Propagation wave effects by a wave power plant (Baja California)

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Summary:

This is a final degree project, carried out at the Instituto de Investigaciones Oceanologicas (IIO) in the Universidad Autónoma de Baja California (UABC), with the collaboration of the Universitat Politècnica de Catalunya (UPC).

The objective of the project is to analize energy production with a farm of wave energy converters (WEC) in Todos Santos bay, Baja California, Mexico and to determine its impact on the wave field and wave induced currents. Wave energy extraction (farm with 4 Pelamis) and its impact where numerically simulated with the SNL-SWAN model. It produces about 0.5887 MW, with a clear seasonal variation between winter and summer.

The impact of the farm is higher near it and reduced on shore (500 meters far).

Keywords: WEC impact, Wave energy, Wave power, Wave modeling, Baja California.

Resumen:

Este es un trabajo de fin de grado, realizado en el Instituto de Investigaciones Oceanologicas (IIO) en la Universidad Autónoma de Baja California (UABC), con la colaboración de la Universidad Politécnica de Cataluña (UPC).

Se prentende analizar la producción de energía con un parque de convertidores de energía undimotriz (WEC) en la bahía de Todos Santos, Baja California, México. Determinar su impacto en el oleaje y en las corrientes inducidas por él. La extracción de energía de las olas (parque con 4 Pelamis) y su impacto se simularon numéricamente con el modelo SNL-SWAN. Produce alrededor de 0.5887 MW con una clara variación estacional entre invierno y verano, de la potencia que se puede generar.

El impacto que genera es mayor cerca de la instalación y reducido cerca de la costa (a 500 metros de los dispositivos).

Palabras claves: Impacto de CEU, Energia Undimotriz, Potencial del Oleaje, Modelaje del Oleaje, Baja California.

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1. Introduction

Mexico is a developing country which still has a long way to go. From the point of view of electricity production and distribution, its electric grid consists of three un connected sub-grids. Almost all country is covered by the main Mexican grid with the exception of Baja California Peninsula which is served by two isolated sub-grids. In particular, Baja California sub-grids has a strong dependency on fossil fuels for electricity production and they don´t cover all the peninsula leaving isolated regions where electricity cannot be supplied.

The installation of power plants on the coast of Baja California could help the territory locally, with clean energy and promoting the development of the area.

2. Theoretical framework

2.1 Wind waves

To understand wind waves, lets first describe a single surface wave. A wave is the propagation of a disturbance, or energy, from one place to another. In particular, surface waves occur in the interface of two media. For wind waves these two media are water and air. As all mechanical waves, they always need a medium to propagate, they does not cause changes in the medium as they propagate, and they travel with a constant speed.

In the ocean the generation of surface waves is the product of non-conservative forces. They can be generated by the incidence of the wind, instabilities on the water surface, forces of tectonic origin, and by the gravitational attraction of the moon and the sun. Here our focus is on wind waves which are solely generated by the action of wind over the ocean. Wind waves have wave lengths in the ranges from few centimetres to hundreds of meters and periods up to 20 to 25 seconds.

In any wave motion there is a restoring force that counter acts the generation force and forces the oscillatory motion. For wind waves the restoring forces are gravity and surface tension, although the later only affects the shortest waves, the capillary waves.

The formation of these wind waves, as its name indicates, is caused by the interaction with the wind. Due to the difference in pressure at the different points of the wave, it creates disturbances on the surface of the sea. As seen in Figure 1. Making the wave grow the longer it is in contact with the wind

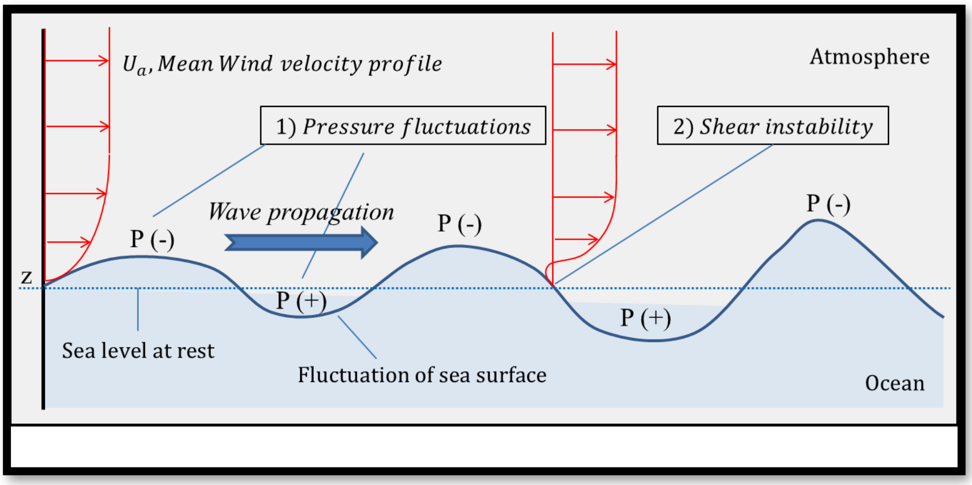

Figure 1. Diagram of the formation of wind waves. (Taken form Wikimedia Commons)

2.2 Wave power

Wave power (P) is simply the energy a wave carries per unit of time, it is commonly expressed in Watts per meter (W/m). From linear wave theory wave power is computed as

$$P = Cg \cdot E\,,$$

where *(E)* is wave energy and *(Cg)* is wave group velocity. This wave group velocity is the differential of the frequency (w) divided by the differential of the waves number (k) as

$$c_g = \mathrm{d}\omega/\mathrm{d}k$$

.

Knowing these parameters, wave power can be calculated at each point in space and different periods of time.

The group velocity is simply the movement of the wave group in a period of time, its magnitude represents the speed at which wave energy propagates over the surface of the sea.

Focus on the concept of energy, waves have two types of energy: potential energy and kinetic energy.

The potential energy of wind waves is gravitatory. It can be computed from the total potential energy of the water column by subtracting the potential energy of the water column at rest, such as,

$$E_p = \overline{\int_{-d}^{\eta} \rho g z \, dz} - \overline{\int_{-d}^{0} \rho g z \, dz} = \overline{\int_{0}^{\eta} \rho g z \, dz},$$

where (ρ) is the density, (*g)* is the gravitational acceleration, (*d)* is water depth, (*z)* is the vertical position with respect to the surface at rest, and the overbar refers to the average over a time equals to the wave period.

By solving the integral, for a linear monochromatic wave potential energy is

$$\overline{\int_{0}^{\eta} \rho g z \, dz} = \overline{\frac{1}{2}\rho g \eta^2} = \frac{1}{4}\rho g a^2,$$

where (η) is the free surface and (a) is the amplitude of the wave.

Secondly, the kinetic energy, this depends on the movement of the body. It is an energy that depends on the speed it as

$$Ec = \frac{1}{2} \cdot m \cdot v^2,$$

where the *(m)* is the mass and *(v)* the speed. For wind waves kinetic energy is associated with the circular motion of the water particles that the wave induce on the water column, by the so called orbital velocity. So, for wind waves *(v)* is the horizontal component of the orbital velocity.

By using linear wave theory, the kinetic energy, integrated over the water column and averaged over a wave period, of a monochromatic wave is

$$Ec = \frac{1}{4} \cdot \rho \cdot g \cdot a^2$$

There are a very interesting thing, the two types of energy, potential and kinetic, have the same formula. This concept is known as the equipartition of energy and it is common to mechanical waves.

By adding the two equations the total energy that the wave have is

$$E = \frac{1}{2} \cdot \rho \cdot g \cdot a^2.$$

3. Case of study

3.1 Justification of the area

The Bay of Todos Santos is one of the most neuralgic points of Baja California. It's located the Municipality and the city of Ensenada. Ensenada has the most important port in the State. This contributes to its growth and the activation of the economic sector of the region.

The area presents an increasing need for resources in order to supply the demand of drinking water, waste management systems, food supply and electricity. The demand of this services will be increasing as the city modernizes and expands.

In addition, electricity production in the region depends on fossil fuels with the consequent emission of greenhouse gases. Therefore, there is a need for energy transition into a cleaner systems based on renewables to replace power plants using fossil fuels.

Wave power in Baja California and in Todos Santos Bay was analysed in previous a studies made as part of the Mexican Center for Innovation in Ocean Energy (CEMIE-oceano) project. Those studies concluded that along the coast of Baja California there are sites with enough wave power to be suitable for exploitation. In particular, two promising sites are located in Todos Santos bay region: San Miguel reef and Santo Tomas point.

In this study it's analyse wave energy production with a farm of wave energy converters installed in San Miguel reef, as well as, its impact on the onshore wave field.

Todo santos bay is delimited by point San Miguel in the North, point Punta Banda in the South and Todos Santos Islands (TSI) in the West. The bay has two entrances the Norther entrance between Point San Miguel and TSI point the southern entrance between ITS and Punta Banda.

The bathymetry of the Bay of Todos Santos is relatively shallow, with a mean depth around 40 m. It has a shallow reef near the northern entrance, known as the Bajo de San Miguel. The reef makes the depth change from 200 meters to 18 meters, approximately (Figure 2).

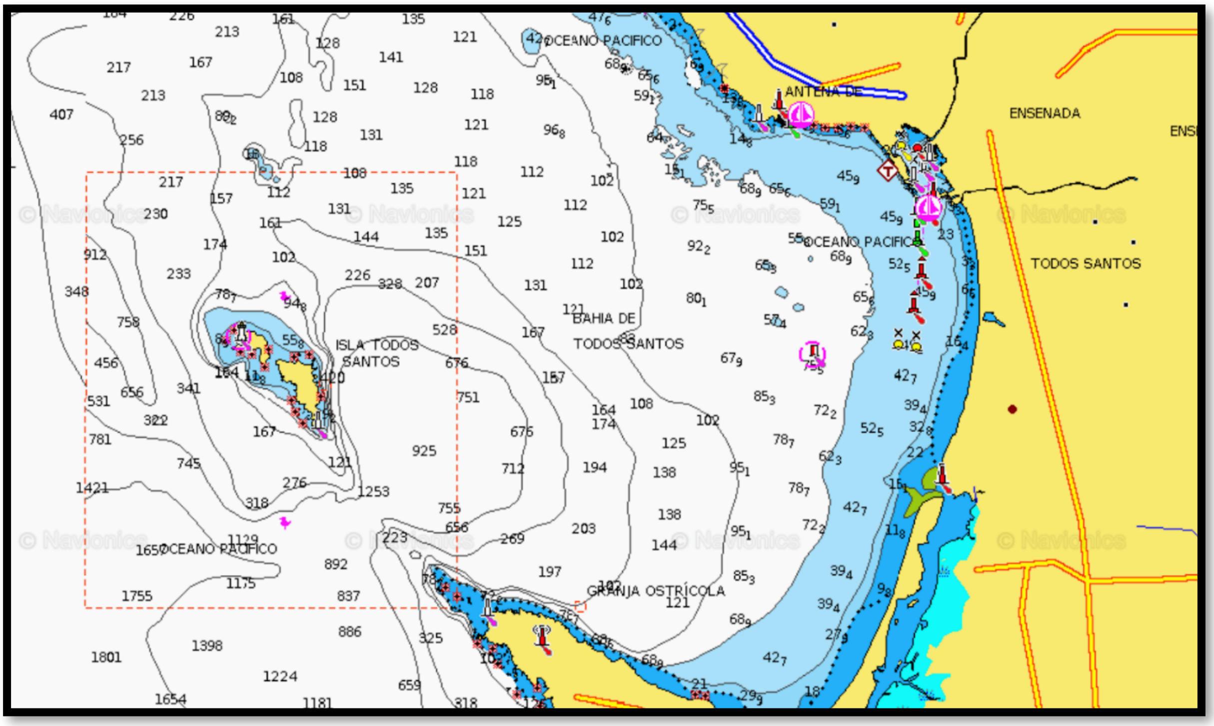

Figure 2. Bathymetry of Todos los Santos Bay, Baja California. The red dashed line denotes the Natural protected area. Taken from Navionics.

