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

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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
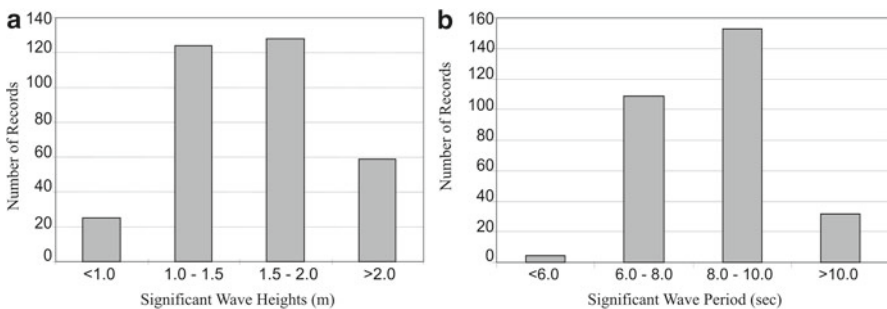
Fig. 2.1 Distribution of significant heights (**a**) and periods (**b**) in Tramandaí between 1962 and 1963 (Wainer 1963) (Adapted from Strauch et al. 2009)
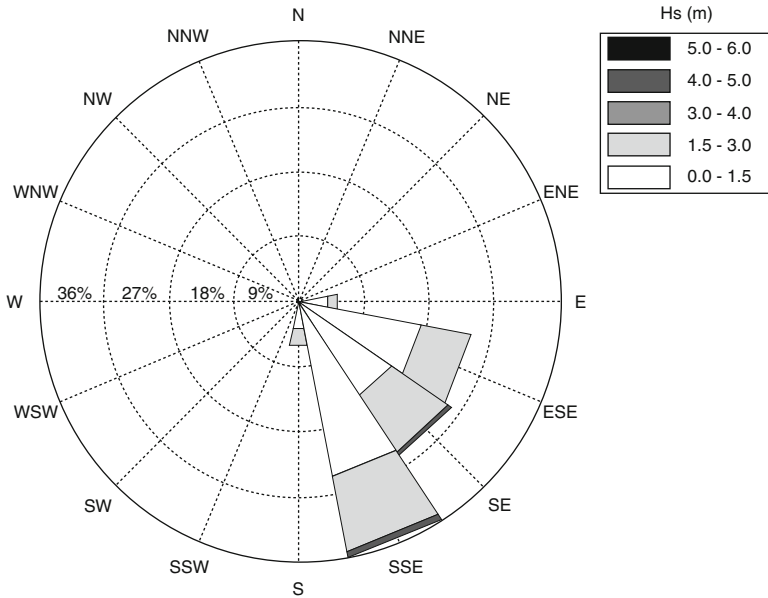
Fig. 2.2 Directional distribution of the significant wave height at the mouth of Lagoa dos Patos (RS) (Strauch 2001)

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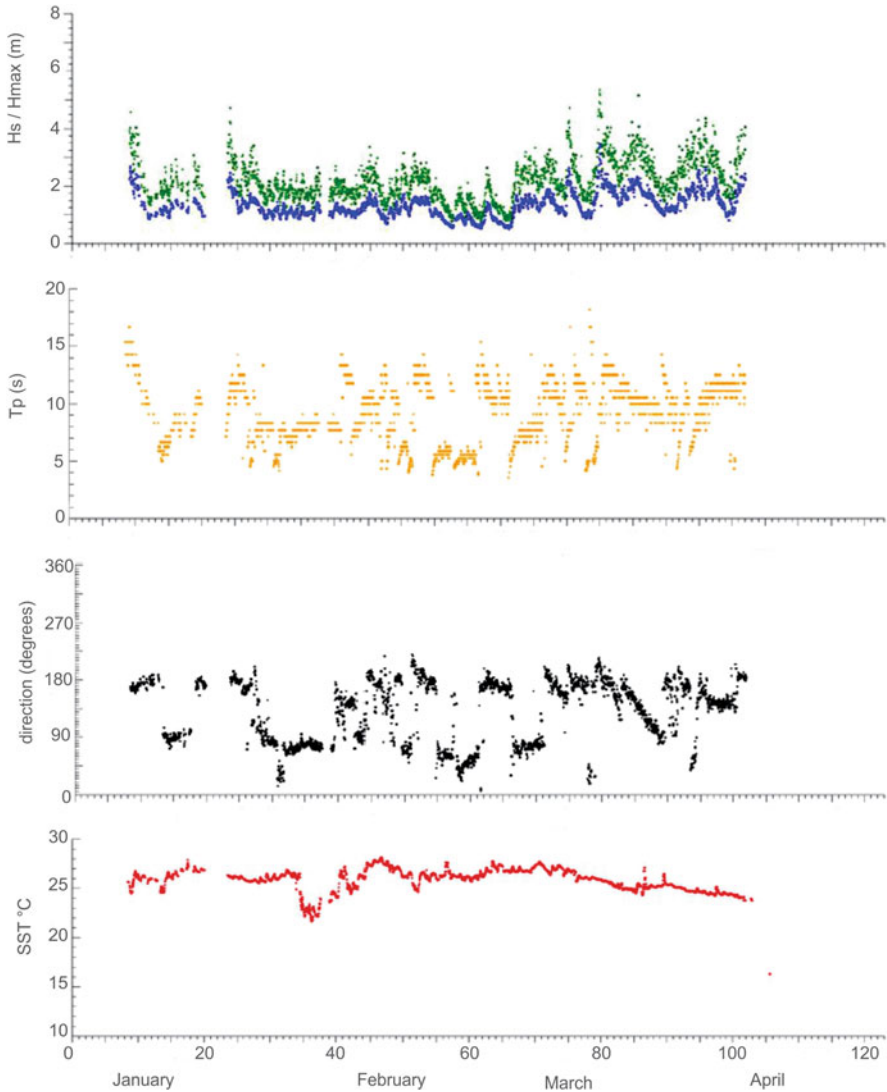
Fig. 2.3 Time series of parameters measured in the first quarter of 2003 off Santa Catarina island. Significant heights (H$_{1/3}$ – *blue*) and maximum (H$_{max}$ – *green*); peak period (T$_p$); Direction corresponding to T$_p$; and sea surface temperature (*SST*)

