Energy 121 (2017) 176–184

Contents lists available at ScienceDirect

Energy

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

Numerical evaluation of wave energy potential in the south of Brazil

Rodrigo C. Lisboa [a], Paulo R.F. Teixeira [a, *], Conceição Juana Fortes [b]

[a] Engineering School, Universidade Federal do Rio Grande – FURG, Av. Itália km 8, Campus Carreiros, Rio Grande, RS, 96203-900, Brazil
[b] Hydraulics and Environment Department, Laboratório Nacional de Engenharia Civil, Avenida do Brasil, 101, Lisboa, 1700-066, Portugal

ARTICLE INFO

Article history:
Received 11 August 2016
Received in revised form
30 September 2016
Accepted 2 January 2017
Available online 3 January 2017

Keywords:
Wave energy
Wave propagation and generation
Numerical simulation
Spectral model

ABSTRACT

Wave energy extraction in coastal regions may be an excellent alternative due to the increase in global demand for renewable energy. The viability study of this extraction depends on the evaluation of the wave energy potential that is higher in regions located in high latitudes. Therefore, this study shows evaluation and characterization of wave energy in the south of Brazil. Numerical simulations were carried out by the Mike 21 SW spectral model which was calibrated and validated in the region measurement campaigns. Annual, seasonal and monthly means and the temporal variability of the wave energy potential in a 10-year wave hindcast were analyzed offshore and nearshore. Annual mean fluxes in three points nearshore had similar values; the highest one was 6.7 kW/m, while the wave energy flux offshore was 22.3 kW/m. The refraction and the bottom friction dissipation were responsible for the wave attenuation from offshore to nearshore and, consequently, for the decrease in wave energy. The annual, seasonal and monthly variabilities of wave energy fluxes were moderate offshore and high nearshore. A directional analysis showed that the dominant wave directions were S and NE offshore whereas they were SSE and E nearshore.

1. Introduction

Researchers' and engineers' recent studies of wave energy extraction have been motivated by the increase in the demand for renewable energy. The global wave energy potential is around 32 TW/year [26] and 2 TW/year near the coastline (neglecting islands and poles) [17]. Global distributions of wave energy in deep water have been evaluated by many researches [29,3,9,26]; which show satisfactory wave energy potential ranges from 20 kW/m to 70 kW/m front wave, located in moderate and high latitudes [14]. The annual mean energy flux in deep water on the Brazilian coast varies between 5 kW/m and 20 kW/m [26] with low seasonal variability, a characteristic of the southern hemisphere. Wave energy extraction in this region is very attractive due to the high energy flux in deep water that is typical of places in high latitudes. It is worth emphasizing that there has not been any wave energy evaluation nearshore along the Brazilian coast so far.

Researches of wave energy extraction have been developed in two lines of study over the last decades: i) development, design and experiments of wave energy converters (WEC) to convert wave energy into electrical energy, as reported in review papers, such as [14] and [23]; and ii) evaluation and characterization of available wave energy in coastal regions, as shown by Refs. [1,2,16,32] and [5].

The aim of this study is to quantify the available wave energy in the south of Brazil offshore and nearshore, near Rio Grande, a city located in Rio Grande do Sul (RS) state (Fig. 1). Numerical simulations are carried out by the Mike 21 SW spectral model, developed by the Danish Hydraulic Institute (DHI) [13]. The Wavewatch III third-generation model is used for imposing the wave boundary conditions in deep water, whereas the wind data from the National Center for Environmental Predictions (NCEP) are forced along the domain. The Mike 21 SW model is calibrated by data of a directional Waverider buoy, deployed at 25 m depth, and of an Acoustic Doppler Velocimeter (ADV), at 12 m depth, in May, June and July, 2005. Data collected between 1996 and 1999 by a directional Waverider buoy deployed at 15 m depth are used for validating the model. The evaluation and characterization of wave energy potential in the region are carried out in 10-year wave hindcast (1997–2006). Detailed analyses are shown in deep water (at 80 m depth) and three regions nearshore (at 14 m depth), in front of Querência (QUE), Cassino (CAS) and São José do Norte (SJN). These nearshore regions are adequate to install a cluster of WEC in

* Corresponding author.
E-mail addresses: lisboa_r@hotmail.com (R.C. Lisboa), pauloteixeira@furg.br (P.R.F. Teixeira), jfortes@lnec.pt (C.J. Fortes).

http://dx.doi.org/10.1016/j.energy.2017.01.001
0360-5442/

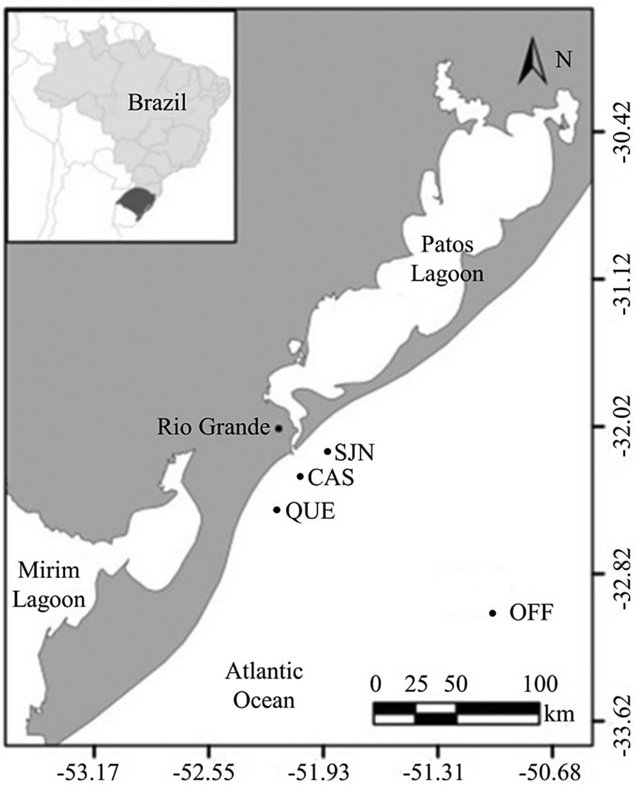

Fig. 1. The study Region.

breakwaters.

