Environmental Modelling and Software 116 (2019) 131–152

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

SMC$_\varepsilon$, a coastal modeling system for assessing beach processes and coastal interventions: Application to the Brazilian coast

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A R T I C L E I N F O

Keywords:
Littoral processes
Coastal interventions
Coastal numerical modeling
Coastal management
Brazilian coasts
Climate change
2000 MSC
86A05

A B S T R A C T

A user-friendly system designed to understand local littoral processes and design/evaluate coastal interventions, named the Coastal Modeling System (SMC$_\varepsilon$) is presented. The system, which comprises a set of numerical models, state-of-the-art methodologies and numerical databases, is prepared to provide a method for coastal practitioners, researchers and decision-makers to address coastal issues, such as erosion and flooding or to evaluate coastal defense structures. The system incorporates a method to transfer numerically generated, calibrated and validated wave series to the surf zone; to estimate the sediment littoral drift by means of up-to-date formulations; and to estimate the flooding level and impacts such as those produced by climate change. In this paper, these skills are detailed. The system, which is adaptable to any coastal region, was implemented for the Brazilian coast (SMC-Brasil). The implementation includes databases and methodological adaptations to local characteristics, a dissemination plan and the development of several study cases.

Software and data availability

- Name: Coastal Modeling System, (SMC$_\varepsilon$)
- Developer: Environmental Hydraulics Institute of University of Cantabria. Email: smc@ihcantabria.com
- Year first available: 2013
- Software required: Windows 7, Windows 8 or Windows 10.
- Hardware required: Any recent PC with a minimum of 2 GB of RAM.
- Availability: The Brazilian version (SMC-Brasil) is available, for federal and state practitioners, coastal consultant firms and researchers in Brazil, from http://smcbrasil.ihcantabria.com.
- Cost: SMC-Brasil is freely available for those who demonstrate their expertise in the field. Expertise can be demonstrated through a 40-h course (face-to-face or online). Courses and downloads can be requested through the SMC-Brasil official website

1. Introduction

Coastal zones have become poles of commercial and industrial development at the global level. This has generated a significant increase in population in this area, and consequently a high deterioration of the coastal area. Some governments, concerned about this situation, have sought ways to establish development policies based on specific criteria. In particular, in the 1990's the Environmental Hydraulics Institute of the University of Cantabria (IHCantabria) released a Coastal Modeling System (González et al., 2007) with the aim of establishing a methodology to evaluate coastal projects and their effects on the coastal zone for the Spanish Ministry of Environment. The philosophy of the system consisted of grouping together a set of state-of-the-art models and essential data within the framework of a global integrated methodology to study the impacts on the coast for the short-, medium- and long-term via a numerical system available for coastal practitioners,

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https://doi.org/10.1016/j.envsoft.2019.03.001
Received 13 September 2018; Received in revised form 4 January 2019; Accepted 6 March 2019
Available online 11 March 2019
1364-8152/

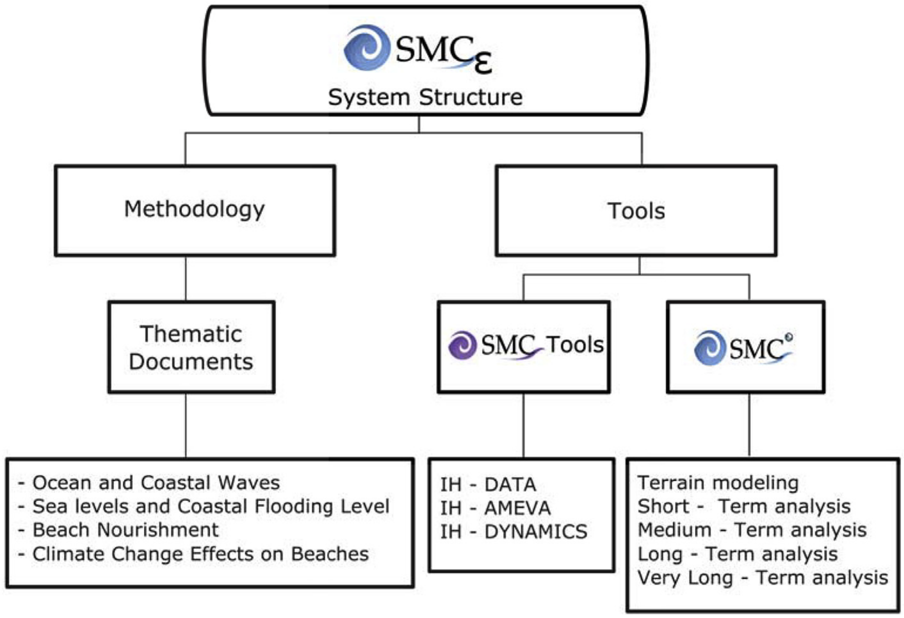

Fig. 1. Coastal Modeling System (SMC_ε) system architecture.

researchers and decision-makers. This framework let coastal issues be analyzed following a method leading to stable solutions. This system has been successful, in the last 20 years, dealing with coastal issues *e.g.*, beach nourishment or beach changes due to coastal inerventions, that has reached more than a thousand users in Spain and presence in more than 60 countries incluiding being officially exported to Taiwan (Yu, 2010), Colombia and Tunisia.

During the last decade, IHCantabria has made a very significant effort to upgrade and develop new methodologies, models and databases to face new requirements for coastal management and society. The result of this effort is a new system prepared to face the current needs regarding coastal engineering and management, named SMC_ε, in which the philosophy of a former system is conserved. The following is an example of the evolution of the system, in the former, the sea waves database was obtained from visual observations of waves reported by ships of the Voluntary Observing Fleet, but in the new system it is obtained by means of a sea waves reanalysis performed using an in-house methodology (*i.e.*, Camus et al. (2011)) producing a set of 60-year time series of sea waves along the domain. These wave series, among other databases, are accessible through the system to be applied on a set of methodologies to lead the user through every stage of coastal interventions design or evaluation.

In the last years, several tools have been presented to deal with specific elements of the coastal proccesses observed on the coast (*i.e.* sediment transport and beach profile changes (Li et al., 2002), diffussion of pollution on coastal waters (Yuan et al., 2007), or coastal flooding (Smith et al., 2012)) to help the decision-makers. However, the coast is a complex system so when an intervention is evaluated it is necessary to consider all the elements involved. For this reason SMC_ε is prepared to study the most important impacts on the coast *e.g.*, flooding, and erosion, and provide a customized methodology according to the problem, and evaluate pertinent short-, medium-, and long-term processes. Furthermore, the system includes a set of tools to estimate, for the very long-term, future potential impacts of climate change on beaches.

The system relies on four fully integrated and operative databases of bathymetry, coastal waves, sea levels and climatic change. The coastal wave and sea level databases are generated numerically and calibrated by means of in-house methods described below and are validated by comparison to *in situ* data from tidal gauges and wave buoys.

The main objective of the system is to provide an engineering tool that adequately reproduces coastal processes, but which is also capable of transforming them into specified results for decision-makers. These specific results are always supported by a theoretical framework fully explained in the thematic documents of the system. In this way the system is able to deal with the main challenges identified by Allison et al. (2018).

The system can be adapted to any country or coastal region of the world by adapting the databases and some results or methodological details according to local regulations. The system was implemented for Brazilian coasts as part of an agreement between IHCantabria, the Brazilian Ministry of the Environment (Ministério do Meio Ambiente do Brasil) and Union Patrimony Secretary (Secretaria do Patrimônio da União) with the support of the Spanish Agency for International Development Cooperation (AECID), producing SMC-Brasil. Adaptation of the system to Brazilian coast is used here to ilustrate the strengths and capabilities of the system. The adaptation was performed in two main stages, in the first one numerical reanalysis for databases and adaptation of the software were performed. The second part focused on the dissemination of the system by means of short courses, and the development of four case of studies from the Brazilian coast in which typical problems with different characteristics are addressed.

In this article a formal introduction of the SMC_ε is presented based on the implementation to the Brazilian coast. First, a general description of the architecture, databases and capabilities of the system is provided. Secondly, to demonstrate the strengths of the system, it is applied to study the undergoing erosion on Massaguaçu Beach and propose a solution. Next, the dissemination plan of the system is described, and finally, some conclusions of the whole system, implementation and application to the case of study are shown.

2. Model description

SMC_ε is composed of four thematic documents and two user-friendly systems (Fig. 1) to guide the users to employ the most appropriate methodology and the correct tools for evaluating and performing coastal interventions according to the requirements of the project.

In contrast to other systems, the purpose of SMC_ε documents is to provide an extensive background and to provide users a guide to the theoretical framework and methodologies to address coastal interventions and, therefore, select the most appropriate tool to address them from initial stages like understanding how the beach system operates to

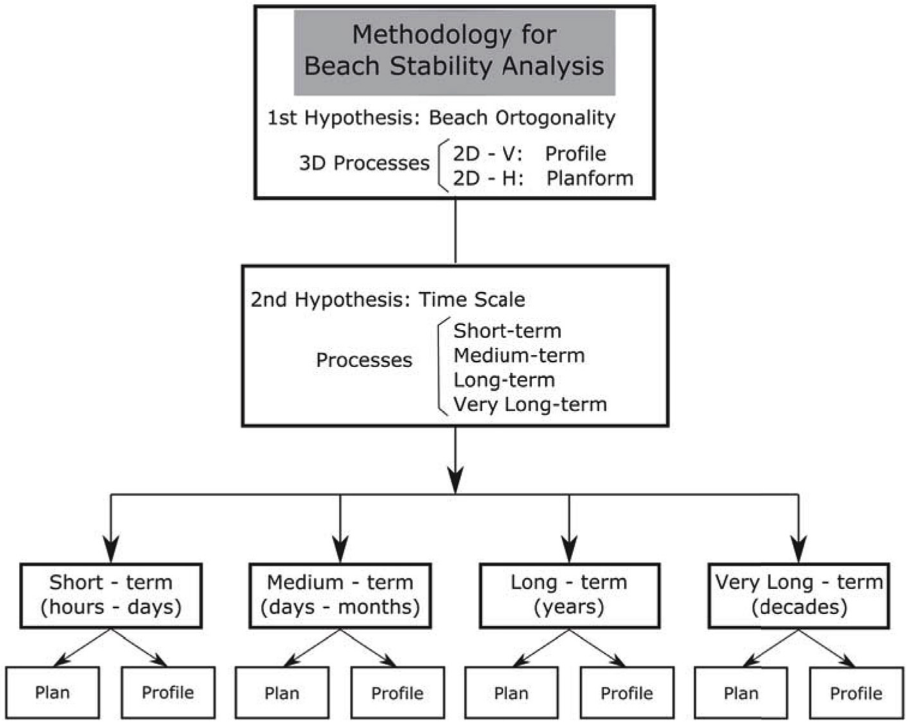

Fig. 2. The SMC$_\varepsilon$ methodology is based on two assumptions: *i)* beach orthogonality and *ii)* temporal scales, which can be analyzed independently. This leads to analyzing four time scales, (*i.e.,* short-, medium-, long- and very long-term), and two dimensions, (*i.e.,* the beach planform and beach profile).

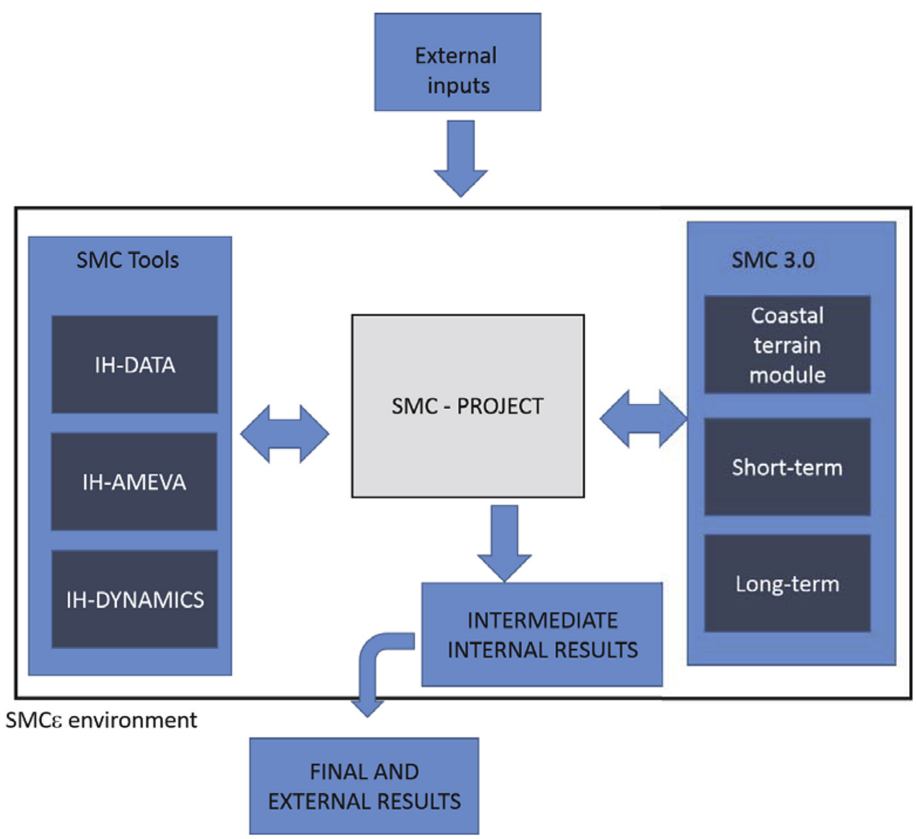

Fig. 3. The architecture of the SMC$_\varepsilon$ is shown. The system consist of a working environment where projects are developed. The SMC 3.0 and SMC-Tools interact continusly on each step of the development following the methdologies described on the documents.

