Wave energy map in intermediate and shallow water depth in Chile based on a 30 year long validated 2D spectral hindcast of the Pacific Ocean

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Abstract

Wave energy maps in deep waters have been developed by several researchers, based on hindcasts from numerical models or measurements, mainly from satellites. Although these provide useful information, they are not useful for proper site selection, since they do not consider the wave transformations from offshore to shallower waters, where converters are designed to be installed.

A wave energy map in intermediate and shallow water depth is developed by using linear spectral transfer of long term average 2D spectra from a 30 year long hindcast of the entire Pacific Ocean, which was properly validated against 30 measurements in intermediate and shallow waters and 22 offshore. The technique reduced effectively the computational time and effort, being applied in the central Chilean coastline between Taltal and Chiloé with 2200 km approximately. Several maps were created, accounting for yearly, seasonal and monthly variations and permitted a properly informed site selection.

Keywords: Wave energy map, validated long term wave hindcast, Pacific Ocean, Numerical models.

1. Introduction

Previous studies of the wave energy potential in Chile (Acuña & Monárdez, 2007; Monárdez, Acuña & Scott, 2008), confirm that Chile is probably provided with the best conditions in the world for wave energy generation in terms of quantity and availability of said resource. Due to the above, Endesa Chile S.A. engaged Baird to perform a wave energy map of the zone serviced by the Central Interconnected System (Fig. 1).

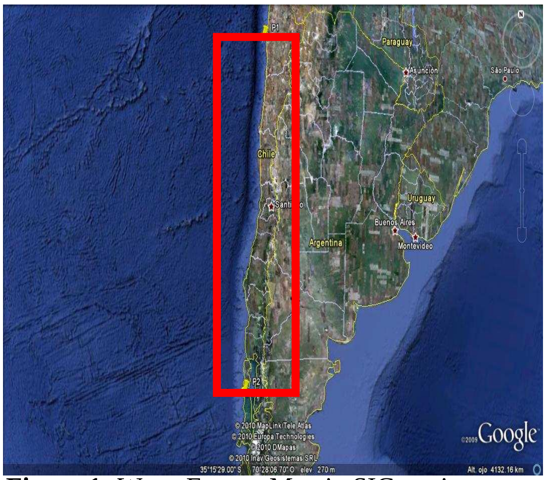


Figure 1: Wave Energy Map in SIG environment

The customary method to perform wave energy assessments is described below:

a) Creation of wave energy maps at a global scale with information obtained from satellite measurements or numerical models of wave generation in deep waters. These maps provide figures which can represent a certain geographical area; however, these do not adequately represent the wave energy in areas where it is actually feasible to install wave energy converters, that is, in near shore in intermediate and shallow waters.

b) Assessments of wave energy resources in intermediate and shallow waters in specific points in the ocean previously selected, either with field measurements or numerical simulations. This type of detailed analysis of the wave climate and energy generation in specific points in the ocean are very useful once the potential sites for installation have been defined.

Although the above practices make it possible to evaluate wave energy at any given point, for a selection of sites it is considered more adequate to use a continuous map to visualize the spatial variability that waves may have in shallow or intermediate waters, and thus be able to detect the areas with a greater amount of energy (*hot spots*). To achieve this, a methodology was elaborated to create this type of maps.

The wave energy map in shallow and intermediate waters would be complementary to the other two methods utilized in these assessments, as shown in Fig.2.

In order to create the wave energy map, a wave database was created by means of a chain of numerical models which simulated wave generation in deep waters during 30 years (1980-2009) in the entire Pacific Ocean, duly validated with 22 measurement (satellites and buoys), in deep waters, and the subsequent propagation towards shallower waters, in areas where it is feasible to install *offshore* devices (between 25 and 100 m water depth). The final products of the simulation are wave summary parameters: Significant spectral height (Hmo), Energetic Period (Te), Mean Wave Direction (Dm) and Wave Power (P) in a grid with a resolution of 100 meters which includes 2200 kilometers of coastline. The results were incorporated into a Geographic Information System (GIS).

