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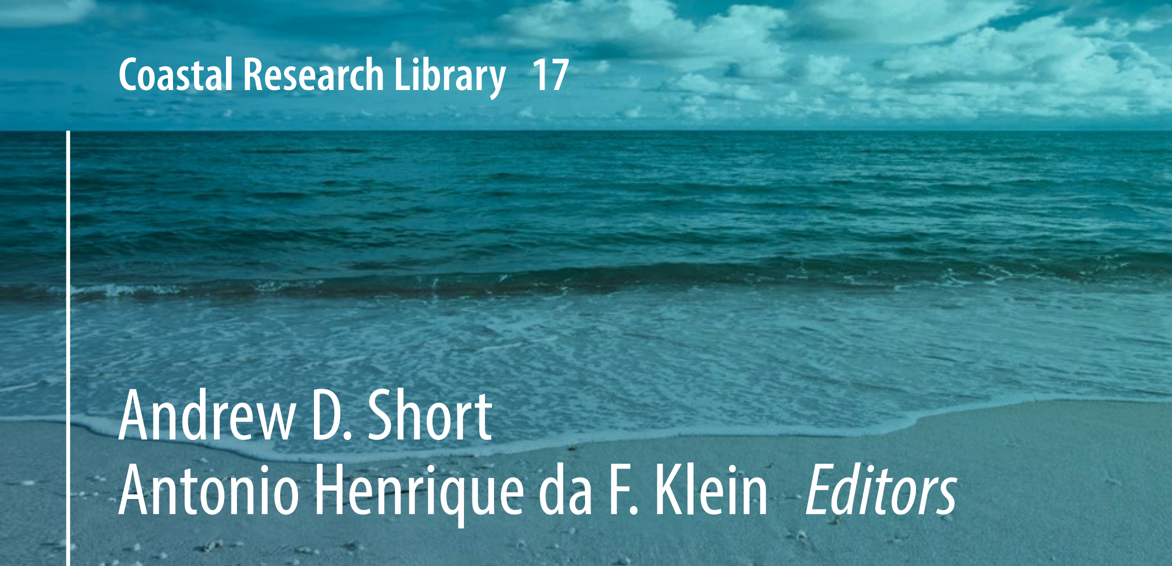

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Antonio Henrique da F. Klein *Editors*

Brazilian Beach Systems

Springer

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Brazilian Beach Systems

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To ***Professors Dieter Carl Ernst Heino Muehe and João José Bigarella (in Memoriam)***
for ongoing leadership in Brazilian beach research

Foreword

It's likely that no one on Earth has visited more beaches than Andrew Short. In Australia alone, he visited 11,670, publishing seven books. Andy studied at the Coastal Studies Institute at Louisiana State University (LSU) where studies of applied coastal morphodynamics in the beach environment began. Then in the 1970s to 1980s, he was part of the University of Sydney's Coastal Studies Unit, which demonstrated the co-evolution of morphology and hydrodynamics explaining more thoroughly and completely the behavior of the beach and surf zone. In this way, a series of basic and logical parameters were defined and adapted, to provide the key elements to a global classification system of sandy beaches. These parameters that define beach systems were well-received internationally due to their simplicity and efficiency in explaining the interaction of sand and waves in beach behavior. Surprisingly, Andy and his colleagues defined beach stages and their behavior through years of morphodynamic field observation by the naked eye, a decade before the application of video monitoring of surf zones complimented their findings. Equally notable, they applied their findings to improve beach safety, focusing on the risks and dangers of the beach environment.

In reality, Andy has frequented the coast of Brazil since 1975 when he was part of one of the first morphodynamic studies conducted in Brazil on beach systems of Sergipe and Pernambuco. I met Andy in a hotel bar in Chile during the Sandy Beach'94, where we made notes and diagrams on napkins over a few cups of pisco sour. It cost us a hangover, which was only cured after a dip in the cold waters of the Valdivia beaches. Sixteen years ago, I had the privilege of showing him the beaches of my home state from Cassino beach to Chuí, RS. On this trip, we climbed up two lighthouses, Albardão and Fronteira Aberta, to observe the beach systems: fortunately the latter of the two only collapsed two weeks after our visit.

Antonio Klein began his Brazilian beach excursions in the 1990s during his undergraduate studies at the Universidade Federal do Rio Grande (FURG). At this time, Klein and I were doing beach surveys of the southern coast with a level and rod; Klein, who was new to the marine environment, would only move seaward after sounding the sea floor with the rod. Even so, he decided to study Concheiros do Albardão, a beach unique to the southern littoral of Rio Grande do Sul for its deposits of seashell fragments and quartz sand. With this research, he completed his master's at the Universidade Federal do Rio Grande do Sul (UFRGS) in Marine Geology. He continued his work as professor at the Universidade do Vale do Itajaí (UNIVALI) in the state of Santa Catarina, where he researched the application of coastal morphodynamics in beach safety, eventually developing an award-winning project that reduced the number of swimming accidents on the Santa Catarina coast. Between 1999 and 2004 in Portugal during his PhD, he pioneered some of the first notable studies on the beaches of Santa Catarina, focusing on embayed beaches limited by rocky headlands, which constitute the majority of Santa Catarina's beaches. In 2010, he moved to Federal University of Santa Catarina (UFSC), and this book is a result of his first research project at this university.

It is not surprising that the collaboration of these two beach enthusiasts, Andy and Klein, would result in a book of this scope and importance. This book is an unprecedented approach to Brazilian beach systems from Amapá to Rio Grande do Sul. The book begins by locating Brazilian beaches in a global classification model according to the relative importance of their principal variables: tide range and wave energy, as well as presenting the evolution of Brazilian beach studies, including management, erosion, and beach safety. This initial focus is followed by the classification of the Brazilian coastal provinces by geological inheritance, geomorphology, hydrodynamic regime, and climate. They assembled researchers with different areas of expertise in coastal geology and geomorphology from the seventeen Brazilian coastal states to improve our present knowledge of Brazilian beach systems. The book concludes with a summary of all that is known about Brazilian beach systems and what still needs to be investigated to improve our knowledge of the system as a whole. It recommends directions for future research and is a valuable tool for those responsible for coastal management.

This book is a unique opportunity in that it presents the physical variability of Brazilian oceanic beaches in a logical and accessible form, particularly for those passionate about the study of beach systems and their connections to other areas of knowledge. Students and professionals in areas such as oceanography, geography, geology, coastal engineering, and coastal management will find this book a valuable resource in their development and understanding of the mechanisms that govern beaches, hopefully using this knowledge in real life application to benefit their communities. This work is essential in the library of all those that are fascinated by oceanic beaches.

Institute of Oceanography
Federal University of Rio Grande (FURG)
Rio Grande, RS, Brazil
November 15, 2015

Lauro Júlio Calliari

Preface

This book is a culmination of decades of fieldwork, research, and publications on the many beaches that line the magnificent coast of Brazil. This research commenced tentatively and sporadically in the 1960s and mushroomed in the 1990s, cumulating in 2000 with the First Brazilian Sandy Beaches Symposium, which contained 67 presentations by Brazilian coastal researchers.

Today coastal and beach research is underway in every one of the 17 coastal states, as evidenced by the contents of this book. The first editor was introduced to the Brazilian coast in 1975 and has returned multiple times to visit and work on the coast from Amapá in the north to Rio Grande do Sul in the south. The second editor introduced embayed beach morphodynamics and beach hazards and risk to Brazil and has supervised 18 graduate students, most with coastal-beach topics, many of whom have gone on to form the basis of the next generation of Brazilian coastal scientists and managers.

This book is about the beaches of Brazil. These beaches are both a vital and the major component of the Brazilian coast, and a source of endless fascination and recreation for the Brazilian people. All Brazilians know about their coast and beaches and most seem to want to vacation there in the summer months. This combination of people and coast has however resulted in some problems, ranging from a personal level with beach safety, to a national level with coastal development. In order to address these problems, one must begin with a good knowledge of the beaches and how they behave. This book addresses both these problems as well as documenting our present knowledge of the Brazilian coast and its beautiful, abundant, and wide-ranging beach systems.

This book contains 20 chapters written by 58 authors, who between them know all that is presently known about the Brazilian coast and in particular its beach systems. Seventeen of those chapters provide a state-by-state assessment of the beaches in each state, together with introductory, island beaches, and final a review and overview chapter.

If you are wondering why an Australian is editing a book on Brazilian beaches, it has to do with my 40-year association with the Brazilian coast and the assistance of a wonderful group of Brazilian coastal colleagues who have taken the time to show me, talk about, and discuss their beautiful coast and its beach systems. I also have the good fortune to see and visit much of the Brazilian coast, always with my Brazilian colleagues. I would particularly like to thank the following for taking their time to show me some of the following coasts:

Amapá – Valdenira Santos; Pará – Nils Asp and Luci Pereira; Ceará – Jader Onofre Morais; Rio Grande do Notre – Helenice Vital; Natal to Recife – Rodolfo Angulo; Fernando de Noronha – Lauro Calliari; Recife to Vitoria – Pedro Pereira and Lauro Calliari; Espírito Santo – Jacqueline Albino; Rio de Janerio – Dieter Muehe; São Paulo – Michel Mahiques; Paraná – Rodolfo Angulo; Santa Catarina – Antonio Klein; Rio Grande do Sul – Lauro Calliari, Sergio Dillenburg, and Elírio Toldo.

Sydney, NSW, Australia — Andrew D. Short
Florianópolis, SC, Brazil — Antonio Henrique da F. Klein

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This book could also not have been achieved without the support of CNPq – *Science Without Borders Program* which provided funding for a 3 years (2013–2015) Visiting Professor Grant at UFSC – Graduate Geographer Program and Graduate Oceanographer Program, project no. 400302/2012-8 (Coastal Hazards and Headland Sediment Bypassing Assessment in Different Coastal Environments), part of which resulted in the compilation and editing of this book. This work also had the financial support of the following programs: Programa de Formação em Recursos Humanos em Geologia da Petrobras (PFRH-PB 240); Fundo Clima – Ministério do Meio Ambiente, project MMA-Riscos; and SMC Project (MMA) and Bolsa de Produtividade em Pesquisa – Nível 2 [Proc. No. 303550/2012-0]).

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Chapter 2
Brazilian Coastal Processes: Wind, Wave Climate and Sea Level

Mauricio González Rodríguez, João Luiz Nicolodi, Omar Quetzalcóatl Gutiérrez, Verónica Cánovas Losada, and Antonio Espejo Hermosa

Abstract The coast of Brazil has substantial physical and environmental diversity, constituting a constant challenge for coastal management. This diversity is characterized by heterogeneity regarding the morphology of the coast and its hydrodynamic components, such as waves, tides, sea level changes and atmospheric pressure gradients. In this chapter an historical review regarding the existing observed data is presented.

Also a detailed description of the wave climate, astronomical tide and storm surge along the Brazilian coast is provided, based on the SMC-Brasil databases: Downscaled Ocean Waves (DOW), Global Ocean Tides (GOT) and Global Ocean Surges (GOS). Finally a briefly description of the SMC-Brasil is provided focusing on it is principal characteristics and an example of it is application to the Massaguaçu beach is shown on Appendix.

2.1 Introduction

The coast of Brazil has substantial physical and environmental diversity, constituting a constant challenge for coastal management. This diversity is characterized by heterogeneity regarding the morphology of the coast and its hydrodynamic components, such as waves, tides, sea level changes and atmospheric pressure gradients. In

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general, there is increasing energy of incident waves from north to south, a reverse trend occurring in tides, with tidal range decreasing from north to south.

Another relevant factor is the storm surge, which can be defined as the difference between the observed tide and astronomical tide. The storm surge is responsible for the increase or decrease of sea level in relation to predicted astronomical tides. This phenomenon usually involves intrusion of seawater into low areas, causing flooding. However, when negative, the meteorological tide can adversely affect coastal activities, such as the dynamic of ports.

The combination of positive storm surge with the wave setup may result in extreme values of run-up (maximum vertical excursion of swash on the shoreline), which can result in inundation, destruction of dunes and coastal defences (i.e. seawalls), especially when these storms coincide with astronomical spring tide.

In Brazil, the impact of these processes varies along the coast: The northern Amazon gulf region is highly dynamic, with interaction between the massive water and sediment discharge, the high annual precipitation, wave action, and especially the meso to mega-tidal regime (Pereira et al. 2010). The trade wind generated southeast and northeast waves are generally less than 1.5 m (Innocentini et al. 2000), reaching 3 m in summer off the Amapá coast (Cachione et al. 1995), however they remain low at the shore after crossing the low gradient shelf-nearshore. The January-May wet season raises water level along the coast, while the high tides dominate most of the year.

Along the Northeast coast, the wave climate is maintained by the trade winds generated by Tropical South Atlantic Anticyclone, with waves arriving from east, northeast and southeast. The highest incidences of waves occurs between June and September, arriving from the south and southeast with heights 1–2 m and average period between 7 and 12 s (Tessler and Goya 2005). The tidal range is about 4 m (meso-tidal), decreasing to 3 m in estuarine areas.

The subtropical Southeast coast between Cabo Frio (RJ) and Chui (RS) receives southerly waves generated by high latitudes storms in the South Atlantic (Pianca et al. 2010). The northeast trade winds are also influential during much of the year. The predominance of southerly waves generates northerly longshore sediment transport, which can be observed through the orientation of river mouths and morphology of ebb deltas. The south to southeast waves have an average period of 10–16 s and average height 1–4 m (Tessler and Goya 2005). Tides are 2 m in the north decreasing to 0.5 m in the south.

The action of these hydrodynamic variables, especially when combined with the storm surge, can result in damage to coastal communities, through the deposition of fluid mud on the beach (Calliari and Faria 2003), loss of land, destruction of properties and natural habitats, devaluation of property and tourism, lowering of tax collection and the loss of lives (Teixeira 2007).

In Brazil, coastal erosion exceeds shoreline progradation, with higher rates of erosion on beaches, cliffs and estuaries, in that order, while in the estuaries, the reports of erosion and progradation are equivalent, though in some states the erosion is mainly concentrated in the vicinity of river mouths, such as the coast of Santa Catarina and Paraná (Muehe 2006). Severe erosion is occurring at the mouth of the São Francisco and Paraíba do Sul rivers, mainly due to damming of the rivers, which traps sediment upstream and changes the sedimentary balance of coastal zones

(Muehe 2006). Along the Rio Grande do Sul coast severe beach erosion is occurring due to the seabed topography refracting and concentrating wave energy on sections of beach (Calliari and Speranski 2006). In Rio Grande do Norte between Guamaré and Macau severe erosion is affecting long stretches of coast, which threatens the oil pumping installations (Costa Neto 2001). The erosion is a product of the large tidal range and the consequent high velocity tidal currents as well as the constant wave-driven westerly sediment transport (Muehe 2006).