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://redeon-das.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}.
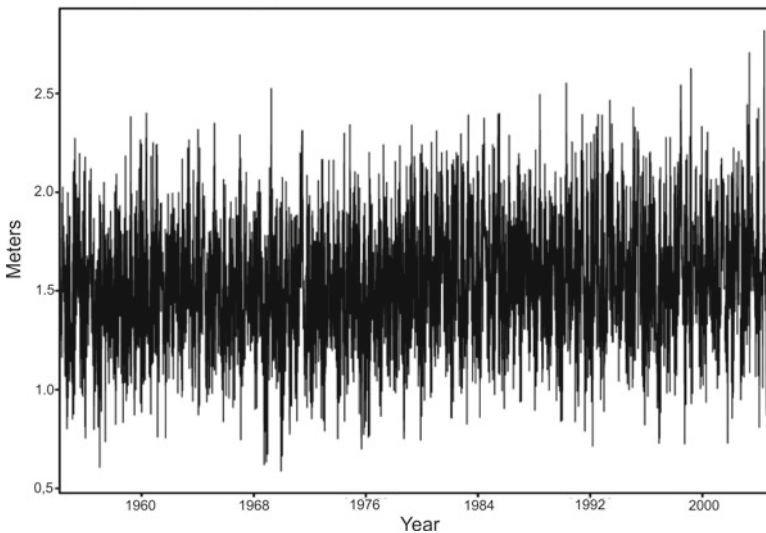

Fig. 2.4 Relative sea level in the region of Cananeia, São Paulo

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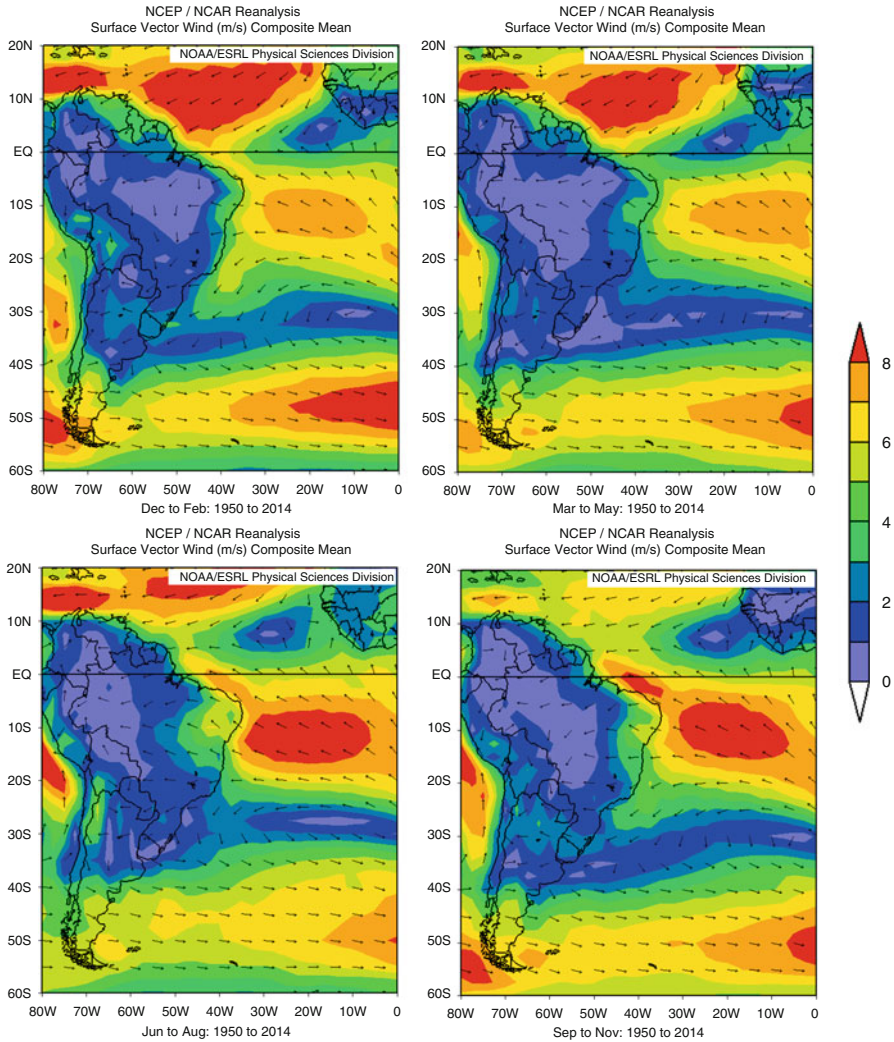
Fig. 2.5 Seasonality of the South Atlantic winds (Data from NCEP/NCAR reanalysis)

