



Wave Energy Potential's Assessment of the Seas Adjacent to Cuba

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Abstract: The research shows an analysis of both wave energy potential in the seas adjacent to Cuba and extreme meteorological phenomena that could damage the facilities exploiting such resource. The data of the parameters of the sea states were obtained from the outputs of the WAVEWATCH III model, in the 2000-2018 period, available in the database of the United States' National Oceanic and Atmospheric Administration. The analysis of extreme meteorological events affecting the western and eastern regions showed that the former is more likely to be affected by such phenomena. Despite the limitations imposed by the resolution of the grid used, it was found that the wave potential in the seas adjacent to Cuba is generally limited, and there are usable wave power density levels only at the western and eastern ends of the island.

Key words: renewable energy, wave power, wave potential.

Evaluación del potencial energético undimotriz de los mares adyacentes a Cuba. Resumen:

En la presente investigación se muestra un análisis del potencial de la energía de las olas en los mares adyacentes a Cuba y de los fenómenos meteorológicos extremos que pudieran dañar las instalaciones para el aprovechamiento del recurso. Los datos de los parámetros de los estados de mar de las olas fueron obtenidos de las salidas del modelo WAVEWATCH III, en el periodo 2000-2018, disponible en la base de datos de la Administración Nacional Oceánica y Atmosférica de los Estados Unidos. El análisis de los eventos meteorológicos extremos que afectan a las regiones occidental y oriental mostró que la región primera es más propensa a ser afectada por este tipo de fenómenos. A pesar de las limitaciones impuestas por la resolución de la rejilla utilizada se pudo constatar que el potencial undimotriz en los mares adyacentes a Cuba es limitado en general, y que solamente en los extremos occidental y oriental de la isla existen niveles de densidad de potencia undimotriz aprovechables.

Palabras clave: energía renovable, energía undimotriz, potencial undimotriz.

Introduction

Currently, power generation is based primarily on fossil fuels. This prevailing energy model with

the predominance of the exploitation of coal and oil, finite by nature and mainly responsible for CO₂ emissions, turns out to be unsustainable from an

environmental point of view (Bekun, *et al.* 2019; Dong *et al.* 2018; Feng *et al.* 2018). The emission of greenhouse gases is, definitely, a serious problem to fight against if there is a will to stop global warming and, consequently, climate change (Lin & Zhu, 2019; Sarkodie & Adams, 2018). In addition, during the second decade of the 21st century, a deep economic crisis has prevailed in which most countries have been affected, including those belonging to the European Union. Therefore, it is essential to search for strategies that allow humanity to achieve energy satisfaction in a safe way and with a minimal risk; thus, reducing the vulnerability of different countries (Rodriguez-Delgado & Bergillos, 2021).

In the United Nations Framework Convention on Climate Change held in 2015, in Paris, the goal of limiting the global rise in the average temperature in the 21st century to 2.0 °C was established (UNFCCC, 2021). A recent study carried out by the International Renewable Energy Agency (IRENA) indicates that CO₂ emissions have grown by 1 % annually in the last decade (IRENA, 2021). Meanwhile, the analysis carried out by the International Energy Agency (IEA) on the Covid-19 impact on the energy sector unfolds that the disturbances caused are greater than the ones found in recent history (IEA, 2021). The data analysis on energy demand in the first quarter of 2020 indicates a decrease of around 3.9 %, compared to the same period of 2019. This is mainly due to the reduction in economic activity and mobility (Rusu & Rusu, 2021). However, the Covid-19 aftermaths will not produce a decisive break in CO₂ emissions to reverse its trend, so the deployment of clean energy technologies must continue (Hepburn *et al.* 2020; Kuzemko *et al.* 2020). By 2040, the world energy consumption is estimated to be approximately 30 % higher than in 2010 (Xu *et al.* 2019). The European Union's position has been striking as it became a pioneer in the transition towards a scenario of 100 % use of renewable energy sources, setting a goal for its realization 32 % by 2030 (European Parliament, 2018), which is a byword for the rest of the countries worldwide.

