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Energy converting structures in the Southern Brazilian Shelf: Energy conversion and its influence on the hydrodynamic and morphodynamic processes

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Abstract

This study is a preliminary investigation into the influence of the installation of energy converters in the Southern Brazilian Shelf (SBS) and possible modifications in the natural hydrodynamic and morphodynamic processes. The study is based on the application of a three-dimensional numerical model to simulate hydrodynamic and morphodynamic processes. The energy converting structures are represented in specific points along the continental shelf using the turbine concept. The results indicate that coastal currents could be used for the

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conversion of electric energy. Mean and maximum values of approximately 3 and 79 MW of electric power, respectively, could be obtained at specific points considering the wind driven circulation as the principal forcing mechanism. Considering a set of 6 turbines (20 m radius), an integrated annual rate of approximately 5 GWyear^{-1} is estimated for the conversion of electric power. The presence of energy converters removes part of the kinetic energy from the coastal currents, generating divergence and convergence zones in accordance with the dominant direction of the currents. The major consequence for the natural ecosystem during the period simulated is the decrease of the intensity of currents and the increase of the suspended sediment concentration near the site of the converters.

Keywords: Southern Brazilian Shelf, hydrodynamic, morphodynamic, energy converters, turbines

1 Introduction

The SBS, located between 28°S and 35°S, is a freshwater-influenced region with complex interactions of large-scale coastal currents and tidal and wind effects (Figure 1). Previous numerical modelling studies on the SBS have considered aspects of large-scale coastal currents with low resolution in space and time [1, 2, and 3]. Piola et al. [1] investigated the importance of the alongshore component of the wind stress controlling the seasonal variability of the La Plata plume. Soares et al. [2, 3] conducted realistic hydrodynamic simulations for the SBS and investigated the buoyancy-driven currents in the area, highlighting the contributions of the wind and tidal currents.

Numerical modelling studies of the SBS that consider dynamic aspects with high resolution in space and time are presented by Marques et al. [4] and Marques et al. [5, 6, and 7]. Marques et al. [4] studied the physical forcing controlling the formation and behaviour of the Patos Lagoon plume based on a three-dimensional hydrodynamic numerical model. Marques et al. [5] investigated the importance of straining and advection for the evolution of stratification inside the Patos Lagoon coastal plume for each of its known physical modes using potential energy anomaly budgets. Marques et al. [6] investigated the contribution of the Patos Lagoon coastal plume to the deposition pattern along the inner continental shelf, providing estimates of estuarine-shelf suspended sediment exchange.

The SBS can be considered a well-studied region regarding the dynamic behaviour of natural processes. However, man-made structures are commonly built in the coastal environment to promote industry products, harbour activities and energy conversion from currents in electrical energy.

According to [8], the energy in flowing river streams, tidal currents and other artificial water channels is considered to be a viable source of renewable power. Gorlov [9], in studying gravitational tides and approaches to energy extraction, concluded that these are a substantial potential source of clean renewable energy for future human generations. However, hydrokinetic conversion systems are in the early stage of development and have production costs. The development of new, efficient, low-cost and environmentally friendly hydraulic energy converters suited to free-flowing waters, such as triple-helix turbines, can make tidal energy available worldwide [9].

Previous studies for the SBS indicate that wind-driven circulation (meteorological tides) is the most important mechanism controlling the distribution of properties at time scales varying from days to weeks. Otherwise, studies investigating the influence of certain man-made structures for hydraulic energy conversion on the natural dynamics of this coastal system do not exist. Therefore, the aim of this study is to investigate the potential for energy conversion and the influence of the installation of a set of energy converters in modifying the natural hydrodynamic and morphodynamic processes along the

Southern Brazilian Shelf.

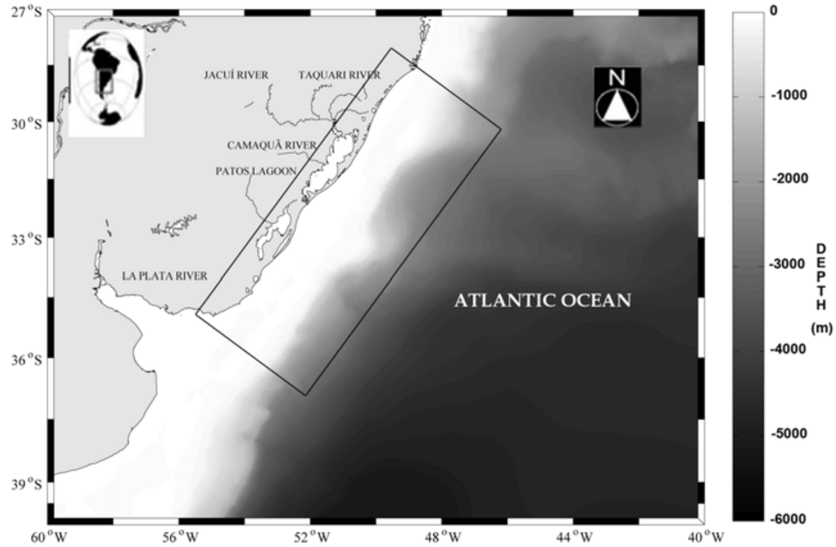


Figure 1: The Southern Brazilian Shelf (rectangle), the Patos Lagoon and its principal tributaries

2 Methodologies

This study is based on the application of three-dimensional numerical modelling techniques of the hydrodynamic and morphodynamic processes. The energy converters are represented as sink energy structures in specific positions of the numerical domain.