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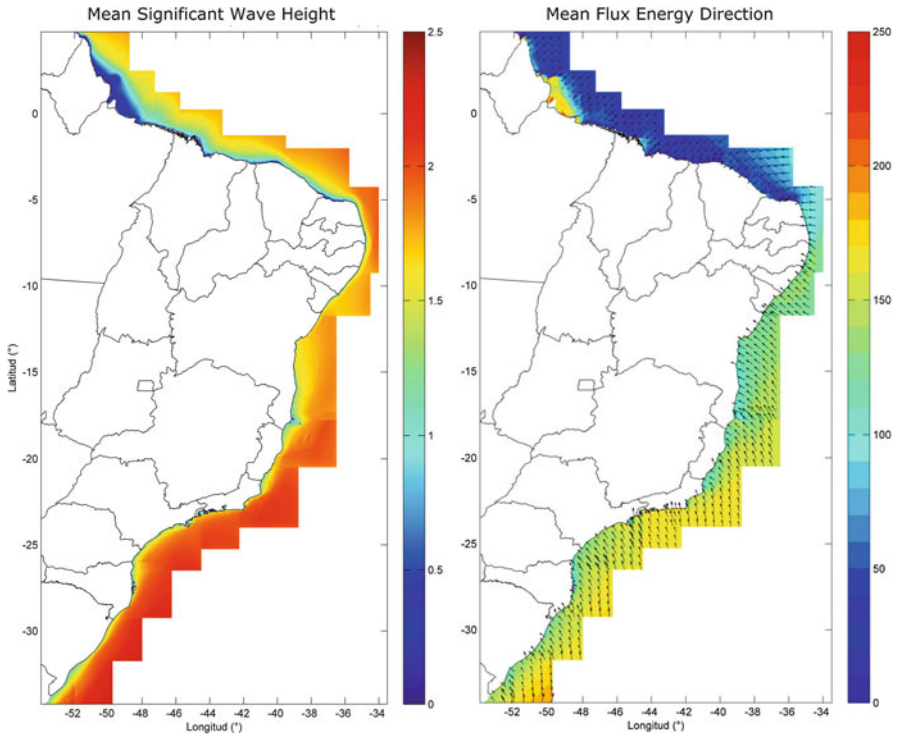
Fig. 2.6 Annual mean H_s (*left*) and FE (*right*) along the coast of Brazil from DOW database for the 1948–2008 period