All the aforementioned has helped raise awareness of the inescapable need to undertake transformations in the current energy framework. According to scientists, betting now on renewable sources of energy is the only way out to fight against the imminent climate change, and in turn, activate economic recovery (Rusu & Onea, 2018).

Among the renewable sources of energy, we have oceans, which contain most of the 70.8 % of the water that covers the Earth's surface (Farrok *et al.* 2020). The water in the oceans is in constant motion; hence, the oceans constitute, indisputably, a huge reservoir of energy. The estimated world theoretical potential that this source could contribute is around 151,300 TWh/year, which is of the same order of magnitude as the world demand for primary energy. The estimate attributed to the global theoretical resource of wave power, by itself, is of the order of 16,000 to 18,500 TWh/year, although it is not homogeneous since it varies over time and location (Clemente *et al.* 2021; Reguero *et al.* 2019). The existence of those amounts of energy has stimulated many investors and researchers to direct their efforts towards finding a way to harness this energy, which has led to the creation of over 200 companies and institutions worldwide dedicated to the development of wave energy converters (Clemente *et al.* 2021; Magagna *et al.* 2018).

In this context, it turns out crucial to assess the energy potential of the different regions and countries as a previous step to the installation of technologies for the use of wave power. In recent decades, researchers from several countries have evaluated the wave power potential of their respective countries or regions (Gonçalves *et al.* 2020; Lo Re *et al.* 2019; Sun *et al.* 2021). For achieving so, they have used the results of the sea states' simulation through third generation wave spectral models, either simulated by themselves (Dong *et al.* 2020; Ribal *et al.* 2020; Yang *et al.* 2019) or obtained from open access databases. In this work, a preliminary assessment of the potentialities of wave power in the seas adjacent to Cuba was carried out in order to envision its future exploitation, using the results of the sea states' simulation every three hours, with the WAVEWATCH III model, available in the databases of the U.S. National Oceanic and Atmospheric Administration (NOAA).

Materials and methods

Characterization of the study area: Cuba is located in the American Mediterranean, between 19° 49' 36" and 23° 17' 09" north latitude and 74° 07' 52" and 84° 54' 57" west longitude (Figure 1). It limits to the north with the Gulf of Mexico, Saint Nicholas and Old Bahama channels, and with the Florida Straits; to the south, with the western Caribbean Sea and the Columbus Strait; to the west, with the Yucatan Channel and to the east with the Windward Passage