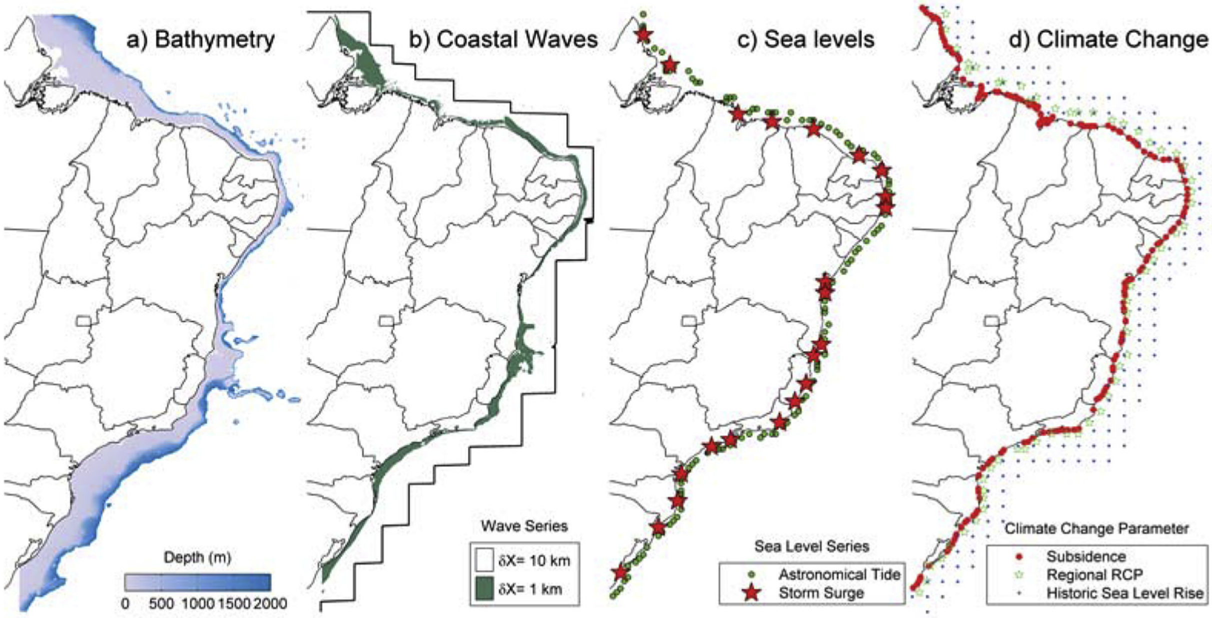

Fig. 4. SMC-Brasil database (IH-Data). *a)* Bathymetry: the shallow part of the bathymetry is shown. *b)* Coastal Waves, the area where waves series can be obtained is indicated. The white zone indicates the area where DOW points have a separation $\delta X = 10$ km, and the black zone is the region where points have a separation $\delta X = 1$ km. *c)* Sea levels, the position where astronomical tide and storm surge series are located is indicated. *d)* Climate Change: the location of three of the parameters used in the climate change calculations is shown on the map.

Table 1
IPCC Global scenarios projections of sea level rise for the 2070 and 2100 horizons.

RCP	variable	2070	2100
4.5	15%	0.25	0.36
	median	0.35	0.53
	95%	0.45	0.71
8.5	15%	0.31	0.53
	median	0.42	0.74
	95%	0.54	0.98

propose solutions to mitigate human interventions. The documents are *i)* Ocean and Coastal Waves, *ii)* Sea Levels and Coastal Flooding Level, *iii)* Beach Nourishment, and *iv*) Climate Change Effects on Beaches. The first two describe the wave and sea level time series reanalysis databases, with methodologies following for the generation of databases, calibration and validation procedures. Furthermore, the Ocean and Coastal Waves thematic document details the methodology to propagate a multiannual hourly wave series to a position of interest near the shoreline or the surf zone by considering local bathymetry and sea level variations. This methodology is fully operational on the system.

The Beach Nourishment thematic document describes the proposed methodology to be followed in a beach stability study and focuses on the diagnosis, predesign and design stages. This methodology is based on two main hypotheses, with the first one related to beach orthogonality (*i.e.,* planform and beach profile processes can be treated independently) and the second one related to the scale of the processes (*i.e.,* processes that occur on different scales must be analyzed with diferent tools). The thematic documents elaborate these hypotheses and explain the tools and models used to analyze the spatial and temporal stability of beaches for the short-, medium-, long- and very long-terms (Fig. 2). Regarding the very long-term, to understand the impacts of climate change on an existing or planned beach, the Climate Change Effects on Beaches document explains how the wave height, wave direction and sea level variations affect the stability of a beach in different scenarios.

The methodologies and databases have been implemented in two numerical tools: a renewed version of the former system, named SMC 3.0 and SMC-Tools. SMC 3.0 retains improved version of *i)* the short-term evolution module composed by a cross-profile 2DV model and a beach planform 2DH morphodynamic model, *ii)* a medium- and long-term module in which equilibrium formulations are implemented, and *iii)* a coastal terrain module to edit bathymetries and design engineering structures (see Fig. 3). A detailed description of these modules can be found in González et al. (2007).

On the other hand, SMC-Tools is a new tool that comprises three main components (see Fig. 1): IH-DATA includes the appropriate databases to be used in system calculations as sources of information. IH-AMEVA is a statistical tool designed for coastal engineering, and IH-DYNAMICS contains the methodology to transfer sea states series to points near the coast and surf zone. This module also calculates the mean wave energy flux of the waves (direction and magnitude), sediment transport (littoral drift time series along the surf zone) and other coastal dynamic time series. Description of IH-DATA and these components is done next, based on the Brazilian version of the system.

2.1. Databases of the system (IH-DATA)

One of the major advantages of this system is the inclusion of several databases, which allows analysis of a coastal area almost with no need of external data. IH-DATA is composed of four databases specifically prepared to provide the required information to be used in coastal studies: *i)* bathymetry; *ii)* coastal sea waves; *iii)* sea levels; and *iv)* climate change scenarios. The IH-DATA databases are accessible through SMC-Tools and represent the most up-to-date available data to be applied through the system. Fig. 4 shows the spatial distribution of the SMC-Brasil databases contained in IH-DATA. IH-DATA represents the most appropriate up-to-date validated data available for Brazilian coasts to be applied in the SMC-Brasil methodologies; nevertheless, databases can be updated according to the most recent models or new methodologies included in the system. This is particularly important for the climate change methodologies, and this capability makes the SMC_ε a dynamic system that can easily be updated to incorporate state-of-the-

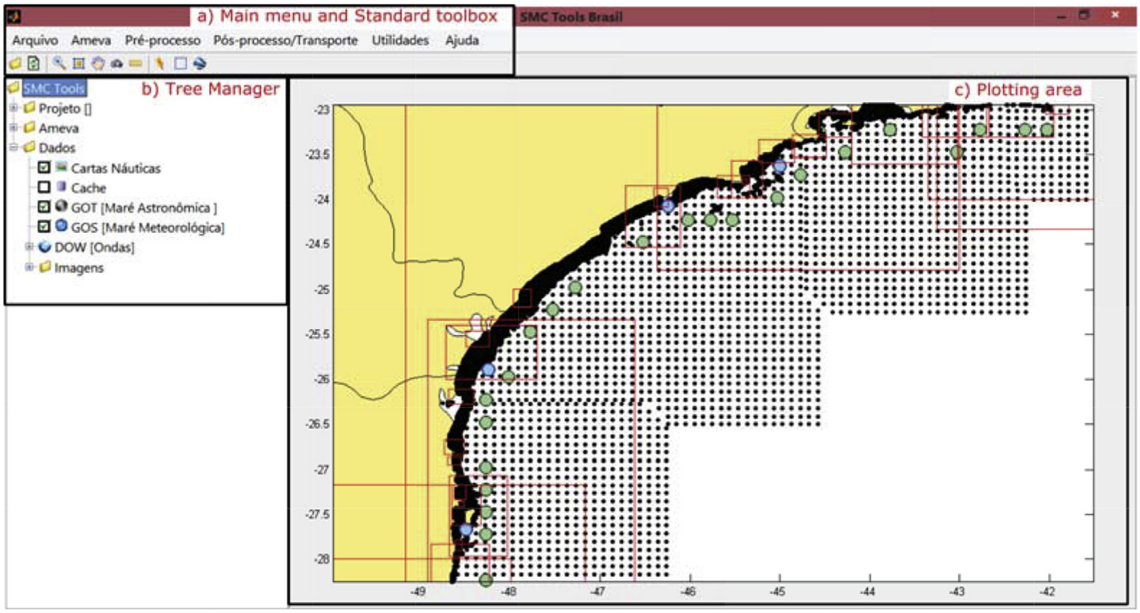

Fig. 5. Overview of main screen of SMC-Tools. a) Main menu and standard toolbox; b) tree manager to navigate between projects, databases, and statistical tools; and c) map and result plotting area. In this figure the tree manager shows the available databases, and the plotting area shows an area with the locations of astronomical tide (green dots), storm surge (blue dots) and wave (black dots) series for this region marked. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

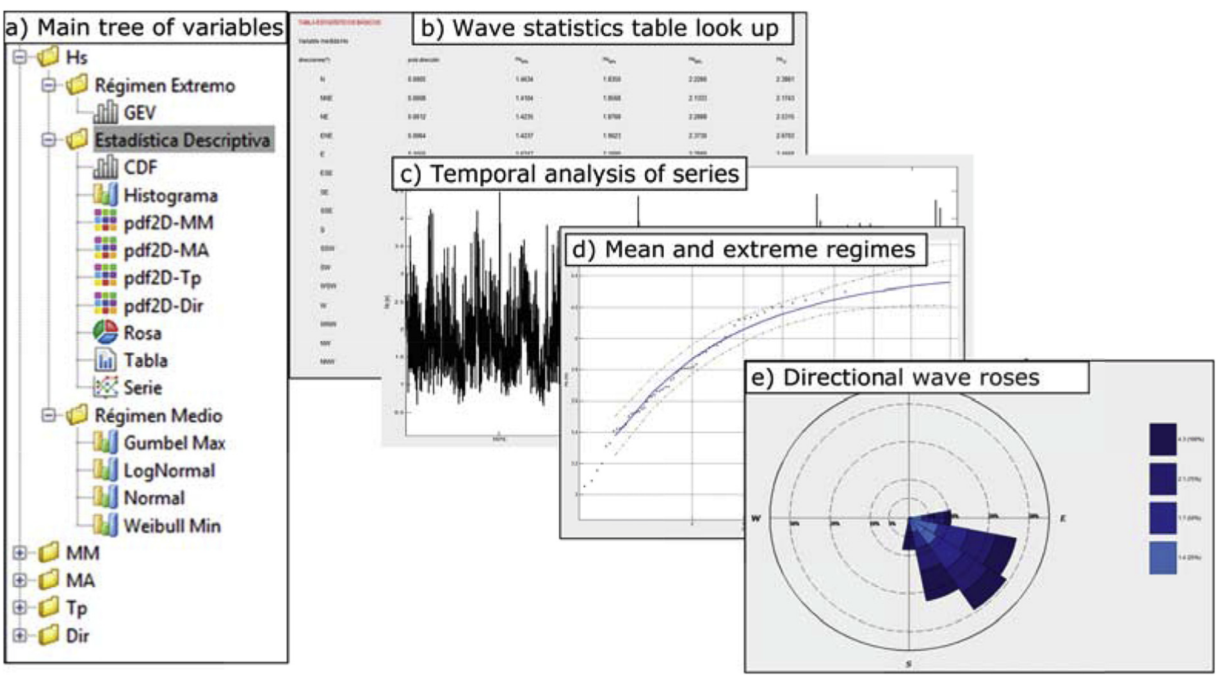

Fig. 6. Overview of statistical analysis available in IH-AMEVA. *a)* Main tree of IH-AMEVA, *b)* wave statistics table, *c)* time series of wave height, *d)* extreme regime of wave height and *e)* directional wave rose.

art methodologies.

The regional bathymetry database along the Brazilian Coast main purpose is to provide a general overview of the sea floor in the nearby area to be used for wave propagation. The bathymetry was created combining 90 nautical charts, of scale higher than 1:100000, from the Brazilian Nautical Charts of the Brazilian Navy (*Diretoria de Hidrografia da Marinha (DHN)/Centro de Hidrografia da Marinha (CHM)*) and GEBCO (IOC, 2003) for depths greater than 50 m. The merged bathymetry data are constructed in such a manner that the best-quality and most-recent data are prioritized. Bathymetry is available through the system; nevertheless, the available data do not have sufficient resolution to adequately define the surf zone and sea floor features in shallow water, which are fundamental for local wave propagation. Therefore, the data must be enhanced by users, with detailed bathymetry with resolution of the order of 20–50 m of the area of interest. SMC-Brasil provides a specific tool for this process. Fig. 4a shows the IH-Data bathymetry, resulting from combining the nautical charts and GEBCO.

The coastal waves database is composed of two main elements: a set of global waves series (GOW) (Reguero et al., 2012) located at depths on the order of 50 m, which acts as source of the wave climate, and a set

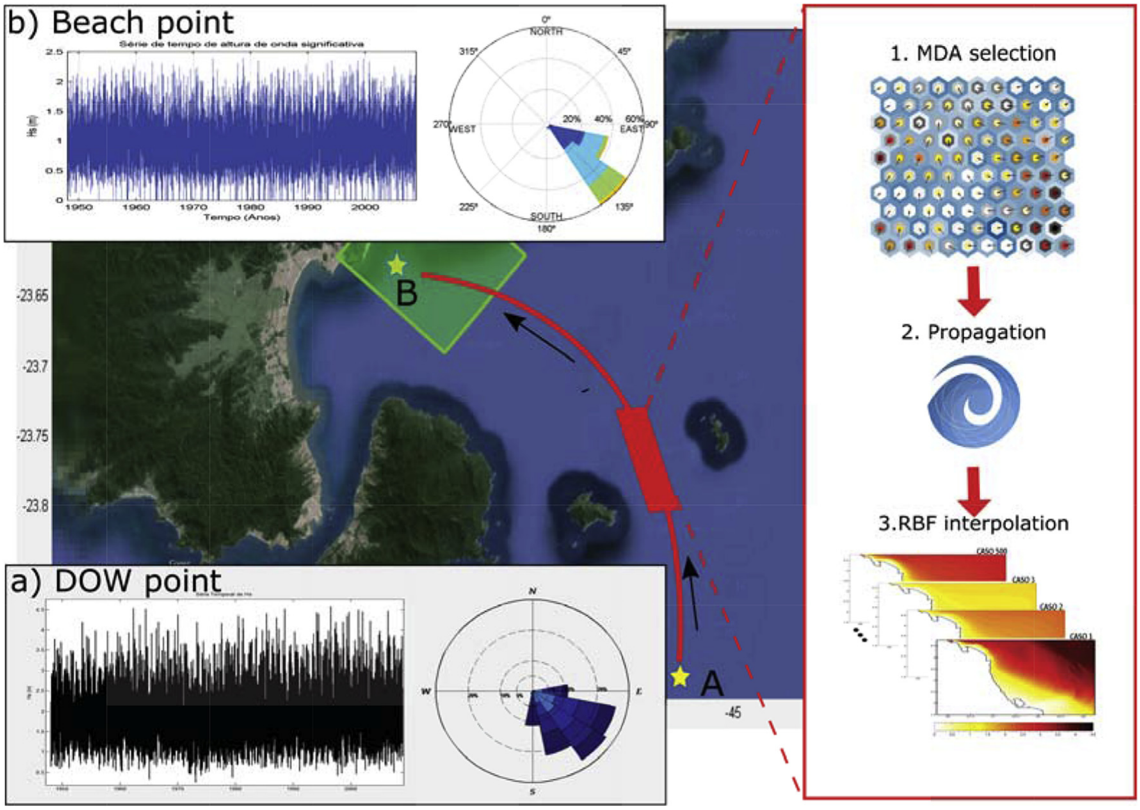

Fig. 7. Diagram describing the methodology of wave propagation from the DOW database (**A**) to the surf zone (**B**). The process has three steps: 1) selection of most representative wave states, 2) propagation of selected cases, and 3) reconstruction of the series.

Table 2
List of available coefficients implemented for the bulk longshore sediment transport formulas.