2. Methodology

Wave studies usually utilize 2D spectral wave databases in deep waters, for example 30 years every 3 hours (containing 89400 spectra for each deep water node). These databases are transferred from deep waters towards shallower waters utilizing a wave propagation model. The usual practice is the modeling of various spectra of unitary wave height with different directions and periods, creating linear transfer functions which are subsequently utilized to escalate the wave conditions. This method, named quasi purist transfer(Nicolau del Roure et al, 2004), significantly reduces the quantity of simulations and makes it possible to obtain results equivalent to those that could be obtained with the modeling of all spectra in the database (purist transfer method).

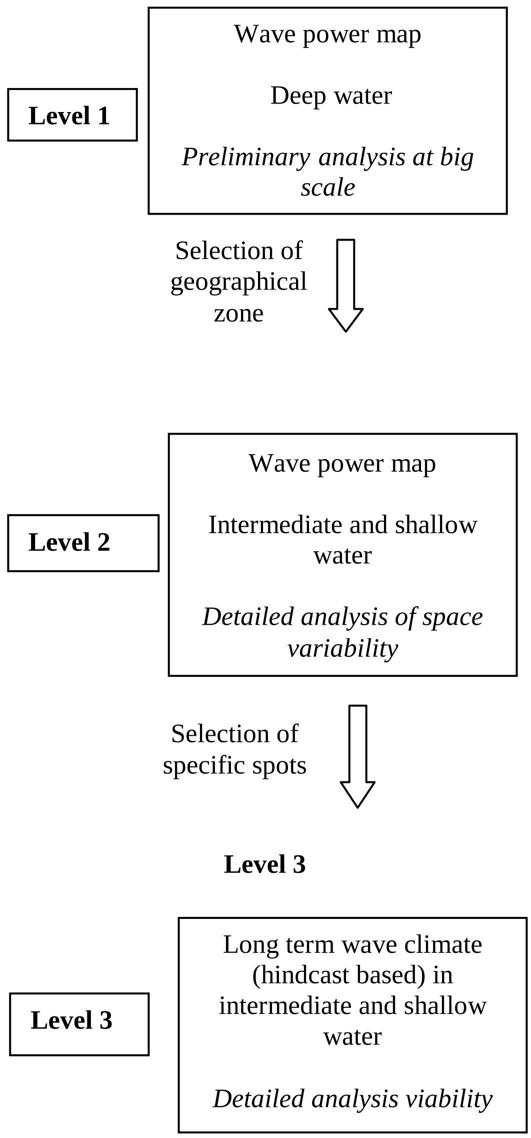


Figure 2: Requiered information for wave energy generated plant site selection

In order to develop a continuous map in shallower waters with information in millions of points along the coast, a supplementary method was defined in order to reduce the quantity of simulations. This consists in the direct or purist spectral transfer of mean spectrum obtained from the hindcast in deep waters.

In the application of the above mentioned method, it is assumed that the propagation of the spectra can be performed by applying linear transformation models to each of the frequency and direction components of the spectra. This means that the energy associated to a (narrow) frequency band remains within that band during the transformation and that the processes allow linear superimposition. For each frequency band, the amount of energy contained and which is quantified times the square root of free surface displacement is a non variant during the transformation. As a consequence, the laws and methods to quantify the transformation of monochromatic trains can be applied directly to each one of the spectral components taking into account that its energy travels along the corresponding ray with its group velocity.

That is, if there are two deep water spectra S_{01} and S_{02} propagated to the same node in shallower waters, the linear superimposition property is assumed to be valid to obtain the resulting spectrum S_i:

$$S_i = H(S_{01} + S_{02}) = H(S_{01}) + H(S_{02}) \tag{1}$$

where H is the transfer function which represents wave transformations. The above can be extended for the average of N spectra in shallow waters:

$$\frac{\sum_{i=1}^{N} S_i}{N} = \frac{\sum_{i=1}^{N} H(S_{0i})}{N} = H\left(\frac{\sum_{i=1}^{N} S_{0i}}{N}\right) \tag{2}$$

This means that the average of N spectra in shallower waters at a certain node is equal to the average of the corresponding N spectra in deep waters transferred to this node.