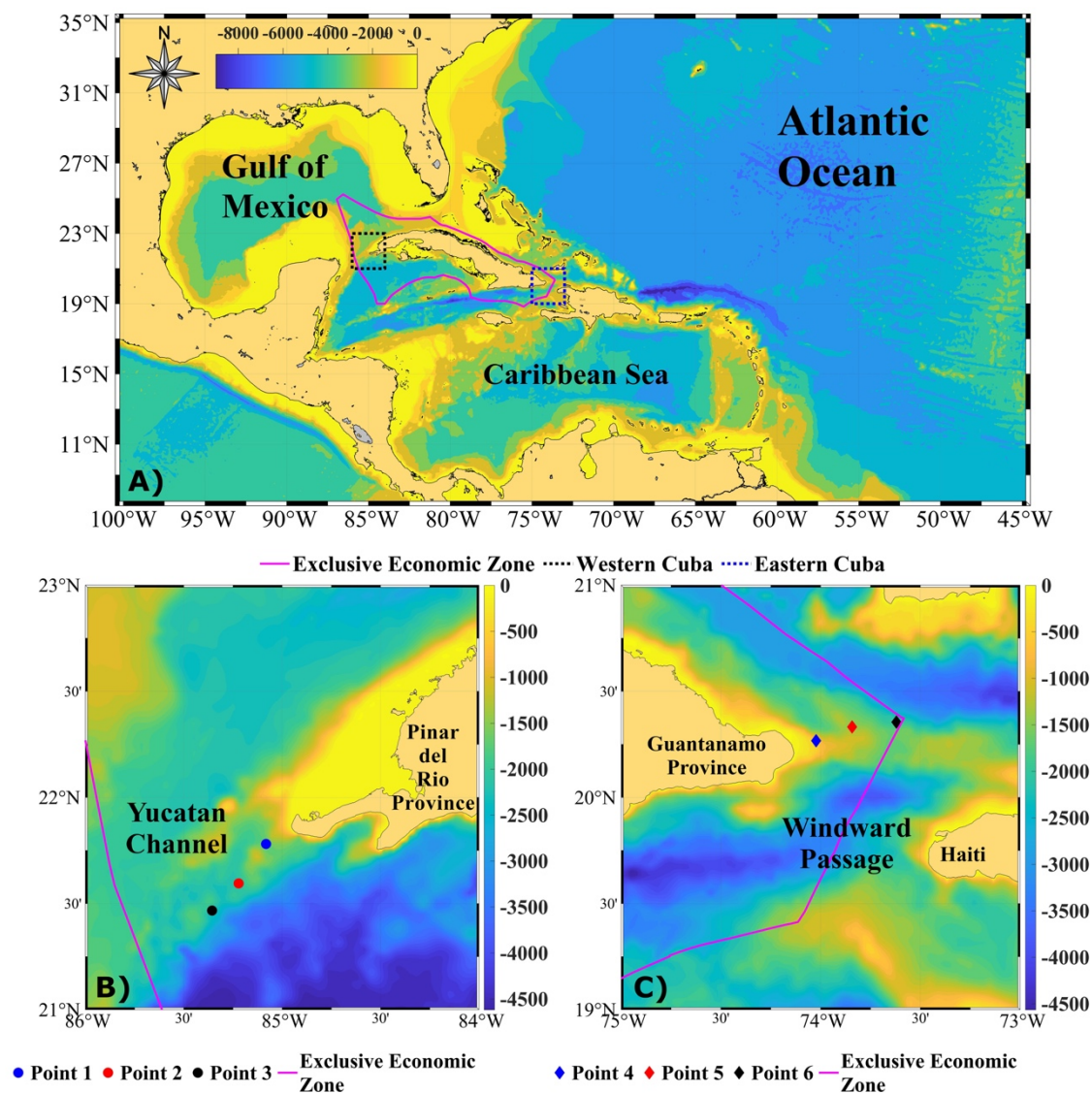


Figure 1. Regional environment of the Republic of Cuba. A) Bathymetric contours of the waters surrounding Cuba and delimitation of its Exclusive Economic Zone (adapted from Casals et al. 2022). B) Western Cuba (western end of Pinar del Río province - Yucatan Channel). C) Eastern Cuba (eastern end of Guantanamo province - Windward passage).

(Planos *et al.* 2013). The main island has a long and narrow configuration, with a length of 1,250 km from Cape San Antonio, in the western end, to Punta Maisi, in the eastern end. The outer border in the coastal zone is defined by the steep decline of the insular slope. In the shallow shelf, four zones are identified: the north-west, the north-east, the south-east and the south-west (Planos *et al.* 2013).

To determine the study area, decree-laws 1/77, 2/77 and 266/09 were analyzed, referring to the delimitation and description of territorial waters and the Exclusive Economic Zone of the seas adjacent to Cuba, enacted in the Official Gazette of the Republic of Cuba (Consejo de Estado, 1977a, 1977b, 2009). As can be seen in Figure 1A, this area is made up of all the marine waters; of both the four main areas of

the Cuban insular platform, and the oceanic waters that surround it and define its Exclusive Economic Zone. The oceanographic and meteorological characteristics of the area under study were obtained from the archives of the Cuban Institute of Meteorology (INSMET).

Analysis of the influence of extreme meteorological phenomena in the study area: For analyzing the events, which could damage the installation of a wave power plant either due to the action of strong winds or coastal floods, the INSMET map files and the reports of the U.S. National Hurricane Center in the 2000-2018 period were reviewed, available at <http://www.nhc.noaa.gov>. Reports of the occurrence of meteorological phenomena such as tropical cyclones; frontal systems; south winds and the joint

action of high migratory pressures with low extra-tropical pressures, mainly due to the presence of the El Niño-Southern Oscillation event, in the 1966-2000 period were studied as well (Hidalgo *et al.* 2017; Mitrani, 2009; Mitrani *et al.* 2016).