2. Materials and methods

2.1. Characteristics of the region

The study region, which has NE-SW coastline orientation, is characterized by open sandy beaches totally exposed to ocean waves (Fig. 1). The inlet of the Patos Lagoon separates the shoreline, which stretches for 640 km, from Torres headland (in the north) to Chui estuary (in the south). The Southern Brazilian Shelf (28-35°S) is characterized by a large shelf (from 110 km in the north to 170 km in south) with a smooth slope. It breaks at about 180 m depth [11,24]. The bottom is composed of sand, from fine to very fine, and some mud deposits near the Patos Lagoon inlet [7]. Wind data analyses have shown that NE winds are the dominant ones in this region, with some significant variations along the seasons. However, there are stronger S, SW and W winds and the highest variability occurs in Rio Grande [8].

Although the region has a mixed microtidal regime, with diurnal dominance, the highest sea level fluctuations are caused by meteorological tides [25]. The wave climate of the RS coast is characterized by sea and swell generated by local winds and distant storms, respectively. Both can act simultaneously with alternate dominance [31]. Preliminary data analysis of Cassino experiment that was carried out from May 13 to June 25, 2005 by a directional Waverider buoy deployed at 25 m depth, indicates dominant waves with significant wave height (*Hs*) from 1.0 m to 3.0 m, mean period (Tm) of 6.0 s and dominant peak direction of NE and S [11,18]. Thirty-year hindcast of wave climate offshore RS was carried out by Ref. [30] by applying a splitting routine to the spectra. They showed that there was balance between waves from dominant directional sectors of S-SSE and NEE-ENE, with approximately equal percentage of occurrence. Besides, high occurrence of seas from NE-SE and swells from SE-SW was observed.

2.2. Numerical model

Mike 21 SW is a third-generation spectral wave model which is able to simulate wave growth, dissipation and transformation in oceans and coastal areas. This model has been widely applied to ocean, coastal and port structure designs, in which accurate knowledge of the wave climate conditions is important to carry out safe and inexpensive projects. The model is validated and used to wave forecast and hindcast in global, regional and local scales [13]. It is based on the finite volume technique to solve the governing equations, taking into account the following physical phenomena: wind wave generation, refraction, shoaling, white-capping, bottom friction, wave breaking dissipation, nonlinear wave-wave and wave-current interactions [12]. Two formulations are available: directional decoupled parametric formulation [19] and fully spectral formulation [21]; [35]. The latter is used in this study and the governing equation is the wave action balance equation, given by

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}N.c_{g,x} + \frac{\partial}{\partial y}N.c_{g,y} + \frac{\partial}{\partial \theta}N.c_{\theta} + \frac{\partial}{\partial \sigma}N.c_{\sigma} = \frac{S}{\sigma} \quad (1)$$

$$S = S_{in} + S_{nl4} + S_{ds} + S_{nl3} + S_{bot} + S_{surf} \quad (2)$$

where $N(\sigma, \theta)$ is the action density spectrum, σ is the relative radian frequency and θ is the wave direction. The first term on the LHS represents the local rate of change of action density in time whereas the second and the third ones are the action density propagation in x and y geographic spaces with propagation velocities $c_{g,x}$ and $c_{g,y}$, respectively. The fourth term is related to the depth-induced and current-induced refractions with propagation velocity c_θ in θ-space. The fifth term represents shifting of the relative frequency due to variations in depth and currents with propagation velocity c_σ in σ-space. S (Eq. (2)) is the energy source term that contains a superposition of source functions which represent relevant physical phenomena. S_{in} represents the generation of wind energy, S_{nl4} is the wave energy transfer due to quadruple wave-wave interaction, S_{ds} is the dissipation of wave energy duo to white-capping, S_{nl3} is the wave energy transfer due to triple wave-wave interaction, S_{bot} is the dissipation of wave energy due to bottom friction and S_{surf} is the dissipation duo to depth-induced breaking [20].

The growth rate of the wind-generated waves, which is calculated by a coupled model, depends on the friction velocity and the sea roughness. In this study, the Charnock parameter is 0.01 (default value). The technique that separates the wind-sea and the swell applies the white-capping dissipation only to the wind-sea part [6]. The wave height is limited by a constant breaker parameter of 0.8 to take into account the depth-induced breaker [4]. Two time formulations are used: instationary, with variable time step, determined so that the CFL Number is lower than 0.8; and quasi-stationary, that considers a steady state solution.

2.3. Computational domain and space discretization

The computational domain, the mesh and the bathymetry are shown in Fig. 2. The external boundaries are sufficiently far from the study region to ensure that input data of Wavewatch III are in deep water and to avoid the influence of lateral boundaries on the results. The topography dataset has been interpolated by natural neighbor interpolation from the nautical chart of DHN (Directorate of Hydrography and Navigation of Brazil).