This sudden change in the seafloor has a direct impact on the dynamics of the waves. A refraction effect is generated on the waves approaching the reef. Refraction is an alteration in the direction of the wave front, linked to the conservation of the kinetic energy of the front. The refraction caused by the reef is of the convergent type, the waves turn their direction of propagation towards the point of less depth and wave rays tend converge in a focal point. This convergence, due to wave energy flux conservation, produces an increase in wave energy at the focal point which is located leeward of the reef. The increased wave energy in this region makes it attractive for energy extraction. The differences of converging and diverging refraction can be seen in Figure 3.

As will be shown later, San Miguel reef focalizes wave energy creating an area where available wave power is higher than its surroundings. This makes this area an attractive place for wave energy projects.

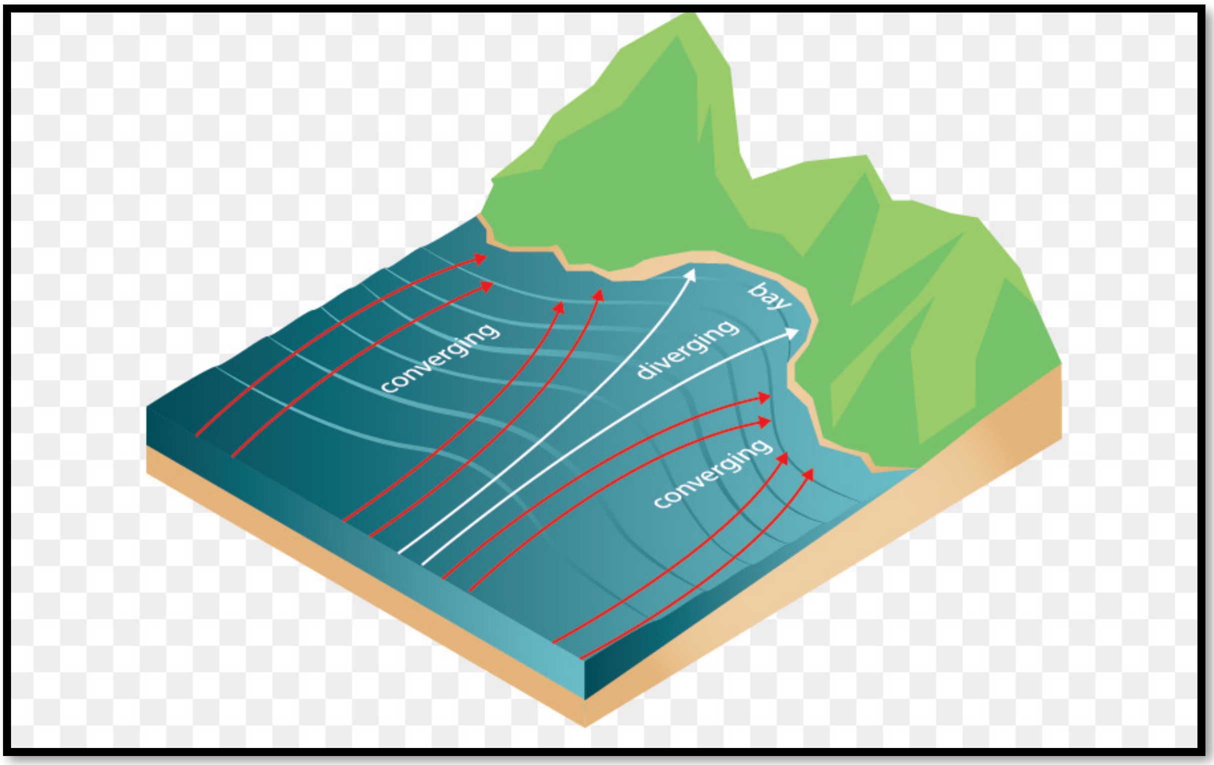

Figure 3. Diagram representing the phenomenon of wave refraction (taken form freepng https://www.freepng.es/png-mlcp8i/)

The second case that is interesting to study is the Bajo de Santo Tomas, a location to the south of the bay. Where is also a great accumulation of energy.

Todos Santos Islands are a natural protected area located less than 0.3 nautical miles away from San Miguel reef. Furthermore, the outer limit of the reserve includes part of the reef (see Figure 1). This is important for energy projects because, being a natural park, there are restrictions to the activities that can be done in that delimited area. This will be discussed later in terms of legislation.

Based on 10 years wave simulations made as part of the CEMIE-Oceano project, it was determined that wave power within the bay is around 5 kW/m, and outside the bay there are 10 kW/m. In San Miguel reef available power is around 12kW/m (see Figure 4).

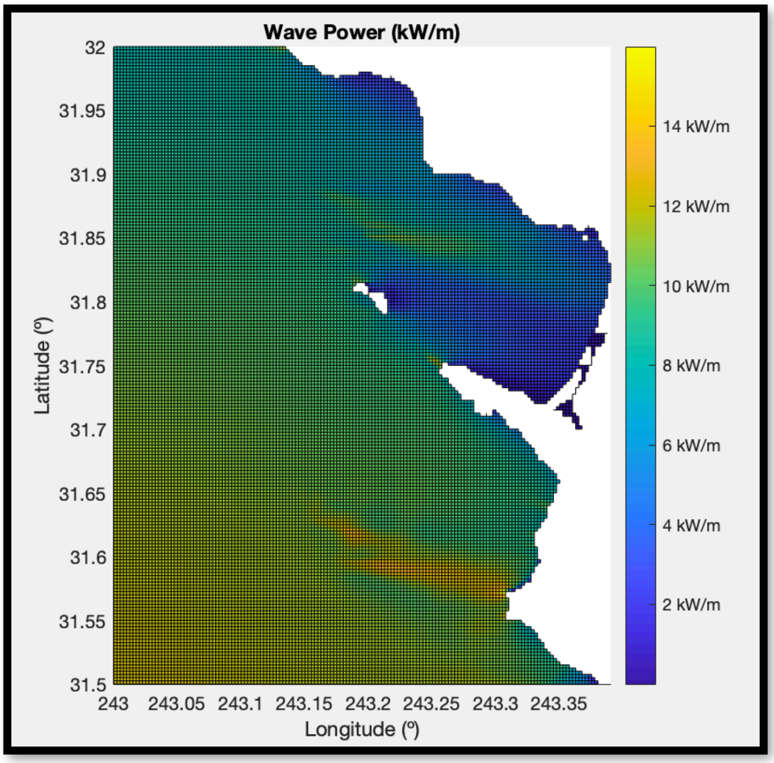

Figure 4. Mean wave power (kW/m)for the year 2008 to 2018.

Using the ten-year wave data from previous simulations, was analyse the variability throughout the year. How does the available power vary along the year. In Figure 5 it can be seen that in the winter months wave power is higher, there is more energy available than in summer, when power is significantly reduced. In winter wave power can be four times higher than in summer.

This variability in Sant Miguel (SM) is a little less than in Santo Tomas (ST). In SM between the maximum power and the less power are around 10 kW/m^2. And in ST, this variability is around 15 kW/m^2.

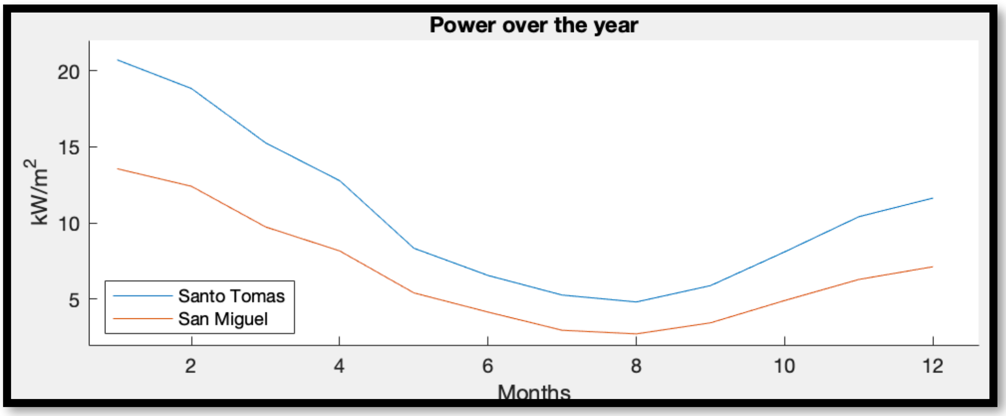

Figure 5. Monthly wave power climatology for the years 2008 to 2018. Blue line is wave power in point Santo Tomas and red line is San Miguel reef.

In the graph are two lines, the blue one corresponds to the potential of the Santo Tomas reef zone and the orange one to the San Miguel reef zone.

It's could already see this difference in Figure 4, where the potential is represented on the map.

About the mean values in the zone, in SM are around 7 kW/m^2 in a year. In the zone of ST, the mean values are around the 13 kW/m^2.

3.2 Bathymetry

In order to run a wave model in coastal areas, it is vital to know what the bathymetry of the seabed is like. The seabed, in shallow waters, is a factor of critical importance.

For this work a high resolution bathymetry of the studied region was used. Bathymetric data include local surveys made by the Waves and Coastal Processes Laboratory of the IIO-UABC, obtained with different projects, and where complemented with data digitized from official bathymetric charts. The bathymetry covers an area of 0.5º x 0.5º, from 117W, 31.5N to 116.5W, 32N, with a regular grid of 201 x 201 nodes which provides a spatial resolution ~250 meters. with values between 1200 m and -1400 m. Knowing that this matrix covered, It was georeferenced and put in spherical format on the figure. In order to appreciate the terrain, the dates was entered the data into MatLab to graphically represent the bathymetry of the area.

We can also mention that negative values are depth and positive values are emerged territory or land. And of course, the values equal to 0 are the coastline, marked with a thin black line in the figure 6.

We can also see the islands of all saints at the entrance of the bay, those two polygons in the middle of the figure.

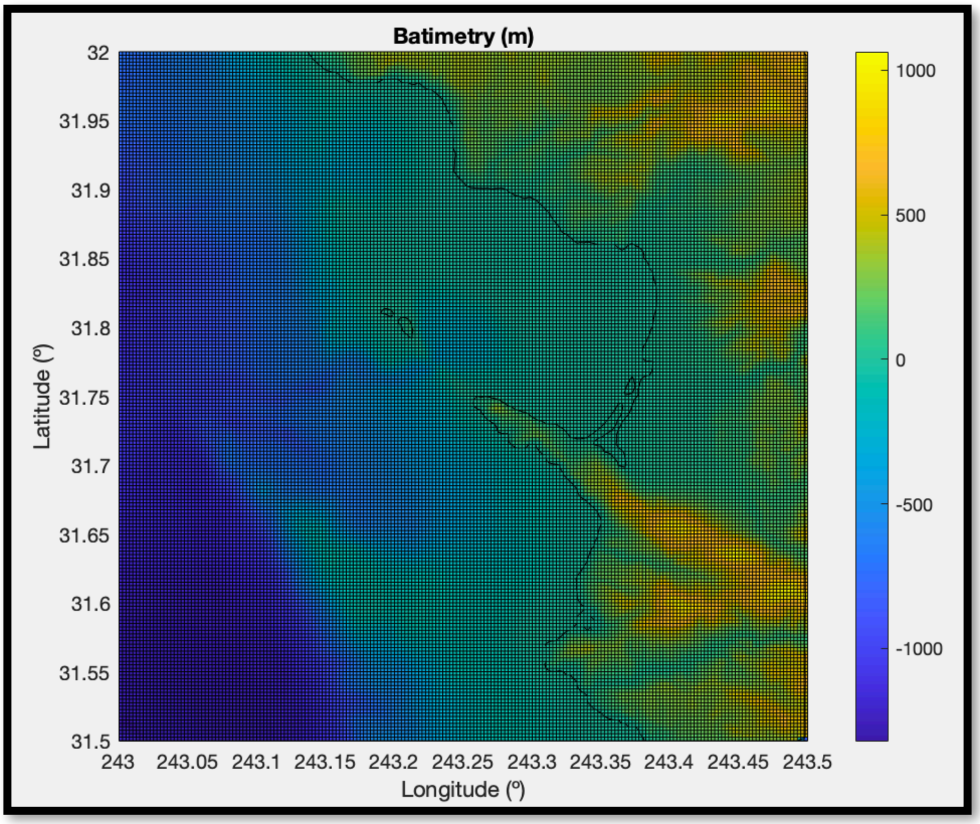

Figure 6. Bathymetry of the area. Data provided by IIO.