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 for the coastal zone, so that steps may be taken in response to existing hazards as well as the new scenarios of global warming, rising sea levels and coastal erosion (Nicolodi and Pettermann 2011). It is worth emphasizing that while there is in Brazil a reasonable degree of knowledge on the subject, the systematic monitoring of waves and tides is still incipient.

The main initiative for the wave and tide data measurements has been the *Global Ocean Observing System* (GOOS). The aim of GOOS/Brazil is the implementation, expansion and consolidation of a system of oceanographic, meteorological and climatological information in the South Atlantic for the purpose of producing knowledge, to enable oceanographic and meteorological forecasting in the maritime area of national responsibility, and thereby reduce vulnerabilities and risks from extreme events and climate change.

It is in this context that the major networks for monitoring waves and tides of Brazil are:

- *Buoys National Program* (PNBOIA): drifting and anchored buoys in the coastal region to provide real time meteorological and oceanographic data to the scientific community. In 2014 five buoys anchored near the shelf break were operational: Recife (PE), Porto Seguro (BA), Cabo Frio (RJ), Santos (SP) and Rio Grande (RS).
- *Monitoring Network Waves in Shallow Water*: a network of buoys anchored in shallow waters along the Brazilian coast, to monitor the real-time wave climate. This aims to provide data for understanding the interactions between the continent and the ocean, coastal engineering projects, port and ocean, marine mining, navigation, studies of variations of the shoreline and coastal processes. In 2014 there was one operational buoy (Recife) and two in maintenance (Rio Grande and Santos)
- *Global Sea Level Observing System* (GLOSS-BRAZIL): monitoring sea level to support environmental research that will improve the social and economic planning of the country. In 2014 eleven tide gauges were operational along the Brazilian coast.

Even with the development of these networks, there is a serious shortage of long and reliable coastal data series in Brazil. The reason is the small number of operational systems, the short operational time of these networks and logistical difficulties of maintenance and support. This situation has resulted in only short series and data gaps owing to long periods of inactivity. More detailed information about these networks can be obtained in http://www.goosbrasil.org/.

A considerable part of the data on Brazilian waves and tides was obtained through research projects, with inherently limited periods of monitoring and private data. A study of existing publications (which used wave data) in major databases available on the Internet indicates that most of these publications (60 %) obtained information about wave parameters from visual estimation. Data from buoys occur in only 21 % of papers, and in most cases the buoys were anchored only during the period of the scientific project.

In this context, this chapter is intended to present and discuss data from waves and tides existing in Brazil. Based on these data it is possible to analyze the current coastal dynamics, especially with the use of tools that combine numerical models and measured data. An example is the *Coastal Modeling System* (SMC-Brasil, http://smcbrasil.ihcantabria.com/), which is an initiative of the Ministry of Environment in partnership with the Spanish government to transfer methodologies and tools to support the Brazilian coast management.

This chapter is structured as follows: a data review section, followed by a section on wind hindcast, in which results of atmospheric reanalysis are presented, as well as wind characterization sources and temporal variability of the wind. This is followed with the results of wave climate hindcasting, with emphasis on Global Ocean Waves (GOW) reanalysis and the wave height calibration. The next topic at issue is a Downscaled Ocean Waves (DOW), where a hybrid downscaling methodology to transfer the wave climate to coastal areas has been used, especially with the SWAN model (Booij et al. 1999), version 40.85 together with an overview on the spatial and temporal variability of the wave climate. Sea level hindcast data is analyzed, focusing on Global Ocean Tides (GOT) and Global Ocean Surges (GOS), with specific emphasis on the characterization of these variables along the Brazilian coast. In the Appendix a description of SMC-Brazil, the coastal modeling and management system developed for Brazilian coast, together with a study case to illustrate the application of the system is presented.

2.2 Data Review

In Brazil, there are just a few records of wave and tide measurements, especially with a long and reliable data series. This chapter summarize the key initiatives and briefly describe the available data.

2.2.1 Waves

Waves can be measured by three main methods: visual estimations, in situ techniques and using satellite sensors. Visual estimates are still used today, especially in smaller projects, and have been validated by several researchers (Jardine 1979; Bryant 1979; Guedes Soares 1986; Plant and Griggs 1992).

Visual observations, especially wave heights, are fairly reliable if carried out by experienced observers who follow specific instructions. Observations should be recorded as they are often the only source of information (Holthuijsen 2007).

In situ instruments may be located at the sea surface (e.g. floating surface buoy) or below the sea surface from a fixed location (e.g. pressure transducer, ADCP). All are used to acquire time records of the up-and-down motion of the surface (Holthuijsen 2007).

Measurements from satellite sensors are a more recent alternative, particularly for global scale, and they have been used to calibrate global models of wave propagation (Aage et al. 1998).

The most common way of measuring waves is to follow the three-dimensional motion of the water particles at the sea surface. This can be done with buoys, which measure the vertical acceleration with an onboard accelerometer, while modern buoys can also acquire directional information. The data is transmitted by radio communication to a land based receiving station and more recently with satellite communication and position detection by the Global Positioning System (GPS).

As mentioned in the previous section, waves monitoring programs in Brazil are currently under the coordination of GOOS-Brazil. The history of Brazilian wave monitoring dates back to the 1960s, with the pioneering buoy measurements of Wainer (1963), on the coast of Rio Grande do Sul (Tramandaí Beach) for 9 months. This was one of the first series of wave data using this type of equipment in Brazil and the significant wave height (Hs) and period (Ts) can be observed in Fig. 2.1. From these data, it was possible to predict significant and maximum waves for return periods of 30 and 100 years (Strauch et al. 2009).

While more wave buoys have been used in recent years, they are not popular because of the high cost of equipment and maintenance and the high risk of accidents.

However, the urgent need for wave data in Brazil, motivated researchers from the Federal University of Rio de Janeiro (UFRJ), with the aid of the Brazilian Navy, to create an alternative project 'the Sea Sentinels'. The aim of this project is to monitor nearshore wave conditions in Brazil by means of visual observations. In order to

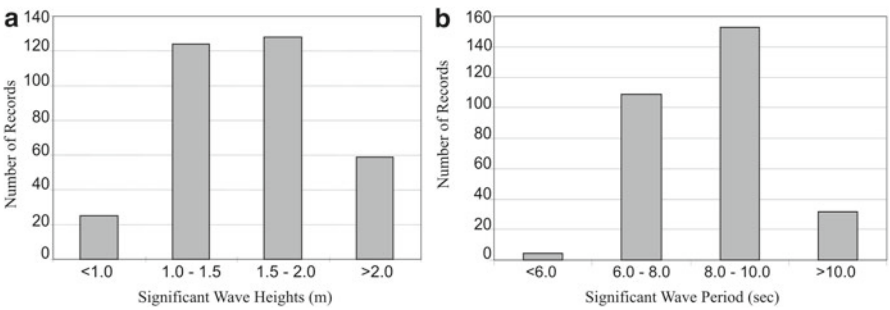

Fig. 2.1 Distribution of significant heights (**a**) and periods (**b**) in Tramandaí between 1962 and 1963 (Wainer 1963) (Adapted from Strauch et al. 2009)

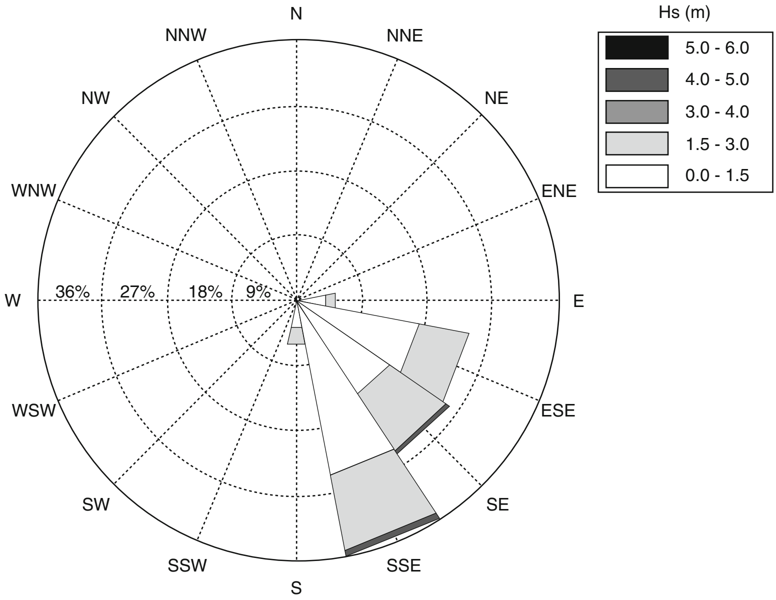

Fig. 2.2 Directional distribution of the significant wave height at the mouth of Lagoa dos Patos (RS) (Strauch 2001)

obtain the observations, a group of 25 surfer volunteers from the eight coastal states were trained by the Brazilian Navy and UFRJ to act as the sentinels. This project monitored wind direction and velocity, wave height, wave period, wave direction and nature and direction of the alongshore current (Melo 1993).

The qualitative results of this project contributed to the definition of three coastal regions and their wave climates: A southern region exposed to South Atlantic southern swell; an eastern region dominated by locally generated sea waves; and a northern region, under the constant action of southeast trade wind waves and also exposed to northern hemisphere swell (Melo 1993).

In southern Brazil, the Federal University of Rio Grande (FURG), in partnership with the Center for Development of Nuclear Technology (CDTN), anchored a non-directional waverider at the mouth of the Lagoa dos Patos, in Rio Grande. This equipment worked for 28 months, contributing to the understanding of wave climate of the region, as shown in Fig. 2.2

In Santa Catarina state, researchers from the Federal University of Santa Catarina (USFC) implemented the Coastal Information Program (PIC online), which maintained a buoy anchored off Santa Caterina island of between 2001 and 2003. The program monitored waves, sea surface temperature and indirect information about currents on the Santa Catarina platform. The data was freely available in real time via the internet. A summary of the program and the data analysis can be found in Melo (2004) and Pimenta et al. (2004). Data from this program are available on UCSD website (http://cdip.ucsd.edu/?nav=historic&sub=map&xmap_id=24). The significant height, peak period, mean direction and temperature for 2003 are shown in Fig. 2.3.

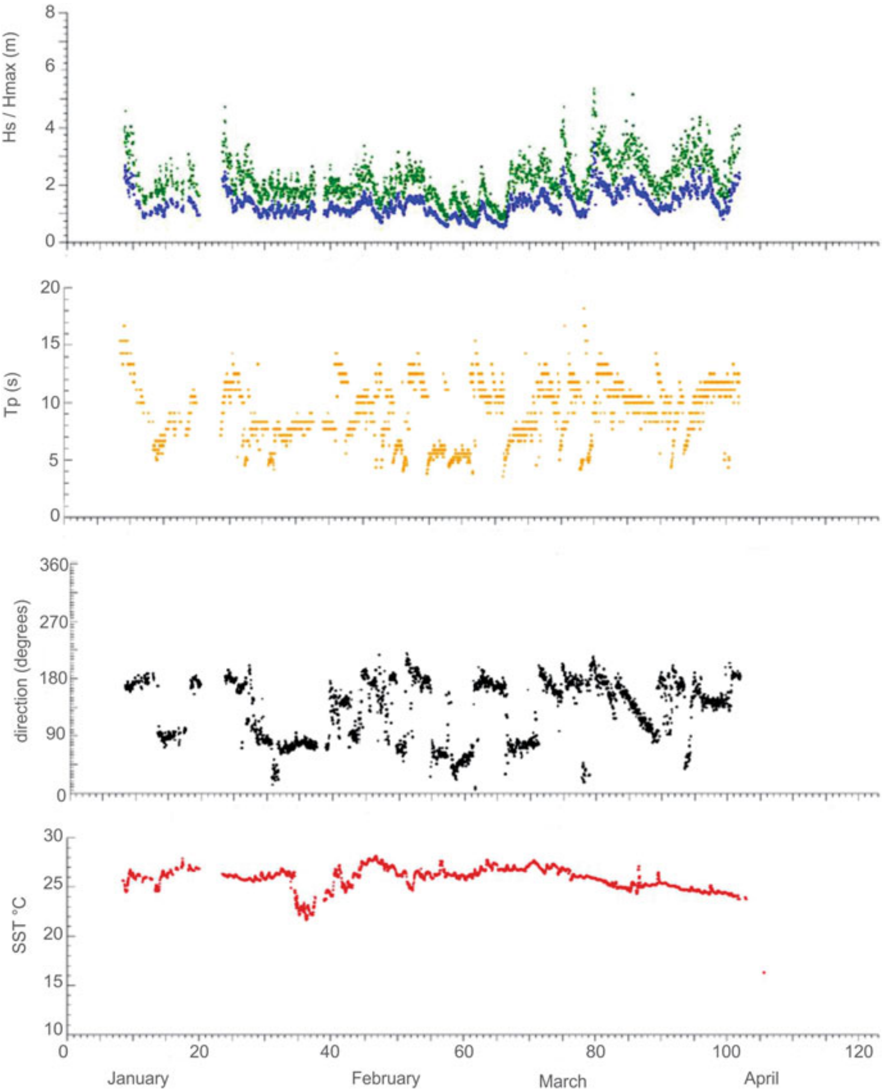

Fig. 2.3 Time series of parameters measured in the first quarter of 2003 off Santa Catarina island. Significant heights ($H_{1/3}$ – *blue*) and maximum (H_{max} – *green*); peak period (T_p); Direction corresponding to T_p; and sea surface temperature (*SST*)

At governmental level, the GOOS-Brazil Program maintains two networks that measure wave parameters: the National Program Buoys (PNBOIA) and the Monitoring Network Waves in Shallow Water (REDE ONDAS).

The PNBOIA have a network of drifting and anchored coastal buoys to provide meteorological and oceanographic data in real time to the scientific community. In 2014 five buoys were operational: Recife (PE), Porto Seguro (BA), Cabo Frio (RJ), Santos (SP) and Rio Grande (RS). These buoys are anchored near the shelf break.

Wave data is also received via satellite through the Argos system. The Argos program is jointly administered by the American agency, NOAA, and the French CNES. The data from this program can be obtained from: http://www.goosbrasil.org/tiki-index.php?page=PNBOIA%20Data#.

The WAVES NETWORK is a network of buoys anchored in shallow waters along the Brazilian coast, to monitor the wave climate through real-time knowledge of sea conditions. In 2015 there were five operational buoys (Recife, Praia do Forte, Paranaguá, Tramandaí and Rio Grande) and one in maintenance (Santos). The data from this government-university joint operation can be obtained at: http://redeondas.herokuapp.com/.

