effects of climate change on coastal ecosystems in Brazil, in an objective and regional manner, the following scientific goals have to be achieved urgently:

1) Validation of regional climate models based on local observational data;

2) Geodetically controlled measurements of sea level accompanied by altimetric surveys, integrating terrestrial and nautical cartography of important coastal regions of Brazil with scenarios for the twenty-first century;

3) Acquisition of long and sustainable time series of physical, chemical and biological processes in coastal waters;

4) Greater understanding of factors controlling the processes of erosion and coastal progradation;

5) Evaluation of the potential consequences of climate changes on aquatic biogeochemical cycles;

6) Analysis of the responses of physiological and ecological populations, marine, estuarine and freshwater communities and ecosystems on climate change;

7) Assessment of variability in fish stocks and other natural resources of economic importance;

8) Evaluation of social and economic vulnerability of coastal populations, particularly those that directly depend on coastal resources and traditional activities.

The advances in scientific knowledge on coastal ecosystems, with emphasis on the topics outlined above, will lead to better insights of the effects of climate change on coastal regions. Investments in environmental sciences in coastal areas, with emphasis on climate change are essential, therefore, for greater understanding of these important ecosystems and their vulnerabilities.

In this context, we recommend to the government and organized society that actions be created or strengthened to promote:

• The immediate reduction of emissions of greenhouse gases (GHGs) in order to contribute to slowing down global warming;

• The immediate deterrence of deforestation in different regions of the country;

• Advances in scientific knowledge on coastal ecosystems, with particular emphasis on topics already presented above, through the induction and effective support for research in these subject areas;

• The strengthening of the monitoring system of the Brazilian Coastal Zone;

• The development and implementation of management plans that promote the use, conservation and restoration of coastal ecosystems, considering climate change scenarios, thus strengthening existing and incidental public policies on this zone (National Coastal Management Program, “Orla” Project, Sector Plan for Sea Resources, National Plan for Water Resources, The Conservation National System, Local Agenda 21);

• The promotion and encouragement innovative solutions and actions that encourage adaptation measures in coastal cities and towns facing the new climate scenario;

• The expansion of the critical insight and awareness of society regarding the Climate Change, through formal education (via educational institutions) and non-formal (via the media, nongovernmental organizations, civil organizations etc.), with dissemination of clear and contextualized information about scientific aspects of the topic in the appropriate language.

For the implementation of these recommendations to be successful, depend on decision from local, State and Federal public policies engaged to Climate Change. Agility and long-term commitment are essential requirements to support and encourage the efforts of science and technology to confront and adapt to the challenges posed by climate change.

Rio Grande, October 20th 2009.

Declaration approved by 124 scientists linked to 20 federal and state institutions (distributed in eight states of the Brazilian coast) and three foreign institutions, belonging to leading groups in research on issues related to the sciences of the sea.

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