With this scale of values, the bathymetry of the reefs cannot be well appreciated. For this reason its re-represented the values. But this time with only depth values. And limiting the color palette from 0 meters to 150 meters deep. All values above 150 meters depth are painted in the same color. In this way the variations between these two values will be more appreciable.

Now yes, in the Figure 7 you can see the reef of San Miguel and the reef of Santo Tomas, this second one more to the south of the bay.

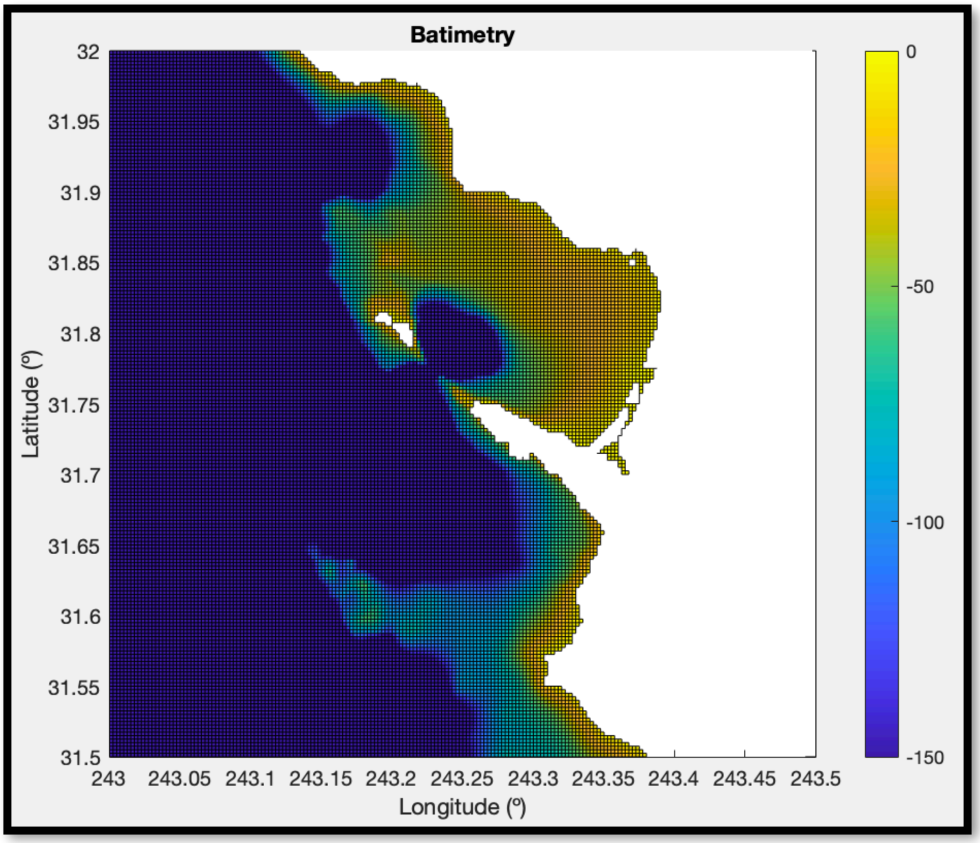

Figure 7. Bathymetry of the area. Data provided by IIO.

3.3 Wave energy converters

In recent years there has been an increased interest in marine renewable energy. This interest has come both from institutions, as well as from the private sector. Therefore, in recent years there has been an increase in the development of techniques and devices for harnessing wave energy.

In this work the wave energy converter (WEC) Pelamis is used, this WEC was selected based on the work of Gorr-Pozi et al. (2021) who found that it has the best performance within the study area. In the Annex 1 explained how the Pelamis device is.

3.4 Legislation

For maritime activities, as is the case of WEC farms installation, its must always observe current regulations which affect the project. The national regulations, the state regulations, and the more local regulations, the municipal.

In particular, for a WEC farm in the reef of San Miguel area, as its already mentioned before, is necessary to consider the existence of a nearby natural park a National Protected Area. The purpose of these areas is to preserve their particular biological richness, so they have special regulations that restricts some activities within the area.

Current environmental law regulations in Mexico, have some flexibility regarding energy production in these protected areas. The 'Reglamento de la ley general del equilibrio ecológico y la protección al ambiente en materia de áreas naturales protegidas' includes an appendix that talks about this specific topic. In the sixth title, uses, exploitation and authorizations (p.25) it mentions that resources of natural parks can be exploited, as long as they promote local development. Which would correspond to the intention of this project. As reference, Annex 3 include the articles that talk about it.

In addition, the last energy reform that the country is carrying out, they intend to nationalize the electric grid. And give more self-sufficiency internally. Therefore, all these types of projects could have a better posibility to be accepted by the responsible authorities.

3.5 Maritime traffic

As also mentioned earlier, Ensenada Port is the most important ports in the Baja California peninsula, which includes the Mexican states of Baja California and Baja California Sur, and one of the most important in Northern Mexico. The port activities generates a daily traffic of large merchant ships and smaller boats. This is also something to consider because for a WEC farm installation an area of prohibited navigation would have to be delimited.

However, as can be seen in the figure 8, the transit of large ships will not be affected. Small boat traffic that cross the area surrounding San Miguel reef will probably have to be modified and go around the WEC farm. Since they do not have restricted mobility, these fishing and recreational boats can easily adjust their trajectories without a significant increase of time.

As can be seen in Figure 9 maritime traffic around point Santo Tomas are scares, just few isolated boats. Therefore, at this point there would not be problems to delimit a restricted navigation zone.

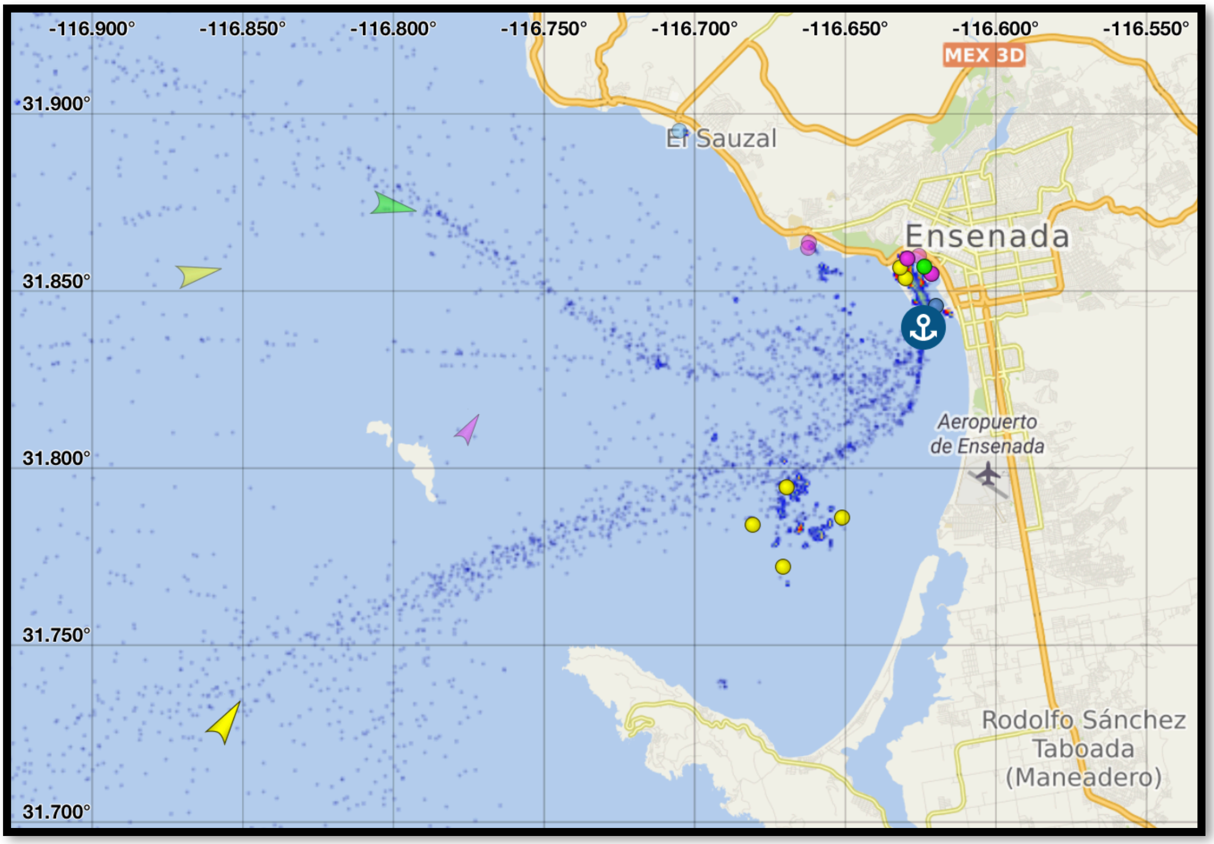

Figure 8. The Track History of one working day. Image of the vesselfinder online program.

Zone of the bay of Todos los Santos. Taken form freepng (https://www.vesselfinder.com/es.)

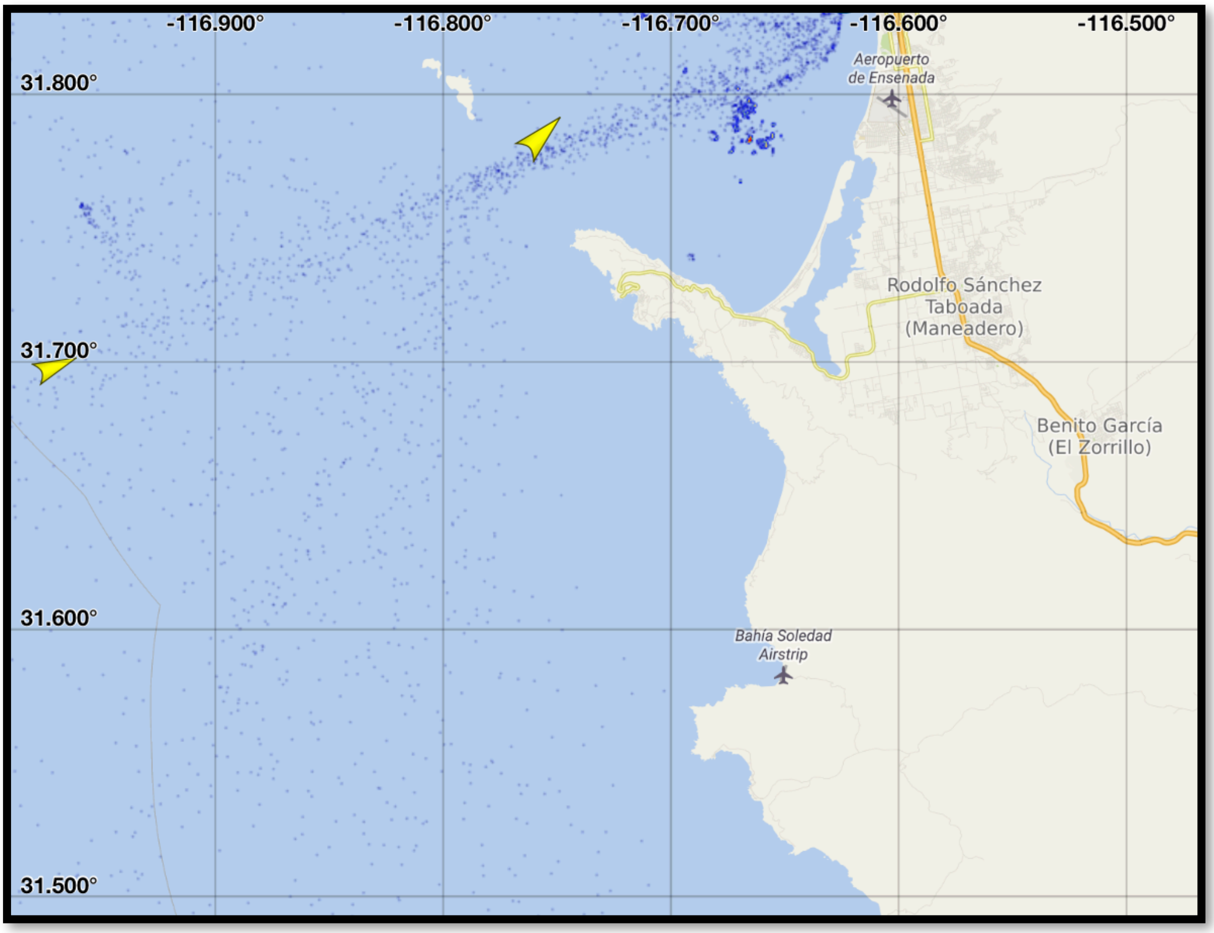

Figure 9. The Track History of one working day. Image of the vesselfinder online program.