Formulas	Coefficients
(USCERC, 1984)	(del Valle et al., 1993)
	(Mil-Homens et al., 2013)
(Kamphuis, 1991)	(Kamphuis, 1991)
	(Schoonees and Theron, 2001)
	(Mil-Homens et al., 2013)
(Bayram et al., 2001)	(Bayram et al., 2001)
	(Mil-Homens et al., 2013)

of targets points distributed along the coast, where wave series are transferred by means of an in-house downscaling technique that combines a numerical wave model with mathematical tools developed by Camus et al. (2011).

In the target points, located at a resolution of 1 km for depths less than 20 m and 10 km for deeper areas (see Fig. 4b), a downscaled coastal wave series spanning 60 years (1948–2008) can be obtained. Downscaled variables include significant wave height (H_s), mean wave period (T_m), peak period (T_p), peak direction (θ_p), mean wave direction (θ_m), and directional spread.

The downscale methodology inlcudes three steps: *i)* selection of wind and wave conditions for propagation, *ii)* wave propagation of every selected condition, and *iii)* reconstruction of wave time series by means of the RBF interpolation technique (Franke, 1982).

The source points, from which conditions for propagation were selected was based on a 60-year Global Ocean Waves (GOW) reanalysis (Reguero et al., 2012) performed with the WaveWatchIII (WWIII) model version 2.22 (Tolman, 2002) on a regular global grid of $1.5^o \times 1.0^o$ and a subgrid of $0.5^o \times 0.5^o$ on the Brazilian coast. Bathymetry data were obtained from GEBCO and the simulation was driven by NCEP/NCAR reanalysis winds and ice fields (Kalnay et al., 1996). Source series were calibrated using satellite altimetry data following the method of Mínguez et al. (2011) to reduce deviations between the probability distribution functions. To perform the downscaling, the Brazilian coast was split into 17 detailed grids with resolution of 1×1 km. The grids were designed such that the GOW nodes coincided with the boundaries. Therefore, for each grid, a total of $M = 500$ wind-wave conditions were selected by means of Maximum Dissimilitude Algorithm (MDA) (Snarey et al., 1997). MDA method consists of the selection of a set of the most different sea states based on the geometric distance. The method starts with a seed that correspond to the highest sea state (maximum wave height and peak period), then by means of an iterative process select the farthest sea state. This process continues until M sea states have been selected. To take into account the effects of sea level variation on the wave propagation, three sets of M conditions were propagated, *i.e.,* the Highest Astronomical Tide (HAT) level, Mean Sea Level (MSL) and Lowest Astronomical Tide (LAT) level. A total of 1500 simulations were performed for every grid using the SWAN model (Booij et al., 1999) and bathymetry data were obtained from the SMC-Brasil database described previously.

These first two steps have already been precalculated; therefore, the coastal wave database, stored in SMC-Brasil, consists of the results of 1500 propagations at each of the target points (Fig. 4b). The third step of this process, which is performed on demand by SMC-Brasil users, produces a 60-year coastal wave series for the selected target point using the precalculated propagations in just a few minutes. This reconstructed series are ready to be used as input for any of the methodologies included on the system. A detailed description of GOW and DOW methodologies, calibration, and validation processes can be found in the *SMC-Brasil: Ondas* thematic document (IHCantabria, 2013a).

The sea levels database is composed of 60-year astronomical tide and storm surge time series along the Brazilian coast. The astronomical tide database, named Global Ocean Tides (GOT), is a set of 130 series,

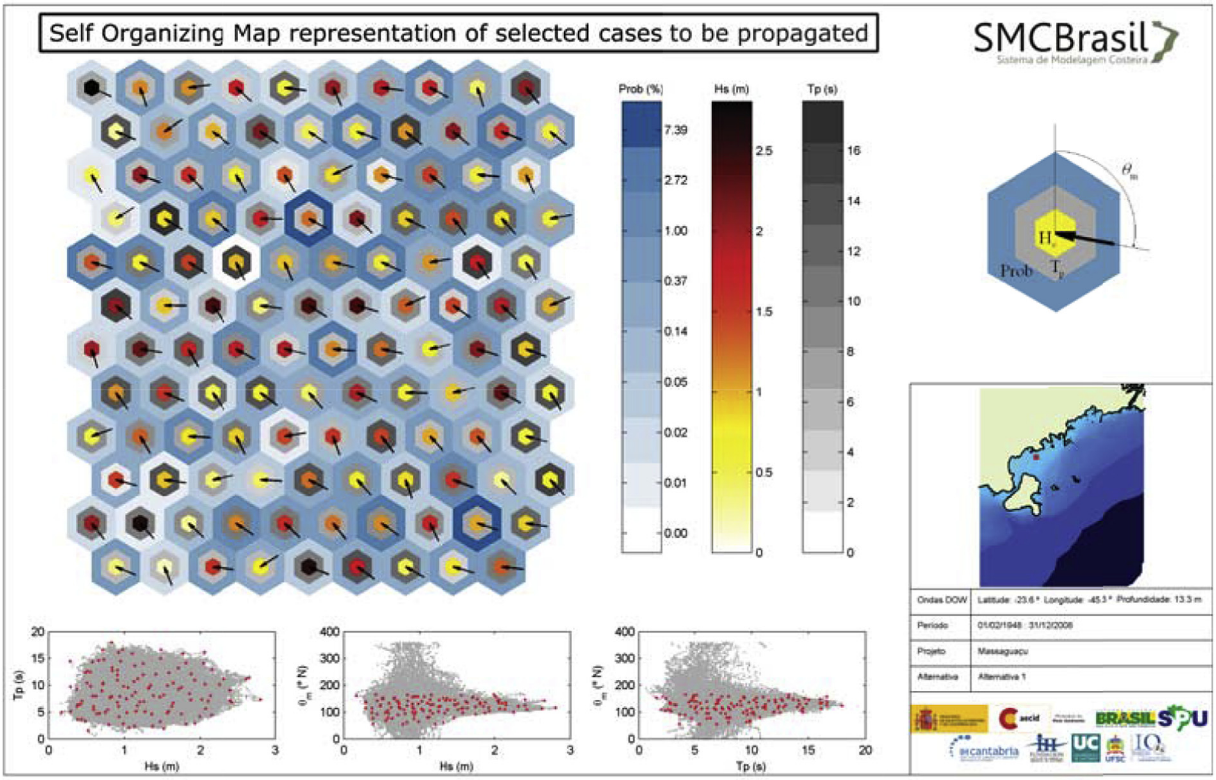

Fig. 8. Example of a report of selected sea states for propagation. The main plot of the report shows a self-organizing map (Kohonen et al., 2001) that represents all the variables of the selected sea states to be propagated and their corresponding probabilities. At the right of the report appears a graphical description of the variables representation: probability is indicated on blue tones; significant wave heights are represented from yellow to red colors, and the peak period is in gray tones; finally, the direction is indicated using vectors. The three plots below show two-dimensional representations of the four dimensional space of classified variables. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

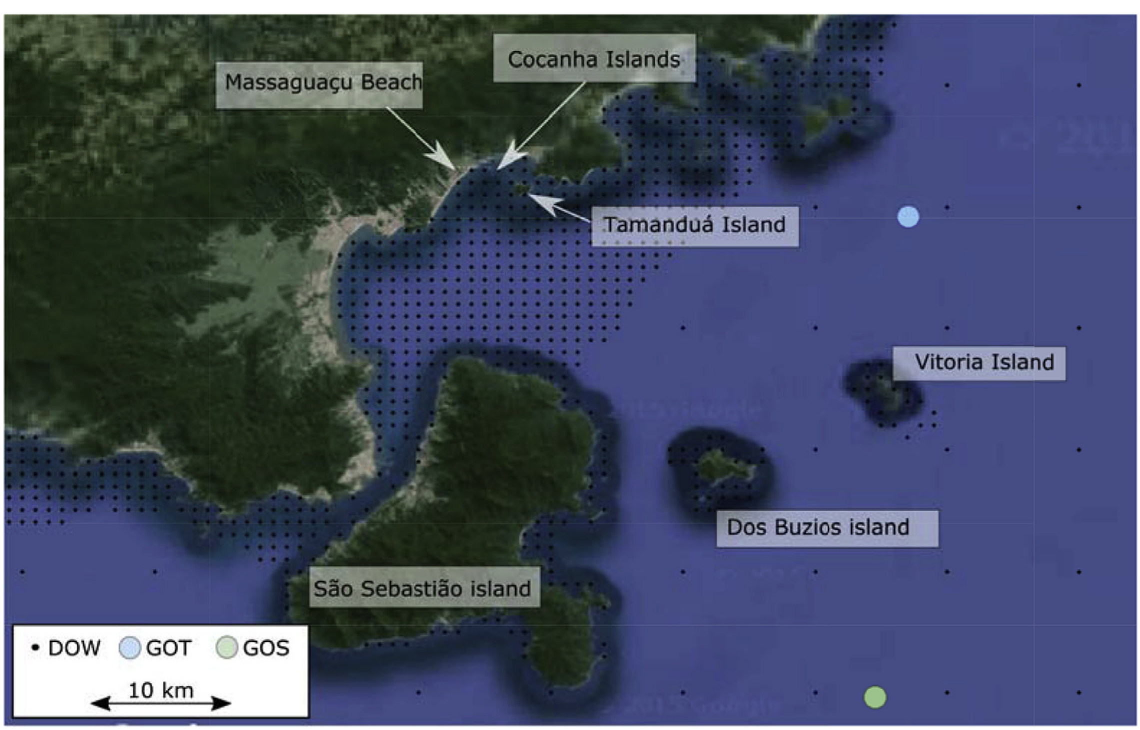

Fig. 9. Detail of Massaguaçu Beach on the São Paulo coast. The most important features of the area are indicated and the position of the wave, astronomical tide and storm surge series available for the area are shown.

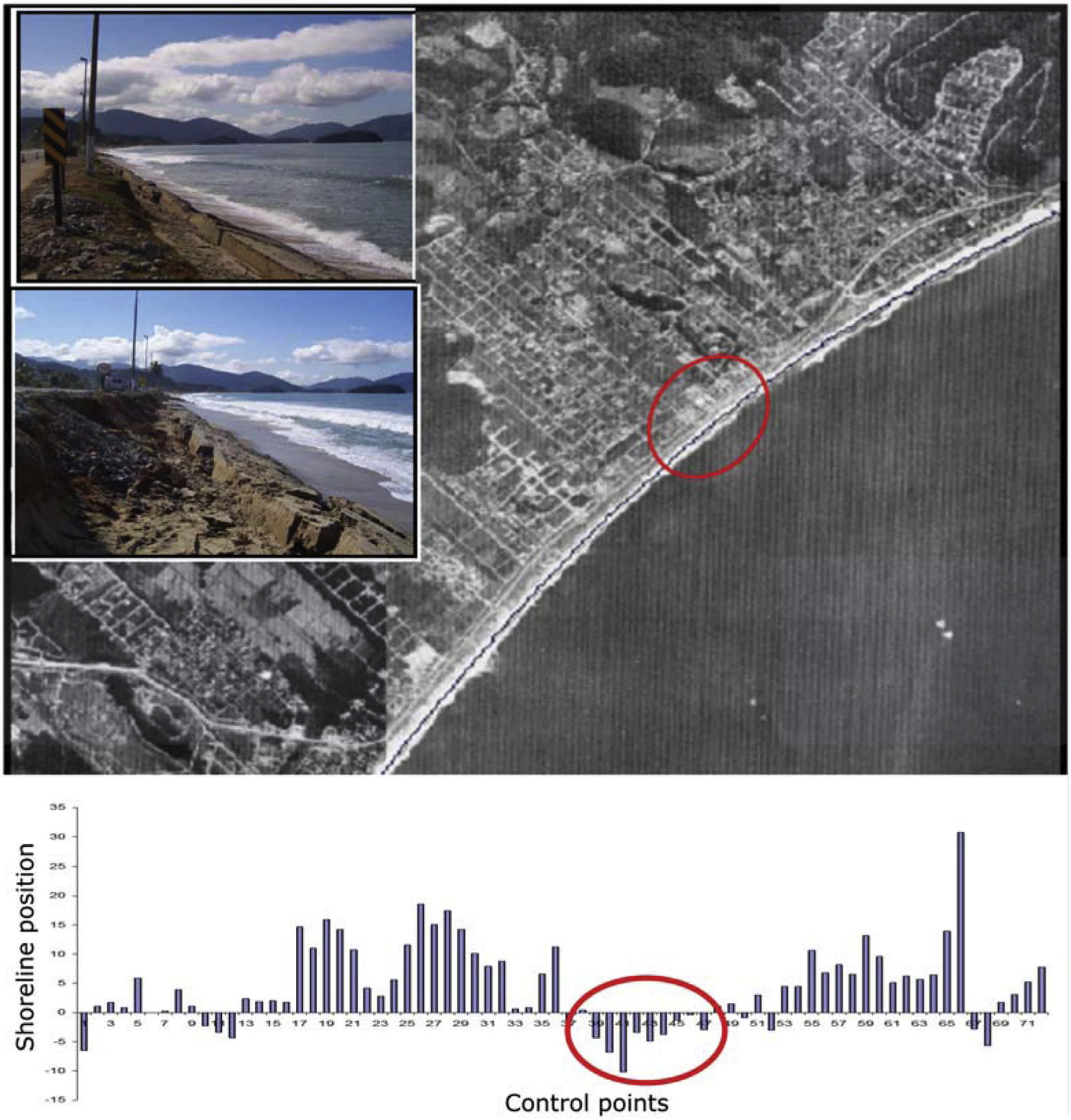

Fig. 10. Image of Massaguaçu Beach; the red ellipse indicates the area where erosion has been observed. The pictures in the upper part show details of the eroded area, and the histogram in the lower part presents the coastline position change between 1977 and 1994, adapted from Nuber (2008). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

with separation of 50 km approximately and depths of approximately 20 m. Series were calculated based on the harmonic constituents of the TPXO Global Tidal Solution developed by Oregon University (Egbert et al., 1994, Egbert and Erofeeva, 2002) using the *RomsTools* package developed by the *Institut de Recherche pour le Development* and the harmonic analysis program *t_tide* (Pawlowicz et al., 2002). The storm surge series, named Global Ocean Surges (GOS), group variations of sea level due to wind drag effects and low-pressure gradients. The database is composed of a set of 24 series, such that the spatial variations can be observed along the Brazilian coast. Simulation was performed using the Regional Ocean Model System (ROMS), originally developed by Rutgers University (Shchepetkin and McWilliams, 2003), on a 0.25° grid. The reanalysis was forced with six-hourly wind and atmospheric pressure provided by the NCEP/NCAR reanalysis (Kalnay et al., 1996). Due to the spatial and temporal resolution of the forcing, GOS does not include elevations produced by hurricanes or river dischargues. Both databases were validated using tide gauges series from *Instituto Nacional de Pesquisas Hidroviárias (INPH)*, *Marinha do Brasil* and the University of Hawaii Sea Level Center (UHSLC). A detailed description of the GOT and GOS methodologies, calibration and validation processes can be found in the *SMC-Brasil: Níveis e cota de Inundação* thematic document (IHCantabria, 2013c). Fig. 4c) shows the distribution of the GOT and GOS series included in database. A detailed description of the spatial behavior of sea waves and sea levels databases was presented in González et al. (2016); here the emphasis is on the methodologies followed to obtained and the selection of series to be included in the system.