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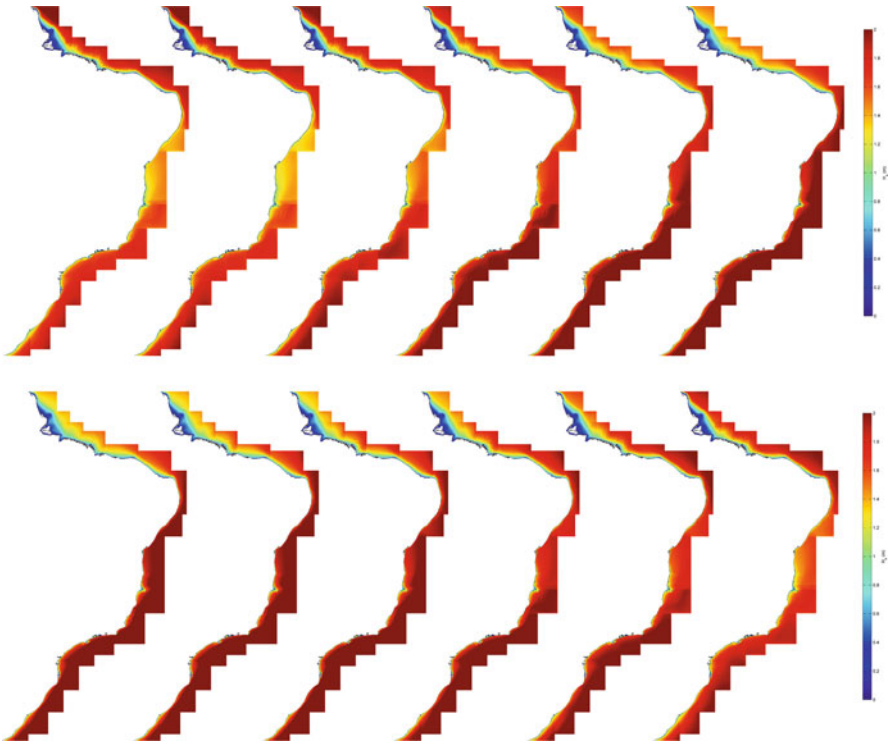
Fig. 2.7 H_s seasonality maps (from January to December) (in meters) on Brazilian coast from DOW database for the 1948–2008 period

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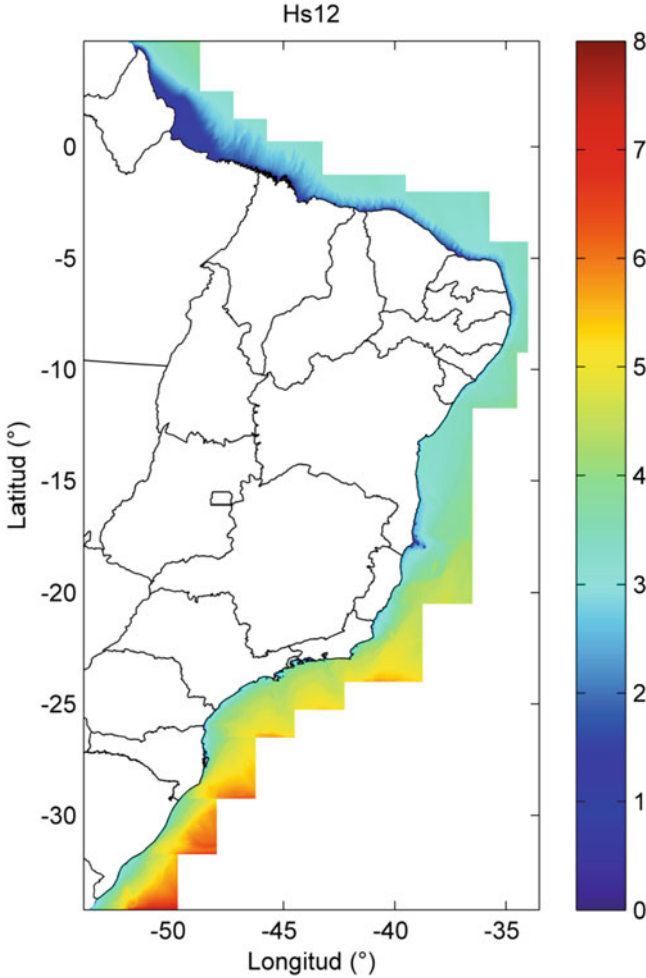
Fig. 2.8 Hs_{12} values (in meters) along the Brazilian coast from DOW database for the 1948–2008 period

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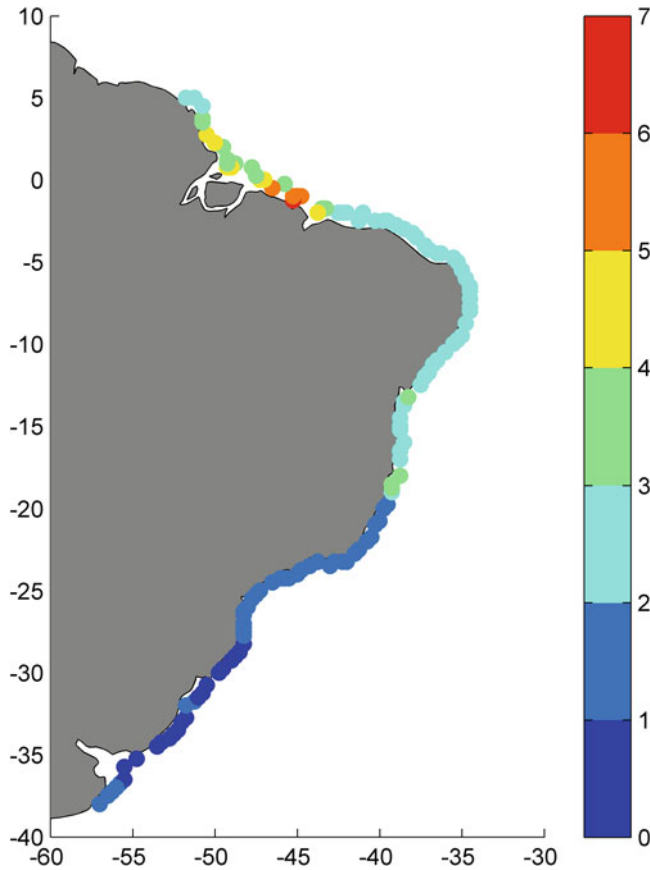
Fig. 2.9 Maximum tidal range along the Brazilian coast from the GOT database along the Brazilian coast for the 1948–2008 period