The southern area of the bay of Todos los Santos. Taken form freepng https://www.vesselfinder.com/es.

4. Methods

4.1 SWAN model

It is a wave modelling program specially designed to study wave propagation and transformation from the deep ocean to the near shore and to get realistic estimates of the waves and their parameters.

Swan is a third-generation spectral wave model. It is based on the concept of directional wave spectrum and on the wave action balance equation.

The wave kinematics that use are the flower ones:

$$\frac{d\vec{x}}{dt} = (c_x, c_y) = \vec{c_g} + \vec{u} = \frac{1}{2}\left(1 + \frac{2kd}{\sinh(2kd)}\right)\frac{\sigma\vec{k}}{k^2} + \vec{u}$$
$$\frac{d\sigma}{dt} = c_\sigma = \frac{\partial\sigma}{\partial d}\left(\frac{\partial d}{\partial t} + \vec{u}\cdot\nabla_{\vec{x}} d\right) - c_g\vec{k}\cdot\frac{\partial\vec{u}}{\partial s}$$
$$\frac{d\theta}{dt} = c_\theta = -\frac{1}{k}\left(\frac{\partial\sigma}{\partial d}\frac{\partial d}{\partial m} + \vec{k}\cdot\frac{\partial\vec{u}}{\partial m}\right)$$

Where (cx) and (cy) are the propagation velocities of wave energy in spatial. On the x and y axis. (cσ) and (cθ) are the propagation velocities. The (d) is the depth, (s) is the space co-ordinate in the wave propagation direction of (θ) and (m) is a co-ordinate perpendicular to (s). The expression for (cθ) is presented here without diffraction effects.

The total derivative, d/dt, along a spatial path of propagating energy is described with the formula:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + (\vec{c_g} + \vec{u})\cdot\nabla_{\vec{x}}$$

These equations are extracted from the Technical Documentation of WAN Team. In a manual where it is explained technically how SWAN works.

SWAN can be used in coastal areas, estuaries and lakes. The Inputs with which it works are the wind, the bathymetry of the area and the currents. These parameters can be stationary or non-stationary.

This program working with two main types of grids. Structured and unstructured grids. The structured ones are those that its elements, or grid cells, are quadrilaterals delimited by 4 points, called nodes, and can be rectilinear and uniform or curvilinear. On the other hand, the unstructured grids consist of triangular grid cells in which the number of adjacent cells can be greater from 4. For this reason, the level of flexibility at the moment of distributing the points in the area is higher, with the unstructured ones, and a greater resolution could be achieved in some areas without too much increase of computational nodes.

It also allows nesting, to work more specific areas of space with a higher resolution. For example, in processes near the coast, where it is intended to have more details of the area.

For ocean scales, it is recommended to use other types of models, such as WAM or the WAVEWATCH III. Models designed specifically for oceanic applications an order of magnitude more efficient in those scales as compared with SWAN as the user manual of SWAN says, from the SWAN team of Delft University of Technology. SWAN is intended more for transitions from oceanic scales to coastal scales. Transitions where non-stationarity can be an issue.

4.2 SWAN- SNL

The power that its can get from WECs in a region can be computed with a SWAN extension. This extension is known as SNL-SWAN. A modification of the open source SWAN made by the Sandia National Laboratory of the USA. It includes a module for WEC analysis and performance studies.

Some of the parameters with which its regulate are the transmission of the obstacle and the reflection. These two parameters are the two main ones that is necessary to evaluate the energy transfer.

To know how much power each device can extract, performance tables are used: for each wave condition a performance of the device is specified. This table was obtained from a previous study of Francisco Haces-Fernandez, Hua Li, and David Ramirez, *'Assessment of the Potential of Energy Extracted from Waves and Wind to Supply Offshore Oil Platforms Operating in the Gulf of Mexico' (2018)*, and is included here as reference (Figure 10).

This type of information is very complicated to obtain, since manufacturers usually reserve this type of information, since it is usually of commercial interest and may be of interest to their potential competition.

Tp (s)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	20
Hs (m)	Hs: wave height (meter) Tp: wave peak period (second)																
0.125	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	11	27	50	62	64	57	49	41	34	28	23	0	0	0	0
1.5	0	0	26	62	112	141	143	129	110	91	76	63	52	43	36	30	23
2	0	0	66	109	199	219	225	205	195	162	135	112	93	77	64	54	41
2.5	0	7	93	171	279	342	351	320	274	230	210	174	145	120	100	84	65
3	0	91	180	246	402	424	417	369	343	331	275	229	208	173	144	120	93
3.5	0	86	211	326	484	577	568	502	421	394	330	312	260	216	196	164	140
4	105	216	326	394	632	616	583	585	494	454	374	361	339	283	236	197	153
4.5	94	233	371	467	735	744	738	634	626	520	473	390	382	319	299	250	208
5	259	364	469	539	750	750	750	750	644	641	531	482	399	394	330	308	274
5.5	428	497	566	612	750	750	750	750	750	635	642	532	482	400	399	341	322
6	597	630	663	684	750	750	750	750	750	750	616	633	525	476	396	386	329
6.5	750	750	750	750	750	750	750	750	750	750	723	592	617	513	458	430	384
7	750	750	750	750	750	750	750	750	750	750	750	692	566	560	500	474	425
7.5	750	750	750	750	750	750	750	750	750	750	750	748	610	607	542	518	467
8	750	750	750	750	750	750	750	750	750	750	750	750	630	653	584	562	509
8.5	750	750	750	750	750	750	750	750	750	750	750	750	650	699	626	606	551
9	750	750	750	750	750	750	750	750	750	750	750	750	670	746	668	650	592
9.5	750	750	750	750	750	750	750	750	750	750	750	750	691	750	710	694	662
10	750	750	750	750	750	750	750	750	750	750	750	750	711	750	750	738	734

Figure 10. Table of the Power extracted for each devices, for the different wave conditions.

Imatge extracted of 'Assessment of the Potential of Energy Extracted from Waves and Wind to Supply Offshore Oil Platforms Operating in the Gulf of Mexico' (2018) article.

Knowing the characteristics of the waves, it is possible to know how much energy would be extracted for each of the conditions. These values are entered in the SWAN-SNL program so that the program itself returns the total.

4.3 The wave model

4.3.1 Previous simulation data

Wave data used as references and as boundary conditions come from previous simulations done by the Waves and Coastal Processes Laboratory of the IIO-UABC. Those simulations conform a local wave hindcast of Todos Santos bay that spans from 2008 to 2018. Local hindcast is based on an offline nesting within a larger parent model. This was done to obtain a higher resolution of the area of interest.

The parent model is the IOWAGA hindcast developed be the French institute Ifremer. IOWAGA produces several kinds of wave-related information. The particularity of these modernizations is that they are made worldwide. Are values from anywhere in the world, from 80ºS to 80ºN, in all longitudes. In addition, these hindcast is reviewed and updated annually. From the comparisons of the results obtained and the values collected at sea, a readjustment of the code is made to improve the simulations.

IOWAGA uses a multi-grid scheme to increase spatial resolution in different regions of the globe. However, the mesh resolution in the Mexican Pacific is very large, the distance between the nodes is ~18 kilometers, which is not surprising, since the computational power required for this type of calculation is enormous. Therefore, to work with small areas as Todos Santos bay, is necessary do a downscaling with a coastal model.

What was done was to take IOWAGA wave parameters as boundary values for the study area and, with these inputs, run the local nesting with a higher resolution. For the local hindcats SWAN model was run in non-stationary mode and provided outputs every hour. From does outputs daily, monthly and annual values were obtained. The grid used had a spatial resolution of 0.0025º of Latitude and 0.0025º of Longitude, having nodes every ~250 meters, in an approximately square mesh.

The Figure 11 is the plot of the mean wave height. Between 2008 and 2018.

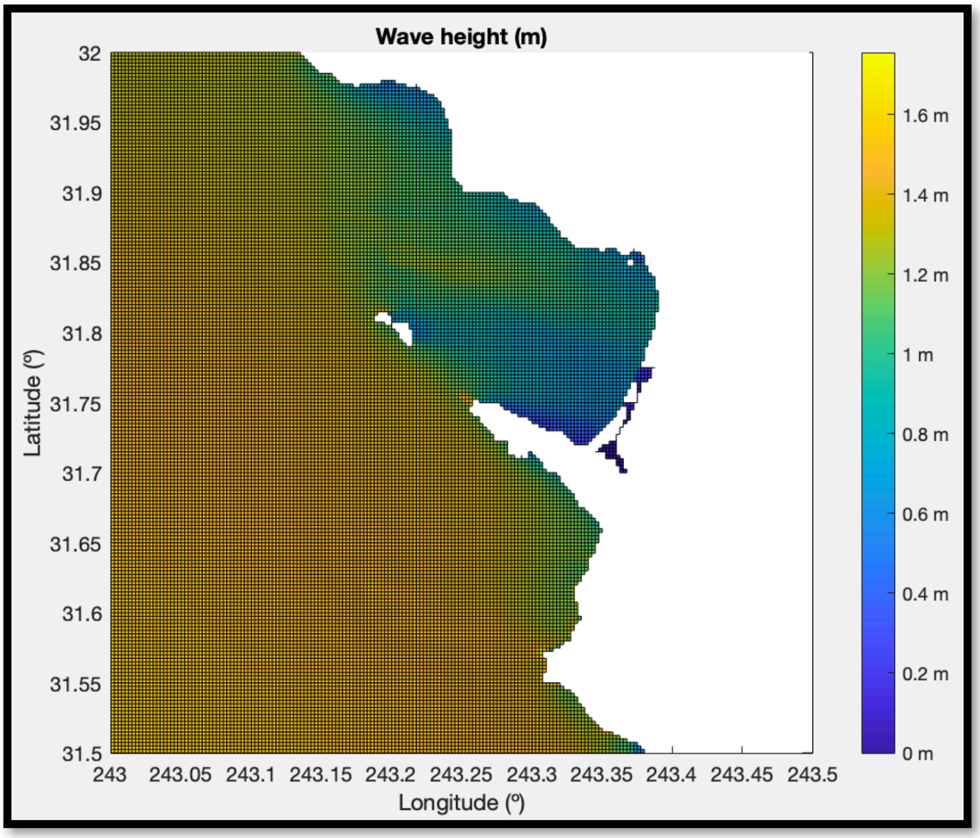

Figure 11. Mean significant wave height from the years 2008 to 2018 for the Todos Santos bay area.

4.3.2 WEC farm modelling

For WEC farm modelling SNL-SWAN was implemented in a two nested grid scheme. To work simultaneously on two different zones, with different needs in each area.

SWAN only have one-way nesting. Information can be only passed from a parent grid to the nested grid but not vice versa. This pose a problem because is necessary to have a very high resolution in the WEC farm area but also want to simulate a large portion of the bay to see the fram impacts in its surroundings. The solution is an off-line nesting in two areas as seen in the Figure 12.

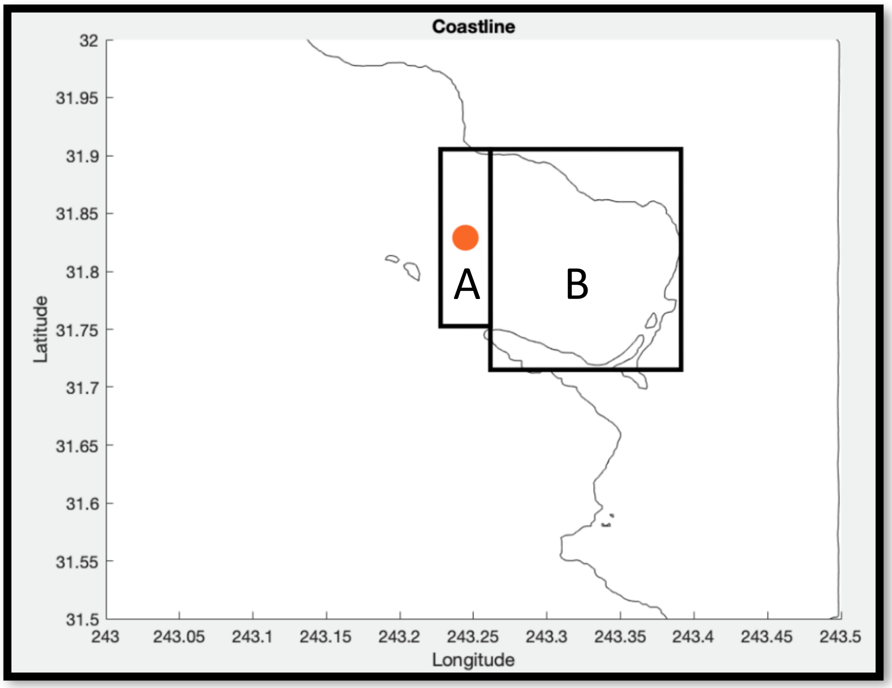

Figure 12. Represented coastline. With the two areas that ran. The orange dot is the location of the devices.