It should be noted that, in order to obtain a consistent comparison between a mean spectrum and the series of spectra which generated it, the prorated average of each series of summary parameters was calculated in accordance with equation (2) and according to the definition of each of these parameters, resulting in the equations 3 to 6 shown below:

$$\bar{P} = \frac{1}{n}\sum_{i=1}^{n} P_i \tag{3}$$

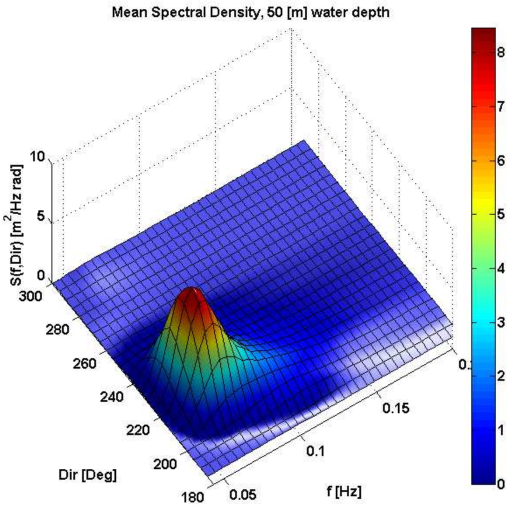
$$\overline{H_{m0}} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} {H_{m0i}}^2} \tag{4}$$

$$\overline{T_{m-10}} = \frac{1}{\overline{H_{m0}}^2}\frac{1}{n}\sum_{i=1}^{n} {H_{m0i}}^2 {T_{m-10i}}^2 \tag{5}$$

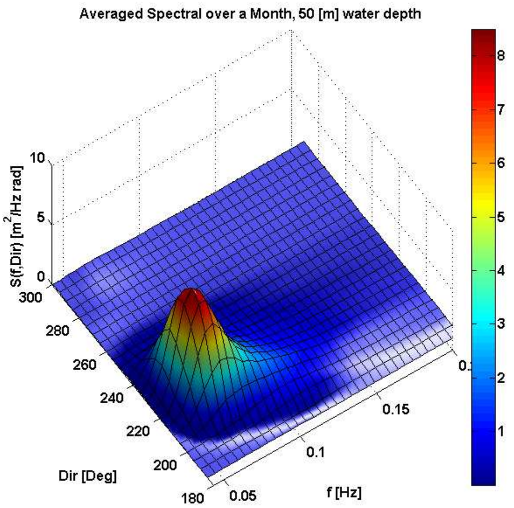
$$\overline{\theta_m} = atan\left(\frac{\sum_{i=1}^{n} \sin(\theta_{mi}) {H_{m0i}}^2}{\sum_{i=1}^{n} \cos(\theta_{mi}) {H_{m0i}}^2}\right) \tag{6}$$

where P is wave power, Hmo is significant spectral height, Tm-10 is energetic period, θm is mean direction and n is the quantity of spectra in the series.

Fig. 3 shows the comparison between the propagated mean spectrum against the new spectrum obtained after propagating 240 spectra (30 days, 1 spectrum every 3 hours) from deep waters to the same spot in shallower waters. Since the procedure is assumed to be linear, the result is the same.



a) Propagated mean spectrum



b) Average of propagate 240 spectra

Figure 3: Comparison between mean spectra

In total 47 mean wave scenarios were simulated, generating a map for each scenario. The simulated scenarios are shown below:

a) The total mean spectrum representing 30 years (1980-2009)
b) 12 mean monthly spectra

c) 4 mean seasonal spectra
d) 30 mean annual spectra

3. Modelling of waves in deep waters

Wave database in deep waters, named Olas Del Pacífico (Pacific Waves) was obtained from a hindcast based on a numerical simulation with WAVEWATCH III model (Tolman, 2002), utilizing a grid which covering the entire Pacific Ocean with 1 degree of resolution and a simulation period between the years 1980 and 2009 every 3 hours (Pantoja et al; 2005). A grid was added to this model with 0.25 degrees resolution (25 km approx.) which encompasses the study area between Taltal and Chiloe.

Fig. 4 shows a long term comparison of wave summary parameters in deep waters between hindcast model and buoy measurements.

In order to obtain the mean spectra it was necessary to modify the source code of WAVEWATCH III to average the resulting spectra every 3 hours and generate a database with the mean spectra for all nodes in the nested grid.