2.2.2 Tides

The Brazilian initiative of measuring the sea level can be grouped into three distinct periods. The first 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 (Lemos and Ghisolfi 2011).

As a very detailed description of first and second periods can be found in Lemos and Ghisolfi (2011) the following briefly reviews the three periods.

2.2.2.1 1st Period (1910–1980)

Between 1910 and 1920 the DHN and INPH (National Institute of Hydrologic Research) made the first sea level measurement, initially focusing on navigation, harbour applications, elaboration of nautical charts and altimetry surveys (Neves 2005).

Between 1919 and 1920, the Brazilian General Chart Commission (now extinct) operated a tide gauge in the city of Torres in the Rio Grande do Sul state.

During the 1970s, 281 sites throughout the Brazilian coast were sampled, with most sites lasting less than a month.

The first geographic readjustment of the Torres datum was established in 1952. By that time, more than 5000 reference levels had been set near the Brazilian tide gauges.

In 1959, after 9 years of observations (1949–1957), by the Inter-American Geodetic Survey the Datum was readjusted and moved to the city of Imbituba (SC). However during the 1960s other important tide-gauge stations were deactivated

2.2.2.2 2nd Period (1990s)

In 1994, the IBGE took over the tide gauge located at Porto de Imbetiba in the city of Macaé (Rio de Janeiro) and upgraded the station to become a pilot station for the future PTNG. The PTNG was established in 1997 and stations were located at Imbituba (SC), Macaé (RJ), Salvador (BA), Fortaleza (CE), and Santana (AM). The network became operational effectively from 2001, after the installation of digital equipment in Macaé and Imbituba.

Unfortunately, the majority of the tide gauges, once active, were either not maintained or destroyed. An exception is the Cananéia station, where the time-series is more than 50 years old. According to Pirazzoli (1986), who analyzed the data of long-term variations of MSL measurement from a data set available in the Permanent Service for Mean Sea Level (PSMSL), the rate of variation of the MSL had a period of 20 years. Hence, the studies on long-term tendency should have at least 50 years of data.

2.2.2.3 3rd Period: The Present

Currently, the most important initiative for monitoring tides is the GLOSS-BRAZIL. It is a network to monitor sea level, managed by the Brazilian Navy. The GLOSS-Brazil Implementation Plan was finalized in October 2004, and in 2014 eleven tide gauges were operational along the Brazilian coast.

As an example, we highlight the oldest tide gauge station in Brazil, which is located on the south coast of São Paulo, in Cananeia. This station has the longest time series, with measurements carried out since 1954 by the same AOTT tide gauge. Costa (2007) analyzed the data between 1954 and 2004 (Fig. 2.4). In this study, the authors estimate a sea level rise on the order of 4.2 mm year^{-1}.

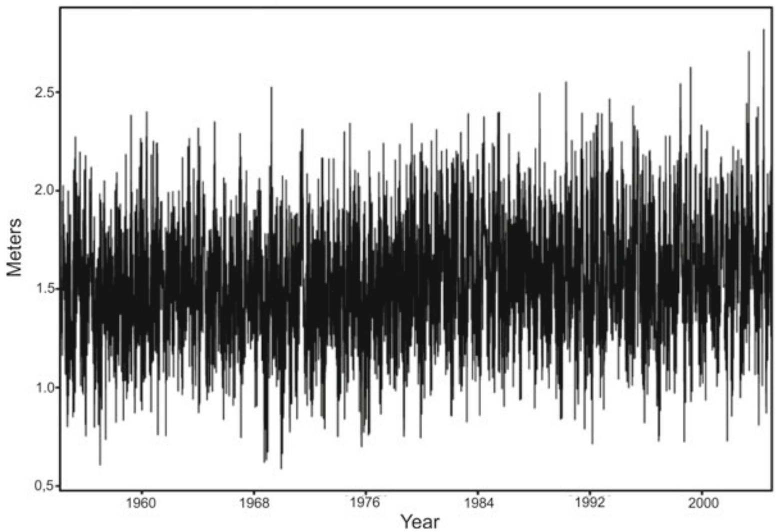

Fig. 2.4 Relative sea level in the region of Cananeia, São Paulo

2.3 South Atlantic Wind Systems

2.3.1 Spatial and Temporal Variability

South Atlantic atmospheric circulation is dominated by anticyclonic flow around the subtropical gyre, which is strongly influenced by interoceanic connections. At the Brazil-Malvinas Confluence (between approximately 30–50°S), there are sharp thermal contrasts between the cold circumpolar and South Atlantic warm air masses that form strong east-tracking lows east of the Drake Passage (Garcia et al. 2004). These lows are the leading source of the southerly swells that dominates Brazil's southeast facing coasts.

Further to the north, in the ITCZ region (between approximately 30°N–30°S) the easterly trade winds flow onto the north and east facing coast of Brazil. These extensive and persistent winds, while not as powerful as the mid-latitude westerly lows, are able to generate short period seas of moderate height. Seas are also be generated locally by thermal sea-breezes at the coast. Both the westerlies and trade winds, have seasonal fluctuations as indicated in Fig. 2.5.

Regarding trade winds, which are the leading source of most of the northern Brazilian wave energy, it is worthwhile to differentiate between North and South Hemispheres. Whereas the Northern Hemisphere northeast trades, are stronger during winter and spring, the Southern Hemisphere, southeast trades are almost constant, with minor seasonal fluctuations. The most striking seasonal feature (austral spring-summer) is the directional shift occurring between 10°S and 20°S, in which the winds turn their direction from the southeast to the northeast readjusting to the land contours.

2.4 Brazilian Wave Climate: Spatial and Temporal Variability

Description of wave climate along the Brazilian coast was based on the SMC-Brasil waves database. This database was obtained by improving the spatial resolution by means of a downscaling (DOW) of a global ocean waves hindcast (GOW). The database consists of 60 year temporal series along the Brazilian coast.

GOW, have been simulated using the Wave Watch III model (WWIII, Tolman 2009). Simulations are computed on a global grid with a spatial resolution of 1.5° in longitude and 1° in latitude. More details about GOW can be found on Reguero et al. (2012). GOW have been calibrated by means of a directional methodology proposed by Mínguez et al. (2011). The procedure is based on altimetry measurements. Although the comparison is only made when there is coexistence of both data sources, GOW and satellite, the correction is applied for the full period of wave hindcast. The preliminary validation using both buoy and satellite altimetry data showed a good agreement between the different satellites and, as a consequence,

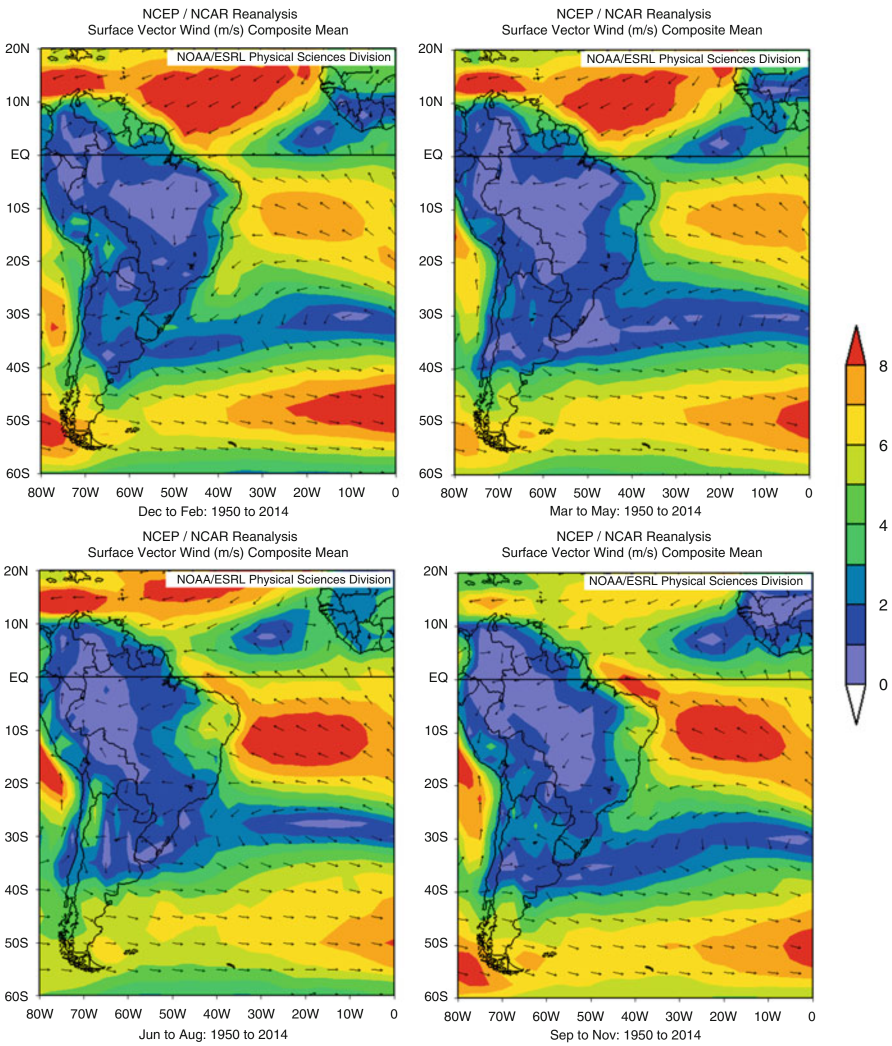

Fig. 2.5 Seasonality of the South Atlantic winds (Data from NCEP/NCAR reanalysis)

they are combined for comparison with reanalysis results. Temporal coverage of the satellite data extends from 1992 to 2008. The satellite wave height calibration procedures summarized in Cotton (1998) and Woolf et al. (2002), and later updated by Hemer et al. (2010). More information about this topic can be found in IHCantabria (2013a).

GOW database does not offer appropriate description of waves in coastal areas, therefore a hybrid downscaling methodology, described in Camus et al. (2011), and SWAN (Booij et al. 1999) simulations were applied to increase the resolution of wave climate on shallow areas. This improved database was named DOW.

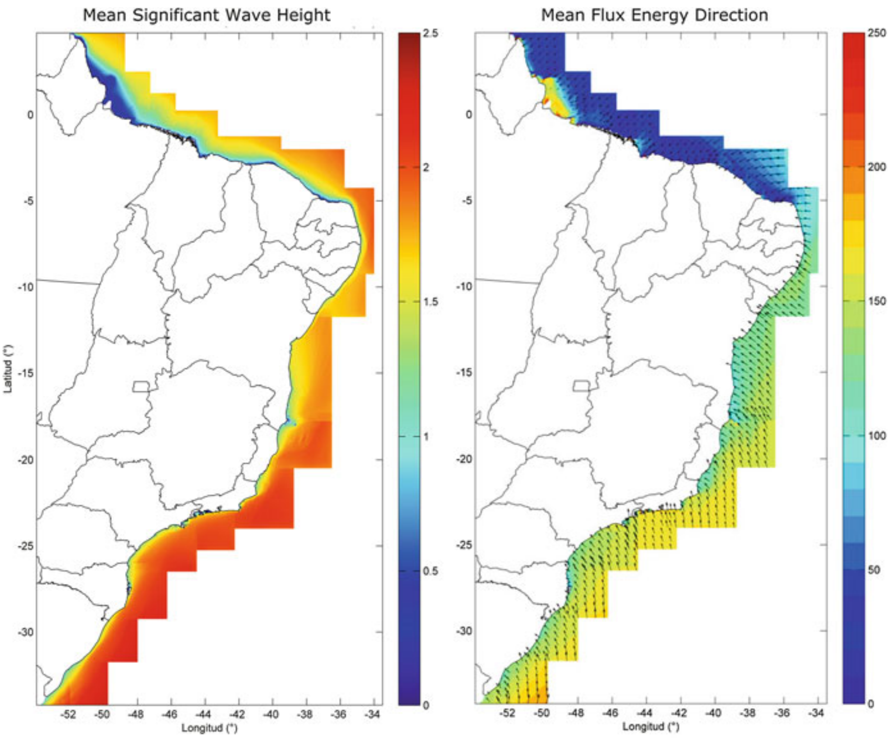

Fig. 2.6 Annual mean H_s (*left*) and FE (*right*) along the coast of Brazil from DOW database for the 1948–2008 period

2.4.1 Mean Waves

In order to characterize mean coastal wave conditions along the Brazilian coast, the annual mean significant wave height H_s and the mean wave energy flux (FE) have been determined making use of the DOW from 1948 to 2008.

Figure 2.6 illustrates the H_s and FE along the Brazilian coast based on GOW. Surprisingly to some extent when compared with the wind maps shown in Fig. 2.5, larger waves are found along the southern coast (down to 20°S) due to the action of the extratropical lows that are able to produce longer period waves than the trade winds, which dominate the northern coast. Longer periods means more propagation capacities of swells when compared with seas. This fact can be corroborated when observing the FE mean direction, presenting a dramatic shift around 5°S.

Seasonality of the coastal wave climate can be observed in Fig. 2.7. As expected, wave climate fluctuations are the response to the regional winds seasonality. The north coast receives more energetic waves during summer due to the intensification

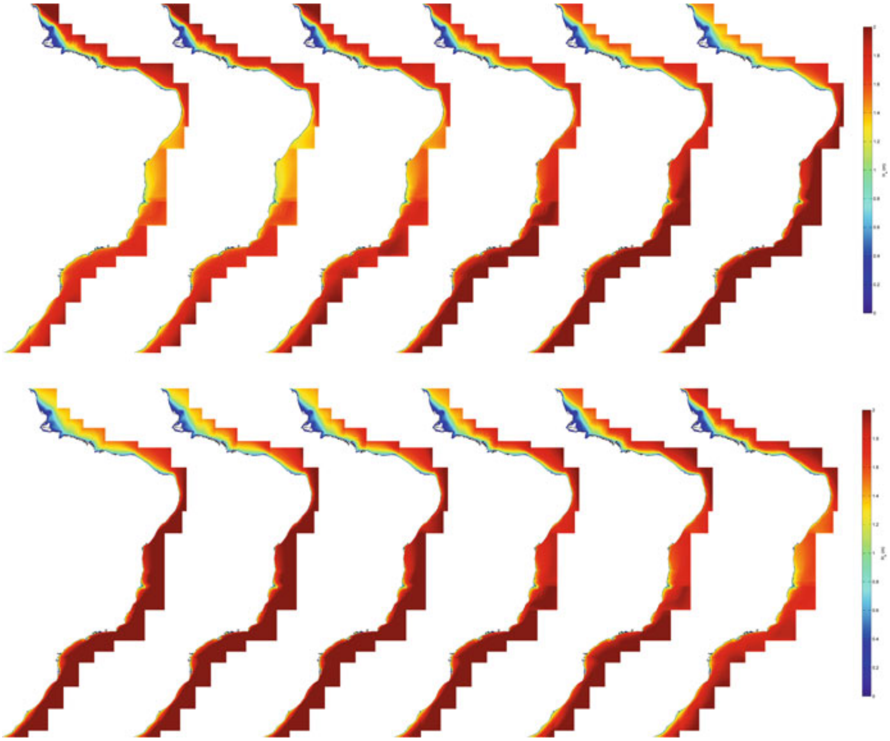

Fig. 2.7 H_s seasonality maps (from January to December) (in meters) on Brazilian coast from DOW database for the 1948–2008 period

of the Northern Hemisphere trades. Between 10 and 15°S H_s peaks during winter owing to the strength of Southern Hemisphere trades. Further to the south larger H_s during winter months are due to the more frequent and deeper lows forming over the Drake Passage.