The first area (A) covers the opening of the bay and has a 20 meters resolution. In this area is where the devices are located, for that reason it has to have a good resolution, otherwise the devices would not be seen by the model.

The second zone (B) covers the inside of the Todos Santos Bay with a 50 meters spatial resolution. Since in this area only the waves have to be propagated such resolution is appropriate and a high computational power is not necessary. This reduces computational time more than a half. The two grid scheme implemented in an 8 processors workstation last about 48 hours of computation to run the 182 runs needed to characterize the WEC farm behaviour.

To force the first grid at its open boundary data from the Todo Santos Bay local-hindcast where used.

In SNL-SWAN, WECs are included as obstacles. For arrays each WEC should be specified as an independent obstacle providing its position but all will be of the same type. For practical purposes, the pelamis device can be studied as just one point, since the potential it can have is expressed in meters, which is kW per meter. This meter is the length of the wave front with which it is in contact.

Therefore, what is done when delimiting the objects is to work on that objects were on one of the nodes. When our object cuts one of the nodes, the model recognizes it as an obstacle at that point and it no longer goes unnoticed in our grid. Here 4 devices were introduced to simulate a farm that produces around 0.5 MW in order to comply with a decentralized energy distribution scheme as proposed by Gorr-Pozzi et al. (2021). However, this scheme can be replicated for WEC arrays with a larger number of devices.

This first distribution is with the first device, the one that is further north, located at the latitude of 31.8344º North and 116.745º West. The other 3 devices are in south, 150 meters between them. This distance has been designed to avoid possible collisions between devices. If the waves change direction, that the devices have room to rotate on themselves, to adopt the new angle of attack, this angle must always be perpendicular to the direction of the waves, always facing the waves that arrive.

Therefore, the devices are between the latitudes of 31.83º and 31.8344º North, approximately 500 meters.

In fact, they are not just above the San Miguel reef, but abut a kilometre from the reef towards the coast, in an area where wave focussing occur. Also as discussed in Emiliano's work, 'Wave Energy Resource Harnessing Assessment in a Subtropical Coastal Region of the Pacific', it is because of the depth, Pelamis has a working depth, with which very shallow depths are not good. In addition, there is a second point to have to look at, maritime traffic. For this reason, the chosen location is not on top of the same reef.

SNL-SWAN model was run for different sea states in stationary mode, to add realistics factors to the models. A total of 182 conditions were considered which represent approximately 98% of the hourly-sea states found on the Local-hindcast.

These conditions were extracted from the availability matrix (Figure 13) of the boundary node in front of the devices. Grouping waves in ranges between Hs values from 0.25 to 5 meters (each 0.25m) and periods betwwen 4 to 20 s (each 0.5s) obtaining how common those conditions are. The data is in percentage but represents the probability of occurrence of each wave condition and can be interpreted as the fraction of time that a particular sea state occurred during a year time.

All times in each range of the availability matrix are known and to obtain the mean conditions for each range on each boundary node. This allowed us to include the spatial variability along the boundary.

In this way the model gain reliability in our model, since there is not a single condition on the entire boundary. Spatial variability at the boundary is critical to our simulations, since just before the boundary of our model are the islands of Todos Santos, which greatly mitigates the waves in the southern area our domain (Figure 13).

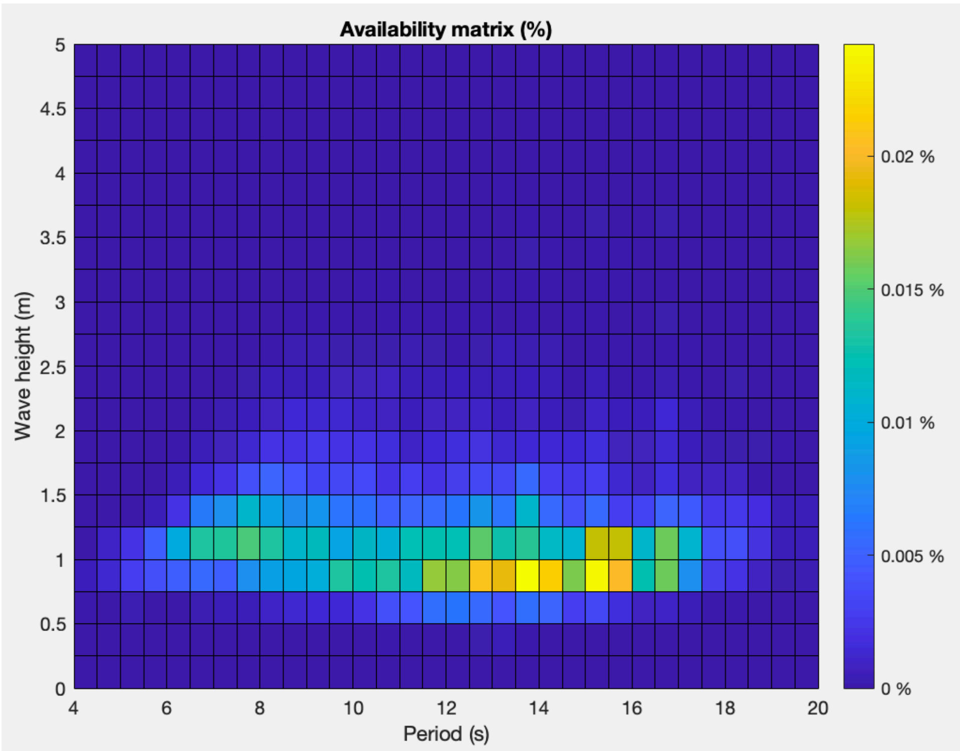

Figure 13. Availability matrix. Variability of conditions in %. How likely it is that there will be different swell conditions.

5. Results

The main results of the modelling are shown hereafter in terms of mean wave heights and wave power. As be seen in Figure 14. It can be seen that in the north the waves are more significant than in the south. In the northern part of the bahai there are bigger waves. In the middle of the entrance of the bay there is the island. This greatly alters the swell in the area, as can already be seen. An area more protected from interaction with the waves and therefore, the waves in that area will be less. In the area behind the island, east of it. Behind the WECs the swell changes, the swell decreases. As can also be seen in the following figure. Figure 14.

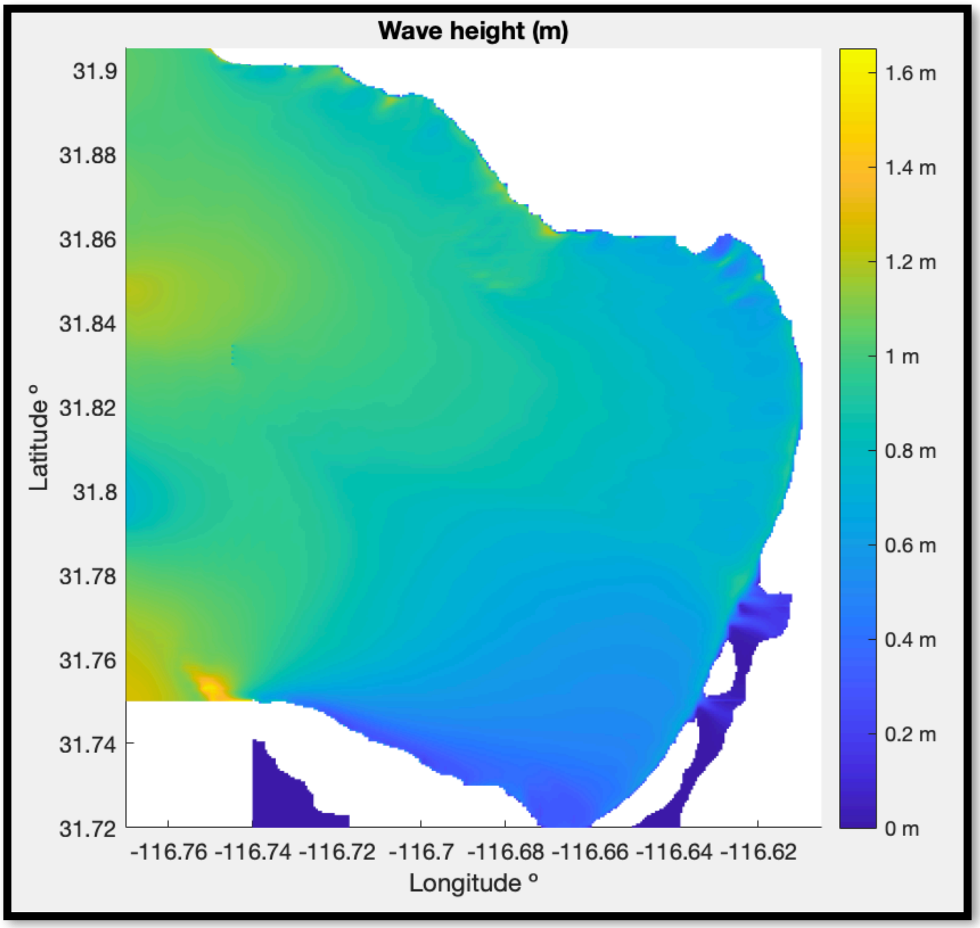

Figure 14. Mean significant wave height in meters for the simulations with 4 Pelamis.

As already mentioned above, wave energy is proportional to the squared of the significant wave height. Thus, the effect of a WCE farm is spected to be grater in wave power. This can be seen in Figure 15. Where the same effects on the waves can also be seen. More potential in the north of the bay and less potential behind the island and the WEC's.

But the size of the devices and the island are incomparable. Since the zone of influence of alteration is much more that of the island than that of the devices.

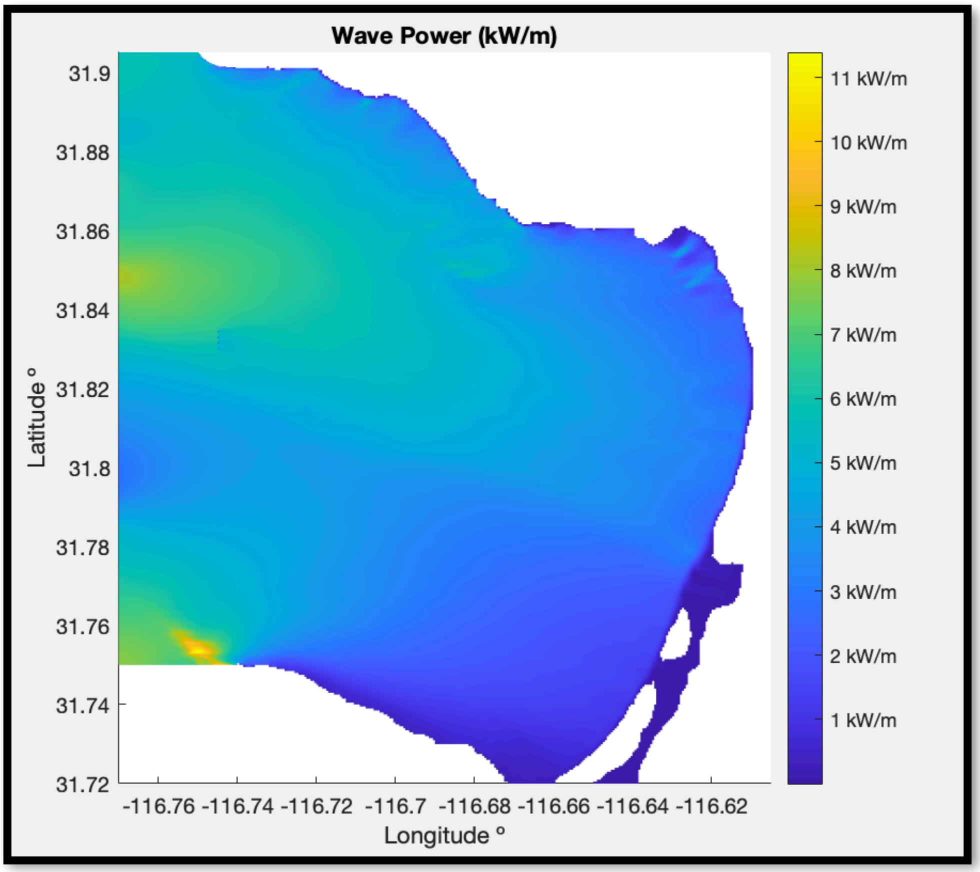

Figure 15. Mean significant Power in kW/m. Simulations with 4 Pelamis.