Data on sea states in the study area: The estimated values of the characteristic variables of the sea states used in this paper (Hs - significant wave height and Te - energy period) were collected from the NOAA database. These values are generated monthly by running the WAVEWATCH III (WW3) model, using as input data the wind speed and direction fields obtained by the Global Forecast System (GFS) model. It should be noted that these retrospective estimates are available for the Earth's entire surface. The characteristic data of the sea states are split in the temporal dimension into two groups (WW3DG, 2019):

- NWW3/ - First version of WW3 (grib 1 format), simple grid with 27 km of spatial resolution, from July 1999 to 2005.

- multi_1/ - (Production Hindcast Multigrid). Multiple grid WW3 model, from 2006 to 2018, with 18 km of spatial resolution (grib 2 format).

Taking into account the above, a bilinear interpolation was carried out to integrate the two groups of the aforementioned data in a common grid of 18 km of spatial resolution. Such interpolation was implemented using the Climate Data Operator (CDO) tool version 1.9.3, developed by the Max Planck Institute in Germany. In this way, the grid used to make the wave energy potential maps was defined between 18° and 24.5° north latitude, and 72° and 86° west longitude, with a spatial resolution of 18 km in both directions. For the operations and manipulation of the variables, the software Grid Analysis and Display System (GrADS) version 2.2.0 was used.

Calculation of the wave energy power: The calculation of the depth variable used during the estimation of the energy potential for each node of the grid was programmed in Python v3.8. To achieve so, it was necessary to previously prepare the maps of the coastline of the seas surrounding Cuba, with the inclusion of the bathymetry obtained from the GEBCO 2020 Atlas (GEBCO Compilation Group, 2020).

The general wave energy assessment equation (GWEAE) was used to estimate the power of the wave energy at each node of the grid, both in deep and shallow waters (Equations 1 and 2). It was proposed by Liang *et al.* (2017), and validated by Mahmoodi *et al.* (2019).

$$P_w = \frac{\pi \rho g h H_s^2}{16 T_e} \left[\frac{1}{\mu} + \frac{2}{\sinh(2\mu)} \right] \quad (1)$$

where P_w , ρ , g , h , H_s , T_e and μ are the energy flux per meter of wave front, the density of seawater, the acceleration of gravity, the water depth, the significant height of waves, the energy period and the dispersion parameter, respectively. The last parameter was calculated using the equation proposed by Simarro and Orfila (2013).

$$\mu = \frac{\mu_{\square}^2 + \mu_0 \cosh^2(\mu_{\square})}{\mu_{\square} + 0.5 \sinh(2\mu_{\square})} \quad (2)$$

Equation 2, in turn, uses another approximation of the wave number $\mu_{\square}$ estimated by the explicit wave dispersion equation proposed by Beji (2013) and improved by Vatankhah and Aghashariatmadari (2013) (Equations 3,4):

$$\mu_o = \frac{\mu_o + \mu_o^{1.986} e^{-(1.863 + 1.198 \mu_o^{1.366})}}{\sqrt{\tanh(\mu_o)}} \quad (3)$$

$$\mu_o = \frac{4\pi^2 h}{g T_e^2} \quad (4)$$

Treatment of estimated P_w data: From the results of the calculations of the waves' energy potential through equations 1-4, using the data obtained from the outputs of the WW3 model (with a frequency of 3 h), and the bathymetric profile (GEBCO), the matrices corresponding to each period of time were made up. The treatment of the database in grib2 format was carried out in Python 3.8 and the Scipy-1.4.1 library; in addition to the Numpy-1.18.2 library for the numerical and matrix calculation. The P_w values obtained were averaged in monthly, annual, dry and rainy periods to make the maps of this variable from 2000 to 2018, as well as the map of the average wave power for the entire data series. Based on previous studies (Appendini *et al.* 2015; Guillou *et al.* 2020), three study areas were selected to analyze the potential maps: the entire Cuban archipelago, the western region and the eastern region. Honing in on the last two, since they have a higher probability of presenting the highest wave energy potentials of the seas adjacent to Cuba, given their geographical characteristics. The results were visualized using the Python Libraries Basemap-1.2.1 and Matplotlib-3.2.1.