SMC-Brasil is prepared to estimate some effects of climate change on beaches with the aid of several parameters stored in the Climate Change database. In particular, the database includes *i)* historic sea level rise variation, *ii)* Intergovernmental Panel on Climate Change (IPCC) global sea level rise scenarios, *iii)* IPCC regional sea level rise scenarios, and *iv)*

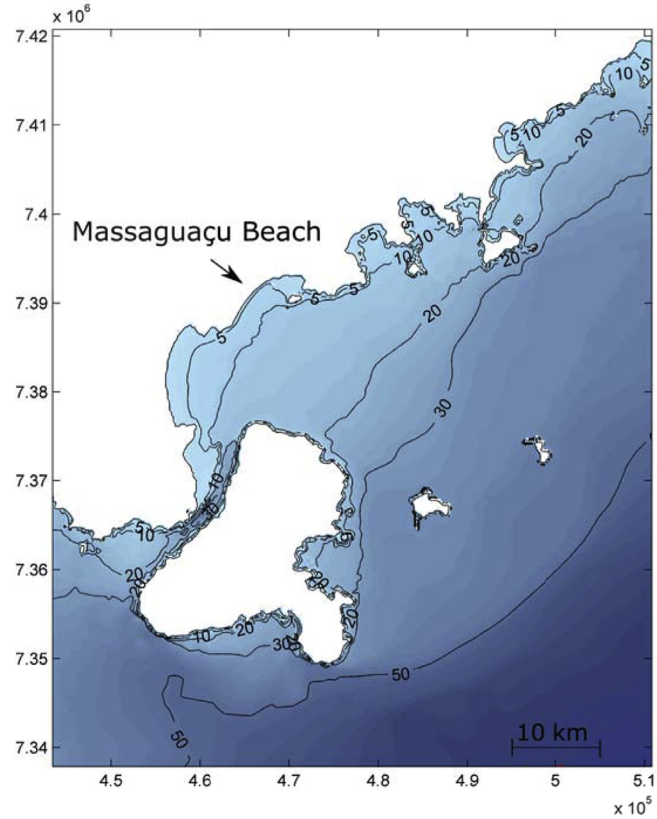

Fig. 11. Regional bathymetry of Massaguaçu Beach.

subsidence values along the Brazilian coast.

The historic sea level rise database includes series of monthly distributions of large-scale sea level variability and changes over the period from 1950 to 2000 for the global ocean. This database was originally obtained by Church et al. (2004). In SMC-Brasil are included a set of series along the Brazilian coast, which are used to estimate sea level trends and take them into account in calculations of the flooding level and beach erosion.

Regarding the IPCC global (Solomon et al., 2007) and regional scenarios (Slangen et al., 2014), the database considers two possible scenario (*i.e.,* Representative Concentration Pathways (RCP) 4.5 and RCP 8.5), and two projections (*i.e.,* 2070 (mid horizon) and 2100 (far horizon)). For the global scenarios of sea level rise, Table 1 presents the values considered.

Finally, the Subsidence database collects information related to sea floor vertical movements (Peltier, 2001). This parameter is especially important in areas near deltas and rivers, which are common on the Brazilian coast.

Fig. 4d) shows the parameters included in the SMC-Brasil climate change database. This database is especially important for calculations in which the mean sea level must be considered, such as changes in the flooding level.

A detailed description of the climate change methodologies and database can be found in the *SMC-Brasil: Mudanças climáticas em praias* thematic document (IHCantabria, 2013b), which forms part of SMC-Brasil.

The integration of the databases allows users to apply SMC_{ε} to any coastal issue without the need for measured local data.

2.2. SMC-Brasil capabilities

In this section, some capabilities of the SMC-Brasil are explained, emphasizing the SMC-Tools skills, as they are completely novel aspects of the system. In particular, how to create new projects and mine

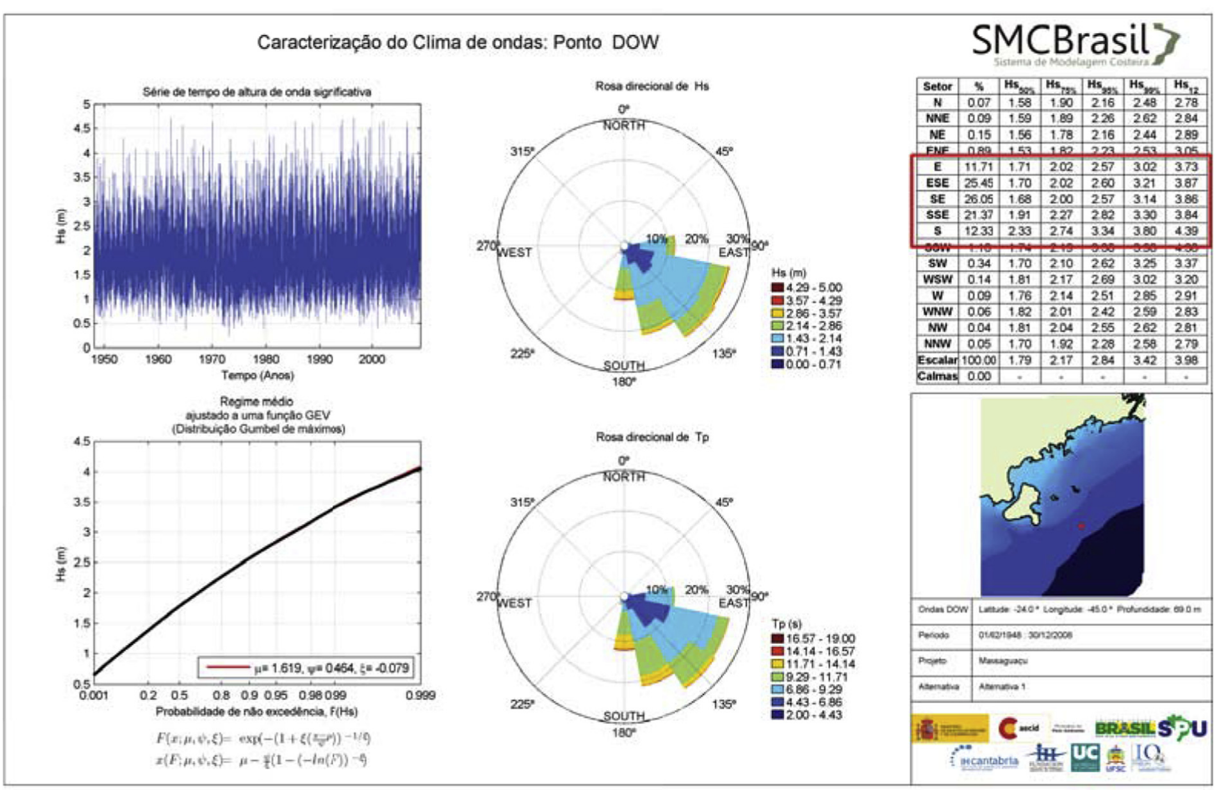

Fig. 12. Report of IH-DATA DOW point located at 45° W and 24° S. The red rectangle indicates the most likely wave directions at this DOW point. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

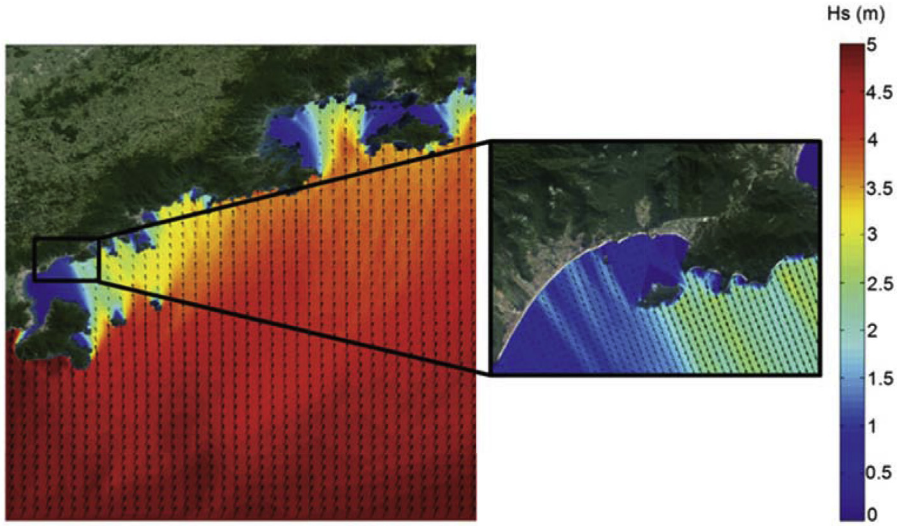

Fig. 13. Southern storm wave propagation (Hs = 5 m and Tp = 15 s.) on (left) the approximation area and (right) Massaguaçu Beach (adapted from González et al. (2016)).

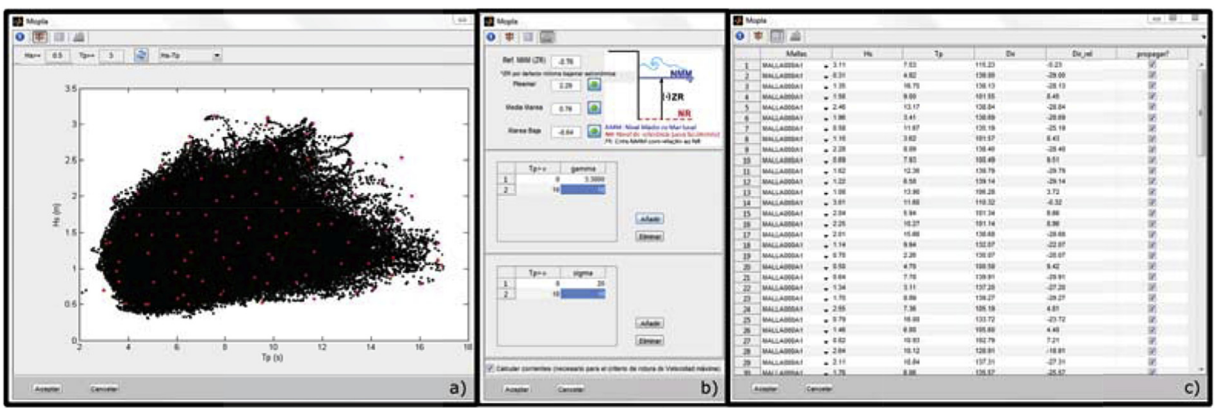

Fig. 14. SMC-Tools selection of the most-representative cases to be propagated. The interface has three panels: *a)* the first panel helps to select the wave cases to be propagated by means of the MDA; *b)* the second panel guides the user in the sea level selection for propagation and the spectra characteristics of waves and, finally, *c)* the third panel indicates the most appropriate grid for each propagation.

databases, transfer the wave climate to the coast, calculate sediment littoral drift, determine the direction of the mean wave energy flux, compute the flooding level, predict the impacts of climate change and produce reports, are explained.

2.2.1. Project creation

The SMC-Tools interface provides an overview of the coast and the ocean waves and sea levels databases (Fig. 5). This interface includes typical tools to move and zoom over the map, making it easy to find areas of interest.

Through this interface, IH-Data can be explored and, by applying the statistical tools of the system, series can be analyzed. Once the area and dynamics are explored, the *project creation* tool allows the user to select an area to create a project that includes bathymetry, coastlines, images, and the selected ocean waves and sea level series. This project is ready to design coastal interventions (*e.g* coastal structures and beach nourishments).

2.2.2. Statistical analysis of data

SMC-Brasil includes a set of mathematical and statistical tools, referred to as IH-AMEVA, to characterize and analyze any series in the system. The series to be analyzed could be not only from IH-DATA, (*e.g.,* coastal waves, astronomical tide or storm surges) but also series produced via application of models or methodologies in the system (*e.g.,* propagated wave series or, flooding level series).

IH-AMEVA can be launched at any time and situation of the development of a project in SMC-Brasil. Therefore, it is an essential tool to understand the processes occurring on a beach. The analyses included in IH-AMEVA, range from descriptive statistics to temporal series analysis, distribution fitting, regression analysis, and data mining. Regarding the distribution fitting, the normal, log-normal, Gumbell and Weibull distributions are available for mean regimes, whereas the generalized extreme value distribution is used for extreme regimes. The data mining techniques, including the maximum dissimilitude algorithm (Snarey et al., 1997), self organizing maps (Kohonen et al., 2001), and radial basis functions (Franke, 1982) among others, are employed for high dimensional analysis of series, such as the selection of wave states to be propagated for time series transference.

The IH-AMEVA tool (Fig. 6) has two parts, a main tree (a) in which the variables and tools to be analyzed are selected and graphic areas where the results are shown. As an example, some graphs of a DOW series analysis are shown incluiding a directional statistics table (b), time series (c), extreme regime fitting (d) and directional wave rose (e).

2.2.3. Wave propagation from DOW points to the surf zone

To understand beach dynamics it is necessary to analyze the wave climate on the surf zone at different spots. SMC-Brasil provides a database of wave series close to the coast; nevertheless, these series are

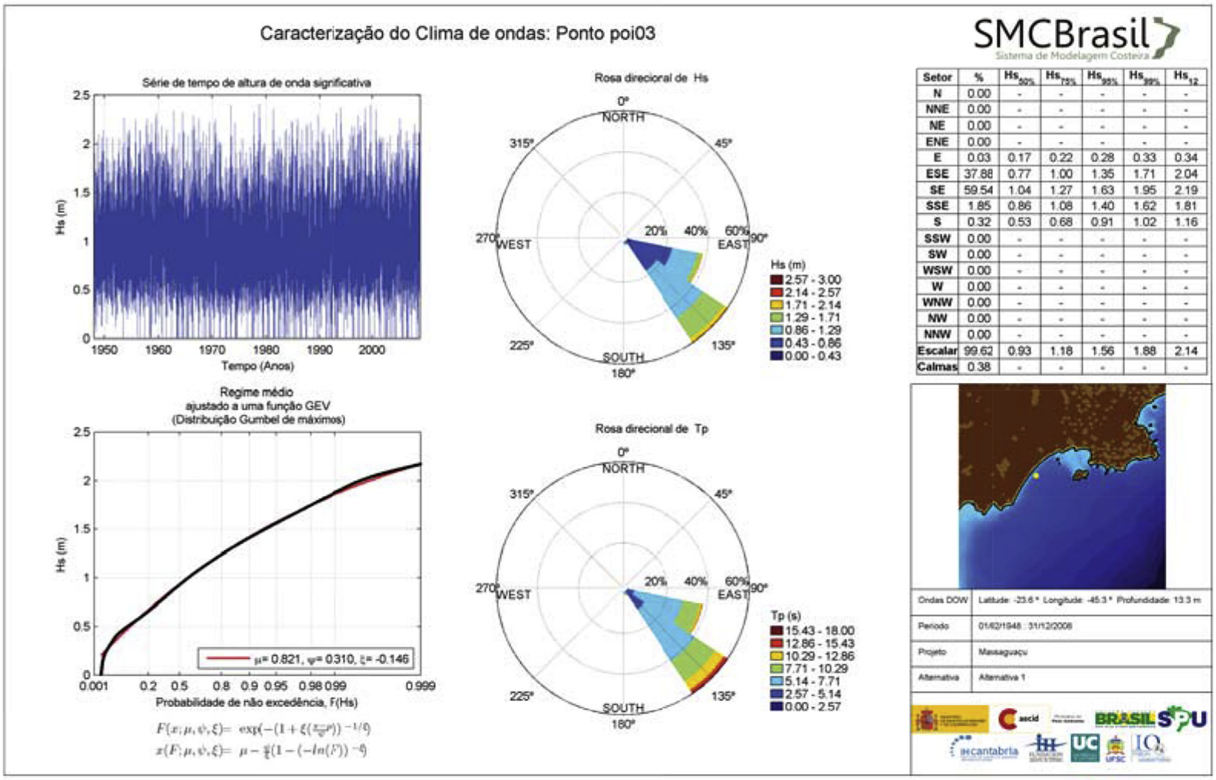

Fig. 15. Report of wave climate on a reconstructed point on Massaguaçu Beach (at depth 13 m). The report shows information about the mean regime and directional roses of the wave height and peak period.

not sufficiently close to the surf zone and were not obtained using detailed bathymetry. Therefore, the bathymetry must be enhanced by users and the wave series must be propagated from DOW points (*e.g.*, Point A in Fig. 7) to the area of interest (*e.g.*, Point B in Fig. 7). SMC-Brasil provides a series of tools and a fully integrated methodology for this purpose.