In Figures 14 and 15, are the effect of the WEC farm on the wave field but it's not appreciate the difference with respect to the conditions with no farm. In order to better appreciate this difference, the difference between the model runs was calculated without WEC farms and the model runs with a farm. Simply its represented the variation between them and it's analyse how the wave field have changed due to the WEC farm.

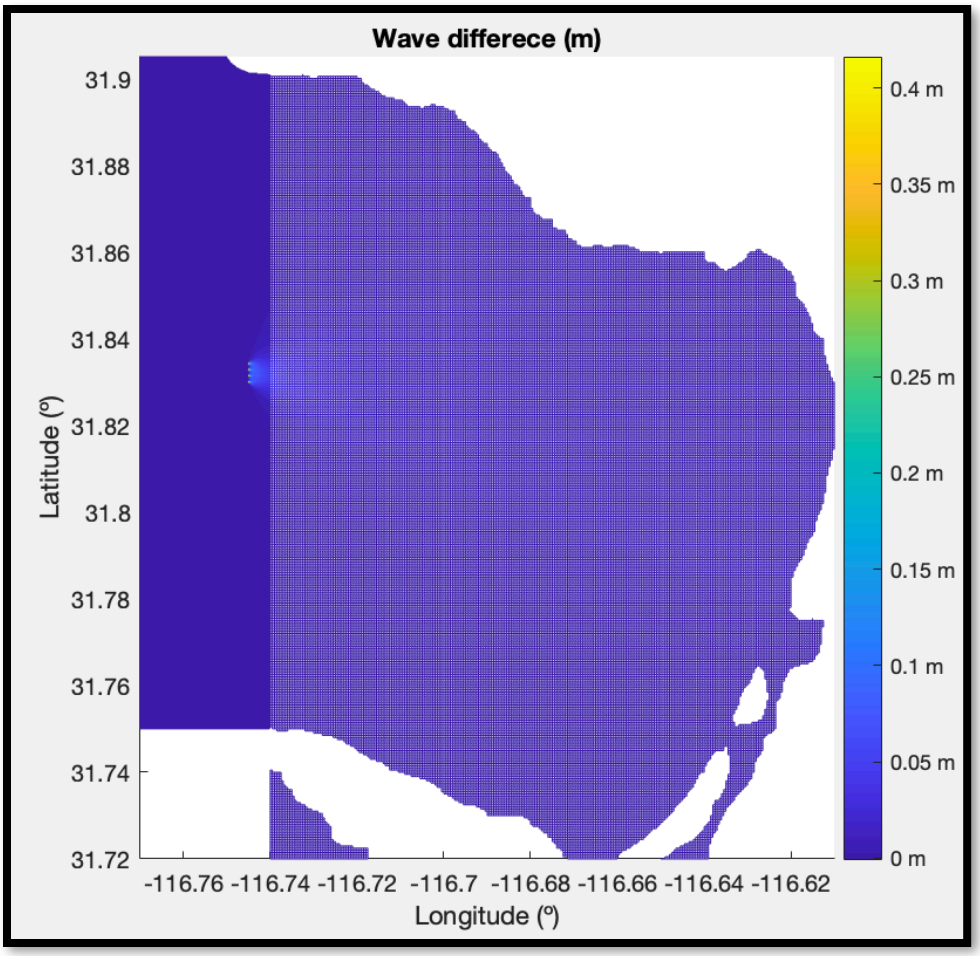

Figure 16. Variation of the wave height in meters, the wave height simulation without devises minus the wave height simulation with the 4 devises.

Figure 16 shows the difference in Hs due to the WEC farm. The figure shows that the changes only occur in the area behind the devices, these changes are from 0.1 to 0.15 meters. As far as the rest of the area is concerned, it can be seen that the variation is practically 0. To better visualize the differences was computed the relative variations with respect to the undisturbed condition. As can be seen in Figure 17. Where you can see a little more variation within the bay. This variation does reach the coast, but the variations that reach it are less than 4%. The alterations that are seen are really very small. It is important to notices that the highest differences observed behind the WEC farm are around 60% however, to better visualize differences induce inside the bay, are restrict the colour palette, in blue are the areas that present a variation greater than 25%.

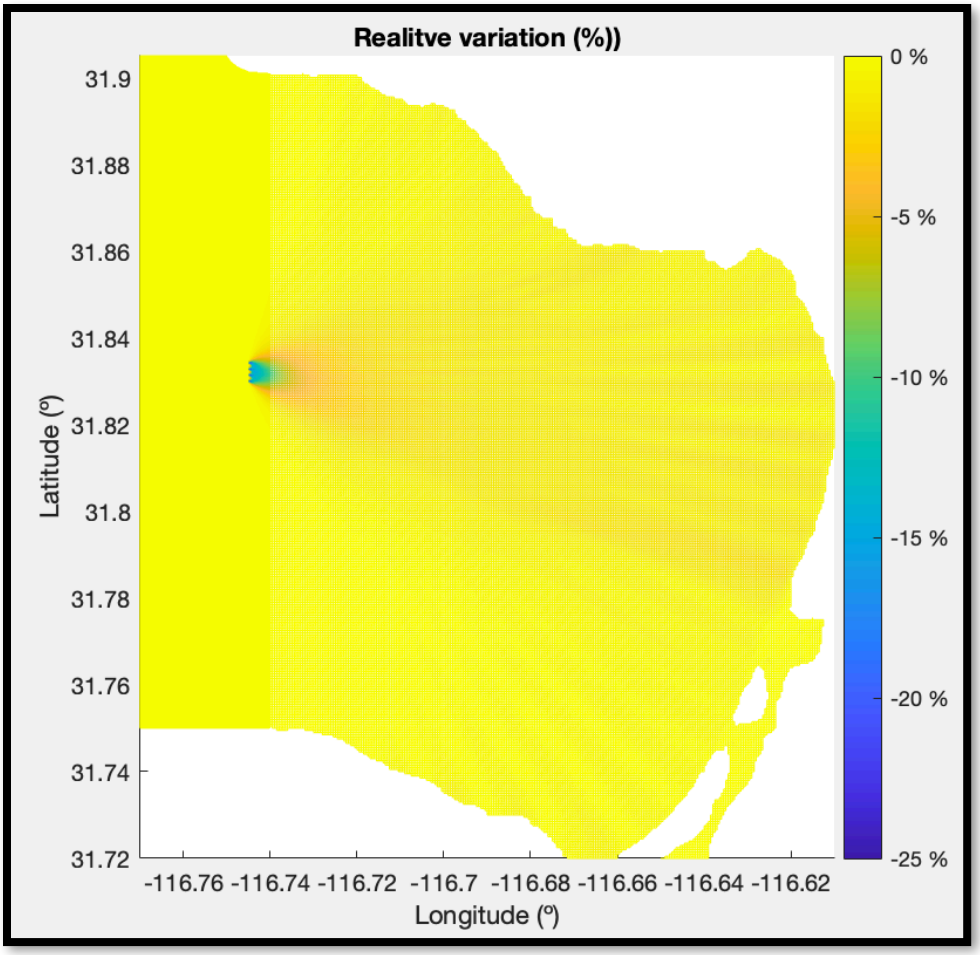

Figure 17. Relative variation in % of Power. Percentage varies the power with the simulation without the devices and the simulation with the 4 devices.. The values represented in the value scale are [0% to 25%].

In order to make a better comparison, what has been done is work with control zones. They are areas where it is evaluated how it changes from one simulation to another. These longitudinal cuts helps to see the cross-sections that are on the same line, in same latitude profile, and better visualise the changes induced by the WEC farm as there is move farther form the farm.

The first point of interest is the limit that unites both grids. The lee side of the mesh devices. And the front of the second mesh, the mesh bay. This line is a perpendicular line, over the same length. This longitude is 116.74 West. Which turns out to be the entrance to the bay of Todos Santos. Figure 18. This point is located about 500 meters from the beginning of the device, which considering that the device is 150 meters long, is being analyzed the dynamics of the waves 350 meters after the obstacle. This distance was considered good, in the part closest to the device there are many interferences from refraction with the same devices, there is a lot of turbulent flow. Therefore, at 350 meters, the small disturbances have disappeared and only the real conditions of the waves remain, the ones that travel inside the bay.

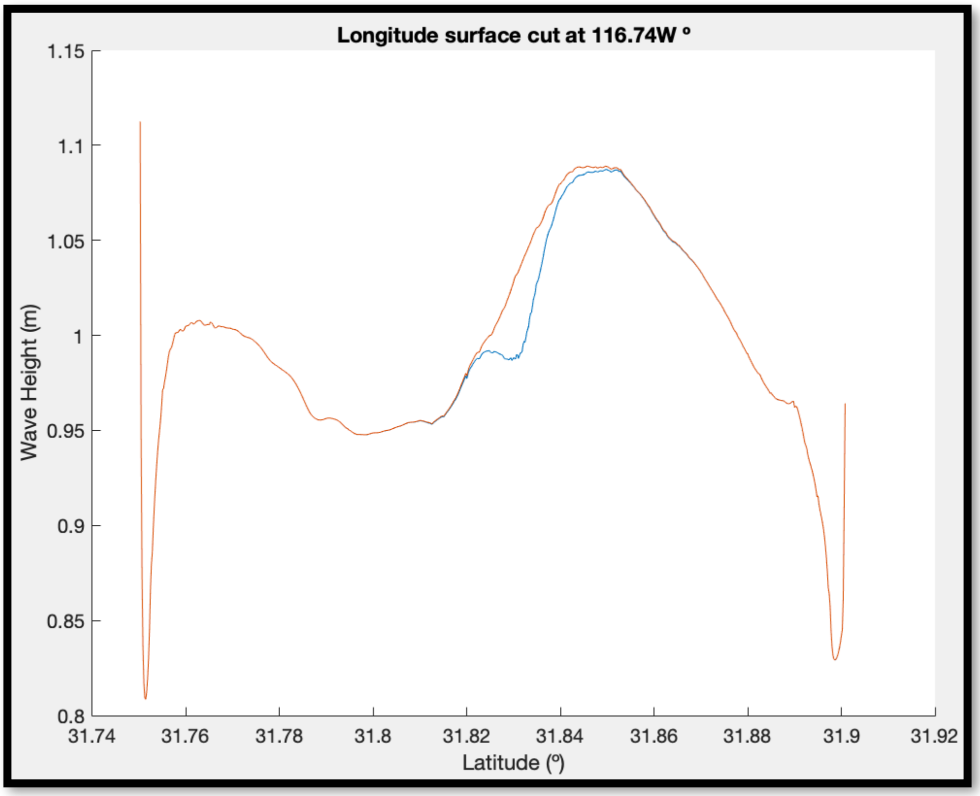

Figure 18. Wave height in the Longitude of 116.74 West, longitudinal cut. The simulation without devises in orange and the simulation with devises in blue.

To better appreciate the difference in the cross-sections, what has been done has been to graph the difference between the two situations. The contrast between one and the other. The original profile without the devices minus the profile obtained with the devices.

Considering that the values at 0 means that there has been no change at that point. Positive values mean that the wave height has been reduced and negative values mean that the waves have increased at that point.

In Figure 19 there are the first cross-sections.. And it shows little change. It only appreciates the change in the area where the devices are located. The maximum variation is around the Latitude of 31.83º North. Result that was already expected to be obtained.