Results and discussion

Influence of extreme meteorological phenomena in the study area: Cuba has a favorable geographical position for the use of marine energy although, it is

not usable on all its coasts due to natural conditions, and the influence of extreme events that could be harmful to the facilities, and even cause their destruction. For example, it is known that the first-ever worldwide Ocean Thermal Energy Conversion facility was located in Cuba, in 1930, but it was in operation for only a few days since the passage of a hurricane destroyed it (Melikoglu, 2018).

Taking into account the aforementioned, a spatial analysis of tropical cyclones that have affected the western and eastern regions of Cuba during the 2000-2018 period was carried out, using United States National Hurricane Center dataset. As shown in Table I, 70 % of these systems influenced the western region, while the remaining 30 % affected the latter. If we analyze only hurricanes, a slightly higher proportion is observed (74 vs. 26 %). On the other hand, of the tropical cyclones that affected the eastern region, only 43 % reached the hurricane category, unlike the western region where 53 %.

These results coincide with those obtained by Parrado *et al.* (2010), in the analysis carried out to prepare the hazard maps for hurricanes and major hurricanes with the corresponding data to the 1851-

2005 period, where it is shown that this type of extreme meteorological phenomena is less frequent in the eastern region of Cuba.

Another natural key factor for facilities built on the coast is the occurrence of coastal flooding. Mitrani (2009) estimated the hazard from upwelling in Cuba's coastal areas due to tropical cyclones, cold fronts and the south winds. Her study determined that the area with the greatest probability of flooding due to cyclonic upwellings is the southern coast from Pinar del Rio to Matanzas provinces (from Estero de los Caimanes to Punta Gorda, which includes the Gulf of Batabano). In general, there is a high to moderate hazard on both the western and central coasts. Meanwhile, the area with a low hazard is located on the northeastern coast from Punta Lucrecia to Punta Maisi, and the southeastern coast from Cabo Cruz to Punta Maisi. The danger of flooding produced by cold fronts affects the northwestern coast from Cape San Antonio to the Hicacos Peninsula, north of Matanzas province; while the south winds affect the southwestern coast from Cape San Antonio to Punta de Cazones in the same province. Finally, Mitrani *et al.* (2016) studied the danger of flooding generated by the combination

Table I. Tropical cyclones that affected the western and eastern region of Cuba during the 2000-2018 period.

Years	East	West	Years	East	West
2000	Gordon (TS)	Debby (TS)	2008	Dolly (TS)	Fay (TS)
	Helene (TD)			Fay (TD)	Hanna (TS)
2001	Michelle (MH)	...		Gustav (MH)	Ike (MH)
2002	Lili (H)	...		Ike (H)	...
	Isidore (H)		2009	Ida (H)	...
2003	Claudette (TS)	...	2010	Paula (H)	Tomas (H)
			2011	Don (TD)	Irene (H)
2004	Bonnie (TD)	Jeanne (TS)		Rina (TS)	
	Charley (MH)		2012	Isaac (TS)	Isaac (TS)
	Ivan (H)				Sandy (H)
2005	Arlene (TS)	Alpha (TD)	2013	Karen (TS)	...
	Dennis (MH)		2014	...	...
	Emily (H)		2015	...	...
	Katrina (H)		2016	Hermine (TD)	Matthew (MH)
	Rita (H)		2017	Irma (H)	Irma (H)
	Wilma (H)			Nate (H)	
2006	Alberto (TD)	Ernesto (TS)	2018	Alberto (TS)	...
2007	Barry (TD)	Noel (TS)		Michael (H)	

Note: TD (tropical depression, winds ≤ 63 km/h), TS (tropical storm, winds between 63-117 km/h), H (hurricane, winds between 117-250 km/h) and MH (major hurricane, winds ≥ 250 km/h).

of high migratory pressures with low extra-tropical pressures, finding a moderate level of danger for the northeastern area of Cuba, between Gibara and Punta Maisi. Taking into account the results analyzed above, the coastal areas least affected by the influence of severe meteorological events in Cuba are the north and south coasts of the eastern region of the island.

Wave energy density analysis in the seas adjacent to Cuba: Once the depth distribution shown in Figure 1A was obtained, corresponding to the study area, the power per meter of wave front was calculated at each node of the established 18 x 18 km grid.