2.4.2 *Extreme Waves*

In order to characterize extreme significant wave height values at the coast, the H_{s12} map is shown in Fig. 2.8. H_{s12} is the significant wave height exceeded for about 12 h a year; this value is used characterize the stormiest event throughout an averaged year. As expected, only the most southern latitudes receive H_{s12} waves up to 5 m. Nevertheless, these waves tend to decay rapidly due to attenuation across the continental shelf. As can be observed, sea states up to $H_{s12} = 3$ m are extremely rare on the north facing coast of Brazil.

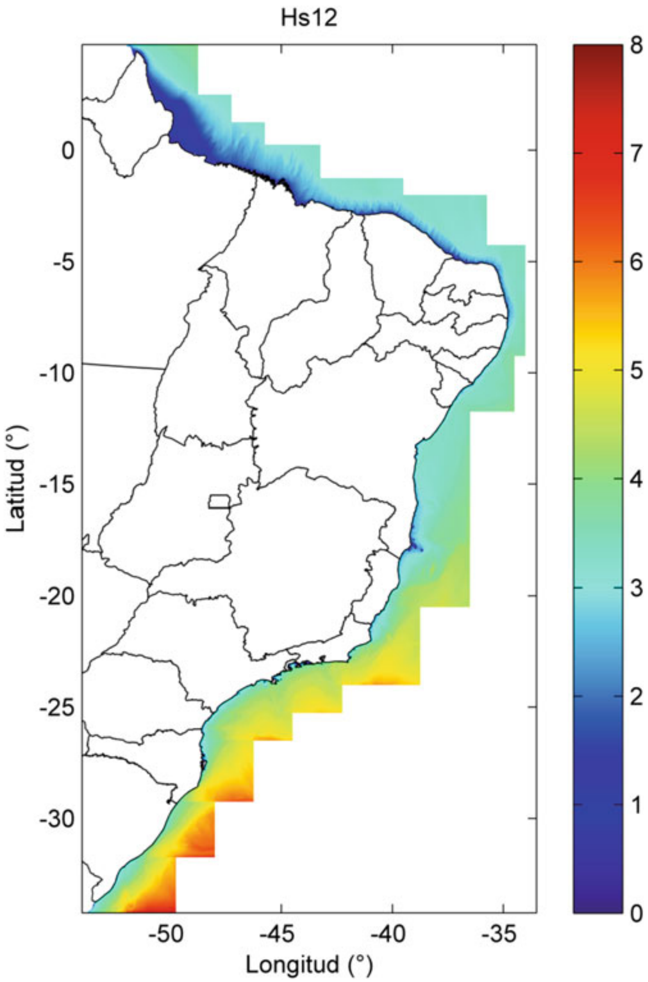

Fig. 2.8 Hs_{12} values (in meters) along the Brazilian coast from DOW database for the 1948–2008 period

2.5 Astronomical Tide Range Along the Brazilian Coast

The characterization of the astronomical tide along the Brazilian coast is based on the Global Ocean Database (GOT) of SMC-Brasil. GOT database is composed by a set of 60 year hourly temporal series along the Brazilian coast. This database was created based on the harmonic constants of TPXO Global Tidal Solution developed by Oregon University (Egbert et al. 1994; Egbert and Erofeeva 2002). The database consists of a 60-year time series of astronomical tide elevation from 1949 to 2009.

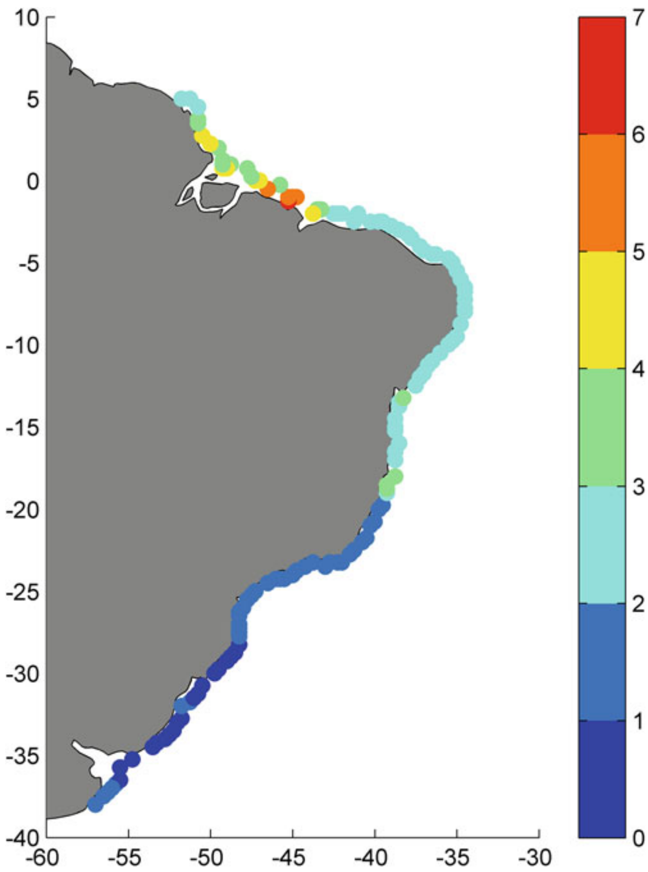

Fig. 2.9 Maximum tidal range along the Brazilian coast from the GOT database along the Brazilian coast for the 1948–2008 period

Database was validated with tide gauges located along the Brazilian coast from University of Hawaii Sea Level Center (UHSLC), the Instituto Nacional de Pesquisas Hidroviarias (INPH) and the Marina do Brasil (MB). Details about the database and validation can be found on IH-Cantabria (2013b).

Figure 2.9 shows the maximum tidal range values, with highest (meso to mega) tides around the Amazon Gulf (Amapá, Pará and Maranháo states), meso-tides along the northeast coast, decreasing to micro-tides down the southeast coast.

2.6 Storm Surge Along the Brazilian Coast

Storm surges are primarily caused by low pressure and strong onshore winds that produce an increase in the sea level on the coast. It is therefore essential to consider storm surge in the calculation of flooding levels on the coast.

The storm surge level variation can be obtained by subtracting from tide gauges the predicted astronomical tide. Unfortunately, real data provided by measurement networks are scarce and present several limitations, both in terms of spatial and temporal coverage (Cid et al. 2014). In order to overcome these limitations numerical models have become useful tools for the generation of long term and high resolution databases. The Storm Surge database (GOS) was obtained by means of numerical simulation and was validated using tidal gauge series. It was simulated using the Regional Ocean Model System (ROMS) developed by Rutgers University (Haidvogel et al. 2000; 2008; Shchepetkin and McWilliams 2005).

The model is set-up for Southern Atlantic covering the area 65°S to 35°N and 20°W to 125°W with a horizontal resolution of 0.25°. The bathymetry is extracted from the ETOPO 2 (NOAA 2006) database, a global topography of 2 min resolution derived from depth soundings and satellite gravity observations (Smith and Sandwell 1997).

GOS database was validated using tide gauge records from UHSLC, INPH and Marina do Brasil. Details about the database and the validation can be found on IH-Cantabria (2013b).

2.6.1 Spatial Variability

In order to characterize the GOS database along the Brazilian coast the following variables were calculated: historical maximum elevation, mean and standard deviation of the elevation, and elevation exceeded the 50 %, 10 % and 1 % of the time.

Figure 2.10 shows the historical maximum elevation along the Brazilian coast. The minimal elevations are found on the northern coast (<0.5 m), while in the south they reach the maximum values (>2 m), where the coast is exposed to extra tropical storms. Parise et al. (2009) found that highest storm surges in the south are related to south-westely winds. Machado et al. (2010) found four patterns of these synoptic situations, the first three confirmed the Parise et al. (2009) observations and the fourth is related to a high pressure system.

The standard deviation (Fig. 2.11) gives a spatial variability measurement of the storm surge. In the northern part it is less than 15 cm meanwhile in the south it could reach the 40 cm.

2.7 Coastal Flooding

The determination of the flooding level on a beach requires taking into account several meteorological and oceanographic variables and the interaction between them. These variables vary spatial and temporally and also interact with the beach morphology. The most important variables are astronomical tide, storm surge and highest level reached by the wind waves over the beach slope.

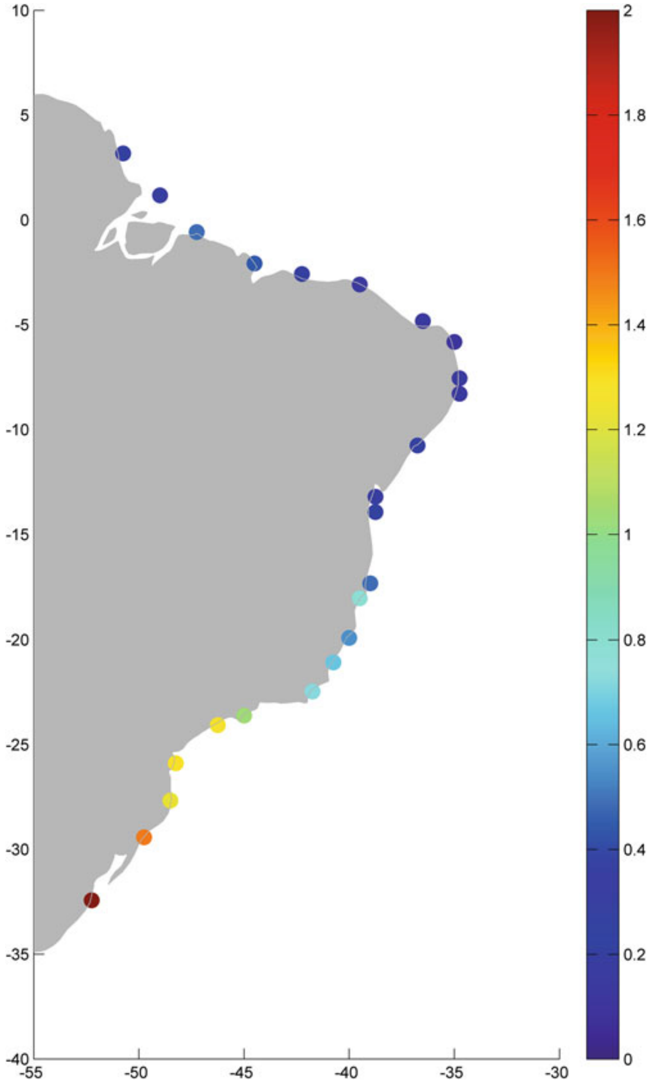

Fig. 2.10 Historical maximum storm surge (meters), obtained from GOS database for the 1948–2008 period

The flooding stage at one instant could be defined as the elevation over a reference level (RL) produced by the combination of the instant tidal level and the run up (Ru). The tidal level is also the combination of the astronomical tide elevation (AT) and storm surge elevation (SS), as is shown in Fig. 2.11. Some of the factors affecting the storm surge and run up are random and have a probability of occurrence.

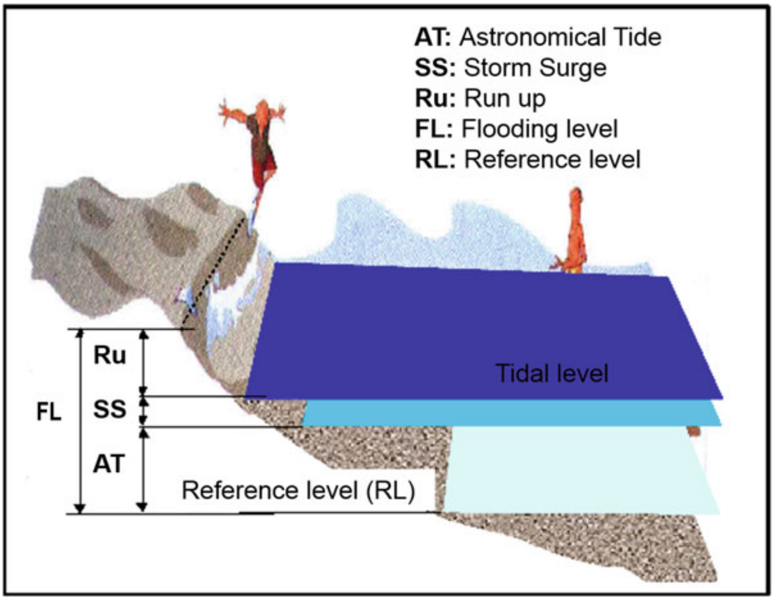

Fig. 2.11 Outline of the factors that define the flooding stage (GIOC 2003)

Therefore, the flooding stage determination is a stochastic problem. The consequences are that it is impossible to calculate a deterministic flooding stage and therefore a probability must be associated to each specific storm. The association of the flooding stage with a probability is fundamental for structures designs, delimitation of public domains, protection of coastal ecosystems, etc.

A simplified approach to this problem, that provides general information about the flooding on coastal areas and can be used to obtain pre-design or rough values of the inundation in a fast and simply way is presented on a simplified flooding Atlas for the Brazilian coast, summarizes these results (‘*Uma Proposta de Abordagem para o Estabelecimento de Regimes Probabilísticos de Inundação Costeira do Brasil’*, Ministério do Meio Ambiente 2014). A second and complex method that uses the astronomical tide, storm surge and wind waves databases described previously for the calculations, as source of forcing is implemented on SMC-Brasil (see Apendix 1). This methodology requires the use of detailed bathymetries, and numerical models to propagate wind waves from deep to shallow water, and find the breaking point. This method must be applied to a specific beach for local flooding assessment. In both cases the flooded area can be determined using the flooding stages as inputs for model simulations.