As far as the rest of the cross-section is concerned, is practically the same. Since no new obstacles have been introduced and the border conditions are the same.

The most significant variation is only a few centimetres in the devices zone.

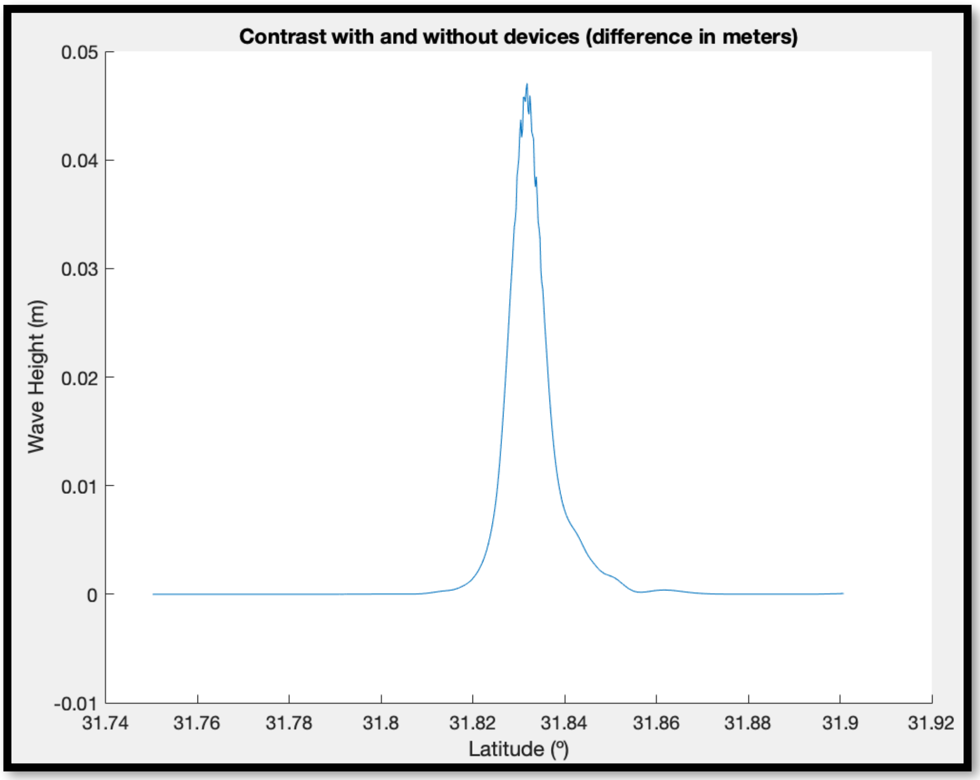

Figure 19. Variation of the wave height, the simulation without devises minus the simulation with devises. In the Longitude of 116.74 West, longitudinal cut.

The second cut that was made was in the middle of the bay, already approaching the coastline. This second point was carefully chosen. Taking into consideration the geology of the region.

If the coastline of the bay is analyzed, the endpoints, the northern and southern edges are cliffs, and they are in a state of active erosion. Highlighting important structural defects of many buildings on the seafront. In them, the sediment that accumulates is not significant. There are few beaches and those that exist are small. Since it is a transport zone towards the center of the bay, where are the most important and largest beaches.

We made this cross section at the latitude of 116.67W. A little before the start of the coastal lagoon in the bay. Figure 20.

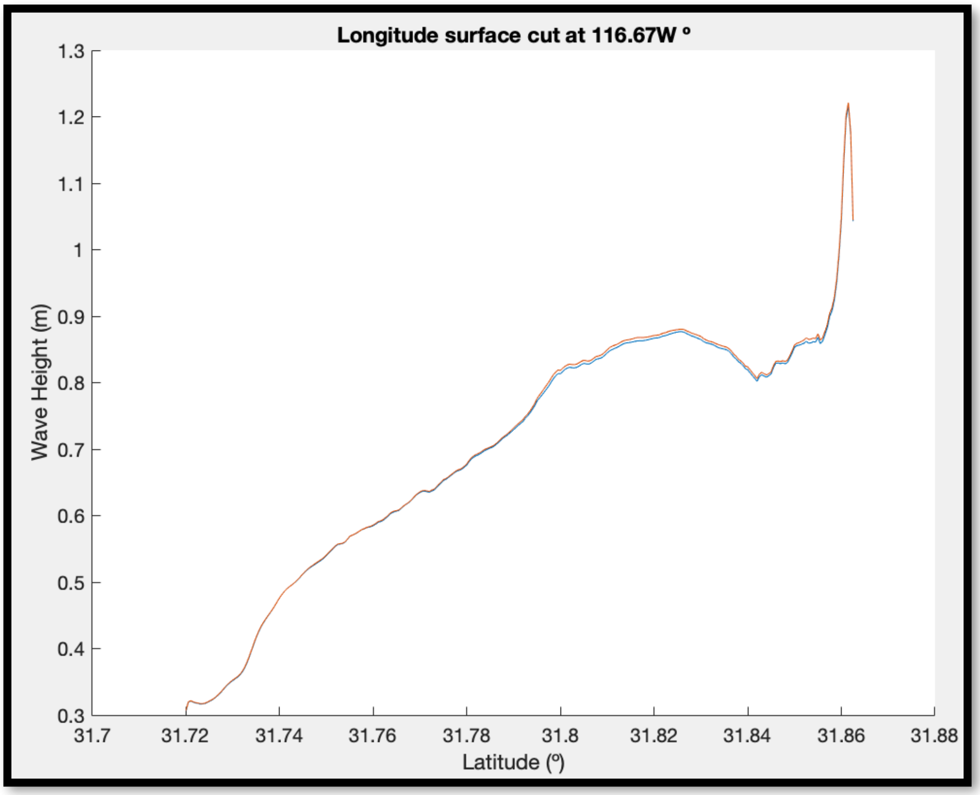

Figure 20. Wave height in the Longitude of 116.67 West, longitudinal cut. The simulation without devises in orange and the simulation with devises in blue.

In this second cross-section are more and more dispersed variation. Since the perturbations generated by the devices have moved throughout the bay. Furthermore, the possible small alterations caused by using different versions of the model have also become more present.

But in general, the variation of the waves is a few centimetres.

The changes in Hs due to the WEC farm can be seen in the Figure 21. This figure represent five cross-sections taken at 100 meters intervals from the WEC farm. It can be seen that in the first there are variations up to 10 centimetres and at 500 meters the variation has been reduced by 50%, with a difference of 5 centimetres between the two simulations.

In the same figure it can be seen that the variability is distributed over space. The conservation of energy is the disturbance generated by the devices is distributed over a larger surface as the waves move.

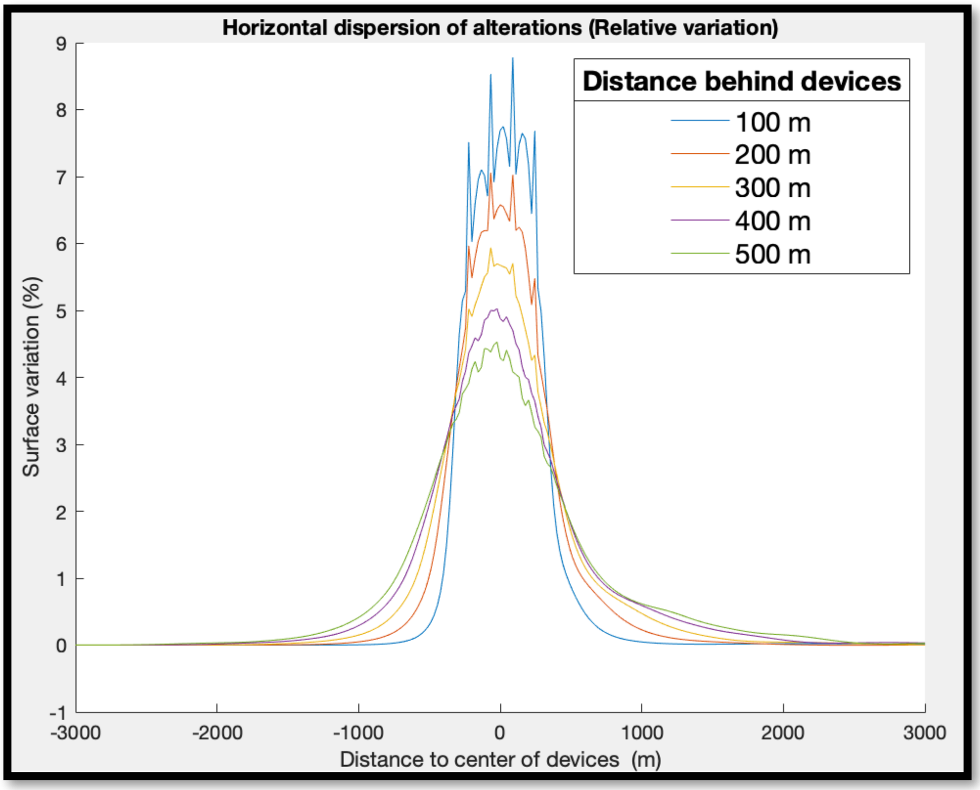

Figure 21. Wave variation behind the devices in %. On the x-axis are the dispersion to the sides in meters. The different lines represent different cross-sections.

Running all conditions and determining what power each of the devices will obtain at each condition, the power matrix is obtained for each device in the WEC array. That matrix is what tells us how much each device can extract for each of the conditions. In Figure 22 are the matrices of the 4 devices.

The matrices are very similar, but if you check the values of each one, they are not the same, since the devices are slightly exposed to different wave conditions. Therefore, their returns will be slightly different.

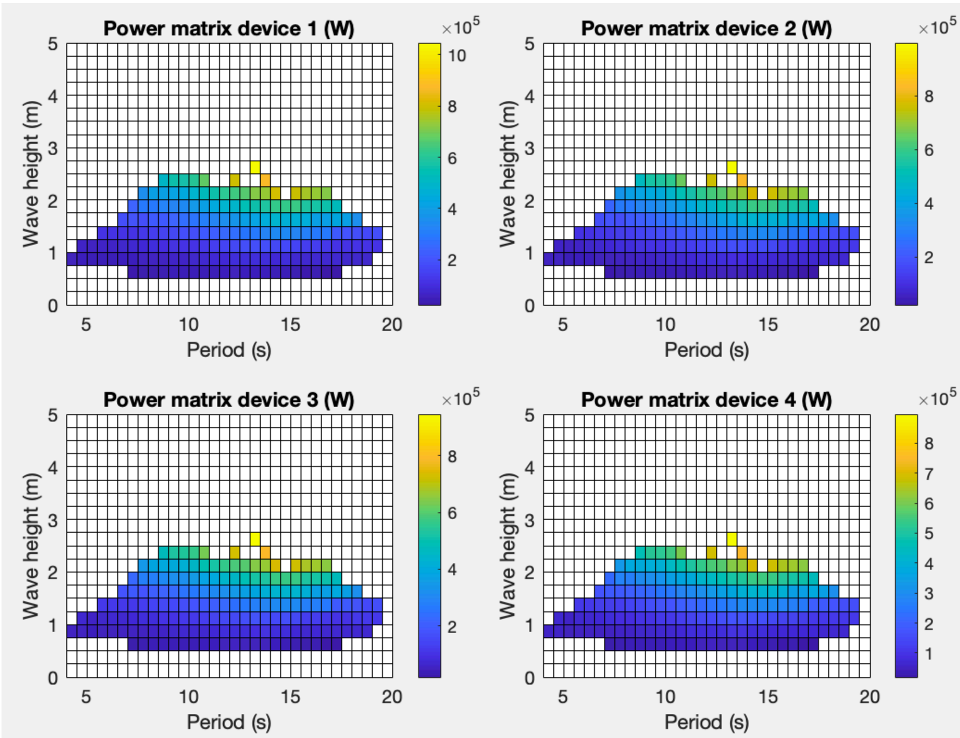

Figure 22. Power matrices generated by each device with different wave conditions.

The mean wave power extracted by each device are in the follow table, Table I.

Table I. Mean extracted wave power by each device in the array.

Obstacle	Power absorbed (MW)
1	0.15
2	0.15
3	0.14
4	0.14

For the first device, the one further north, the generation is 0.154 MW and for the one at the other extreme, the one further south, a production of 0.149 MW. They are higher performance in devices located further to the north.