2.1 The hydrodynamic numerical model

The TELEMAC SYSTEM, developed by ©EDF – *Laboratoire National d'Hydraulique et Environnement* of the *Company Eletricité de France (EDF)*, is used for the hydrodynamic numerical simulations. The TELEMAC3D model solves the Navier Stokes equations considering the local variations in the free surface of the fluid, ignoring the density variations in the mass conservation equation, and considering the hydrostatic pressure and Boussinesq approximations to solve the motion equations. The model is based on characteristics methods and the finite element technique to solve the hydrodynamic equation (detailed information can be found in Hervouet [10].

A time step of 30 s and a Coriolis coefficient of -7.70 x 10^{-5} N m^{-1} s^{-1} (latitude 32ºS) were used in all of the simulations. The horizontal turbulence process was performed using the Smagorinsky model. The mixing length model for buoyant jets was implemented to access the vertical turbulence process, giving a representation of the stratification and the vertical mixing process. This model takes into account density effects via a damping factor that depends on the Richardson number to calculate the vertical diffusion coefficients.

The transport of suspended sediments is calculated by the TELEMAC3D model according to the mass conservation equation. This equation is solved through the finite element method with fractional decomposition in steps [11]. The suspended sediment is treated as an active tracer, but together with salinity and temperature, it can influence the fluctuations of the density field.

2.2 The morphological numerical model

The SediMorph model, developed by the Federal Waterways Engineering and Research Institute (BAW), is a model of morphological and fractionated sediment transport. The model works when coupled with the hydrodynamic model TELEMAC3D calculating at the same time step the bed load transport of sediments, the erosion flux and the bed shear stress to update the evolution of the sea bed [12, 6]. According to Malcherek et al. [13], the SediMorph model solves the bed load equation using a Gauss formula for the integration of the divergence, Euler stepping for the time derivation and explicit time discretisation for the remaining terms.

The SediMorph uses a classification sediment file where the different classes are defined according to the diameter and density of each. This information is used to construct a bi-dimensional non-structured bottom mesh with several vertical levels performing a tri-dimensional mesh of finite volumes. In this work, only one vertical level is used due to the unavailability of information about the vertical distribution of the bottom sediments. At the interface layer where the erosion and deposition processes occur, the model must calculate the bottom shear stress while taking into account the roughness of the bed and the intensity of the flow.

The bed roughness summarises the effects of the geometrical irregularities in the flow. This information is updated during the simulation according to the bed evolution transferred for the TELEMAC3D. The bottom shear stress is calculated by the SediMorph using slightly modified Nikuradse formula [13], and the transport of the bottom sediments is determined using the Hunziker formula [14]. This formulation takes into account the properties of different sediment classes and the properties of the whole distribution.

To obtain the cohesive effects on sediment transportation, the settling velocity is calculated as a function of the sediment concentration, temperature, salinity and velocity gradient according to the Van Leussen [15] formulation. The SediMorph calculates the critical shear stress and erosion flux according to the Malcherek et al. [13] theory using an erosion flux model with quadratic approximation to consider the effects of cohesion and the Van der Waals interaction between the sediments settled over the bottom.

2.3 Initial and Boundary conditions

The initial and boundary conditions applied for the hydrodynamic numerical simulations are described in Marques [12], Marques et al. [4], Marques et al. [5] and Marques et al. [6]. Therefore, this section presents a simple description. The initial conditions of salinity and temperature fields were prescribed for the TELEMAC3D model. The salinity and temperature fields were obtained from the OCCAM Project (Ocean Circulation and Climate Advanced Modeling Project), and were prescribed tri-dimensionally over the entire domain. Water levels of 0.4 m (the approximate mean value of the tides in the study region) and null velocity fields were prescribed as initial conditions in the entire domain.

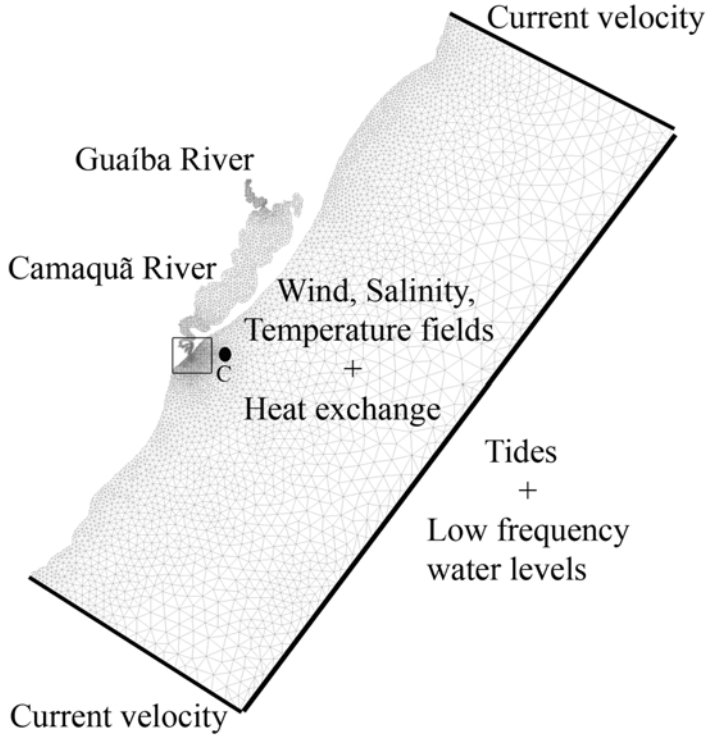


Figure 2: The finite elements mesh highlighting the liquid and surface boundaries. C and the black circle represent the position of 6 energy converting structures. The black rectangle highlights the estuarine region of the Patos Lagoon

The time series of river discharge from the rivers at the north of the lagoon were used to force the continental liquid boundary (Figure 2). The river discharge data were provided by the Brazilian National Water Agency (ANA). The time series of river discharge used for the case study ranges between January 01, 1998, and April 29, 1999. The tidal influence is prescribed at each nodal point of the oceanic boundary (Figure 2) using the amplitude and phase of the five main tidal components of the study area (K1, M2, N2, O1, S2; Fernandes et al. [16]), which were obtained from the Grenoble Model (FES95.2, Finite Element Solution – v.95.2). The surface boundary of the model is forced with space and time variable winds with daily resolution from the reanalysis web page of the National Oceanic & Atmospheric Administration (NOAA). These data are prescribed at each nodal point of the mesh.