Figure 2 shows the power density in the seas adjacent to Cuba for the entire data series used (2000-2018). On average, the study area-maintained energy flux values below 2 kW/m in the areas of the low platform and very close to the coast, and between 4-6 kW/m in the deeper waters. These results are consistent with those obtained by Appendini *et al.* (2015) for the Caribbean region. It must be noted that, from the point of view of exploiting this energy, some authors point out that the resource must have an energy flow higher than 2 kW/m to be a usable resource (Lin *et al.* 2019). This figure also displays that the areas with the greatest wave energy potential are the extremes of the western and eastern regions of Cuba.

Based on the previous results, six grid points were chosen (yellow points in Figure 2), located in the two areas with the highest wave intensity, but which were as close as possible to the coast, three points in the western region (Figure 1B) and three in

the eastern (Figure 1C). It must be highlighted that the further from the coast the energy harvesting facility is, the higher the costs will be to transfer the captured energy to land.

In each zone, three points were selected to develop a comparison of the spatial distribution of wave energy in the respective areas, always taking account of all the points were within Cuba's Exclusive Economic Zone. In addition, the data at these points allowed a more detailed temporal analysis of the Pw values. Next, Table II shows the selected points with their depths and distances from the coast.

Although the depths at which the points are found exceed those usually used for the installation of wave energy converters (<200 m) (Lin *et al.* 2019), the wave power density results obtained from them allow a preliminary analysis of the potential for exploiting this energy resource in the seas adjacent to Cuba, as a first approach to the subject. It must be underscored that the coordinates used are conditioned by the data available in the NOAA database of characteristics of the sea states, which were used for the calculations.

Wave energy potential analysis in the most prospective area of the western region of Cuba: Figure 3A shows the average annual power density, in the 2000-2018 period, for grid points 1, 2 and 3. As can be seen in points 2 and 3, which are located further from the coast, the values are higher than at point 1, with little difference between them despite the fact that the distance between one and the other