2.7.1 Methodology Differences

Although both methodologies can be used to produce flooding charts, and to define flooding contours associated to return periods, there are differences in the character of results, which lead to different approximations and application of the results. The simplified methodology gives a rough idea of the flooding in a coastal area, and was used to generate a flooding assessment document for immediate use; while the detailed methodology provides a fine approach to the coastal flooding taking into all the morphological and dynamical characteristics of a specific beach. In this case, the flooding charts must be obtained through numerical tools implemented on *SMC-Brasil*.

The main differences between both methodologies are on the characteristics of the beach and the wave propagation. Table 2.1 lists the differences between the methodologies.

Table 2.1 Summary of the differences between the simplified methodology, used on 'Uma Proposta de Abordagem para o Estabelecimento de Regimes Probabilísticos de Inundação Costeira do Brasil' (Ministério do Meio Ambiente 2014), and detailed methodology, used on SMC-Brasil, to calculate the flooding level

Elements		Simplified methodology	Detailed methodology (SMC-Brasil)
General	Approximation	Global Brazilian Coast	Local applications
	Spatial approach	For coastal regions (~100 km)	For a specific beach
Levels	Astronomical tide	60 year GOT series	60 year GOT series
	Storm surge	60 year GOS series	60 year GOS series
Wind Waves	Database	60 year DOW series	60 year GOW series
	Wave propagation	Snell's approximation. Using straight and parallel bathymetry	OLUCA-Sp numerical model. Using high resolution bathymetry
	Propagated cases	All of them one by one (hourly)	Propagation of a small number of representative cases
	Breaking wind waves criteria	Defined as $H_b/h_b = 0.8$	OLUCA-Sp (Spectral wave breaking):
			Battjes and Janseen 1978
			Thornton and Guza 1983
			Winyu and Tomoya 1998
	Run-Up	Nielsen and Hanslow (1991)	Nielsen and Hanslow (1991) or flooding numerical model
Beach	Bathymetry	Nautical charts + topography	Nautical charts + local surveys + topography
	Beach slope	Just for reflective and dissipative beaches	Real profile
	Beach orientation	For different Beach orientations in the region	Not relevant

2.8 SMC-Brasil: Hindcast Dynamic Databases and a Coastal Process Numerical Tools

2.8.1 Introduction

Shoreline plays an important role in human life from a socio-economic, commercial, recreational, residential and touristic point of view, as well as being important for its biodiversity and environmental wealth. During recent decades, man has realized the importance of preserving this biodiversity and the need of a good knowledge of dynamics and effects on the shoreline to ensure the coast stability and its conservation through sustainable actions and a proper environmental management.

In order to properly respond to these needs, from 1995 to 2002, the Environmental Hydraulics Institute "IHCantabria" from University of Cantabria developed a Beach Nourishment and Protection Manual, which included a design and evaluation methodology collected in some technical documents and a user-friendly system called Coastal Modeling System (SMC), which took into account all those methodologies.

Since then IHCantabria has been working on the development of new methodologies, databases and coastal models to improve the knowledge of dynamics and effects on the coast and, since 2009 up to now, some of those scientific advances have been integrated in a new advanced version called SMC-Brasil (http://smcbrasil.ihcantabria.com/), which has been developed by The Environmental Hydraulics Institute "IHCantabria", the Coastal Oceanography Laboratory of the Federal University of Santa Catarina (UFSC) and the Oceanographic Institute of the Sao Paulo University (USP), with the support of the International Spanish Cooperation Agency (AECID), the Brazilian Ministério do Meio Ambiente (MMA) and Ministério do Planejamiento, Orçametno e Gestao/ Secretaria de Patrimonio da União (MP-SPU).

The main objective of the SMC-Brasil is to provide a coastal numerical tool and a series of reference documents, that help technicians in the design, execution and monitoring of coastal projects; to establish a strategy in order to prevent coastal erosion and estimate flooding risks of Brazilian littoral zones.

2.8.2 SMC-Brasil

SMC-Brasil is a user-friendly system specifically designed to assist coastal designers and managers in the analysis of marine and littoral dynamics to understand the changes in coastal caused by those dynamics.

The SMC-Brasil is composed of methodological documents for specific coastal topics and two user-friendly systems (Fig. 2.12).

- Thematic documents: these technical documents collects all the database descriptions and the methodologies used to estimate and analyze waves, sediment

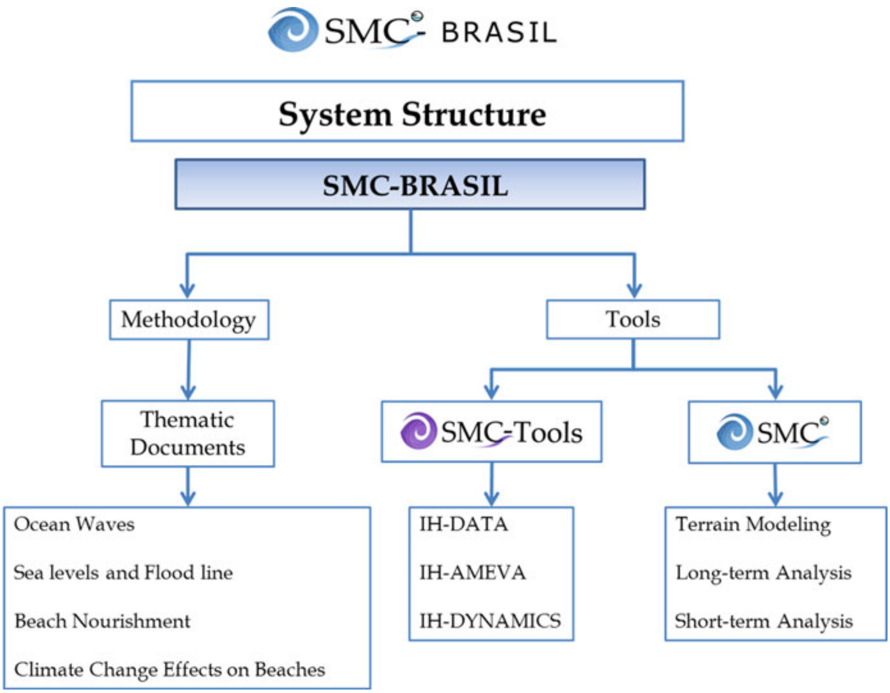

Fig. 2.12 The SMC-Brasil is composed of four methodological thematic documents and two numerical tools

transport, beach stabilization, climate change effects on beaches, etc. All this information has been summarize in four technical documents: Ocean Waves (IHCantabria 2013a); Sea levels and flood line (IHCantabria 2013b); Beach nourishment (IHCantabria 2013c); and Climate Change Effects on Beaches (IHCantabria 2013d).

- Numerical tools: a set of numerical models and statistical tools are used develop coastal projects and manage the coast using the methodology and databases, described in the thematic documents. There are two principal modules: SMC-Tools and SMC. The first one covers bathymetry and marine dynamics databases, obtained by reanalysis. The second one includes numerical model and statistical tools and permits the application of those methodologies and formulations proposed in the cited above documents in Brazilian coastal projects.

SMC-TOOLS was specially developed for SMC-Brasil version in order to help coastal designers and managers to obtain input data (wave and sea level series, bathymetries and images), marine and littoral dynamics on the beach and to readily process all this information to carry out coastal projects and managements.

It is important to highlight that the SMC-Brasil is not a static system, but allows for the incorporation of new databases, methodologies and morphodynamic models, at different time and spatial process scales.

2.8.3 System Skills

SMC-Brasil permits the study of marine and littoral dynamics required to understand the coastal response to those dynamics at different spatial and time scales (short, medium and long-term, or even changes in the near future). This makes it suitable for many coastal engineering applications: sediment transport studies, coastal evolution and stabilization studies, coastal flooding assessment, beach nourishment projects, etc.

In order to show some skills of SMC-Brasil, some results obtained in a study of Massaguaçu Beach (north coast of Sao Paulo) are shown in the Appendix 1.

2.9 Summary and Conclusions

Brazil has a large shoreline (approximately 9000 km), which spans from 5°N to 35°S parallel, resulting in considerable physical and environmental diversity.

This diversity is characterized by heterogeneity regarding the coastal morphology and the marine climate (waves, sea level, etc) and meteorology (atmospheric pressure gradients, winds, etc).

Previous studies reveal wave climate and sea level vary along the coast and there are some specific zones with a large seasonal variability.

In general, wave energy increases from north to south, while tidal range decreases from north to south. However, some zones have a regional behavior and morphology due to the complexity of the dynamics affecting the coast.

For example, Amazon gulf region is conditioned by the interaction of different meteorological and oceanographic agents, owing to the intense water and sediment discharge, the high annual precipitation, wave action, and especially the meso-mega tidal regime (Pereira et al. 2010). These agents also have significant seasonal variability and generate a challenging morphology to study.

In this chapter the diverse behavior has been confirmed by analyzing the reanalysis wave, tide, wind, coastal flooding and storm surge databases generated for Brazilian coast, following the methodologies described in IHCantabria (2013a, b). These databases have been calibrated and validated and reflect a good fit to previous studies, except in Amazon region, due to its complexity.

During the last few decades, the interest in Brazilian coast has increased owing to major environmental and coastal erosion problems. For example, Massaguaçu beach (SP) has an erosion problem in its central part, leading to shoreline retreat and the exposure of littoral infrastructures (see Appendix 1). In order to help in the study of coastal dynamics and their effects on the coast, a new version of Coastal Modeling System (SMC-Brasil) has been developed. It is a user-friendly system specifically designed to assist coastal designers and managers in the analysis of marine and littoral dynamics to understand the changes in coastal caused by those dynamics.

SMC- Brasil includes new reanalysis databases (more than 60 years, every hour), methodologies and tools to analyze local dynamics and its response on the coast in the short, medium and long-term, or even estimate their changes in the future to analyze the potential effects and impacts of those changes on the coast. These characteristics make this system suitable for many coastal engineering applications. For example, this system can carry out studies of sediment transport along the coast in order estimate the potential sedimentation or erosion areas to estimate the gravity of the problem and propose coastal works to reduce the problem.

Coastal flooding is another important topic worldwide, because sea level rise and extremely water levels are flooding some areas that were not previously flooded or are inundated more frequently. In order to help in the estimation of potential inundation zones, a flooding assessment document (Ministério do Meio Ambiente, 2014) was elaborated. This document provides general information about the flooding in coastal areas and can be used to obtain pre-design or rough values of the inundation. However, a more reliable estimation can be obtained by using SMC-Brasil, because it has implemented the required databases and methodologies to consider all the local dynamical processes and morphological variables in the study. This system takes into account the potential climate change effects on the flood line, and consequently, it helps in the estimation of potential flooding risk along Brazilian coast.

Appendix 1: Massaguaçu Beach SMC-Brasil Case Study

Massaguaçu beach is an embayed beach located on the north coast of Sao Paulo in lee of several islands that affect the wave propagation toward the coast and, consequently, the beach morphology. It has an erosion problem along its central part (Fig. 2.13).

Fig. 2.13 Erosion problems in central part of Massaguaçu Beach

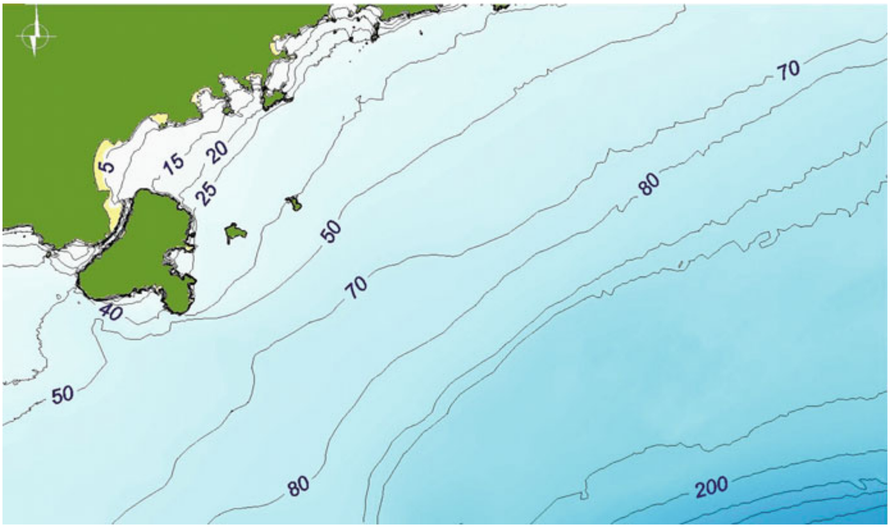

Fig. 2.14 Study area bathymetry obtained from SMC-Brasil (Database generated with General Bathymetric Chart of the Oceans, Brazilian nautical charts and some local bathymetries)

Bathymetry and wave climate data needed to carry out this study were obtained from SMC-Brasil database, which contains offshore and local bathymetry (Fig. 2.14) and wave climate information (Fig. 2.15).

The SMC-Brasil wave climate database, predicts 85 % of the waves arriving from the east-south, with the most energetic waves coming from the south to south-southeast.

Once the offshore wave climate is characterized, it is possible to propagate the wave climate toward the coast using SMC-Brasil. Figure 2.16 shows a southerly storm propagation. As can be seen in this figure, although southern waves are very energetic offshore, the islands provide considerable shelter to Massaguaçu Beach and significantly reduce the wave energy that reaches the beach (approximately 70 % in this case).

The analysis of current patterns for all the wave directions in the study area revealed that there are three main zones along the beach (Fig. 2.17):

- In the south, currents are irregular, with direction depending on the wave direction as well as transverse currents.
- In the center, there is a reduction in current magnitude and a change in direction.
- In the north, currents generally increase toward the northeast, except at the end of the beach, where an offshore rip current is generated for some wave directions.