The seasonal and annual variability is imposed on the numerical simulation considering the low frequency contribution of the coastal currents, the buoyancy terms and the heat exchange along the SBS. Remote wind effects are represented by prescribing the low frequency water levels, and the influence of the coastal currents is represented by prescribing the low frequency current velocity at each nodal point of the oceanic boundary (Figure 2). The data sets of water level and current velocity that were used as boundary conditions were obtained from the OCCAM Project.

The influence of the buoyancy-driven currents from the La Plata River was considered by prescribing a salinity time series at each nodal point along the southern oceanic boundary (Figure 2). The heat balance between the different water masses at the oceanic boundaries was simulated through the prescription of temperature time series. These data were obtained from the OCCAM Project (Figure 2). The heat exchange between the free surface of the model and the atmosphere was considered using air temperature data from the NOAA reanalysis web page with a daily resolution.

The initial conditions of sediment distribution were prescribed according to the measurements obtained between 1975 and 1979. The sediment classes prescribed are distributed in fine silt and fine and coarse sand [6]. Over the bottom of the coastal area, sediments with a diameter of fine sand were prescribed along the whole area. The initial conditions for the suspended matter were prescribed with a constant null concentration along the entire domain. The boundary conditions of the suspended matter were considered constant, with values of 0.5 kg m^{-3} and 0.3 kg m^{-3}. The TELEMAC3D was calibrated and validated in previous studies for the SBS [12, 4, 5]. The calibration and validation of TELEMAC3D and SediMorph was conducted in Marques et al. [6].

2.4 Energy converting structures

The energy converters are indirectly implemented in the hydrodynamic and morphodynamic modules. This preliminary implementation uses a similar concept applied in aeolic energy generators. In this case, the kinetic energy associated with the current velocity along the water column is used to move the turbines, converting the rotation energy into electric energy. The electric power equation generated in Watts (W) is a function of the cubic power of the current velocity.

$$P_e(W) = \frac{1}{2}\eta\gamma(\pi R^2)v^3 \tag{1}$$

Where *Pe* is the electric power converted from the current; *η* represents the efficiency and the dynamic coefficient of the generator, respectively; *γ* represents the water density; *R* is the ray of the turbine rotor; and *v* is the module of the current velocity.

Typical *η* value is used according to Rüncos et al. [17] due to the absence of studies using similar turbines in oceanographic applications. A typical value for density in oceanic waters was applied, and the calculated current velocity from the model was considered to adapt the equation to application to coastal waters. Table 1 indicates the constant values and parameters applied in this study.

The electric power equation was numerically implemented in the hydrodynamic and morphodynamic modules through the generation curve (Figure 3). This curve indicates the relation between the intensity of the current velocity and the liquid electric power converted. The curve also represents the cubic relation between the current velocity and the converted electric power. The nominal power (P_n) of 750 kW is reached when velocities greater than 1.5 m s^{-1} (nominal velocity, v_n) are observed.

Table 1: Parameters used in equation 1.

Parameters	Values (units)
H	0.35
γ	Calculated
R	20 m
v_n	1.5 m s^{-1}
P_n	750 kW
V	Calculated

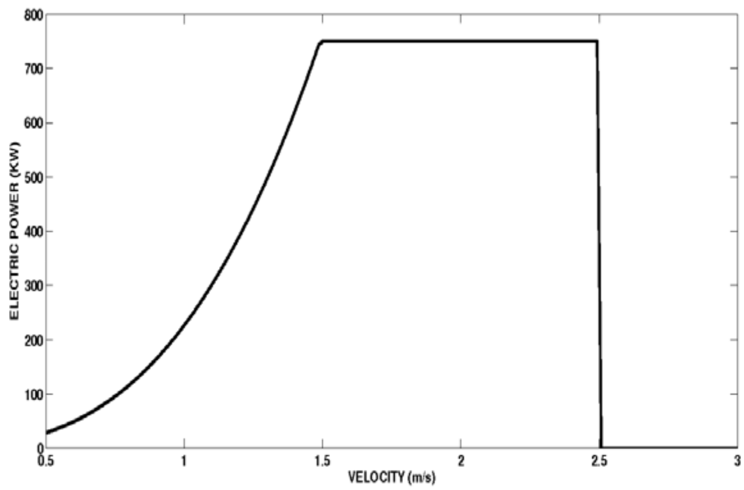


Figure 3: Electric energy curve implemented in the numerical model

The converting structures were implemented in six different points along the adjacent continental shelf to the north of the Patos Lagoon entrance (see Figure 2). The hydrodynamic efficiency (hyd_{ef}) of similar structures was not found in literature. This study considers the constant hydrodynamic efficiency ($hyd_{ef} = 0.3$), indicating that these turbines can linearly convert 30% of the kinetic energy of the currents into electric energy.