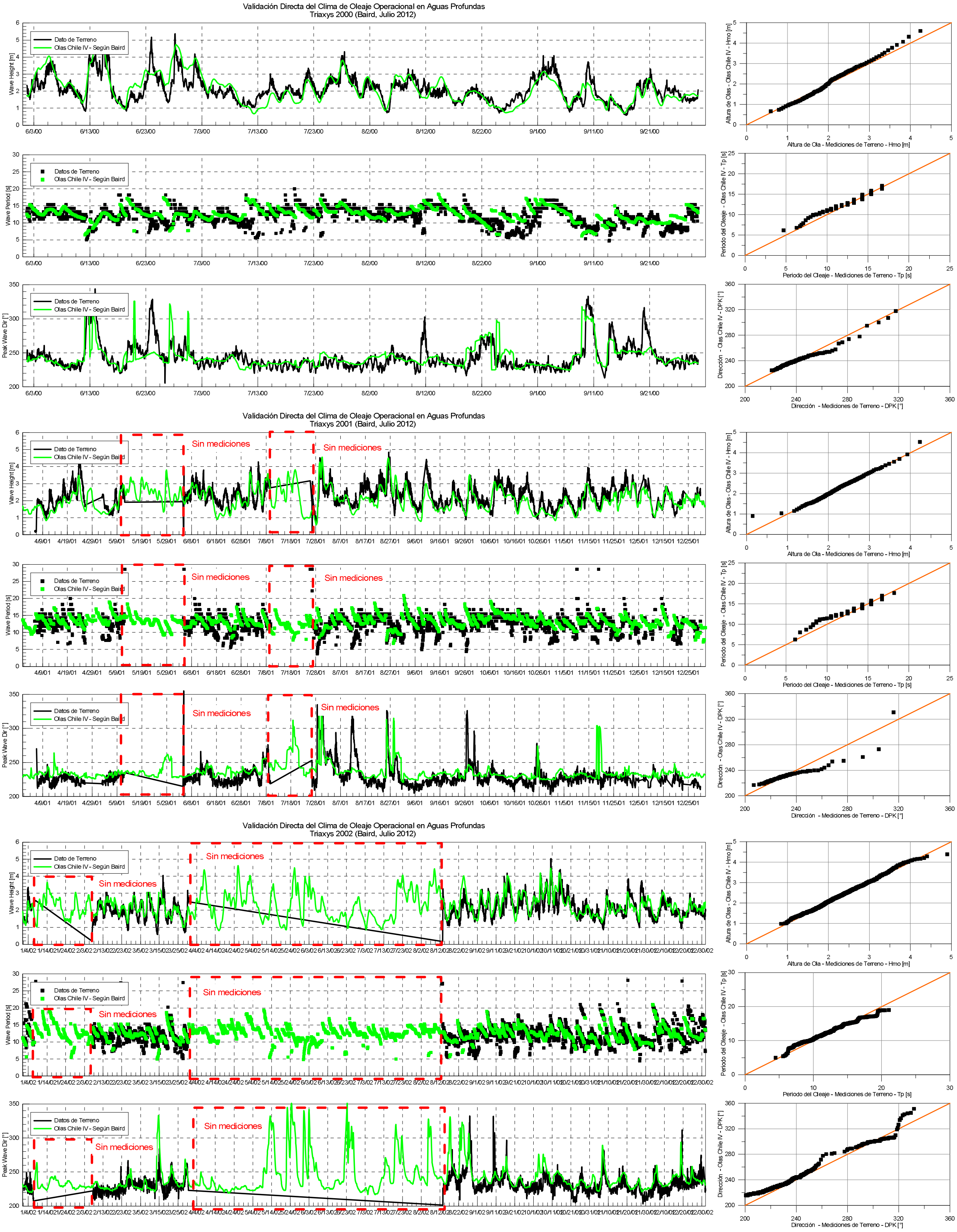


Figure 4: Comparison of wave summary parameters in deep waters between hindcast model and buoy measurements.

4. Modelling of near shore waves.

For the wave spectral transfer from deep waters to shallower waters the numeric model for wave propagation STWAVE (Smith et al, 2001) was used. Additionally a modification of the source code of the STWAVE program was required, in order to incorporate the equation 7 which makes it possible to calculate the wave power density from the spectra in shallower waters:

$$P = \int_0^{2\pi} \int_0^{\infty} S(f,\theta) C_g(f,h) df d\theta \tag{7}$$

Where *S* is the function of spectral density, C_g the celerity of the wave Group, *f* frequency, *θ* direction and *h* water depth. Energetic period *Te*, defined as the quotient between moments -1 and 0 of the spectrum, is already incorporated into the model.