These wave dynamics and currents generate a net sediment transport from the central part of the beach toward the extremes, with a net longshore sand transport toward the north, resulting in an erosional "hot spot" in the center of the beach,

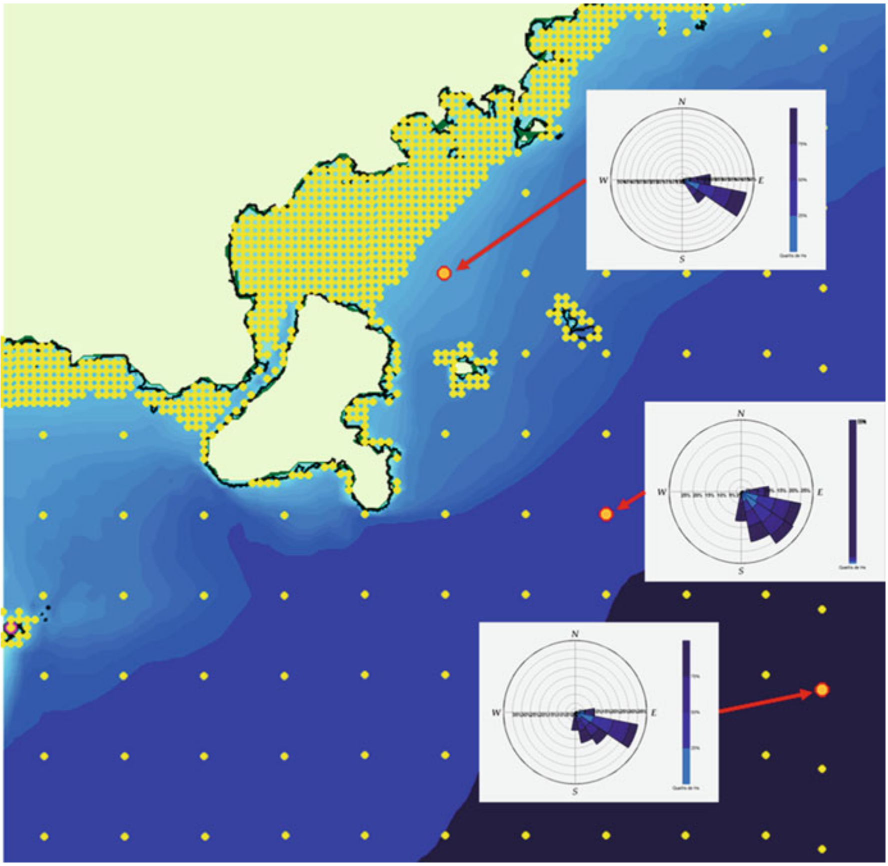

Fig. 2.15 Downscaled Ocean Waves (DOW) points near the study site are shown. Wave climate direction of three points are shown to indicate the variations of wave direction in the area of study

where historically the beach has had erosion problems. In order to check the beach stability, the equilibrium planform of Massaguaçu was obtained by using SMC-Brasil. This system fits different equilibrium planform models based on the wave climate at the control point and the energy flux direction. Figure 2.18 shows the long-term equilibrium planform in blue and the shoreline in 2006 in black, and confirms sediment transport toward the north is responsible for shoreline retreat in central part of the beach.

Once the wave-beach morphodynamic are analyzed, coastal works can be proposed to reduce the erosion problem in the study area. For example, one of the proposed solutions in this study was the construction of a detached breakwater in the north (Fig. 2.19). This solution generates a static equilibrium planform in the central-north zone that could reduce the present littoral drift toward the north. The proposed detached breakwater could generate a 60 m width dry beach in the north and predicts a 40 m shoreline advance at central part. However, it requires a large amount of sand nourishment (approximately 1,400,000 m^3) and there is a lack of

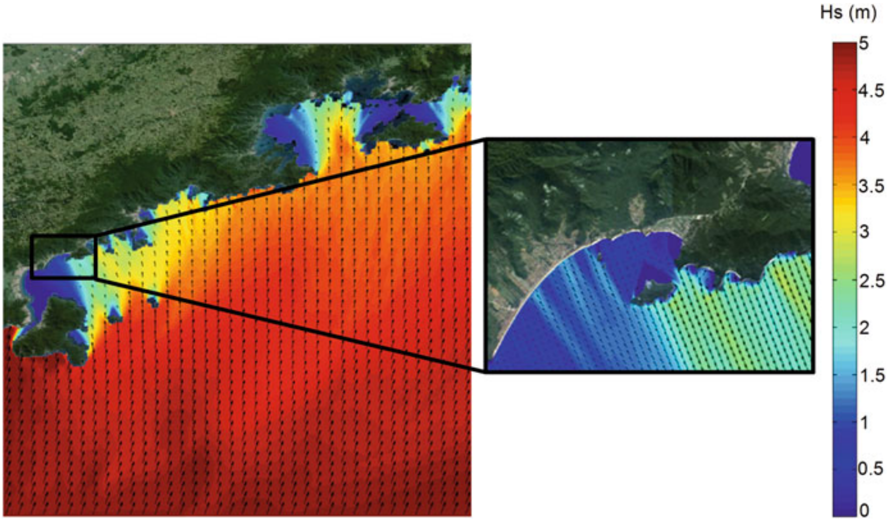

Fig. 2.16 Height and wave direction maps obtained for a southern storm ($H_s = 5$ m and $T_p = 15$ s, approximately). Massaguaçu Beach insert to right

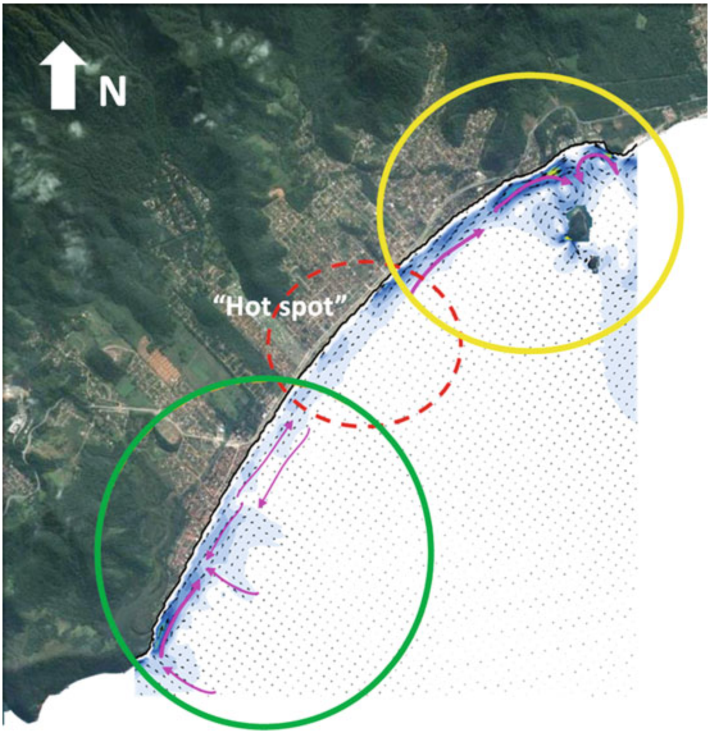

Fig. 2.17 Analysis of current patterns in the three zones of the study area using SMC-Brasil

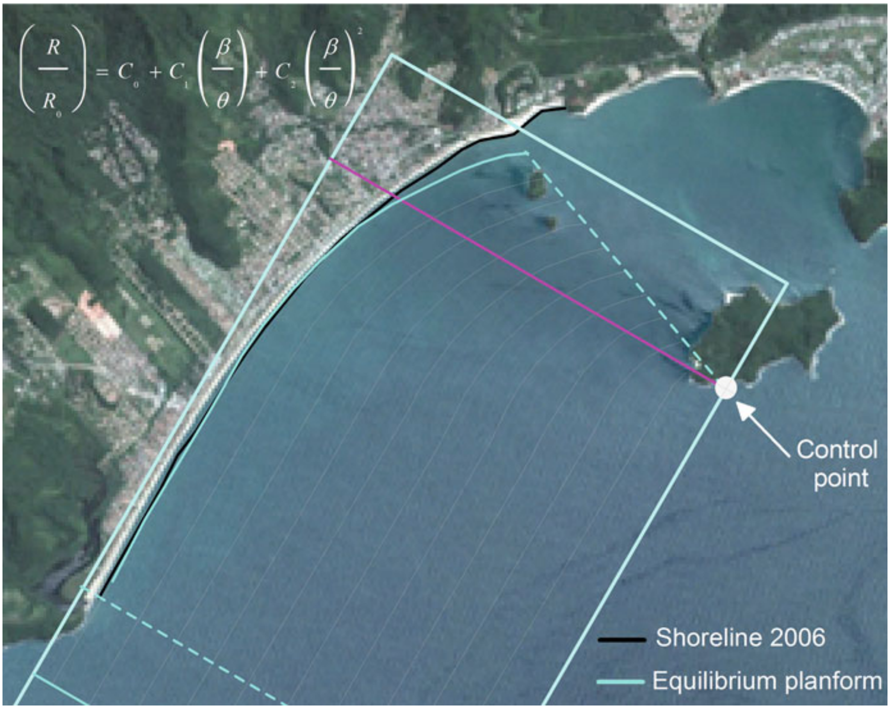

Fig. 2.18 Massaguaçu equilibrium planform

Fig. 2.19 Location of the dettached breakwater and predicted equilibrium planform proposed to solve the central beach erosion

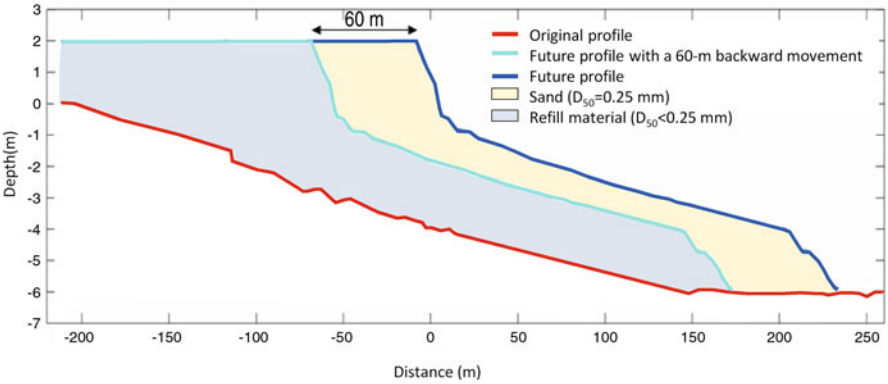

Fig. 2.20 Future equilibrium profile proposed to solve the erosion problem at central part

natural sand sources near the study site. In fact, there is a minimum sand volume required to stabilize the beach, which depends on the dynamics, their variability and the nourishment sand size; but the rest of the refill material can come from other sources, even artificial. In order to reduce the sand volume, it was proposed to nourish the active profile (beach profile affected by dynamics and their variability) with a sediment that permit stabilizing the beach in the middle and long-term ($D_{50}=0.25$ mm), with the non-active profile filled with another material ($D_{50}<0.25$ mm) because it is not affected by the dynamics and their variability. Figure 2.20 shows the associated equilibrium profile.

Finally, the SMC-Brasil can assess the impacts of global climate change impacts in future solutions and can take into account measures to mitigate negative impacts in the present design.

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long as in the case of Rio Grande do Sul and Amapá, or small pockets of sand in embayed beaches. The entire coast of Brazil is exposed to predominately southerly through easterly waves, which result in generally northerly-northwesterly longshore sand transport, though some permanent and seasonal reversals do occur (Dominguez 2009; Toldo et al. 2013). Most of this transport takes place in the surf zone, with breaking waves suspending the sediment, which is then transported northward by the net northerly currents. This transport is extremely critical to beach stability and long-term evolution, i.e. stable, accrete or erode. As a result there have been a number of studies to try and estimate the transport rates. As the rates vary considerably depending on wave climate, shoreline orientation and obstacles (headlands, estuaries, etc.), all studies have focused on local to regional estimates.

The longshore transport can be broken into a number of major cells. Starting in the south at region 7, the Rio Grande do Sul coast is expected to have the highest rates of longshore transport in Brazil, on the order of a few hundred thousand cubic meters per year. In region 6 the transport is largely interrupted by the presence of bedrock headland, islands and large bays, leading to numerous smaller sediment cells. In region 5 northerly transport resumes but is interrupted in places by river mouths, reefs, bedrock and some larger bays. Region 4 has a more continuous coast, but again interrupted by several river mouths and estuaries together with headlands. Region 3, like Region 1, experiences large rates (~ few 100,000 m^3 $year^{-1}$) of northwest sand transport both along the shore and in the massive dune fields. Bypassing and overpassing is common on most of the headlands. Region 2 experiences considerable local west to northwest transport, which is however continually interrupted by the numerous estuaries in the east and bays, headlands and mangroves in the west. The northern region 1 is dominated by fluvial and tidal transport in the Amazon River mouth, with waves, tides and the Brazilian current maintaining northerly sand and particularly mud transport along the northern Amapá coast, which continues for 1500 km to Venezuela.

Estimates of the actual rates of longshore transport are highly conjectural and largely based on empirical formulae, such as the CERC formulae (Shore Protection Manual 1984). They range from 500,000 m^3 yr^{-1} in Rio Grande do Sul (CPE 2009); 20,000 to 500,000 m^3 yr^{-1} in Santa Catarina (Klein et al. 2016); 10,000 to 100,000 m^3 yr^{-1} along the Paraná coast (Sayão 1989; Lessa et al. 2000; Lamour 2000; Lamour et al. 2006), to as much as 700,000 m^3 $year^{-1}$ and reaching a maximum of 1,400,000 m^3 yr^{-1} in Ceará (Pinheiro et al. 2001; Maia et al. 2005; Morais et al. 2006), which seems excessive. On the higher energy southeast Australian coast rates up to 500,000 m^3 yr^{-1} have been calculated and calibrated (Pattearson et al. 2012). Based on these rates we would expect maximum rates along the Brazilian coast to be less, but still on the order of a few hundred thousand cubic meter per year. Clearly considerable more research and monitoring of waves, currents and sand transport is required before acceptable estimates of longshore transport can be obtained.

20.4 Beach Development and Impacts

Much of the Brazilian coast has experienced a large increase in coastal population since the 1970s. This increase is associated with the development of ports and industry; the growth of coastal cities, towns and villages; the spread of second homes at the beach; and the growth in coastal tourism and development. Regrettably much of this development commenced at a time when coastal management was non-existent or in its infancy, and despite the subsequent Brazilian coastal management policy (Nicolodi and Zamboni 2008) and state coastal management plans, much of this development is poorly planned and/or sited, leading to a range of issues along the coast. The most critical are related to:

- development too close to the shore which often removes the foredune and back beach, and in many places has led to the armouring of the beach to protect the development and in worst case scenarios the destruction of the beach (Fig. 20.3a);
- high rise development too close to the beaches resulting in 'coastal squeeze', general congestion and sun shading in the afternoon (Fig. 20.3b);
- beach and water pollution from litter and non-existent or poorly constructed/sited water treatment/sewer, which has led to the closure of some popular tourist beaches;
- ribbon development of second homes extending for many kilometers along the beach (Fig. 20.3c);
- development in active coastal dune fields, which both places property at risk and interrupts or stops the natural dune movement and transport of sand (Fig. 20.3d)
- restricted beach access where private property blocks access along long sections of shore.

All this has resulted in a range of problems including destruction of property constructed in the beach hazard zone leading to costly coastal remediation and a general degradation of the beach, beach amenity and coastal environment. The following provide a snapshot of some of these issues along the Brazilian coast.