2.5 Coupling between TELEMAC3D, SediMorph and the Energy Conversion Module

The coupling procedure between TELEMAC3D and SediMorph is described by Marques [12] and Marques et al. [6]. A simplified sketch of the coupled system is presented in Figure 4. Before initialisation, both modules downloaded the bathymetric mesh, updating the bottom friction. In the first time step, TELEMAC3D calculated the current velocity, flux of sediments, and deposition fluxes for the suspended load. This information was then transferred to SediMorph, which calculated the bed load transportation and erosion flux. This information was used to update the bathymetry and the bottom friction according to the new distribution of sediments. The newest bathymetry, bottom friction, and erosion flux were used by TELEMAC3D to update the sigma levels, and the calculations were continued for the next time step up to the end of the simulation.

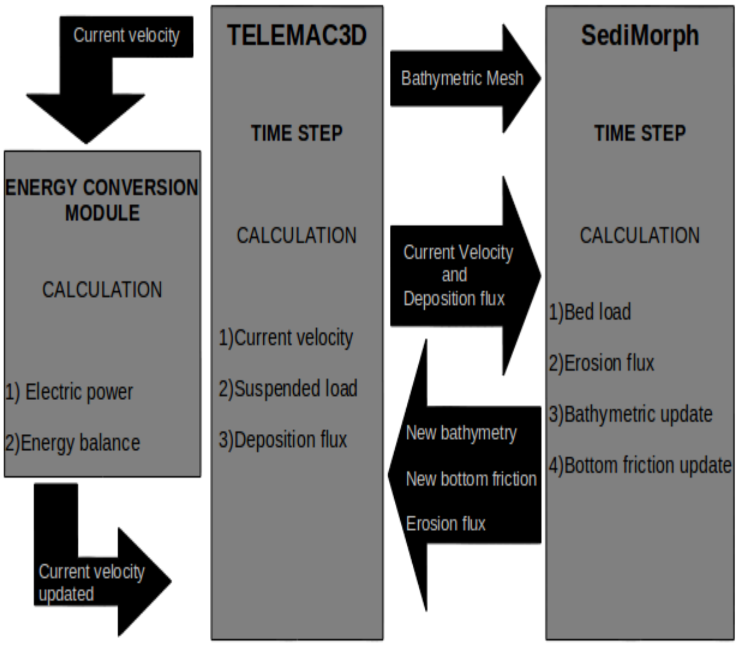


Figure 4: Sketch of the TELEMAC3D, SediMorph and the Energy Conversion Module coupled system

In the SediMorph model, the fluxes of the free surface environment and the bottom sediment movements were considered as a coupled system. Generally, the bottom roughness inserts bed shear stresses in the flux. The flux can transfer momentum to the bed sediments and, due to the shear stress, induce sediment movement. The transportation of these sediments can change the bed form, bed roughness, and bed shear stress, generating long-term modifications in the dynamics of the whole system.

Based on energy conservation criteria, the energy converters are implemented to run when coupled with hydrodynamic and morphodynamic modules. After each time step, the SediMorph transfers the new bathymetry and new bottom friction for the TELEMAC3D, which updates the current velocity. The updated current velocity is transferred to the Energy Conversion Module, which converts some part of the electric energy through the electric power equation. In this module, the current velocity is updated to maintain the mass and energy balance of the numerical model before transferring to the TELEMAC3D.

3 Results and Discussion

To investigate the potential for energy conversion and the influence of the installation of energy converters in the natural hydrodynamic and morphodynamic processes of the SBS, two simulations were conducted for 482 days, applying the physical parameters established in the previous section. The simulated period covers from January 01st of 1998 to April 29th of 1999.

3.1 Energy conversion – Mean values and time series

The residual currents obtained from the first simulation (without the energy converters) indicate the mean conditions of coastal currents for the studied region. The dominant north quadrant winds during the study period drive the south-westward currents alongshore, with mean values ranging from 0.1 m s^{-1} near the coastline to 0.15 m s^{-1} offshore.

The energy converters were implemented over the 50 m isobath (Figure 5B). The filled contours indicate a variable pattern of conversion from kinetic energy to electric energy over this site. This variability is associated with the intensity of circulation, and the mean values of electric power range from 2 up to 10 MW at this area.

During the 482 days of simulation, a local mean circulation pattern was created because of the presence of the energy converters. The energy converters removed part of the kinetic energy from the coastal currents, generating divergence zones north-eastward and convergence zones south-westward of this site. The main consequence is the decrease of the current velocity south-westward, which contributes to the increase of accumulation and further deposition of suspended sediments along this area of the continental shelf.