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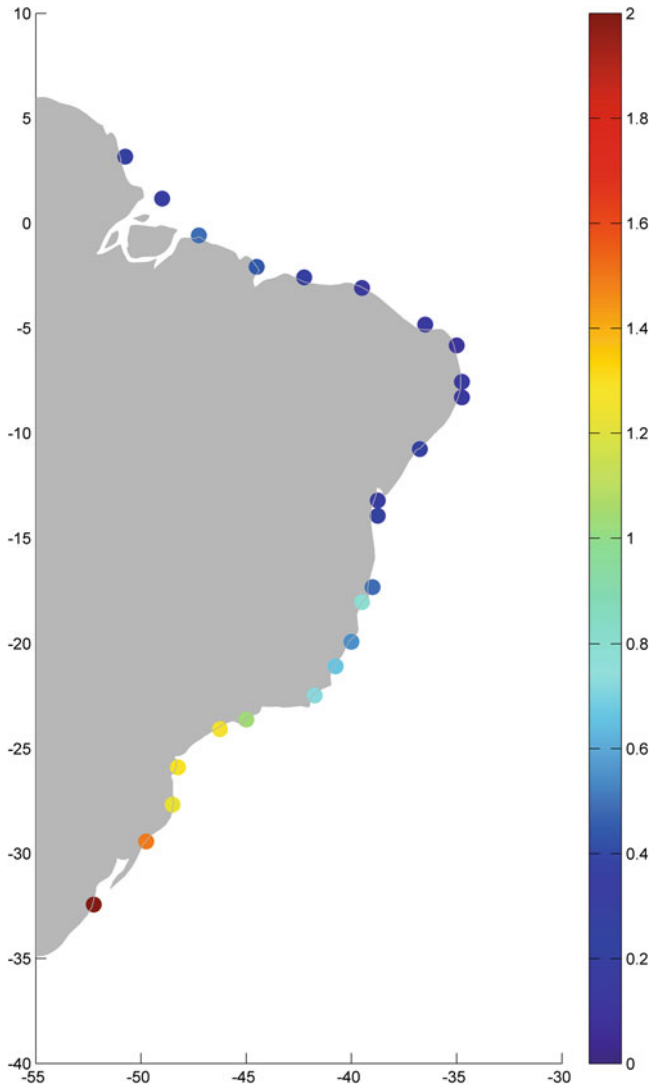
Fig. 2.10 Historical maximum storm surge (meters), obtained from GOS database for the 1948–2008 period

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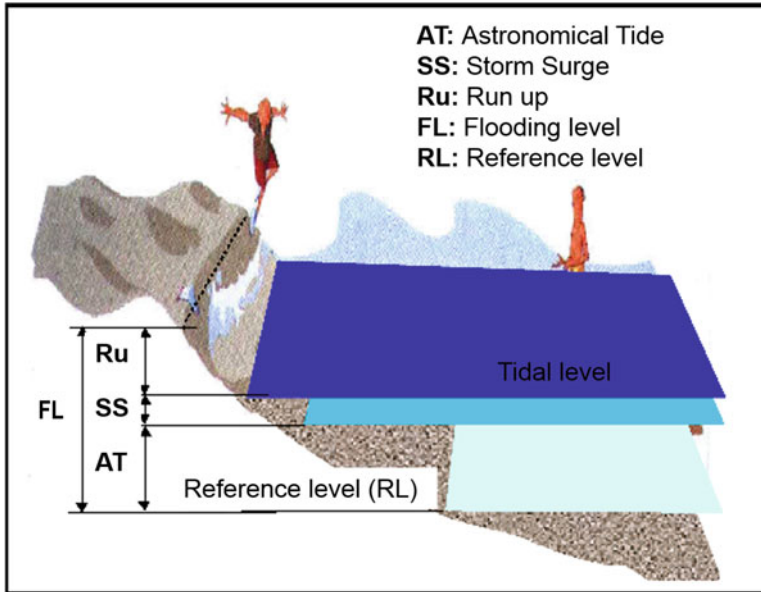
Fig. 2.11 Outline of the factors that define the flooding stage (GIOC 2003)