The transference of the wave series, to points or profiles on the surf zone, is performed using a three step methodology (see Fig. 7):

i) Selection of cases to be propagated: After determining a source DOW point from IH-DATA, a set of sea states are selected using the Maximum Dissimilitude Algorithm (MDA) (Snarey et al., 1997). This algorithm allows selecting a minimal set of sea states that fully represent the wave climate in the area. To take into account differences in wave propagation due to sea level variations, the system allows for the propagation of the selected set of cases on one (mean), two (lowest and highest) or three sea levels (lowest, mean and highest) and subsequently, interpolates to the right sea level. The SMC-Brasil interface (Fig. 14) is prepared to guide the user in these steps: first, to limit the main direction of wave propagation, and second, to select the cases to be propagated.

ii) Propagation of selected cases: The selected cases are propagated to the surf zone using the OLUCA-SP spectral model, which is fully integrated into SMC-Brasil. OLUCA-SP (González et al., 2007), which is based on REF/DIF 5 (Kirby and Dalrymple, 1994), solves the parabolic approximation of the mild-slope equation. OLUCA-SP was especially designed for wave propagation in coastal areas taking into account shallowing, refraction, and diffraction. Nevertheless, it has some operational limitations, such as the relationship between the wave main direction and the grid orientation (the angle must be less than 60°). This restrictiton implies that several grids must be designed to address the full variety of sea states in the original series.

iii) Series reconstruction: After the simulation of the selected cases, wave climate series can be reconstructed, by means of radial basis functions (RBF) interpolation (Franke, 1982) at any point or profile located inside the region of interest (ROI). The ROI is the area common to all of the high-resolution grids used for propagation; it is shown in green in Fig. 7. As results wave series for every one of the sea levels selected for propagation are obtained (*i.e.,* the lowest, mean and highest sea levels). Then, a linear interpolation method is used to obtain the wave parameters for the instantaneous sea level obtained from IH-DATA.

2.2.4. Sediment littoral drift

The sediment littoral drift is calculated, in SMC-Brasil, using the propagated series along beach profiles by means of bulk longshore sediment transport formulas. These formulas are based on the wave parameters at which energy dissipation due to breaking occurs. Because wave breaking occurs at different depths (h_b) along the profile, a specific criterion to determine these positions was implemented on the system.

In SMC-Brasil wave propagation is performed by means of the spectral parabolic model OLUCA-SP, which includes three dissipation models (Battjes and Janssen (1978), Thornton and Guza (1983) and Rattanapitikon and Shibayama (1998)). Therefore, to determine the position at which dissipation due to breaking occurs, a criterion based on the radiation stress concept (Longuet-Higgins and Stewart, 1962) was established. This criterion locates the wave breaking at the same position at which the maximum current velocity, parallel to the profile orientation is observed. Currents are calculated using the COPLA-SP (González et al., 2007) model, which solves the 2D-H equations of conservation of mass and momentum.

As an example, Fig. 17a) shows the wave height and velocity evolution of a wave state along a profile. The breaking position, indicated by the maximum velocity position, is located close to 450 m from the beginning of the profile. Using the results of all propagated cases and their corresponding probabilities of occurrence, density functions are calculated and displayed along the profile, indicating the most likely breaking position for each coastal profile (Fig. 17b).

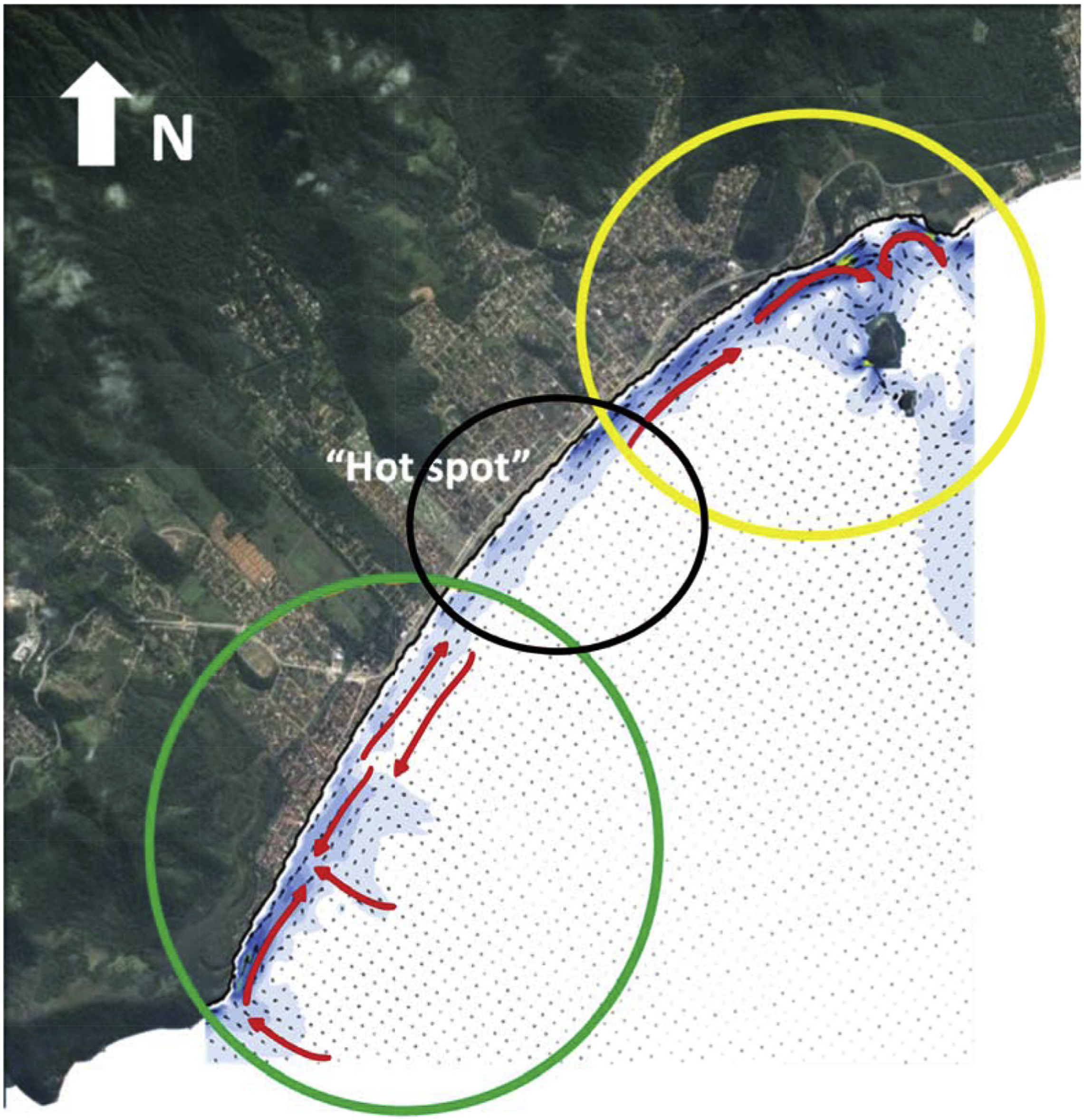

Fig. 16. General pattern of currents on Massaguaçu Beach. The pattern is characterized by three main areas: the first one is located in the south (green circle), where the currents are irregular, and the direction depends on the offshore wave direction; next, there is a hot spot at the center of the beach (black circle), where currents are null, finally, in the north (yellow circle), the currents increase toward the north (adapted from González et al. (2016)). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The USCERC (1984), Kamphuis (1991) and Bayram et al. (2007) bulk longshore sediment transport formulas are implemented to obtain the potential littoral sediment transport in each profile for every sea state. The bulk sediment transport formulas were rewritten as $Q = kX$, where X represents the formula without the calibration factor k. Several options for k are implemented (see Table 2) for each formula; also, SMC-Brasil users can manually introduce an experimental coefficient from a different source.

Longshore sediment transport in SMC-Brasil is calculated along profiles and shown as arrows coming out from the profiles that indicate the transport direction. The littoral drift direction is defined according to the wave direction relative to the beach normal based on the Dean and Dalrymple (2004) convention (*i.e.*, if an observer is set on the beach looking out to the sea, the longshore sediment transport to his right will be positive, and it will be negative in the opposite direction).

2.2.5. Mean wave energy flux direction calculation

The mean wave energy flux direction has significant importance for determining the beach orientation. SMC-Brasil is able to calculate the mean wave energy flux direction at target points inside the ROI or profiles on the surf zone defined the by user after the wave series have been propagated. Calculations on target points are key for the adjustment of equilibrium planforms (*e.g.,* Hsu and Evans (1989), González and Medina (2001)). Moreover, directions on the profile along a straight beach are helpful for comparisons between the theoretical and actual orientation of the beach, providing information about the stability and sediment transport direction on the beach.

Calculations are performed using the reconstructed 60-year wave climate series. In the case of profiles, calculations are performed considering the wave characteristics at the respective breaking positions. Calculations can be performed for mean conditions or specific periods (monthly, seasonal or annual).

2.2.6. Flooding level determination

SMC-Brasil is able to calculate the flooding level on a beach as the combined effect of astronomic tide (AT), storm surge (SS) and waves

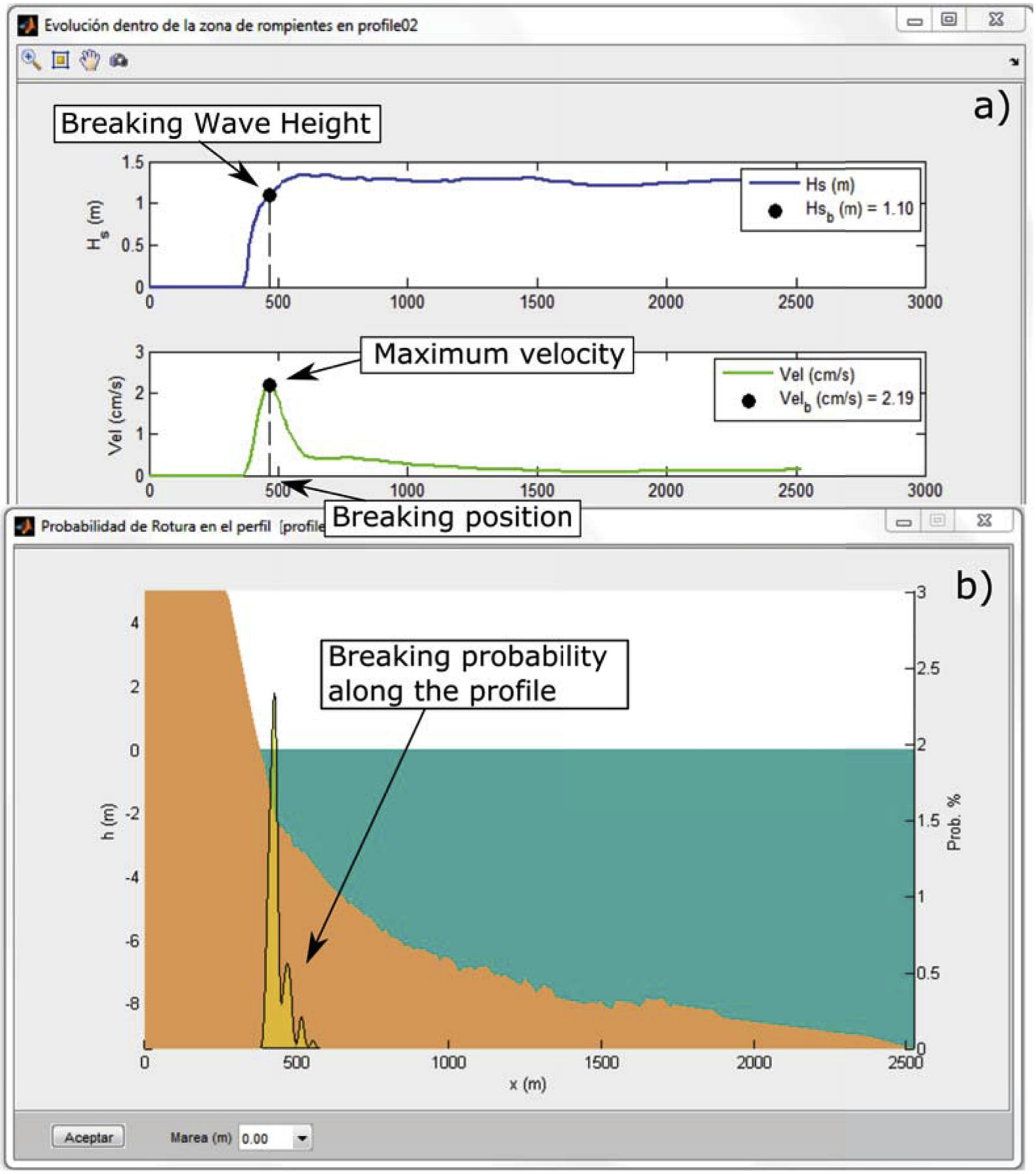

Fig. 17. Breaking position results for a beach profile. a) The maximum elevation of propagation and velocity of a wave state along the profile. The position of the maximum velocity indicates the breaking position and, therefore, the breaking wave height. b) The breaking probability of the propagated series along the profile, indicating the most likely position of wave breaking.

run-up (*Ru*). Calculations are performed for the 60-year time series of levels and propagated waves.