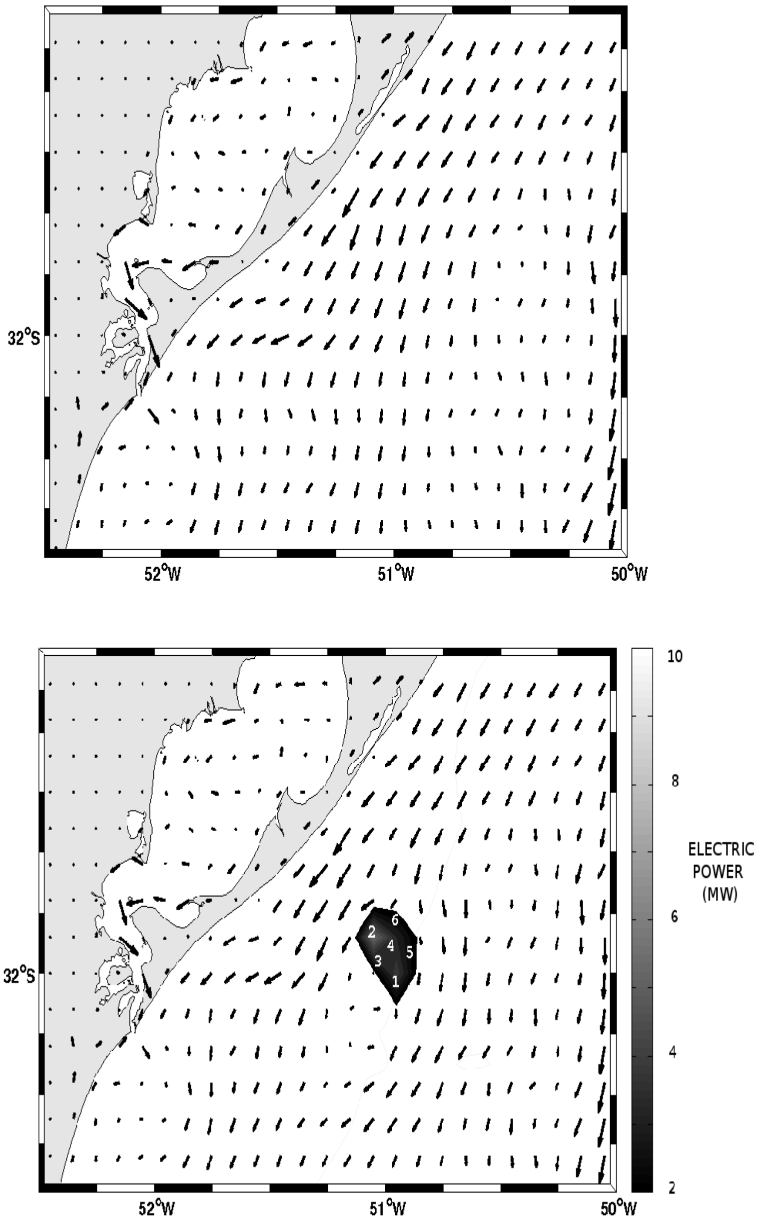


Figure 5: Residual circulation after 482 days without (A) and with (B) energy converting structures. Isolines of mean electric power during 482 days of simulation are presented.

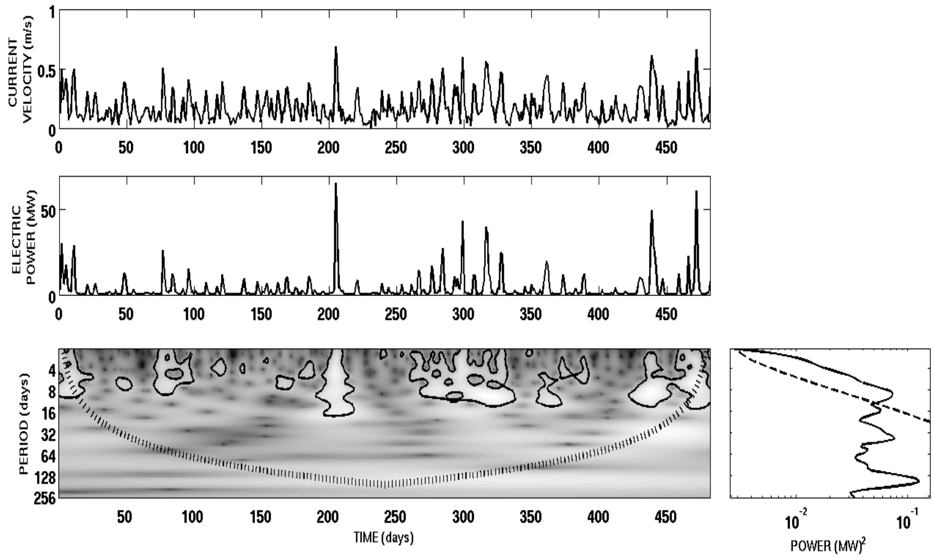


Figure 6: Integrated current velocity (A) and electric power time series (B) used for the cross-wavelet analysis, as well as, the local (C) and the global (D) wavelet power spectrum of the time series using Morlet wavelet. Thick contour lines enclose regions of greater than 95% confidence for a red-noise process with a lag-1 coefficient of 0.72. Cross-hatched regions indicate the cone of influence where edge effects become important.

Time series (Figure 6A) of electric power accounting for the six converters are presented with the mean intensity of the current velocity at this site. The direct correlation between current velocity and electric power is observed, and the most important cycles occur from 2 to 20 days following the passage of the meteorological systems over the study region. The spectral content and the correlation between the integrated electric power and current velocity time series (Figure 6A) were investigated using cross-wavelet analysis. This method locates power variations within the discrete time series over a range of scales and provides the local and global power spectrum. The analysis of the local power spectrum (Figures 6B) corroborated that the physical processes shorter than 20 days were the main mechanisms controlling the electric power conversion along the inner continental shelf. According to the wavelet analysis, the events resulting in considerable electric energy conversion present a well-defined pattern occurring throughout the whole year. The global power spectrum shown in Figure 6C corroborates these findings and indicates the importance of these processes for energy conversion. Mean and maximum values and also the integrated annual rate of energy converted using 6 turbines on the SBS are presented in Table 2.