However, all devices generate around 0.15 MW of electrical power. Therefore, with the sum of the four devices there are about 0.5887 MW.

Compared with other power plants in the same state is not very significant. In Figure 23 are the plants that exist in this state, those that are in the municipality of Ensenada, Tijuana and Rosario. Its total production is 1,380.86 MW. Are also other power production centers in the remote part of the state, close to the capital, Mexicali. Making a total production of 2 651.86 MW.

Ubicación	Inicio operación	Edad a 2004, años	Tipo	Unidades	MW
Rosarito	6 de marzo, 1964	40*	T.C. Comb	1	75
	11 de diciembre, 1964	40*	T.C. Comb	2	75
	31 de agosto, 1963	41*	T.C. Comb	3	75
	18 de marzo, 1969	35*	T.C. Comb	4	75
	1 de agosto, 1991	13	T.C. Comb	5	160
	30 de junio, 1992	12	T.C. Comb	6	160
	6 de Julio, 2001	3	CCC GN	1	248
	6 de Julio, 2001	3	CCC GN	2	248
Tijuana	1 de Julio, 1982	22	TG Diesel	1	30
	5 de agosto, 1982	22	TG Diesel	2	30
	8 de junio, 1999	5	TG GN	3	150
Ensenada	12 de diciembre, 1981	23	TG Diesel	1	27
	12 de febrero, 1982	22	TG Diesel	2	27
				TT	**1380.86**

Figure 23. Electrical power installations in Baja California Coastal Zone. Table extracted from the report *'Baja California perfil energético 2010-2020'*

But it is necessary to highlight that this small WEC farm is intended to provide energy without being connected to electrical grid, in order to do that it cannot provide more than 0.5 MW. Moreover, the power plant would provide energy of totally renewable origin and therefore linked to zero greenhouse gas emissions.

Working with such a small number of devices has its advantages. As there are few devices, the energy production will also be lower, so the regulations to which it is subject are different. By not having large plants, it is possible to have a more decentralized and distributed electrical network. This type of installation can be installed in more places since the initial investment is not so high. Strengthened areas where the arrival of infrastructure is more complicated. Promoting the development of the area.

This installation does not exceed 0.5 MW, the limit with which it is not necessary to have electricity generation connected to the national electricity grid. If the production exceeds this limit, it should already be subject to the same legislation as the large power plants in the area. Below this value can be self-manage the energy that is generate, being able to distribute it through our installation, urban fraction or enclosure.

This is specified in the official document of '*Ley del Servicio Público de energia Eléctrica*'. In annex 4 are the complete regulations that refer to this decree.

6. Discussion

As seen in the results section, the effects on the waves are a few centimeters. This, together with the fact that the devices are 12 kilometers from the coast, the disturbances that reach the beach are practically 0. In the first 500 meters the variation has already been reduced by 50%. And It is a few centimeters variation.

Seeing that the alterations in the waves are very small, the internal dynamics on the coast will be maintained. Will not alter sediment transport.

On the other hand, it has already seen that after 500 meters the alterations are significantly reduced. This is good for future projects. Since taking this into account, this type of installation can be installed in other areas closer to the coast.

Therefore, the sedimentary transport will remain the same. This transportation within the bay was analyzed in the work of Alberto Sanchez and Jose Carriquiry. Where it is seen that the transported is towards the interior. At the ends are cliffs and, in the centre, sandy beaches. Both the northern and southern parts will continue to erode.

We would have liked to reproduce different distributions. But unfortunately, there has been no time to do it. With each of the distributions, the number of simulations that have to be done increases exponentially. Since each of the distributions must be re-run in the whole space.

About the distribution of the devices, the devices in the north have more energy than those in the south. This could be generated by the direction of the waves. The waves probably have a more norther gradient. It may be because of the protection it generates from the islands. When waves arrive with a south vector component. For this reason, the configuration perpendicular to the waves from the west is not the most optimal. If the distribution is changed, more energy could be obtained in total.

7. How to follow this work

Unfortunately, there was no time to do as many models as were the initial intentions. And just analyse one of the potential places for this installation.

Therefore, this study could be repeated in the future.

The next steps would be run the model with more devices. And simulation with other distributions in space.

Energy distribution could also be worked on, transferring the energy generated to the ground and connecting it to the national electricity grid.

In order to do this, a geological and bathymetric study must be carried out in order to trace the best route for the cabled. In addition to analysing the most optimal cabled, a submerged cabled, therefore, corrosion problems must be considered.

A biological analysis could also be carried out. The case of study are in a migration zone for mammals, that could cause damage to populations.

A very common species in the area are the sea lions. Furthermore, dolphins, whales and other species are also found in the area. Attracted by the protection of the bay and the upwellings coming from the California current.

The devices could generate noise pollution.

The project could also continue with the impact study. The economic impacts that it would generate in the area. How would the area develop?

Or with the study of the social impact that it would have. Obviously, it would promote development in the area and improve the quality of life in the area. The electrical grid in the country is not fully developed and shortages in some areas are common.

After studying all these points, it's could try to find financing to be able to carry out the project, presenting a solid project. And go from a theoretical project to a real project.

8. Conclusions

In this work, has been analyzed the alteration in the waves that would be generated by the installation of Pelamis in the Bay of All Saints, Baja California.

The study area has been modeled and work has been done with the SWAN-SNL waves numerical modeling program.

It is can conclude by saying that our simulation would have no effect on the dynamics of the coastline. This was the main objective of this work.

Another conclusion reached is the efficiency of electricity production has also been evaluated. How much energy could be extracted with the proposed devices. And say that for the few devices that have been modelled, the energy is considerable. Although this type of power plants still cannot replace the production capacity of the conventional power plants.

These types of installations must be complementary to the current ones. In order to gradually adopt more measures for the energy transition, with devices 100% of renewable sources.

We recommend this type of installation combined with others. Such as photovoltaic, wind or thermal power plants. Thermals could be a good technique, because the area is a tectonically active zone. With the presence of different active faults.

And from the legislative point of view, an also important issue. Our project is viable. After reviewing the laws that apply, there is no impediment to carrying out the project.

9. Acknowledgment

This work is a contribution of the CEMIE-Océano project funded by CONACyT/SENER sustentabilidad energética (Project No. 249795)

CEMIE-Océano

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Annex 1

1.1 Pelamis Energy

Pelamis is a device designed to generate energy. This energy comes from renewable sources such as wave energy. It transfers the movement of the waves into useful electrical energy.

It is an offshore floating device, formed by multiple cylindrical sections. The independent movement of these sections allows the pumping of high-pressure fluid, which rotates turbines that generate electricity.

Unlike other devices, the generation of electrical energy is carried out in the same device. And it transmits elecrticity by cables to the national grid. The dimensions of the devices, the second generation devices, are 180 m long and 4 m in diameter. With a total weight of 1350 kg.

These devices are already in a pre-commercial phase, they have already been installed in different countries in Europe, such as Portugal and Scotland, analysed in the work of Pablo García, 'Desarrollo de herramienta para la selection de dispositions de enrgia undimotriz'.

Figure 8. Image of the Pelamis in Aguaçadoura (Portugal). Taken from flickr.com.

This device have had good results in the pilot tests that have done. And they are in phases prior to their commercialization.

Annex 2

2.1 Team Viewer

The computer used to run the models was an Apple computer, the 2013 Mac Pro model. Where all the SWAN software was already located. This computer is owned by the IIO. And it had already been used in other numerical moderation projects.

Being a desktop computer, it was in the IIO. But in order to work remotely, Team Viewer was installed. This program allows remote access between computers. This was very useful for working from home, in some cases.

With this program it could connect even on weekends to run code and let it work for several days, the days that it was working on the numerical model.

2.2 Matlab

For most figures and graphs, the program used has been Matlab.

It is a programming language, which with its interface allows us to easily work with matrices, draw functions and many other things. Furthermore, when working with such a volume of data, it simplifies all processes.

All the data that comes out of SWAN has been worked with Matlab, to understand and analyse it.

This program was developed by the company MathWorks.

Annex 3

'Reglamento de la ley general del equilibrio ecológico y la protección al ambiente en materia de áreas naturales protegidas'

TÍTULO SEXTO

DE LOS USOS, APROVECHAMIENTOS Y AUTORIZACIONES CAPÍTULO I DE LOS USOS Y APROVECHAMIENTOS PERMITIDOS Y DE LAS PROHIBICIONES

Artículo 80.- Para los usos y aprovechamientos que se lleven a cabo dentro de las áreas naturales protegidas, la Secretaría otorgará las tasas respectivas y establecerá las proporciones, límites de cambio aceptables o capacidades de carga correspondientes, de conformidad con los métodos y estudios respectivos. Para la elaboración de los métodos y estudios que permitan establecer las proporciones, límites de cambio aceptables o capacidades de carga, la Secretaría podrá solicitar la colaboración de otras dependencias del Ejecutivo Federal, así como de organizaciones públicas o privadas, universidades, instituciones de investigación o cualquier persona con experiencia y capacidad técnica en la materia. Artículo reformado

DOF 28-12-2004

Artículo 81.- En las áreas naturales protegidas sólo se podrán realizar aprovechamientos de recursos naturales que generen beneficios a los pobladores que ahí habiten y que sean acordes con los esquemas de desarrollo sustentable, la declaratoria respectiva, su programa de manejo, los programas de ordenamiento ecológico, las normas oficiales mexicanas y demás disposiciones legales aplicables. Los aprovechamientos deberán llevarse a cabo para:

I. Autoconsumo, o

II. Desarrollo de actividades y proyectos de manejo y aprovechamiento sustentable de la vida silvestre, así como agrícolas, ganaderos, agroforestales, pesqueros, acuícolas o mineros siempre y cuando:

a) No se introduzcan especies silvestres exóticas diferentes a las ya existentes o transgénicas;

b) Se mantenga la cobertura vegetal, estructura y composición de la masa forestal y la biodiversidad;

c) No se afecte significativamente el equilibrio hidrológico del área o ecosistemas de relevancia para el área protegida o que constituyan el hábitat de las especies nativas;

d) No se afecten zonas de reproducción o especies en veda o en riesgo;

e) Tratándose de aprovechamientos forestales, pesqueros y mineros, cuenten con la autorización respectiva y la manifestación de impacto ambiental autorizada, en los términos de las disposiciones legales y reglamentarias aplicables;

f) Los aprovechamientos pesqueros no impliquen la captura incidental de especies consideradas en riesgo por las disposiciones legales y reglamentarias aplicables, ni el volumen de captura incidental sea mayor que el volumen de la especie objeto de aprovechamiento, salvo que la Secretaría, conjuntamente con la de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación, establezcan tasas, proporciones, límites de cambio aceptables o capacidades de carga, así como las condiciones, para un volumen superior de captura incidental en relación con la especie objetivo, mediante acuerdo que deberá publicarse en el Diario Oficial de la Federación cada tres años. En su defecto, el último acuerdo publicado mantendrá su vigencia. Inciso reformado

DOF 28-12-2004

g) No se realice la extracción de corales y materiales pétreos de los ecosistemas costeros, y

h) Tratándose de obras y trabajos de exploración y de explotación de recursos mineros dentro de las áreas naturales protegidas, y en cumplimiento por lo dispuesto en el artículo 20, segundo párrafo de la Ley Minera, cuenten con la autorización expedida por la Comisión Nacional de Áreas Naturales Protegidas, de conformidad con el artículo 94 del presente Reglamento.

Annex 4:

'Ley del servicio público de energía eléctrica'. DOF 09-04-2012

CAPITULO V

Del Suministro de Energía Eléctrica

ARTICULO 39.- Salvo lo dispuesto en el inciso c) de la fracción IV del artículo 36, no se requerirá de permiso para el autoabastecimiento de energía eléctrica que no exceda de 0.5 MW. Tampoco se requerirá de permiso para el funcionamiento de plantas generadoras, cualquiera que sea su capacidad, cuando sean destinadas exclusivamente al uso propio en emergencias derivadas de interrupciones en el servicio público de energía eléctrica; dichas plantas se sujetarán a las Normas Oficiales Mexicanas que establezca la Secretaría de Energía, escuchando a la Comisión Federal de Electricidad. Artículo reformado DOF 27-12-1983, 23-12-1992, 09-04-2012