The flooding level is defined as

$$FL(t) = AT(t) + SS(t) + Ru(t) \tag{1}$$

where *Ru* is defined as that in Nielsen and Hanslow (1991) as the run up transgressed by 2% of the waves during a sea state of 1 h

$$Ru = 1.98Z, \tag{2}$$

where *Z* is

$$Z = \begin{cases} 0.47(H_b L_o)^{0.5} \tan\beta & for\ \tan\beta > 0.1, \\ 0.04(H_b L_o)^{0.5} & for\ \tan\beta < 0.1 \end{cases} \tag{3}$$

The beach slope, tanβ, is obtained from the user defined beach profiles. As a result, the 60-year flooding series, obtained for every defined profile, can be used to define flooding areas.

Therefore, along each profile, a series of flooding events can be determined and, consequently, the mean and extreme flooding regimes can be determined. Based on the regimes, users can define flooding hazard maps of the study area.

2.2.7. Estimation of effects of climate change (very long-term scale)

Regarding the effects of climate change effects in the very long-term, SMC-Brasil implements the methodology described in the *Climate Change Effects on Beaches* Thematic Document, applying the IH-DATA series propagated to profiles or target points on the surf zone. This methodology has two approaches to estimate effects in the short- and long-terms. In the short-term, the propagated series of IH-DATA are used to estimate trends and variations on specific beaches in the next ~ 50 years by means of an heterocedastic model (Mínguez et al.,

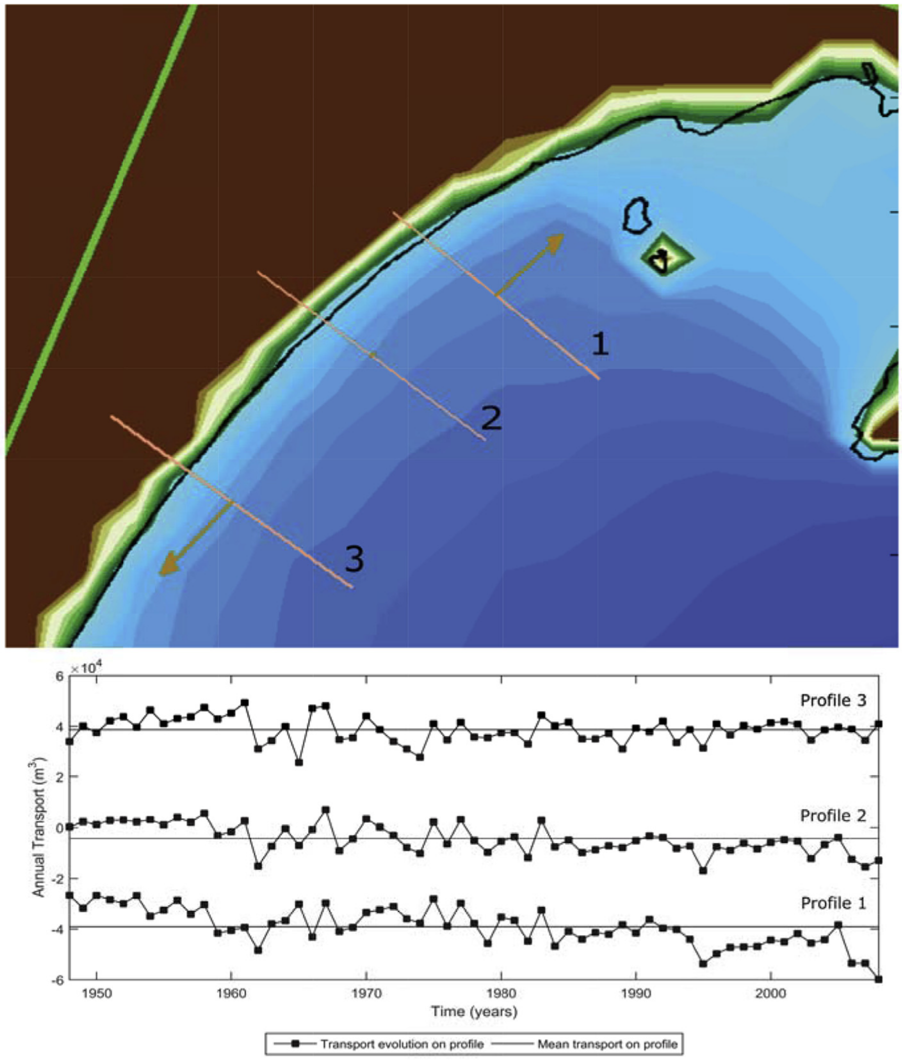

Fig. 18. Sediment transport evolution along profiles on Massaguaçu Beach. In the top panel, the locations of the profiles along the beach are shown. In the bottom panel, the evolution of the net transport along the 60-year series along each profile is shown. Negative values indicate sediment transport to the north, whereas positive values indicate transport to the south.

2011, 2012). This regression model considers that the mean and variance can change with time. For the long-term, climate change scenarios are used for estimations for the next years.

Three main impacts can be analyzed in SMC$_c$: *i)* coastline regression due to mean sea level rise and increases in wave height, *ii)* coastline rotation due to changes in the mean wave energy flux direction, and *iii)* flooding level increases due to changes in storm surge and waves. Impacts are calculated in terms of present and future distributions of dynamics, obtaining a mean regime of regression or rotation of the coast.

2.2.8. *Reports*

SMC-Brasil produces a large number of results. Therefore, for ease of use, the results are organized into reports. These reports synthesize the most important results obtained by the system. The reports are classified into three types: *i)* pre-processed, *ii)* processed and *iii)* post-processed. The pre-processed reports include the wave climate and statistical results of the IH-DATA series. The processed reports include the details about wave transference to a point of interest on the coast, and the post-processed reports present the results regarding the wave climate, sediment transport, wave energy flux, flooding level and the effects of climate change on target points and profiles.

Fig. 8 shows as an example the processed report of the selected sea states to be propagated in the study area. The report shows in a very novel manner a lattice, based on self-organizing maps (Kohonen et al., 2001), that simultaneously map the three variables of the sea states to be propagated (i.e., H_s, T_p and θ_m) and their corresponding probabilities: in each hexagon, the probability is indicated in blue tones, with significant wave height ranging from yellow to red and the peak period in gray tones; finally, the wave direction is indicated using vectors. In the graphs below, three simplified two-dimensional plots presenting the total population of sea states (gray dots) and those selected for propagation (red dots) are shown.

3. Study area and model setup

To illustrate the application of the SMC-Brasil, the case of Massaguaçu Beach (see Fig. 9) is described in detail. Similar to many Brazilian beaches, Massaguaçu Beach is undergoing an erosion process; therefore, SMC-Brasil was used to understand the erosion observed in the area, particularly in the central area, where the BR-101 road was destroyed and to propose solutions. Historically, two aspects of the evolution of Massaguaçu Beach are remarkable, *i)* the population increased, which favored the development of infrastructure, and *ii)* an important erosion process occurred on the central part of the beach. This process was detected in the 1990s; Nuber (2008) quantified a 10-m

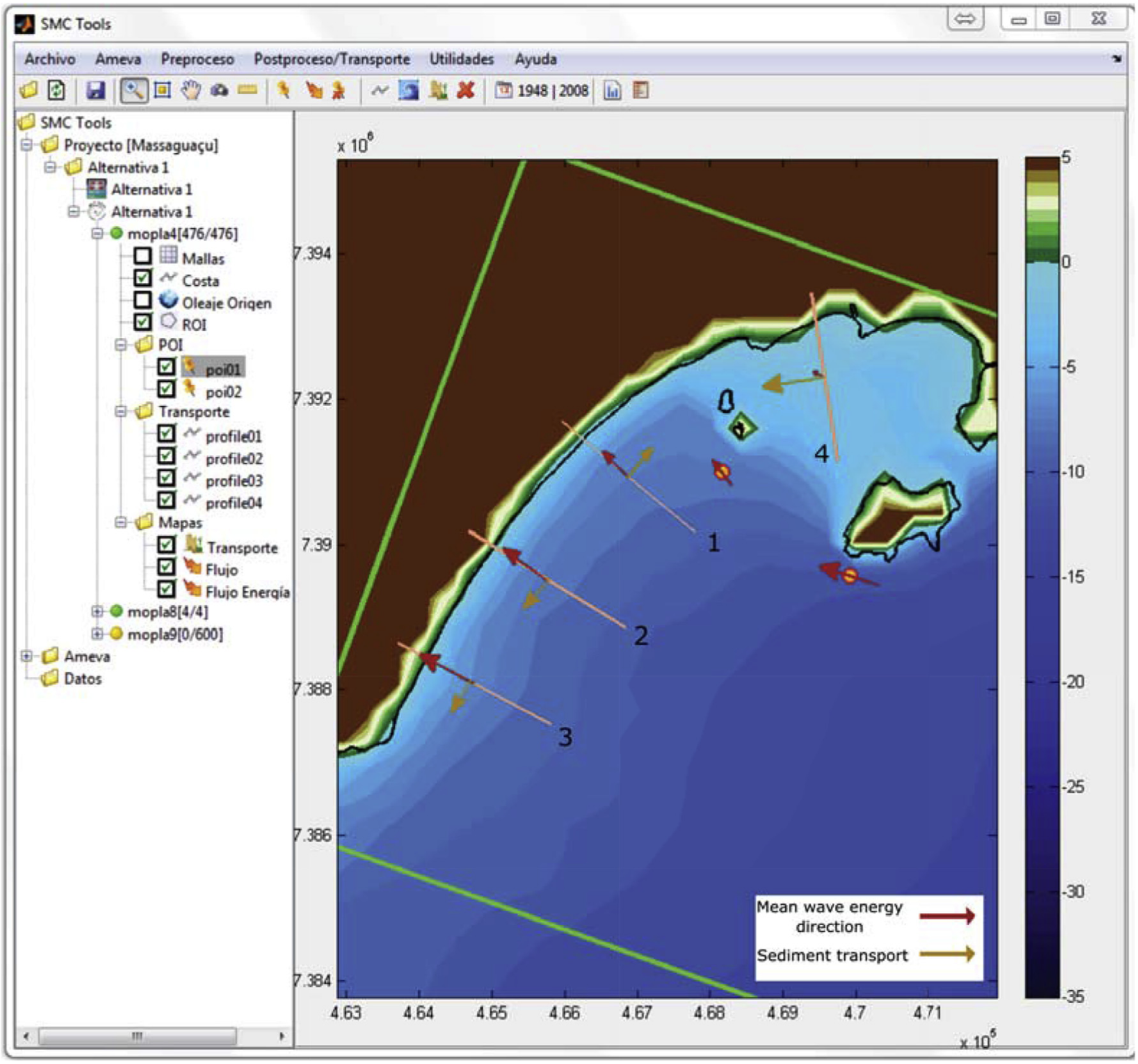

Fig. 19. Mean wave energy flux direction and sediment transport along profiles on Massaguaçu Beach.

retreat in this area from 1977 to 1994. Several mitigation measures were applied without the expected results. Fig. 10 shows the erosion affected area of the beach.

3.1. Morphology of study area

Massaguaçu Beach is part of a system of three beaches located in the municipality of Caraguatuba (on the north coast of São Paulo). The system of beaches is on the lee of several islands (Fig. 9), which protects the area from most waves; in particular São Sebastião Island protects the beach from southern waves. Massaguaçu Beach, approximately 7 km long, is characterized by a slab on the southern limit of the beach and a northern part protected by Cocanha and Tamandua Islands. Coastline retreat has been observed in the central area, whereas at both ends, the coastline has advanced. Based on several aerial images Nuber (2008) confirmed the aforementioned behavior and quantified retreats of the order of 10 m and coastal advances of the order of 15 m at the center and ends of the beach, respectively. To stop this process, several interventions were performed in the cental zone (*e.g.,* longitudinal walls, and geotextile bags) without success.

3.2. Model setup

To analyze the Massaguaçu Beach a project must be created, in order to get access to databases and models included on SMC-Brasil. Creation of the project just require to find the area of interest using the navigation tools of the system, and select the area and local series of dynamics. The system is prepared to create the adequate environment to continue with the study in a straightforward way without any important computational or human effort.

3.2.1. Regional and local bathymetry

Fig. 11 shows the regional bathymetry of the area of interest obtained from SMC-Tools combined with a detailed bathymetry incorporated to improve the structure on the shallow area. The inclusion of the detailed bathymetry is done by means of the coastal terrain module. This is a manual procces and depends entirely on the user's expertise. The bathymetry of Massaguaçu Beach is characterized as having a smoother profile in the south with a slab and isobates almost parallel to the coast, whereas the north profile is steeper. According to the sediment size, the beach presents high spatial variability.

3.2.2. Offshore marine dynamics

Fig. 9 shows the waves target points (DOW) in the nearby area available in SMC-Brasil. Analyzing the wave climate at several DOW points, two areas can be defined: the first one is on the lee of the islands and is characterized by a wide distribution of wave directions, whereas the second is in the protected area, in which the distribution of directions is reduced due to the effects of the islands on the wave propagation.

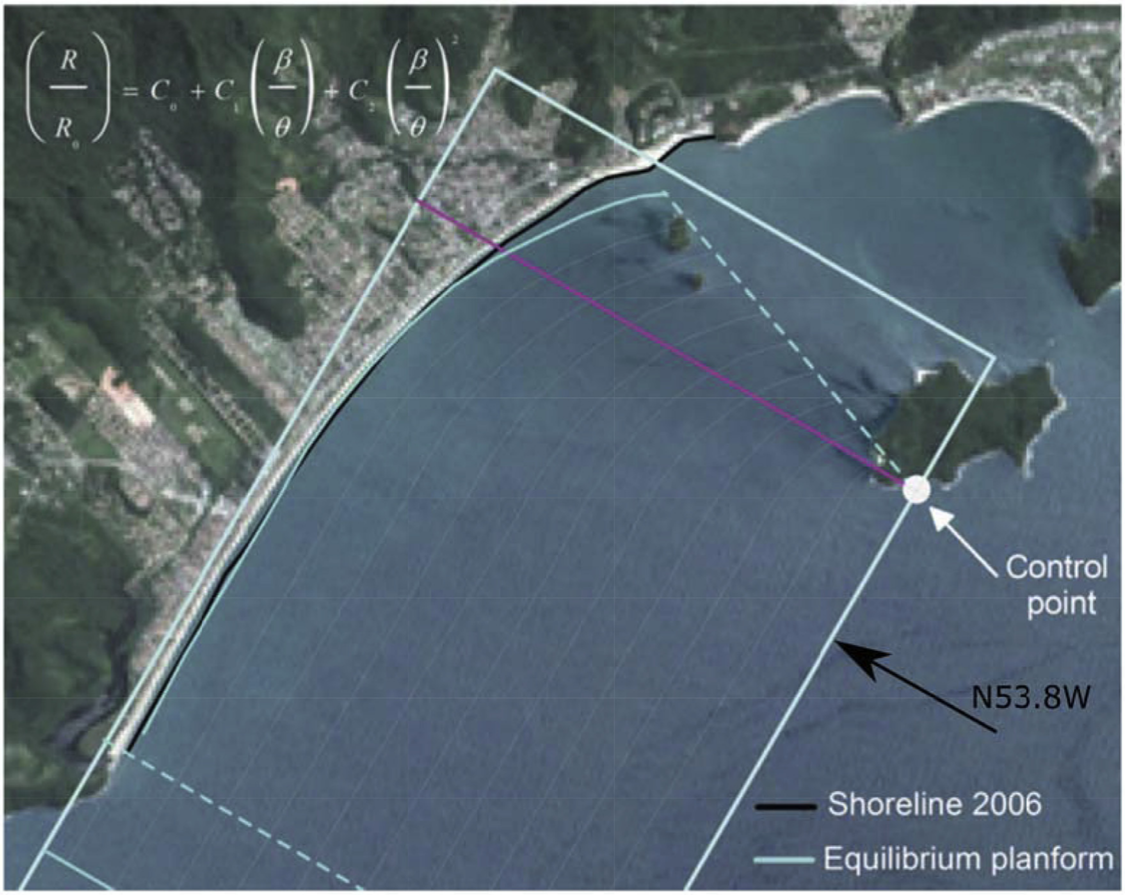

Fig. 20. Detail of Massaguaçu Beach, where the 2006 coastline is highlighted in black, in addition to the equilibrium planform, in blue, which was calculated based on the orientation of the mean wave energy flux (N53.8^{o}W) (adapted from González et al. (González et al., 2016)). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 12 shows the offshore wave climate report for the DOW point located at the coordinates 45° 00′W and 24° 00′S (indicated with a point on the map). Based on this report, it can be stated that in the offshore wave climate, 85% of waves comes from the east-south quadrant; meanwhile, the most-energetic waves come from south to southeast. This report also shows the wave height time series, mean wave height regime, wave height and mean period directional roses and some statistical parameters (*i.e.,* Hs_{50}, Hs_{75}, Hs_{95}, and Hs_{99}), where the significant wave height was exceeded 50%, 75%, 95% and 99% of the time, respectively, and for Hs_{12}, the significant wave height exceeded 12 h per year.