Table 2: Temporal mean, maximum and integrated value for electric power generated at the selected site considering 6 turbines

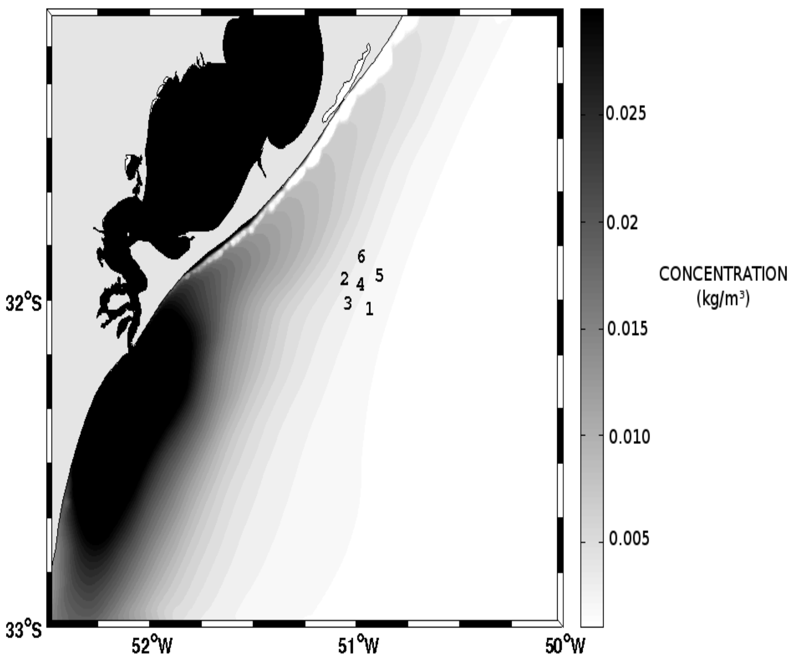
MEAN VALUE (MW)	MAXIMUM VALUE (MW)	INTEGRATED ANNUAL RATE (GW/year)
3.25	79.11	4.72

Several studies have shown that mixing and exchange processes during the low and mean discharge conditions of the Patos lagoon circulation pattern are controlled by wind effects at synoptic times scales coincident with the passage of meteorological systems every 3 to 17 days [18, 19, 20, 21, 7]. Marques et al. [4] found a similar pattern of migration south-westward/north-eastward of the Patos Lagoon coastal plume in accordance with the passage of meteorological systems over the area. Marques et al. [5] verified that straining and advection processes were the most important mechanisms controlling the evolution of stratification in the adjacent coastal region of the Patos Lagoon with the most important events also occurring in periods shorter than 20 days. Thus, it is clear that this time scale variability is characteristic of the area, being also reflected in the electric power generation from the current's energy.

3.2 Influence on environmental properties – Total Suspended Matter (TSM), silt enrichment and bed evolution

A small alteration in the circulation pattern of the area can influence the distribution of suspended matter carried by the Patos Lagoon discharge and the pattern of the bed load transportation alongshore.

The mean TSM concentration during the 482 days of the simulation indicates the development of a hypopycnal and almost symmetrically alongshore oriented plume directly influencing the bed evolution in shallow areas of the adjacent coastal region (Figure 7A). This pattern of evolution indicates regions more susceptible to the initial deposition of sediments associated with the typical circulation pattern of the region. Marques et al. [4] and Marques et al. [5, 6] observed the local wind action as the principal mechanism controlling the fate and behaviour of the Patos Lagoon coastal plume at synoptic time scales.



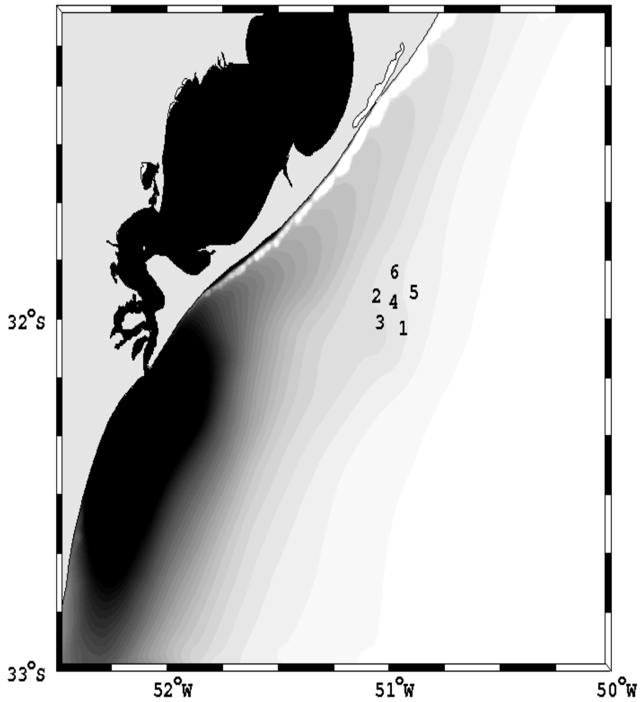


Figure 7: Temporal mean of the superficial suspended sediment concentration (kgm-3) during 118 days of simulation without (A) and with (B) the energy converting structures.
The numbers indicate the position of the 6 energy converting structures.

Considering the time scales presented in this study, small differences can be observed in the mean TSM concentration when considering the energy converters, with a sensible increase of concentration near the region of the converters (Figure 7B). This result suggests that when the TSM reaches this area, the modification of the residual circulation prevents its mixing and further distribution to the neighbouring areas. Marques et al. [5] observed that the bed layer of this plume presents a restricted pattern, indicating that under mean conditions, this plume reaches the bottom only in the shallowest regions of the coastal zone (below 30 m depth). The initial deposition of the TSM in this region is controlled by the local circulation. Therefore, modifications in the intensity and direction of the currents intensify the deposition of fine sediments in the deeper parts of the inner continental shelf near the region of the converters.