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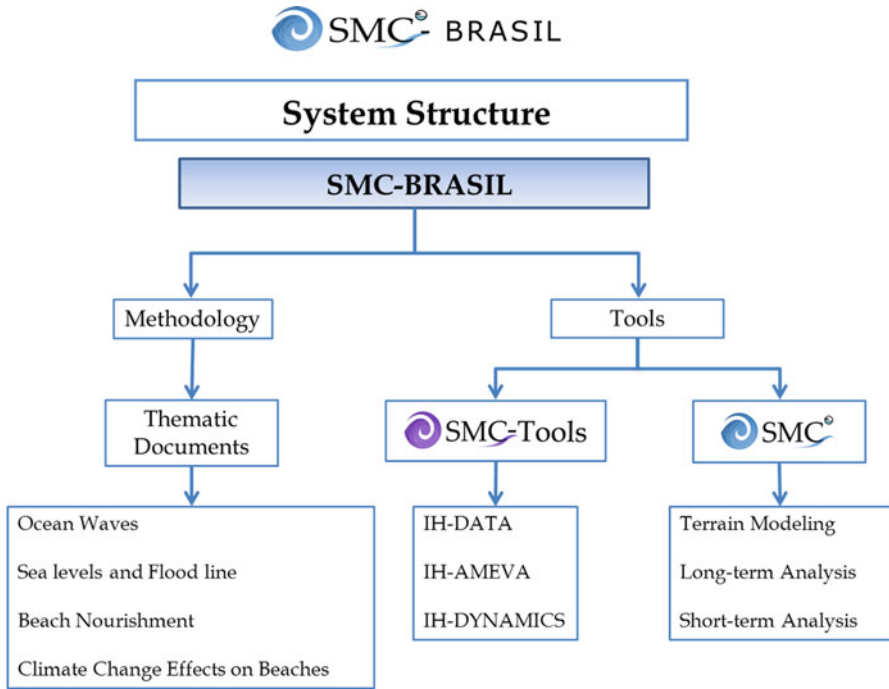
Fig. 2.12 The SMC-Brasil is composed of four methodological thematic documents and two numerical tools

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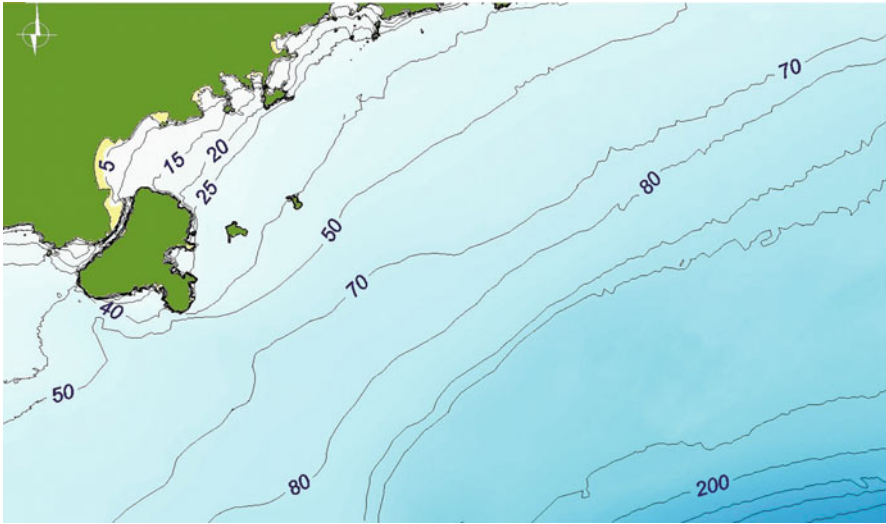
Fig. 2.14 Study area bathymetry obtained from SMC-Brasil (Database generated with General Bathymetric Chart of the Oceans, Brazilian nautical charts and some local bathymetries)