Based on the offshore wave climate, several grids were designed for wave propagation with different orientations to deal with the different wave direction. Grids were tested for propagation of local wave climate. Grid resolution was established of 20 m. Design of grids is one of the key points on the study development, and based on the user expertise, can require a significant effort. As an example of the propagation, Fig. 13 shows the results corresponding to a southerly storm, where the arrows indicate the wave direction and colors denotes the wave height. In these situations, even when the waves are large, the beach is sheltered by the islands, reducing wave energy on a 70%.

4. Results

4.1. Onshore marine dynamics

To transfere the wave climate to the surf zone on Massaguaçu Beach the three steps method described previously was used. Fig. 14a) shows the 60-year time series of hourly sea states (in black) and the 100 representative cases (in red). In panel b), the reference level of propagation is selected, in this case three level of propagation were selected, producing a total of 300 cases. Finally, in c), the selected sea states ready for simulations are shown; this process includes the selection of the most adequate grid for every case.

After 10 h, the 300 numerical simulations, performed in parallel by the OLUCA-SP model on a standard PC were ready and the system were ready to reconstruct wave series on any point or profile on the ROI. Fig. 15 shows the climate wave characterization report for 23.60^o W, 45.30^o S, close to the zone where erosion have been observed. Comparing this with the report related to offshore point (Fig. 12), a reduction of approximately the half of the wave height and a concentration of the wave direction in the SE and ESE are observed. From the analysis of the series at the target points, it can be stated that on the southern section of the beach, the most-energetic waves come from E and ESE, whereas in the central section, waves arrive with more intensity from SSE and SE and, in the northern section, more-energetic waves arrive from SW and S. It is important to note that waves from the S and SSE (the most-energetic waves) undergo diffraction due to São Sebastião Island; therefore, the wave height on the coast is less than half of the wave height in deep water.

To understand the current patterns on the beach, the mean and extreme (storm) situations were determined and propagated. The calculations were performed using the COPLA-SP model included in the system. 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. 16):

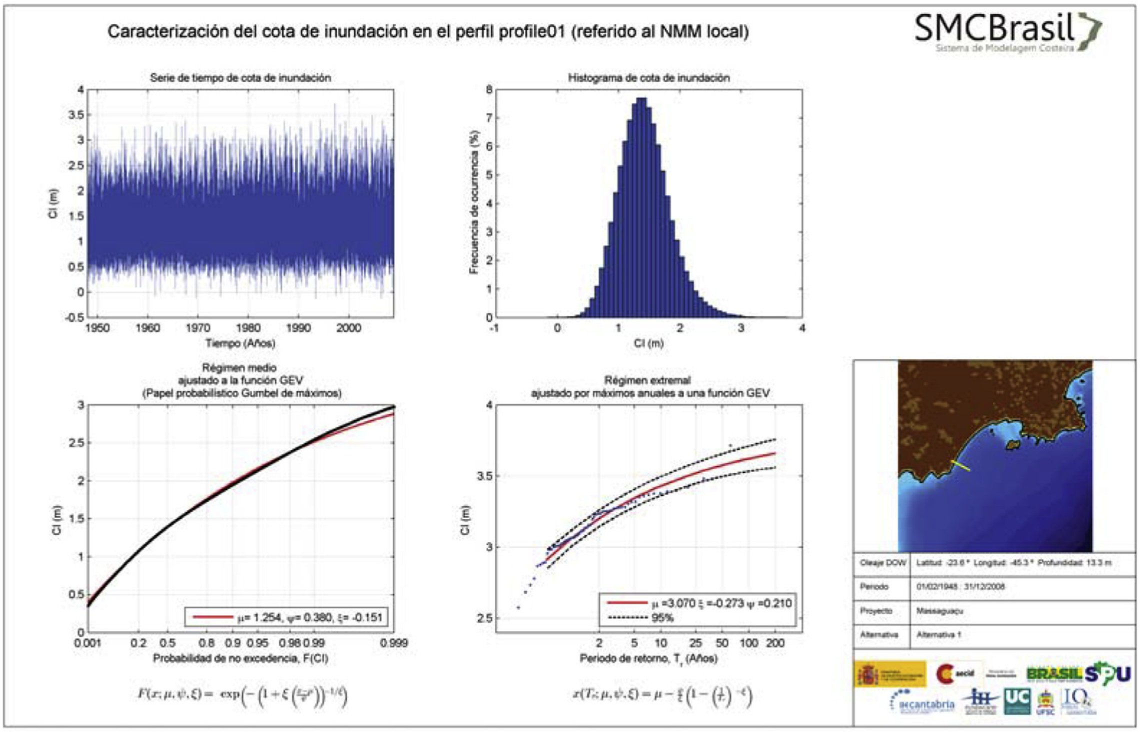

Fig. 21. Flooding level of the southernmost profile. The flooding level series (top left), the histogram (top right), mean regime (bottom left) and extreme regime (bottom right) are shown.

- Southern (green circle in Fig. 16): longshore currents are irregular and the direction depends on the offshore wave direction.
- Center (black circle in Fig. 16): longshore currents are negligible.
- Northern (yellow circle on Fig. 16): currents increase toward the northeast, except at the end of the beach where an intermittent rip current is observed.

4.2. Littoral dynamics

The sediment littoral drift is calculated on the profiles were wave series have been propagated. Fig. 17a) shows the wave height and velocity evolution of a wave state along a profile. The breaking position, indicated by the maximum velocity position, is located close to 450 *m* from the beginning of the profile. Using the results of all propagated cases and their corresponding probabilities of occurrence, density functions are calculated and displayed along the profile, indicating the most likely breaking position for each coastal profile (Fig. 17b).

In Massaguaçu Beach sediment transport was calculated along defined profiles by applying CERC formulation, confirming the pattern observed for currents (Fig. 18), where currents generate a net sediment transport from the central part of the beach toward the extremes following the currents pattern, resulting in a hot spot in the center of the beach, where erosion problems have been observed.

Fig. 18 shows the evolution and mean sediment transport along the profiles. The northernmost located profile (labeled 1 in the figure) exhibits a net mean transport of the order of ~ 39,000 m^3/year always toward the north; the southernmost profile (labeled 3) has a net mean transport on the order of ~ 38,000 m^3/year, always toward the south. Otherwise, the central profile (labeled 2) has a net mean transport of ~ 4,000 m^3/year. The net transport in profile 2 is one order of magnitude less than those of the other profiles because the transport changes direction over the years. This means that the center area of the beach is always acting such as a source of sediment: in some years, sediment moves toward the north, whereas in some others, it moves to the south, but the surrounding areas (profiles 1 and 3) never return sediment to this area. The long-term result is the continuous retreat of the coastline in the central area of the beach, with rare events of accretion produced by large amount of sediment introduced into the system by infrequent massive river floods.

To check the beach stability, the equilibrium planform (Hsu and Evans, 1989; González and Medina, 2001) was determined as a function of the wave climate at the beach control point and the mean wave energy flux direction. SMC-Brasil is able to calculate the mean wave energy flux direction at target points inside the ROI or profiles on the surf zone defined the by user after the wave series have been propagated.

Calculations are performed using the reconstructed 60-year wave climate series. In the case of profiles, calculations are performed considering the wave characteristics at the respective breaking positions. Fig. 19 shows the mean direction of the wave energy flux at some points and profiles on a beach. In particular, it was found that the point number 5 which determines the equilibrium panform of the beach has a mean wave energy flux direction of N53.8^{o}W.

Fig. 20 shows the long-term equilibrium planform in blue and the 2006 shoreline in black. Due to the presence of different diffraction points in the system, the parabolic planform proposed is an average approximation of the real conditions with a main diffraction point at Tamanduá Island. The beach planform has advanced 30 and 250 m in the southern and northern part, respectively, and it has retreated 50 m in the central stretch. The equilibrium planform model, fit to the Hsu and Evans (1989) models by means of the González and Medina (2001) methodology, confirms that the beach does not have an equilibrium shoreline orientation at the northern zone. This is the reason for the existence of cross-shore littoral drift toward the north, which is the responsible for the retreat in the central part of the beach. Profiles along the beach were obtained and adjusted to a Dean (1977) equilibrium profile. Most of the profiles presented a good fit to the equilibrium form, except for the eroded area in the central zone.

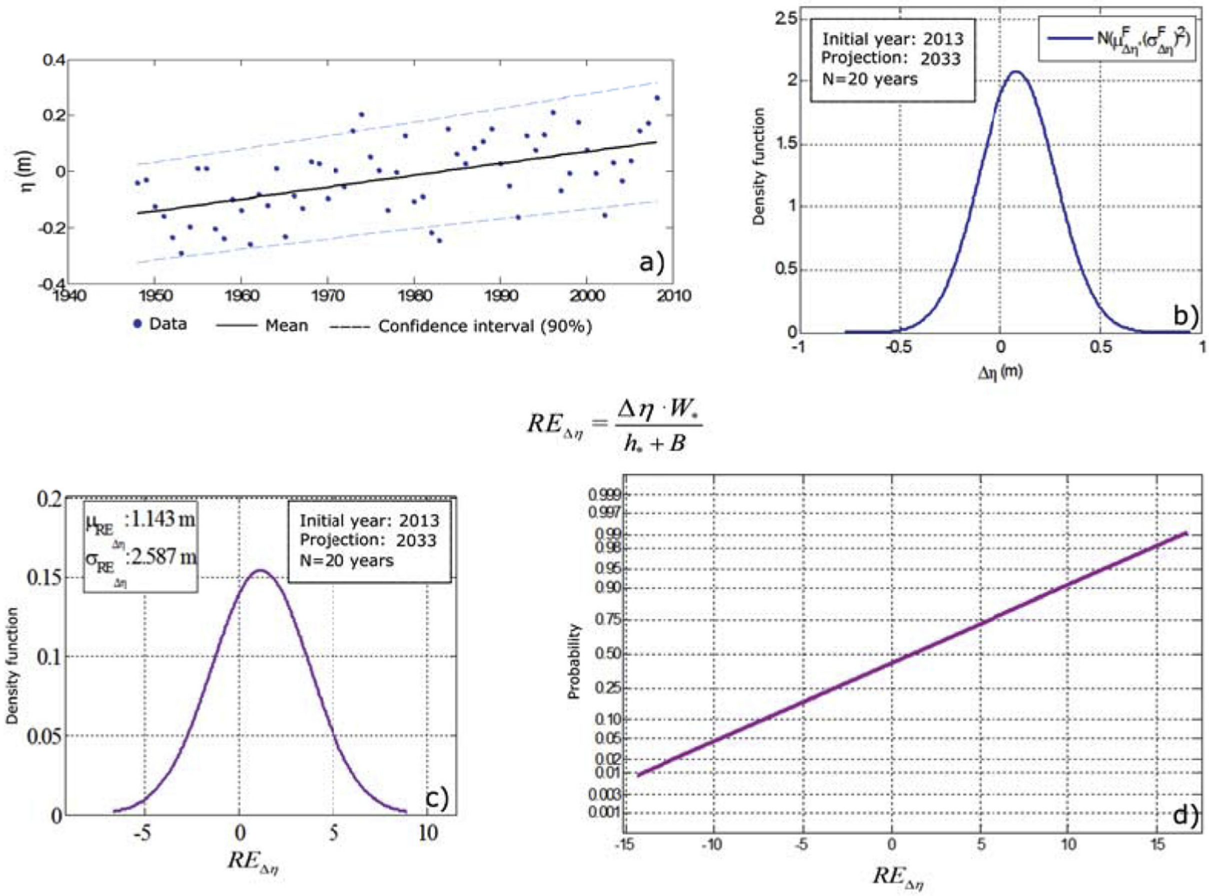

Fig. 22. Estimation of shoreline retreat due to the effects of climate change on the sea level. *a)* Mean and confidence interval of the sea level trend, *b)* projected density function of the sea level for target year 2033 on Massaguaçu Beach, *c)* density function of the retreat (positive values indicate regression, and negative values correspond to accretion) of the coastline position for target year 2033, and *d)* mean regime of the shoreline retreat.

4.3. Flooding level

The beach slope, $\tan\beta$, was obtained from the beach profiles. As a result, along each profile, a series of 60-year of flooding events is determined for every profile and therefore the mean and extreme flooding regimes. Fig. 21 shows the statistics of one of the profiles. The combination of several profiles can be used to define flooding areas.

4.4. Climate change effects (very long-term scale)

Regarding the effects of climate change effects in the very long-term, the shoreline retreat (*RE*) on a beach due to sea level rises and increases in wave height was calculated (Fig. 22). First, the trend of the local sea level (η) distribution is calculated (a). Consequently, a distribution for the variation in the sea level ($\Delta\eta$), is obtained for a projected year (b). By applying the Bruun rule (Bruun, 1962),

$$RE_{\Delta\eta} = \frac{\Delta\eta \quad W_*}{h_* + B}, \tag{4}$$

where W_* represents the active beach profile length, h_* represents the closure depth and B represents the berm height, the distribution of retreat $RE_{\Delta\eta}$ is obtained (c). Here it is important to note that positive values indicate shoreline retreat, whereas negative values indicate accretion. Finally, using the mean regime (d), a relationship with the probability is obtained. Therefore, following the figure, if a user is interested in knowing the probability of a shoreline retreating more than 5 m for the horizon year 2033, on Massaguaçu Beach, then it can be determined that the probability is $(1 - 0.75)$ which is equal to 25% using the mean regime (Fig. 22d).