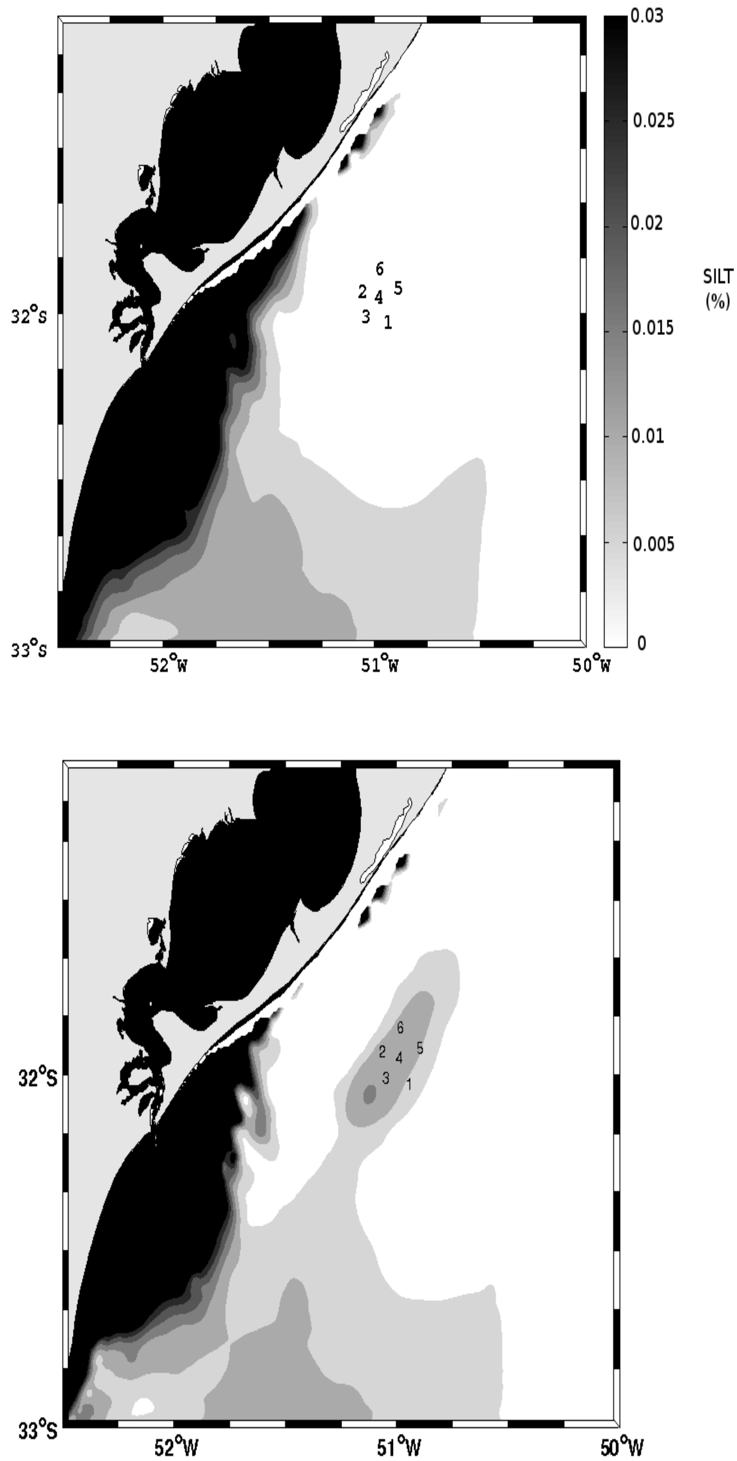


Figure 8: Silt enrichment (%) after 482 days of simulation without (A) and with (B) the energy converting structures. Numbers indicate the position of the 6 energy converting structures.

The initial deposition of sediments along the coastal region results from the competition between erosion and deposition events. In this way, the residual pattern of circulation promotes the increase of the TSM concentration near the converters' area, enhancing the silt deposition provided by the Patos lagoon coastal plume by approximately 0.015% (Figure 8B).

According to Marques et al. [4, 5, 6], the north quadrant winds promote the spreading of the Patos Lagoon coastal plume south-westward, intensifying the stratification of the coastal waters. However, the presence of the converters during these events removed part of the kinetic energy from the coastal currents, generating divergence zones north-eastward and divergence zones south-westward of this site. This scenario favours the deposition of fine sediments previously carried for this region during periods of south quadrant winds, when the sediment plume is naturally attached to the coastal region because of the Ekman transport.

The enrichment caused by the TSM transported and trapped by the circulation pattern depth is indicated by the percentage of silt found along the coastal region after 482 days of simulation (Figure 8B). The enrichment of the coastal region caused by the silt transportation associated with the Patos Lagoon discharge results in a positive bed evolution (Figure 9).

Regions near the coast presented bed evolution values greater than 2 mm during this period (482 days of simulation). The results of the silt enrichment along the coastal region and the bed evolution represent an important natural dynamic process of interaction between the Patos Lagoon coastal plume and the adjacent coastal circulation previously investigated by Marques et al. [5]. The residual pattern of circulation promotes the increase of the TSM concentration near the area of the converters, enhancing the silt deposition provided by the Patos lagoon coastal plume. This behaviour reflects the increase of the bed evolution considering the presence of the energy converters by 1.5 mm compared with the natural scenario (Figure 9B). At this time scale (482 days of simulation), the differences in silt enrichment and bed evolution are almost negligible.