In order to include the entire study zone in a continuous manner, a coupling line was defined between the deep waters model and the near shore wave model approximately parallel to the coastline, with a rotation of 10º towards the East (TN). This line crosses the nested grid of WAVEWATCH III at depths greater than 500 m, defining points every 25 km in which the mean spectra were calculated as input into STWAVE model by means of bilinear interpolation of the mean spectra obtained from WAVEWATCH III.

The bathymetry used on the simulation was defined by means of the digitalization of the naval charts contained in the Chilean Hydrographic Atlas (SHOA, 2001). The shallower water domain, defined by the area between the coupling line and the coastline, was divided in 30 grids with a variable extension and 100 m resolution. Each grid included a certain quantity of points of the coupling line. Only the edge of the coupling line was used to input wave information into the model, which entailed defining elongated grids superimposed upon each other, in order to reduce the transition between them and ensure continuity of the data after joining all the grids. The superimposed areas were subsequently deleted in the output files.

The numerical model calculated the energy spectra in each cell, obtaining as output results, power density *P*, wave height *Hmo*, period *Te* and mean direction *Dm* in each of the cells of the model, which made it possible to generate the wave energy resource map together with the parameters obtained in the nested grid in deep waters.

Figure 5 shows the scope of the nested grid in deep waters (red points), the coupling line (grey line), the total scope of the modeling in shallow waters (large magenta rectangle) and the scope of one of the grids simulated in STWAVE (small magenta rectangle).

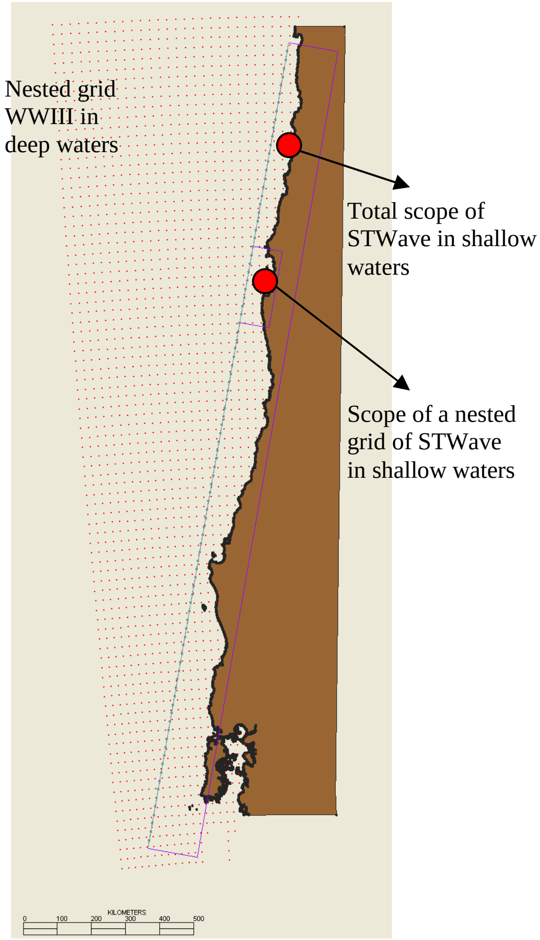


Figure 5: Scope of Wave Energy Map in the modeling

5. Results

Due to the massive amount of data, a geographical information system was created (GIS) named POWER (Planning Of Wave Energy Resources). For each of the 47 wave spectra, independent layers of information were obtained with the variables indicated in the above sections, which were incorporated as described below:

- Wave power (P) can be seen as a map with color contours.
- Mean wave direction (Dm) can be seen as a vectors map.
- The GIS includes a layer with sea bed contour lines 25, 50 and 100 m to clearly exhibit the depth band where it is feasible to install the greater part of the *offshore* wave energy converters.
- Power density (P), wave height (Hmo), energetic wave period (Te), mean propagation direction (Dm) and depth (d) can be seen in the attributes table of each node.

In addition to the wave energy resource maps, information related to infrastructure and facilities available on the coast for the construction, operation and maintenance of a wave energy plant was entered into the GIS.