4.5. Proposed solution

After the exhaustive analysis through the tools, models and databases included in SMC-Brasil, a deep knowledge of the morphodynamic model that rules the beach has been reached. This analysis led to the conclusion that Massaguaçu Beach is not in equilibrium, and the observed erosion in the central area and accretion on both ends (but mainly in the northern zone) are reactions of the system trying to reach an equilibrium state. As a consequence, the traditional local solutions (walls and local protections) implemented did not solve the erosional process in the central area of the beach.

With these concepts in mind, solutions can be proposed. Solutions range from soft (*e.g.* retreatment of the road and sidewalk inland to let the beach evolve to equilibrium) to hard (*e.g.* construction of detached breakwater or a groin). To determine the best option, potential solutions were modeled and evaluated with SMC-Brasil.

As an example, one of the solutions requires the construction of a 400 m-long groin on the northern part of the beach and a nourishment of 1,200,000 m^3. The source of the sediment is on the lee of Tamandua Island (yellow area in Fig. 20); this area has acted as a sediment reservoir eroded from the center of the beach. This solution produces a static equilibrium planform in the central-north zone that reduce the present littoral drift toward the north and produce the shoreline advance of 40 m at the central part of the beach in static equilibrium. The configuration of this solution can be observed on Fig. 23, in which the yellow area indicate the stable beach area, where the sediment size is $D_{50} = 0.25$ mm and the red area can be filled up with unstable sediment.

Finally, the design of the groin length and determination of the final values of the sand and shoreline positions have been performed by

Fig. 23. Proposed solution to solve the erosion problem on the central part of Massaguaçu Beach based on the construction of a groin on the northern part of the beach and a nourishment of 1,200,000 m ^{3}.

taking into account the very long-term trends in wave heights, wave directions and sea level induced by the climate change.

5. Dissemination plan

Regarding dissemination, a system of registrations and licenses was established. According to this system, a registered institution can have several licenses. Licenses can be solicited completely free of charge by federal and state administration practitioners (from coastal offices and harbors authorities) and researchers (from universities and institutes) that demonstrate expertise in the area of knowledge. Expertise can be demonstrated through a 40-h course (face-to-face or online).

Two stages were established for the distribution. The main goal of the first one was to deliver the system to administration practitioners and researchers from several Brazilian universities, which would act as local distributors in the second stage. To achieve this goal, three courses were conducted, at the Oceanographic Institute (IO) – USP in São Paulo in 2012, at the Center of Strategic Technologies of Northwest in Recife in 2013 and at the Environmental Ministry in Brasilia in 2014, with an attendance of approximately 30 people each. As a result, by this time, more than 300 licenses were granted (see Fig. 24), and four pilot cases were studied and published (see Fig. 25): *i)* the Ponta Negra Beach (Natal/RN), where the SMC-Brasil wave climate was used as a basis for the beach erosion study in the region to contribute to the management of public policy regarding the seafront construction (Almeida et al., 2015); *ii)* Candeias Beach (Recife), where a modification of the configuration of the breakwater was planned; SMC-Brasil was used to reproduce the current and future conditions (Gomes and da Silva, 2014); *iii)* Massaguaçu Beach (on the north coast of São Paulo), where erosion has been observed on the central part of the beach; therefore, SMC-Brasil was used to investigate the origin of this process and propose mitigation measurements (González et al., 2014); and *iv)* Piçarras Beach at Itapocorói Bay (Piçarras/SC) where SMC-Brasil was used to study the littoral dynamics due to the loss of beach sediment and to evaluate mitigation measurements (Ribas, 2010). All four cases were studied following the SMC-Brasil methodology, transferring climate waves to the coastal zone to analyze coastal dynamics; when appropriate, mitigation measures were also evaluated.

In the second stage of dissemination, training courses for researchers, coastal engineers, and administration practitioners were conducted in Brazilian coastal states with the purpose of distributing SMC-Brasil to state administrations, universities and consultant firms. In 2017 two courses were conducted, in Florianópolis/SC and Natal/RN, with a mean attendance of 25 people each. At the end of 2017 SMC-Brasil had a presence in the most important coastal cities, with more than a hundred registered institutions and more than 550 licenses issued (see Fig. 24). Additionally, an online book is ready for publication, explaining more than fifteen case of studies in which SMC-Brasil has been applied.

6. Conclusions

A new coastal modeling system, SMC$_{\varepsilon}$, was presented and its application to the Brazilian coasts. SMC$_{\varepsilon}$ is a system especially designed to help coastal designers, researches and managers to address coastal issues. This system includes a set of up-to-date methodologies and databases to aid in every step of a coastal project, from the transference of long wave climate series from deep to shallow waters, to understanding local coastal processes, by means of calculating potential sediment transport or flooding, over the short-, medium-, long- and very long-terms.

The main strengths of the system are, the association of methodologies, numerical models and numerical databases on a closed system to addres coastal issues; the numerical databases, which are calibrated and

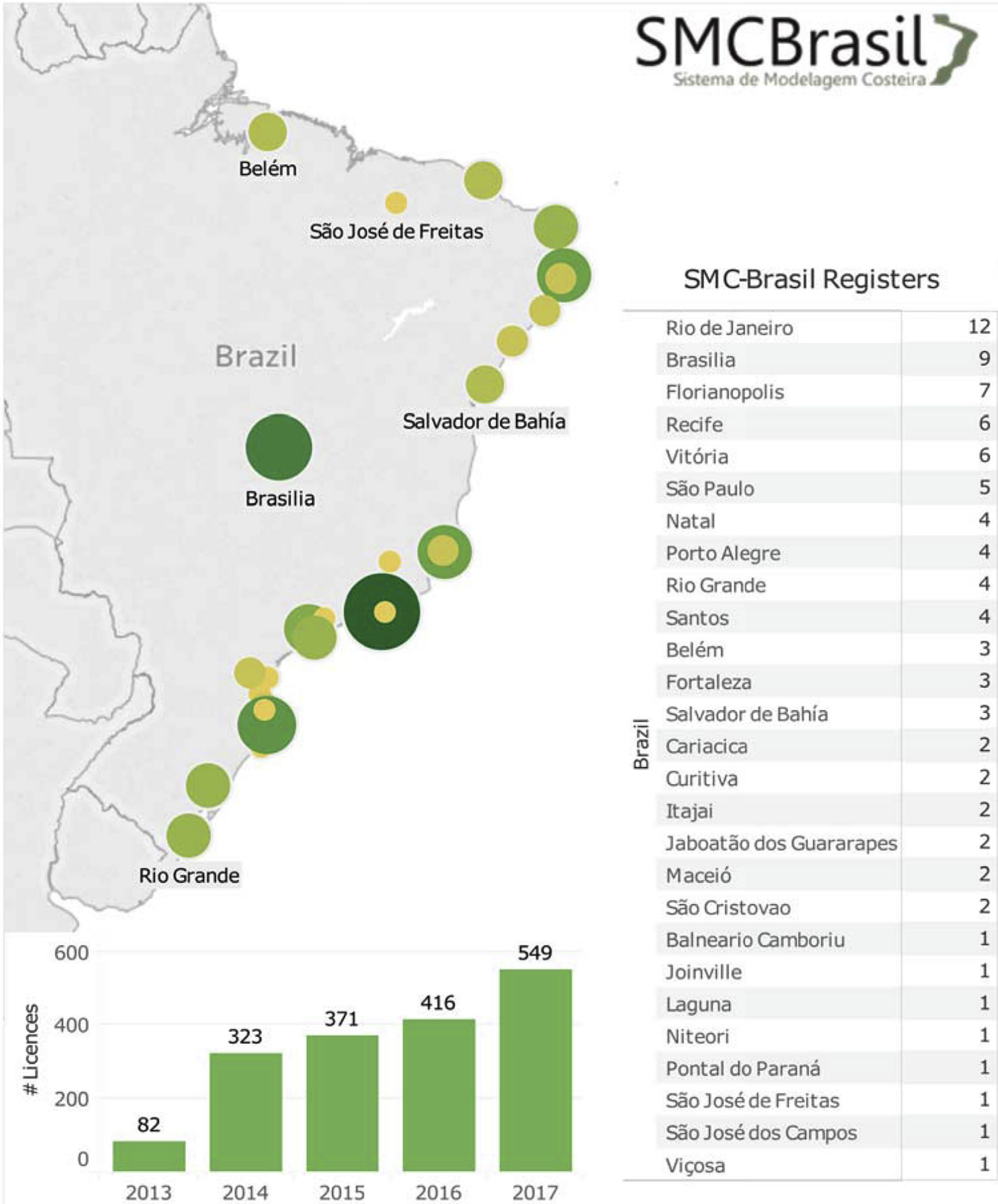

Fig. 24. Map of SMC-Brasil presence in Brazilian coastal cities. The circles on the map and the table indicate the number of Brazilian institutions registered to use the system per city. The bar plot indicates the evolution of the licenses distribution during the period from 2013 to 2017.

validated and ready to be applied through the system to any coastal area; A set of numerical tools to be applied to transform the numerical data to specific results to understand local dynamics; That system is completely free and all models and databases can be updated regularly.

The system consists of two main programs, SMC 3.0 and SMC-Tools, and a set of thematic documents to elaborate the theoretical framework of coastal processes and guide the users in choosing the most appropriate method or data to be applied to address specific issues.

A set of bathymetry, coastal waves, sea levels, and climate change databases, named IH-DATA, are included in the system to be used as sources of information for studies, thus making it possible to study zones with limited or no-external instrumental data. The coastal waves and sea level database are numerically generated, calibrated and validated by means of in-house methodologies.

Regarding the methodologies, the system allows the users to propagate long wave time series to any point on the coast, by means of a fully integrated in-house method. These series are subsequently used to calculate several results, such as the littoral drift, flooding levels, and the mean wave energy flux direction, among others. Regarding the littoral drift, the potential littoral sediment transport, is calculated across profiles by means of the most accepted bulk sediment transport formulations. The flooding level is calculated considering the local levels of astronomical tide and storm surge and the runup of propagated wave series. The system includes a set of methodologies to estimate the impact of climate change on a beach in terms of coastline regression, rotation and flooding level.

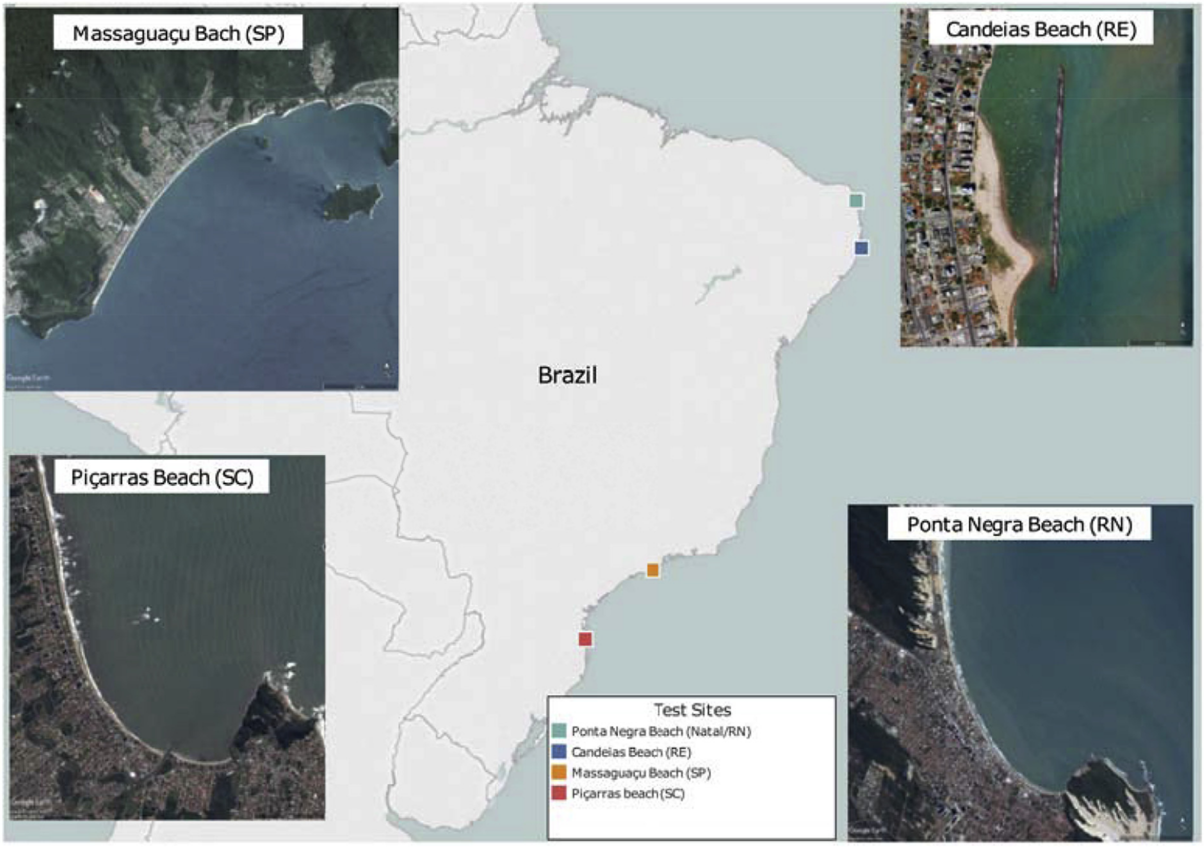

Fig. 25. Images and locations of the four study sites.

SMC$_{\varepsilon}$ is not a closed system; this means that enhanced or new methodologies and databases can be implemented. The system is also ready to be implemented for any country or coastal region by regionalizing databases and adapting the results to local requirements.

As an example of the application of the SMC$_{\varepsilon}$, the implementation for Brazilian coasts, named SMC-Brasil was described. The databases in SMC-Brasil consist of sixty-year series concerning downscaled waves, astronomical tides and storm surges. Downscaled wave series can be obtained by means of a hybrid downscale methodology at resolutions of 1 km for depths less than 20 m and 10 km for larger depths. The astronomical tide and storm surge series are distributed along the Brazilian coast, such that the observed variability is represented adequately. The databases were calibrated and validated by means of in-house methodologies, using available satellite and *in situ* data.

The system has been released for federal and state practitioners, coastal consultants and researchers, reaching (by this time) more than 540 licenses and having a presence in all of the Brazilian coastal states. In addition, more than 150 people have been trained in 5 face-to-face courses (held in Sao Paulo, Recife, Brasilia, Florianopolis and Natal). The system has been tested on four pilot cases, in which typical coastal issues have been addresssed. Here a brief summary of the Massaguaçu Beach pilot case, in which erosion has been observed, was presented. The problem was addressed using the methodology provided by the system, and a solution was proposed.

Acknowledgements

This work was supported by the Brazilian government through the Ministério do Meio Ambiente (MMA), the Agência Brasileira de Cooperação (ABC) and the Agencia Española de Cooperación Internacional para el Desarrollo (AECID). The IHCantabria authors also received support from 'Sociedad para el Desarrollo Regional de Cantabria' (SODERCAN) [grant ID16-IN-045].

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