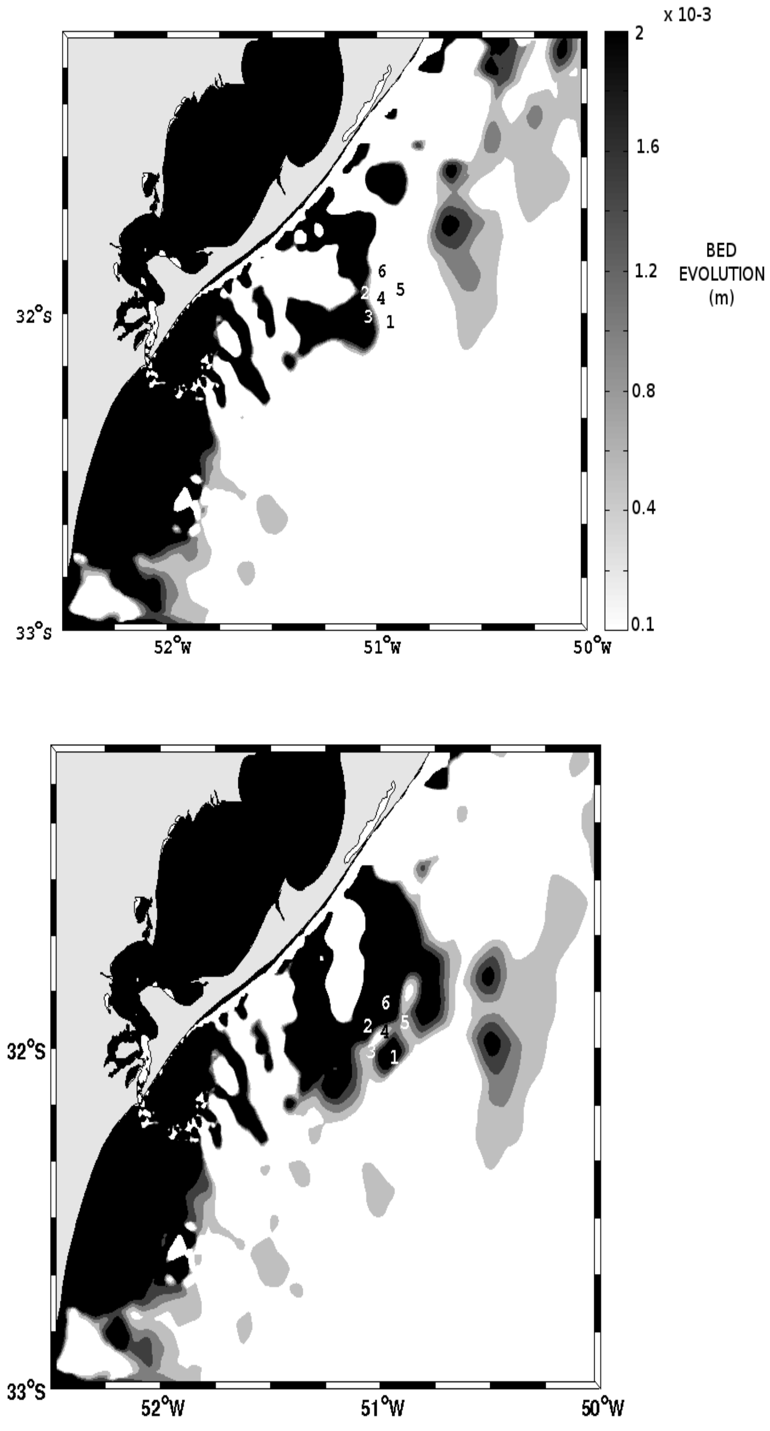


Figure 9: Bed evolution (mm) after 482 days of simulation without (A) and with (B) the energy converting structures. Numbers indicate the position of the 6 energy converting structures.

However, it is expected that when considering longer time scales, the effects of the energy converters modifying the residual circulation and the deposition pattern deserve careful investigation.

4 Conclusions and suggestions

This investigation suggests a considerable energetic potential associated with the wind-driven circulation of the SBS. Instead of the results obtained from the application of an adapted turbine, which neglects the logistic characteristics and availability of technologies present today, the obtained results could be useful as a numerical basis for future renewable energy research. The results indicate that coastal currents could be used for the conversion of kinetic to electric energy using turbines. Mean and maximum values of approximately 3 and 79 MW of electric power, respectively, were obtained at specific sites considering the effects of coastal circulation associated with meteorological processes at synoptic scales. Considering a set of 6 turbines (20 m radius) an integrated annual rate of approximately 5 $GWyear^{-1}$ is estimated for the electric power converted from the wind-driven circulation.

The presence of the energy converters removed some part of the kinetic energy from the coastal currents, generating divergence and convergence zones in accordance with the dominant direction of the currents. The main consequence during the period simulated was the decrease of the intensity of currents and the increase of the TSM at this site. The residual effect associated with the presence of the energy converters was the major siltation and increased bed evolution.

The influence of these structures on the dynamics of the study region is highly dependent on the quantity of converters, the size of turbine radius and the position along the coast. The influence of these structures is still mainly dependent of the time scales analysed. Time scales from a few days to a few months can be more important for water quality and biota. Otherwise, at longer time scales, the influence of these structures will be observed in the depositional patterns.

The next steps forward for this study include the following:

- The implementation of different kinds of converters with a more realistic relationship between the energy obtained and the environmental response.
- An investigation of different sites with variable quantities of converters to obtain annual electric power conversion rates.
- An analysis of longer time scales to investigate the influence of these structures on the most important hydrodynamic and morphodynamic characteristics of the coastal region.
- The establishment of a methodology relating the energy conversion rates and the minimisation of environmental damages caused by the presence of these structures.

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