Figure 6 shows the Wave Energy Map in GIS environment. Figures 7, 8 and 9 are sections of the Wave Energy Map in the area of the river mouth of the Rapel River, considering the total average, for summer and winter between the years 1980 and 2009.

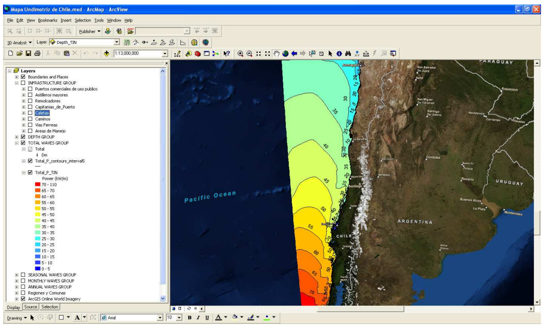


Figure 6: Wave Energy Map in SIG environment

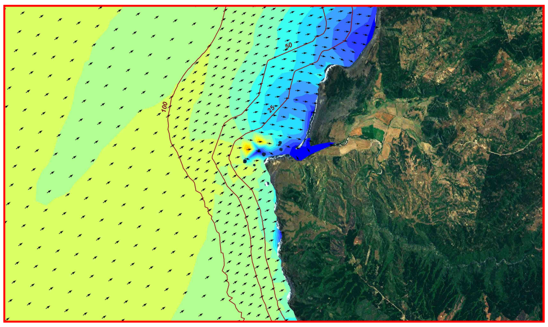


Figure 7: Wave energy power map– total average 30 years.

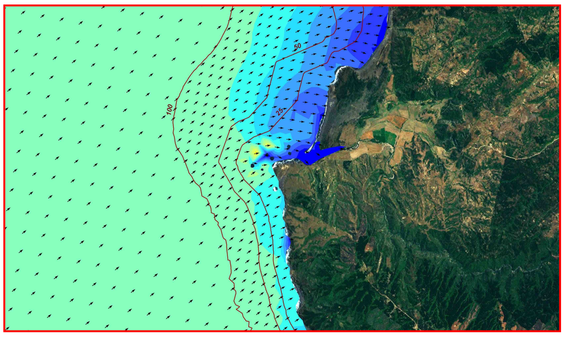


Figure 8: Wave energy power map– summer average 30 years

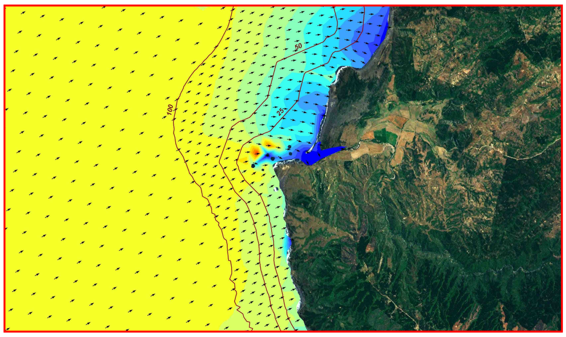


Figure 9: Wave energy power map– winter average 30 years

6. Vality of the Results

It should be noted that diffraction in the STWAVE model is included as a numerical damper of wave energy, in order to avoid very abrupt energy gradients. This methodology is only a numerical approximation of the physical phenomenon of diffraction, therefore the results obtained in areas blocked by islands or peninsulas are not valid. However, these areas are not attractive for the installation of wave energy plant facilities.

In some areas the density of points is very low, while in other places the bathymetric information density is greater. Due to the above, the use of the results is valid only for the preliminary selection of sites.

7. Conclusions

A continuous wave energy map in shallow and intermediate waters was created of the central Chilean coastline (2200 km), with a resolution of 100 m, based on a spectral 2D *hindcast* for 30 years of the entire Pacific Ocean, duly validated with measurements. This map is unique in its type, because it makes it possible to visualize the spatial variability of wave action in shallow and intermediate waters and thus be able to detect the areas with higher quantity of energy in those zones in which a greater majority of *offshore* devices can be installed.

In order to develop a continuous map near shore with information in millions of points along the coastline, the method of purist transfer of mean spectra was defined, achieving the expected results with a reduced quantity of simulations.

8. References

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