In the northern **Amazon Gulf states** (Regions 1 and 2: Amapá, Pará and Maranhão) coastal development is limited in extent, with the coast often too difficult or too hazardous to reach or develop. As a consequence while this is a highly dynamic coast with areas of substantial shoreline erosion and movement, there are relative few erosion hot spots. The main areas of coastal development, especially tourist development, occur on a few popular Pará beaches near Belém and in the north at Atalaia and Ajuruteua. In each of these areas development, including houses and bars have been built on the foredune and even the beach, resulting in erosion and destruction of some of the buildings (Fig. 20.3a; Pereira et al. 2016a). Other problems associated with this uncontrolled development and beach usage include sewer pollution, vehicle congestion, noise (loudspeakers), conflicts between difference beach users and hazardous beach conditions leading to rescues and drownings.

Fig. 20.3 Some issues facing the Brazilian coast. (**a**) Beachfront development and seawall protecting a road undermined by beach erosion, Ajuruteua, PA; (**b**) Balneário Camboriú, SC is a very popular and highly developed and congested beach, which is shaded by the buildings in the afternoon; (**c**) second home development occupies 100's km of the coast and in places extends down onto the beach and foredune, such as here at Balneário Rincão, SC; and (**d**) houses have been built in and in front of the active dune field at Ingleses SC, which has stopped the supply of sand to be beach via headland overpassing, leading to erosion of the beach and destruction of property

The **Region 3** coast is also largely undeveloped owing to the extensive beaches and backing massive transgressive dune systems, particularly in eastern Maranhão, Piauí, western Ceará and northern Rio Grande do Norte. In Piauí only 5 % of the coast is urbanized, however most is exposed to erosion owing to both anthropogenic and natural factors. Unplanned coastal development is a major problem including occupation of Pleistocene dunes that has led to their destabilisation and migrating and subsequent burial of property and river courses (Paula et al. 2016).

The eastern Ceará coast is also in places highly developed and has resulted in a range of major issues, which have been studied by Morais et al. (2006, 2008). They found urbanization, property speculation, second home construction and land subdivision has affected dunes, beaches and estuary margins and exacerbated coastal erosion and been responsible for village stress and coastal urbanization. They found 20 places with coastal erosion, some experiencing very high rates of erosion resulting in serious damage to urban infrastructure as at Bitupitá, Maceio, Taíba, Icaraí, Caponga, Iguape and Redonda beaches. The Fortaleza Mucuripe Harbour presents a classical example of the lack of knowledge of coastal processes. The jetty, built in 1939, changed the wave refraction and stopped the longshore transport, as a consequence the Fortaleza's beaches eroded about 200 m (Maia et al. 1998). At Icaraí, Pacheco, Caponga, Mundaú, Canto Verde and Requenguela there has been damage to roads, sidewalks, kiosks, sheds, and entertainment areas, in addition to problems like rocks, beach erosion, spoils, groins, garbage, and difficulty of beach access (Pinheiro and Rocha 2007; Medeiros 2012; Medeiros et al. 2014). Today, coastal erosion is perceived as the most significant threat to tourism and traditional economic activities.

Region 4 includes the major coastal cities of Natal, João Pessoa, Olinda-Recife and Maceió. Along the eastern coast of Rio Grande do Norte Vital et al. (2016) found that one of the main causes of beach erosion was the construction of hard engineering works, as along the beachfront at Ponta Negra, Natal's most popular beach. At Macau and Guamaré shoreline erosion is endangering oil pumping stations, with the erosion accelerated by the construction of groins at Macau, Caiçara do Norte and Touros beaches. There is extensive erosion along the Tertiary cliffs in all states except SE. Along the highly developed Recife coast Pereira et al. (2016c) found that the unplanned urbanisation allowed development on the beach and foredune, which has in turn led to 20 km of hard engineering works, which have increased the problem, leading to further works. All this was done "*without the proper knowledge of the coastal processes and without any technical support. This did not solve the problem but rather had magnified and transferred it to neighboring downdrift areas*" (Pereira et al. 2016c). They go on to state "*As an answer to (the erosion problems) the state government had started a new project in which most of the beaches of the area will be nourished and several hard engineering structures or will be covered by sand or will be reduced in size so they can not interfere as much with the longshore….*"

The long **Region 5** has a considerable mix of coast and coastal development, with Aracaju, Salvador and Vitoria being the most highly developed coast cities. In Bahia Dominguez et al. (2016b) "*… attribute the most severe erosion to sediment interruption by engineering works associated with port facilities (eg the Port of Ilhéus)..*" as well as other natural processes. In Vitoria bathing is frequently prohibited at the main city and tourist beach because of pollution (Fig. 20.4). Elsewhere in the state Albino et al. (2006, 2016) found "*The intense occupation of the beach, foredunes and ridges increases erosion vulnerability due to reduced sediment availability*". Resulting in "*Roads, parking places and kiosks are frequently threatened by erosion.*" The "*coast have been subjected … to anthropogenic impact, though port construction, urban occupation and uncontrolled touristic development. As a consequence beach sediment transport and morphology have been changed … erosion has been exacerbated by engineering projects …. and longshore transport is interrupted.*"

Sergipe has a relatively short (165 km) coast consisting of several long regressive-stable barriers separated by large dynamic inlets. Outside of Aracaju much of the coast is undeveloped. Aracaju has developed along the mouth of Rio Sergipe and there has been considerable port development, which is protected by seawalls and groynes. The open coast and particularly the popular Atalaia beach is well managed

Fig. 20.4 Example of sign prohibiting bathing owing to polluted waters at Vitoria, ES (Photo: A D Short)

with a broad buffer zone and set back. However further south at Mosqueiro and Caueira bars, roads and restaurants have been built too close to the shore and have been damaged by erosion. The biggest erosion problem is at Saco where development along the shore of the dynamic inlet mouth has led to the construction of 3 km of irregular seawalls.

The **Region 6** has the highest coastal population in Brazil with the major cities of Rio de Janeiro, São Paulo, Curitiba, Joinville, Itajaí and Florianópolis all located on or close to the coast. The result has been extensive and intensive coastal development for ports, industry, urbanization and tourism. In the Rio de Janeiro region Muehe and Lins-de-Barros (2016) found that "*Because they are located in heavily modified urban areas, the beaches of this sector have undergone many interventions including land fill, dredging and the building of seawalls. These modifications have changed the original condition of the beach morphodynamics especially of Copacabana Beach*." Brazil's most famous beach was also substantially modified when in the 1960s coarser dredged sand was used to widen the beach, so as to increase the width of the road. This resulted in the development of a steep reflective beach face. In Guanabara Bay Muehe and Lins-de-Barros (2016) found the shoreline "… *has been modified by landfills including the …. center of the city and its port. Artificial coastlines are also found at Niterói and São Gonçalo …..At the back of the bay, …the … mangrove swamps have been highly impacted by the pollution coming from the rivers..*".

In **São Paulo** Mahiques et al. (2016) found "*Anthropogenic activity along the São Paulo coast is more prevelant along the center-north coast of the state, being most dominant in the Santos lowlands, where several economic activities and urbanization are strongly linked to Brazil's largest harbour. Santos has had severe environmental impacts related to pollution (Torres et al. 2009) and coastal erosion.*" They also used Massaguaçú beach to illustrate the rapid coastal development since the 1960s, which transformed the beach and backshore from a largely natural well-vegetated environment to a densely populated urban city (Fig. 15.9). As a consequence of this development including railways and highway too close to the shore the beach is experiencing erosion, with hard structures being built to protect the infrastructure. Santos has also experienced water pollution (Torres et al. 2009) and coastal erosion (Italiani 2014), much of it related to port installation and activities.

In **Parana** state laws have largely kept development off the beach and foredune and even removed a squatter settlement on the foredune. While most erosion in the state is due to natural causes Angulo et al. (2016) found that "… *the southern coastal sector is heavily occupied with erosion problems related to natural coastline shift induced by ebb-tidal delta dynamics as well as human destruction of foredune ridges and constructions over the beach and the beach dynamic fringe*."

In **Santa Catarina** Bonetti et al. (2012) mapped the coast and found that infrastructure (ports, industry, tourism and housing) occupies 48 km (39 %) of the coast, particularly in the north and in Florianópolis bay. Klein et al. (2006) and Horn Filho (2006) also that ".. *coastal degradation, (was) mostly related to coastal expansion*.." and lack of management plans.

Region 7 includes the long barriers and beaches of southern Santa Catarina and Rio Grande do Sul. While there are no big cities there are a number of larger towns like Torres, Tramandaí and Rio Grande-Cassino on or near the coast. In addition there are extensive areas of second homes spread for many kilometers along the coast of both states, most of which extend down to the foredune and beach (Fig. 20.3c). Esteves (2004) assessed the vulnerability of the RS coast based on four levels of coastal development and shoreline stability. She found that 177 km (29 %) of the coast is in a critical conditions (high development and erosion) particularly in the north and round Cassino. Also at Cassino Lélis and Calliari (2006) and Calliari et al. (2010a) found that the long inlet jetties have both significantly modified the coast, while dredging of the inlet lead to massive mud deposition on Cassino beach, one of the most popular beaches in the state.

20.4.1 Summary

The Brazilian coast has experienced a large increase in population, occupation, tourism and development over the past 40 years. This increase is manifest in the rapid growth of coastal cities and towns, the spread of second homes along the coast and the boom in tourist trade and development along the coast. These same pressures are likely to increase into the future. Unfortunately much of the existing development has been un- or poorly-planned, and where management plans did exist they were often ignored. While integrated coastal management (through the Coastal Management-GERCO) was proposed three decades ago in 1987, not all coastal states have developed their State Plans for Coastal Management (DOU 2004).

In addition there was little or no knowledge of the impact of development on coastal processes. As a result there has been a series of adverse impacts along the developed parts of the coast as mentioned above. While most of the development cannot be undone or removed, there is an urgent need to ensure future coastal development is planned and regulated so as to minimize its impact on the coast and to optimize the use of the coast without degrading it. Unless changes take place soon, the Brazilian coast will continue to be degraded, coastal processes will continue to be interrupted, erosion will increase and the coast will become an increasingly expensive problem, rather than an economic potential.

As Pinheiro et al. (2016) state, in Ceará coastal erosion is the most significant threat to maintaining income in many areas that depend on tourism and traditional economic activities. As a result this is a challenge for both coastal dwellers and the coastal managers to find new ways of living with the coast, including redesigning coastal occupation as well as minimizing the impacts of the sea.

As is evident in this review there is need to break the nexus between coastal development and coastal degradation. It has started to happen in some states. Perhaps the best example is Paraná where there has been a combination of protecting parts of the coast in national parks, while regulating development in the remainder of the coast. The Guaraqueçaba Environmental Protected Area was established in 1985 and the Superagüi National Park, which covers the entire northern Paraná coastal zone, was established in 1989. Also during the 1980s State laws were passed to prevent environmental and urban degradation (Sampaio 2006). However there have been several cases, where the state regulations were not respected. Another good example of coastal tourist development is at Atalaia beach at Aracaju, SE where there is a 100 m wide protected foredune area, which provides an excellent buffer zone between the beach and backing infrastructure; planned wooden walkways cross the foredune to the beach; regulated beach amenities and kiosks are spaced along the beach; and considerable free parking for beach goers. Also in Santa Catarina a number of illegal houses built too close to the shore and in the foredune area were ordered to be demolished and removed by the state.

20.5 Beach Hazards, Risk and Safety

20.5.1 Introduction

Beach hazards are elements of the beach environment that expose the beach public to danger. These hazards may be physical, biological, chemical or anthropogenic. Beach risk occurs when the public is exposed to beach hazards, while beach safety involves programs and resources that are implemented to minimize the level of beach risk. The Brazilian coast, and particularly its 4000 beach systems, has a wide range of beach hazards that pose a risk to bathers, and there has been considerable effort in the form of lifeguards and signage to help minimize this risk. However much more needs to be done as Brazil still has a high level of beach risk resulting in numerous rescues and drowning.

The main hazards along the Brazilian coast are:

- Physical hazards include breaking waves; variable surf zone topography (bars, channels, troughs); surf zone currents that may move onshore, longshore and offshore, particularly rip currents; inlets and river mouths with deep channels and strong currents; beachrock reefs; coastal and algal reefs; rocks and headlands.
- Biological hazards include sharks and marine stingers.
- Chemical hazards relate to beach pollution from sewerage, shipping and ports;
- Anthropogenic hazards include structures such as seawalls and breakwaters; vehicles on beaches; pollution; beach congestion and conflicting usage when bathers, bodyboards, surfboards, jetskis and windsurfers all compete for space.

All of these hazards pose a risk to beach users, with the level of risk a function of the type and number of hazards and the type and number of beach users. Hazards can range from a low of 1 to extreme of 10 based on beach state, wave height and tide range, while local factors such as rocks, headlands, structures and pollution will increase this rating (Short and Brander 2015).

The presence of these hazards and the risk level is manifest in the number of first aids, rescues and fatalities that occur in the beach environment. In Brazil it is estimated there are 60,000 rescues each year and about 1000 drownings along its coast. This is an unacceptably high level. By comparison Australia with a coast three times the length has about 50 beach drownings a year.

Beach safety is aimed at identifying, reducing and minimizing the public exposure to these hazards, thereby reducing the level of risk. The Sociedade Brasileira de Salvamento Aquatico (Brazilian Society for Aquatic Rescue) (SOBRASA) is the lead agency in Brazil dedicated to reducing this level. Formed in 1995 SOBRASA has developed a range of programs and initiatives to help improve public awareness of the hazards and at the beach improve the safety resources, particularly lifeguards, as well as improving medical response to beach injuries and rescues (http://www.sobrasa.org).

The Brazil's 2700 open coast beaches are exposed to low to moderate to occasionally high waves. Many of these beaches have beach rips, and many also have topographic rips flowing out through or against beachrock reefs, rocks, reefs, headland, jetties and other man made structures. SOBRASA has found that rip currents account for between 60 and 70 % of beach rescues, a figure comparable with other countries (Short and Hogan 1994). They also found that the rips and rescues are most common when waves exceed 0.5 m. On a beach and rip-dominated coast like Brazil, rip currents, both beach rips and topographic rips, are therefore the major beach hazard.

Beach hazards only pose a risk to people when they enter the beach environment. Along the Brazilian coast the level of risk can therefore vary considerably between beaches, and is dependent on the number and type of people on the beach. Whereas a group of surfers can usually handle waves, rips and such hazards, a group of children from the interior with no beach knowledge would be at great risk. In addition many popular beaches experience major seasonal variation in beach population, with massive numbers coming to the beaches during the main vacation period. The level of beach risk will therefore varies considerably in both time and space depending on the prevailing level of beach hazards, which depend in turn on waves, tide, beach state and local factors and the prevailing beach population, which depends on season, weather and time and day of week. Assessing both beach hazards and risk therefore requires continual monitoring of the beach environment, which is best undertaken by lifeguards and remotely using video cameras which can view the beach and surf and estimate the beach population.