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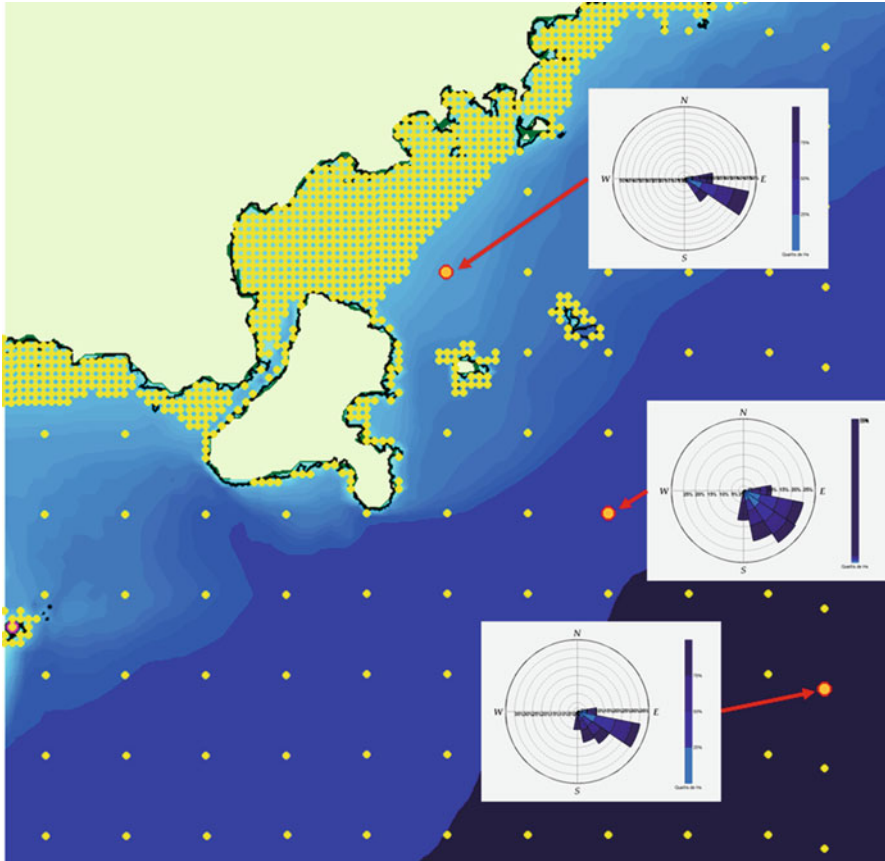
Fig. 2.15 Downscaled Ocean Waves (DOW) points near the study site are shown. Wave climate direction of three points are shown to indicate the variations of wave direction in the area of study

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.
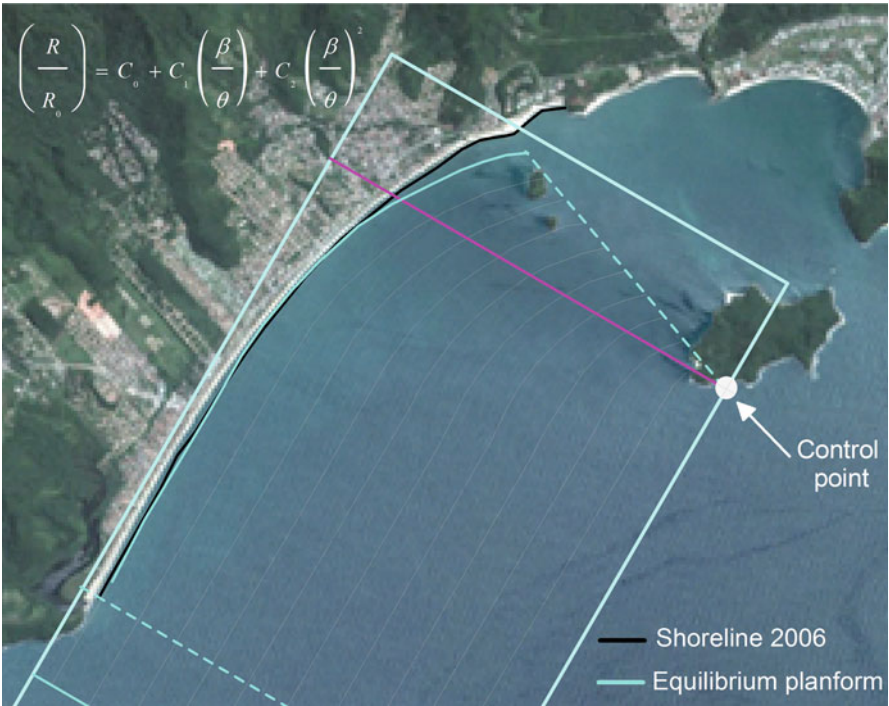
Once the wave-beach morphodynamic are analyzed, coastal works can be proposed to reduce the erosion problem in the study area. For example, one of the proposed solutions in this study was the construction of a detached breakwater in the north (Fig. 2.19). This solution generates a static equilibrium 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 m³) and there is a lack of
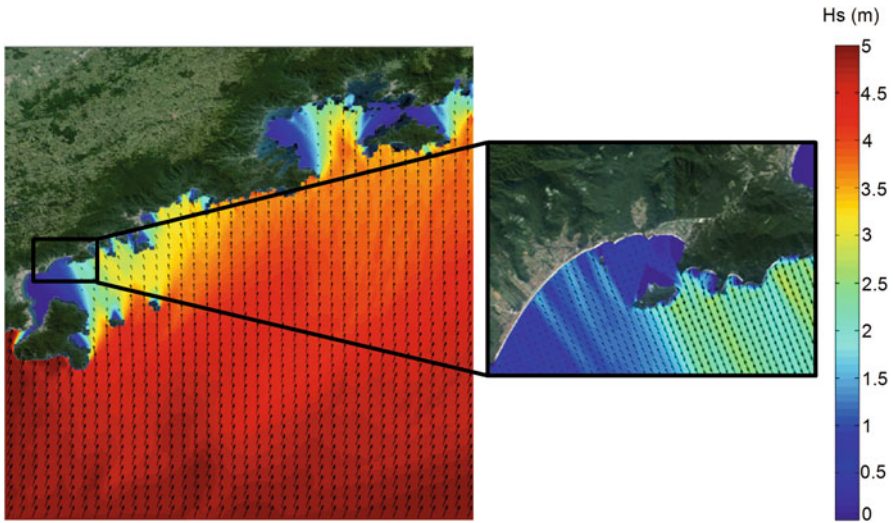
Fig. 2.16 Height and wave direction maps obtained for a southern storm ($H_s = 5$ m and $T_p = 15$ s, approximately). Massaguaçu Beach insert to right
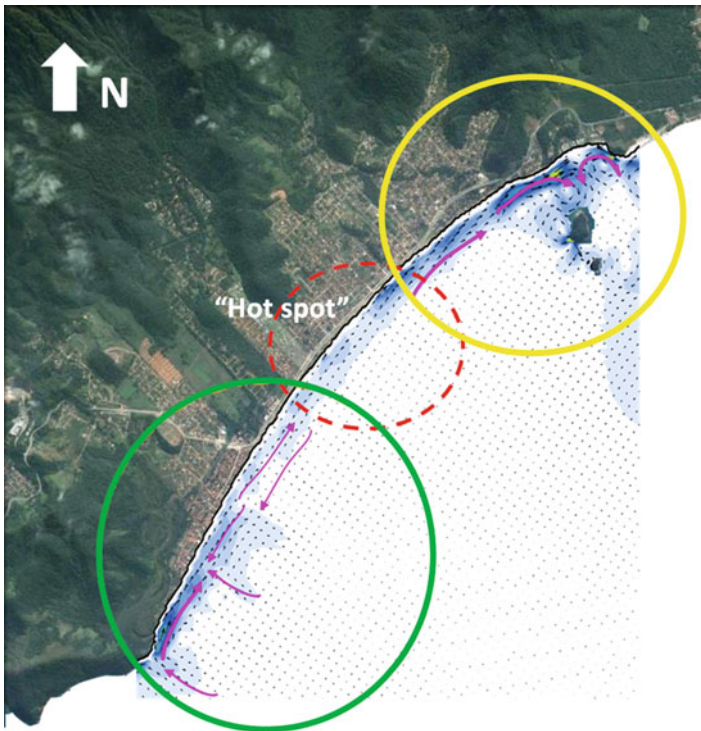

Fig. 2.17 Analysis of current patterns in the three zones of the study area using SMC-Brasil

$$\left(\frac{R}{R_0}\right) = C_0 + C_1\left(\frac{\beta}{\theta}\right) + C_2\left(\frac{\beta}{\theta}\right)^2$$

Control point

Shoreline 2006
Equilibrium planform

Fig. 2.18 Massaguaçu equilibrium planform

60m

650m

Unstable material
Dry beach

Stable zone

Fig. 2.19 Location of the dettached breakwater and predicted equilibrium planform proposed to solve the central beach erosion
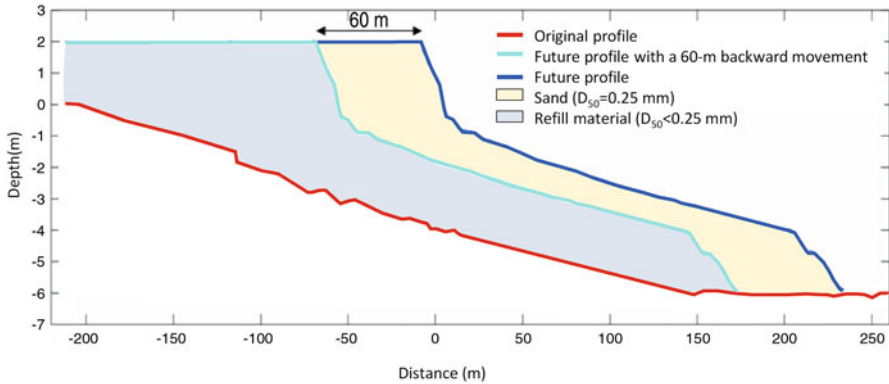
Fig. 2.20 Future equilibrium profile proposed to solve the erosion problem at central part

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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