20.5.2 Regional Beach Hazards

This section briefly reviews beach hazards along the Brazilian coast.

Amapá is the most aquatic state in Brazil with an extensive network of rivers and channels and numerous people living along the channels. However while it was a long coastline, it has very low beach population, little beach usage and relatively low hazard beaches away from the river mouths. It therefore has a low level of beach risk.

In **Pará** the highest level of beach risk on popular beaches is caused by the high seasonal beach population, high waves particularly at mid to high tide, macro tides and intertidal rocks (Pereira et al. 2016a). They also found "*The lack of local coastal management plans together with the large number of beachgoers (and vehicles on the beach), many with low swimming skills and poor perception of physical hazards, results in a high level of beach risk and incidents.*"

While much of the **Maranhão** coast in undeveloped the sheltered São Luís beaches while free of rips, are closed to the public because of pollution from unauthorised sewerage outlets (Pereira et al. 2016b). Along the **Piauí** coast Paula et al. (2016) identified the following hazards to bathers: river mouth currents, channels and shoals; rips currents; beachrock reefs; submerged rocks; steep beaches adjacent to deep water; and sewer pollution.

In Ceará the popular **Fortaleza** tourist coast has a high risk level with 300–400 rescues each year and occasional drowning. Albuquerque et al. (2010) attribute most drowning and rescues to beach rips. They add that this problem is exacerbated by the poor siting of lifeguards towers and lack of signs and media to warn the public of the hazards.

In **Rio Grande do Norte** Vital et al. (2016) found "*The natural hazards include strong rip and longshore currents, breaking waves and variable topography associated with the many beachrock reefs and headlands*", with the level of risk increasing seasonally during the summer vacation period.

On the **Pernambuco** coast Pereira et al. (2016c) identified the greatest hazards were associated with the many beachrock reefs. These reefs are both a hazards in themselves as well as inducing variable bathymetry and strong topographic rips in

Fig. 20.5 Sign warning of sharks at Boa Viagem beach, Recife, PN (Photo A D Short)

gaps between the reefs, including along the popular Boa Viagem beach (Fig. 10.3). On the open coast beach rips and tidal sand shoals also trap people during rising tides, while sharks are a major biological hazards with an average of three attacks per year (Fig. 20.5).

In **Bahia** Carvalho (2002) found that along the popular Salvador coast rips currents were the major beach hazard. Dominguez et al. (2016b) extrapolated these findings to the rest of the coast and found that the more exposed rip-dominated northern and central sections posed the greatest threat to bathers, with lower risk on the more sheltered reflective beaches, apart from the southern coast where seacliff falls is also a hazard.

In **Espírito Santo** in addition to the usual hazards associated with beachrock, beach and topographic rips, the popular Camburi tourist beach has been frequentely closed to bathing owing to pollution from the adjacent major port (Fig. 20.4).

Along the exposed higher energy, micro-tidal **São Paulo Bight** (Rio de Janeiro, São Paulo, Parana and Santa Catarina coasts), the beach are wave-dominated and beach and topographic rips pose the greatest threat to bathers. In Santa Catarina Klein et al. (2016) found that of the 246 beaches in the state, just over half had 670 beach rips between them, together with 65 topographic rips (Figs. 17.5, 17.6, 17.7, 17.8 and 17.9). They added that the high number of rips is compounded by the lack of hazard awareness by the public. In Santa Catarina marine stingers can be a hazard as well as water pollution. In Parana Angelotti and Noernberg (2010) found the majority of bather swam in non-patrolled areas, half could not swim and most did not ask the lifeguard about bathing conditions. The most comprehensive beach safety study was undertaken by Klein et al. (2005) in Santa Catarina where they investigated beach safety management and public knowledge of beach hazards. They used the results to work with the Fire Department (responsible for lifeguards) to implement a range of measures (see below) to improve public awareness and lifeguard effectiveness.

Along the high energy **Rio Grande do Sul** coast Calliari and Toldo (2016) found "*The combination of higher population during summer seasons and rip-dominated intermediate beaches result in the most hazardous beaches along the northern littoral and Hermenegildo beach (in the south).*" Another interesting periodic hazards is the accumulation of fluid mud up to 1.5 m thick on the popular Cassino beach (Calliari et al. 2001). This mud can trap surfers exposing them in winter to hypothermia, while mud deposited on the beach and covered by sand is a hazard to cars driving on the beach and has resulted in serious accidents. They also found that water quality deteriorates after heavy rain owing to sewer contamination, and beach washouts caused by the rain are a hazard to vehicle traffic.

20.5.3 Mitigating Beach Risk

The only comprehensive study of beach risk followed by the development of a program to reduce that risk took place in Santa Caterina. As reported by Klein et al. (2003, 2005) and Mocellin (2006) the Santa Catarina beach safety program implemented the following measures to improve public beach awareness and safety: (1) publicity about the meaning of warning flags; (2) larger flags; (3) more pro-active lifeguards; (4) more lifeguards; (5) better trained lifeguards; (6) a civil lifeguard association; (7) water safety campaign; and (8) beach safety education of children and teenagers. As a consequence the number of drowning decreased by 80 % along the thirteen patrolled beaches in the study. In Fortaleza a pro-active program by lifeguards to warn people about beach hazards resulted in a 50 % reduction in beach rescues (Albuquerque et al. 2010). Calliari et al. (2010b) provide the most recent overview of beach hazards and safety in Brazil. They concluded that the Santa Catarina beach safety program had been successful and that similar pro-active programs should be implemented elsewhere, together with the use of video cameras to monitor beach conditions and hazard along the Brazilian beaches.

On a national scale the lead organization in implementing beach safety measures. SOBRASA (http://www.sobrasa.org) is a non-governmental organization and a full member of the International Lifesaving Federation (ILS), with lifesaving representatives from 24 states. Since its foundation in 1995 it has developed a wide range of preventative programs aimed at both educating the public, particular children about beach safety, as well as working to improve and expand the network of beach lifeguards together with beach safety signage and information.

Based on the above the following is evident about beach hazards, risk and safety in Brazil:

- Brazil has an inherently hazardous beaches and inlets, with the major physical hazards being beach rip currents, topographic rips, beachrock reefs, rocks and headlands; tidal inlets and river mouths, and the large tide ranges;
- The major biological hazard is sharks, particularly in northeast Brazil, but marine stingers can occur elsewhere;
- Pollution is a hazard in a number of developed locations where sewerage flows onto the beach and in some place is derived from shipping in adjacent ports;
- Using this environment is a Brazilian and tourist population that generally has a low level of hazards awareness and ability identify and deal with these hazards, e.g. what to do if caught in a rip current. As a consequence there is a need for beach safety education in general, and in particularly amongst the younger Brazilians;
- Finally, there is a need to increase, expand, improve and co-ordinate the life-guarding services as targeted by SOBRASA. This improvement should include better training, more lifeguards, better equipment (e.g. jet-skis, helicopters, medical facilities); and better signage to both educate and warn of hazards (Fig. 20.6). This should be coupled with beach management plans that provide a well-managed and safe environment for people to recreate and bathe at the beach.

Fig. 20.6 Lifeguards in their distinctive red and yellow uniforms placing red flags to identify and warn of rip currents along Boa Viagem beach, PN (Photo: A D Short)

Until such measures are implemented there will continue to be a high level of beach risk along the coast and a high level of rescues, accidents and drowning.

20.6 Future Beach Research

This book highlights what is known about the Brazilian coast and particularly its beaches at the present time. It shows that there is a good general understanding of the range of beach systems along the coast and to a degree of their behavior. It also examines the impact of coastal development on the beaches as well as assessing the extent of coastal erosion and inundation, together with the beach hazards and level of public risk along the coast. The book also highlights areas where we require more information about coastal processes, particular waves, beach response and longer-term beach behavior.

Brazil has a long and highly variable coastline ranging from a tide-dominated north to a wave-dominated south, together with sections dominated by reefs, rivers and bedrock geology. As a consequence there is a need to conduct research across the full spectrum of Brazilian beach and coastal environments in order to obtain both a comprehensive and at the same time a detailed understanding of the Brazilian coast and its numerous coastal systems. Such an understanding is required to effectively manage the coast, as well as prepare for the impacts of increasing coastal population and development and climate change. The wide range of coastal environments also provide an excellent natural laboratory for Brazilian and other researchers to study a tremendous range of coastal processes (waves, tides, currents, sediment transport, etc.) and systems (beaches, tidal inlets, deltas, regressive and transgressive barriers, beachrock and coral reefs, rocky coast, and their associated ecosystems) from tropical to temperate environments.

There are many issues facing the Brazilian coast and its future. In order to effectively manage the coast – its beaches, their development and the public who use them, a better understanding of the coast, its processes and its behavior, is required. Below are some of the areas where more information, monitoring and research is required and where national coastal programs should be implemented as required. It is important to note that the same recommendations were made by the Brazilian coastal community in the final document of First Brazilian Beach Symposium (Finkl and Klein 2003).

1. Wave climate – Brazil is exposed to waves from a range of tropical, temperate and higher latitude sources and consequently has a varied wave climate along its 9000 km of coast. Long term wave monitoring is required right along the coast to both understand the present wave climate as well as detect climate-induced changes in wave climate. In 2015 there were six operational buoys (Recife, Praia do Forte, Santos, Paranaguá, Tramandaí and Rio Grande) (see http://redeondas.herokuapp.com/), however additional buoys are required particularly for parts of the northeast and the north coast.

2. Tides – Brazilian tides range from 11 m to less than 1 m. The micro to mega-tides have a major impact on both beach behavior and sediment transport. A greater understanding of the role of tides and tidal currents is required, particularly in the higher tide ranges of northern Brazil. Also as rising sea level may affect changes in tide range, monitoring and modeling is required to detect and predict the impact of rising sea level on tides. Tides are presently monitored at eleven sites along the coast, but should be monitored along the entire coast by a national organisation.
3. Winds – Coastal dunes dominate much of the Brazilian coast and transport massive volumes of marine sand inland, as well as via headland overpassing to adjoining beach systems. The source, rates of transport and dune migration and their impact all require further study if the dune systems and the sand they transport are to be effective managed.
4. Sediment cells – Longshore sediment transport is predominately to the north along the Brazilian coast. However estimates on the rate of transport can vary by two orders of magnitude, and the identification of sediment cells boundaries both longshore and offshore remains unclear. In addition headland bypassing and overpassing is common. Research is required to obtain accurate measures of sediment transport, cell topography and boundaries, sources of beach nourishment and the impact of human occupation and climate change on the sediment cells and their sediment budget.
5. Coastal-barrier chronology – the chronology or evolution of coastal sectors is required to both understanding how and when the coast evolved, as well as using this information to predict present and future coastal evolution and changes. In addition there have been very few studies of the inner continental shelf, which can play a major role in shoreline behavior.
6. Coastal ecosystems – the Brazilian coast spans the tropics to temperate latitudes and has a wide range of associated sub-tidal (e.g. coral reefs), intertidal (e.g. mangroves), and subaerial (e.g. coastal dune vegetation) ecosystems, all of which are an integral part of the coastal environment and need to be fully understood in order to effectively manage the coast so as to ensure their viability.
7. Shoreline stability – most of the Brazilian coast is sand (and mud) and is inherently unstable responding to waves, tides and sediment budgets. Monitoring of representative coastal sites is required right around the coast to gauge shoreline stability (stable, accreting, eroding) and the drivers of these changes, particularly their response to climate indicators such as ENSO. This can be undertaken with traditional surveying and/or using video cameras, as it occurring at some sites (e.g. Boa Viagem, PN; Massaguaçu, SP; Cassino, RS) and Lidar.
8. Human impacts – the Brazilian coast has undergone massive changes in the past few decades owing to second homes, residential, tourist, urban and port development. Much of this development is poorly planned and located and having adverse impacts of the coast leading to coastal erosion, degraded water quality, pollution, and ground water seepage onto beaches. Where structures are threatened they are often protected with seawalls and groins, which further

exacerbate the problem as well as degrading beach amenity. Past poorly sited development needs to be removed or rectified wherever possible and all future development needs to be planned and managed so as to avoid further degradation of the beaches and placement of development in the coastal hazard zone.

9. Coastal management – integrated coastal management is required throughout the Brazilian coast. Coastal hazards need to be identified, coastal zoning undertaken, coastal management plan developed and the coast developed in an integrated, sustainable way. Most importantly these plans need to be enforced and illegal development prevented.
10. Beach hazards and safety – Brazil has inherently hazardous beaches which result in an unacceptably high level of beach risk as manifest in the high number of rescues and drowning. Beach safety measures including education, information, signage and emergency medical facilities and an improved and expanded lifeguard service are required.
11. Coastal impacts of climate change – climate change will impact the entire coast directly through rising sea level, changing wave climate, changing tide range and rising water temperature, and indirectly though a wide range of secondary and tertiary impacts, such as longshore sediment transport and coastal squeeze. The drivers and impacts of climate change and its impact along the Brazilian coast require ongoing study.
12. Coastal science and scientists – coastal processes do not stop at borders, and there is an urgent need for integrated, multi-disciplinary collaborative research between institutions throughout Brazil and its neighbors, in order to obtain a comprehensive understanding of the Brazilian coast, an understanding that is required for its effective management.

20.7 Conclusions

This chapter has reviewed the nature of Brazil's beach systems, which have tides range from 0.5 to 11 m and waves from near zero to averaging over 1.5 m. As a result the beaches range from wave-dominated to tide-modified and tide-dominated, and within these three types have the full range of beach states, including those fronted by intertidal rock and reef flats. This book has set out to assess the extent, nature and status of these beaches. It has also found that many beaches are unstable and threatened by erosion. The causes of erosion are both natural and a result of anthropogenic factors, the latter including interruption of longshore transport and development too close to the shore. A response to this erosion has been the construction of seawalls, which in turn can destroys the beach-foredune and exacerbate the erosion. Accompanying this development has been an increase in beach usage, which has lead to an increase in public risk on Brazil's naturally hazardous beaches. This risk is manifest in the high number of rescues and drowning which need to be addressed though an expansion in beach safety education and resources.

Brazil has a long, varied and magnificent coast, a coast that increasingly attracts millions of Brazilians as well as visitors. In accommodating this demand parts of the coast have been unnecessarily degraded. The future of Brazil's coasts and beaches requires greater scientific knowledge of the coast and its behavior; better coastal management that is regulated and enforced; and an expansion of beach safety resources to ensure Brazilians can enjoy the beach in greater safety.

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