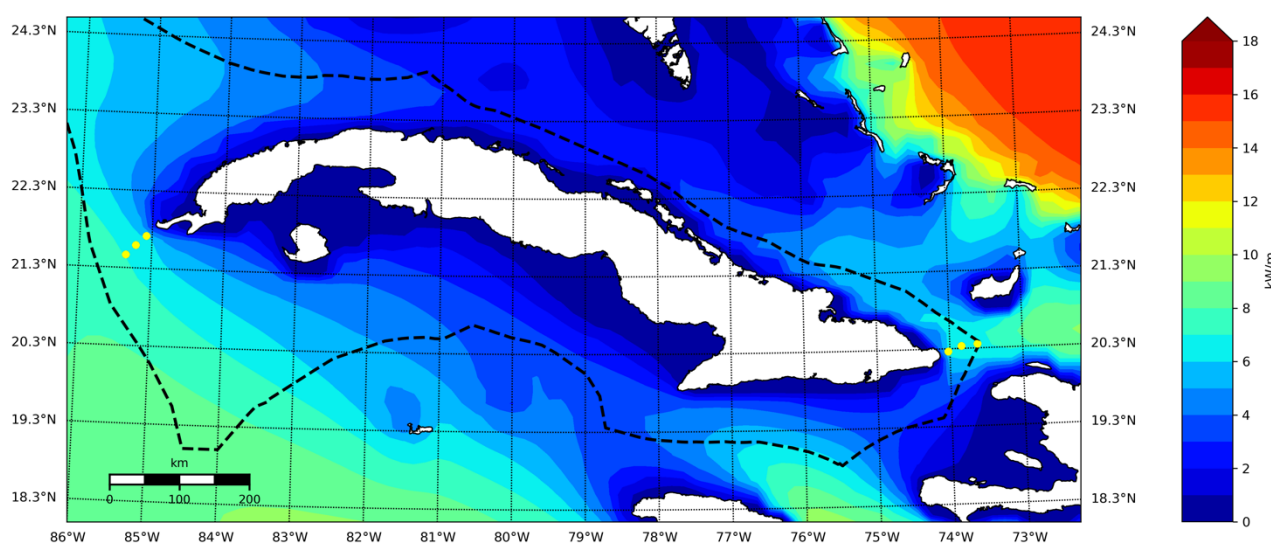
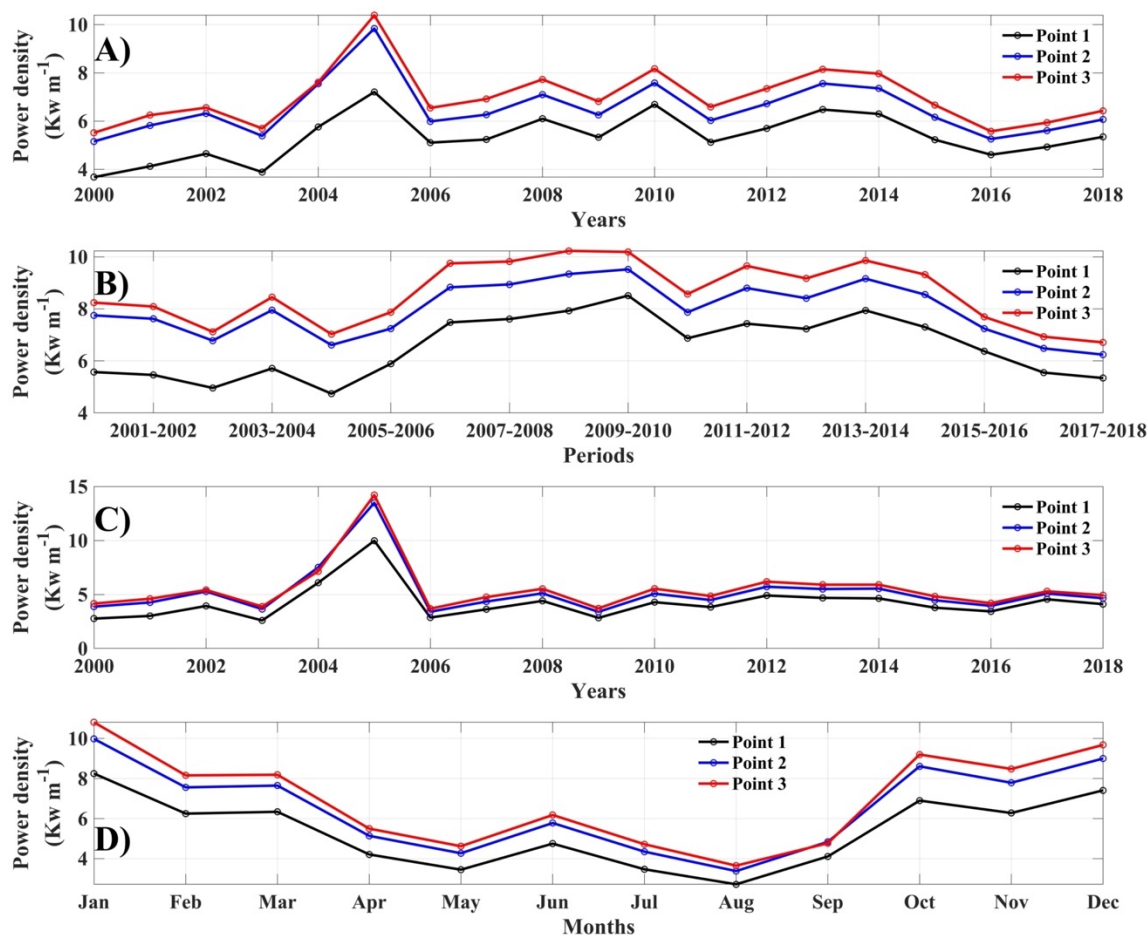


Figure 2. Spatial distribution of wave energy flow in the coasts of Cuba in the period 2000-2018. The points at Cabo de San Antonio (Figure 1B) and at Punta Maisi (Figure 1C) correspond to six nodes located in the areas with the greatest wave potential.

Table II. Grid points selected for wave potential analysis.

	Coordinates	Distance to the coast	Depth	Reference
Point 1	85.082 °W; 21.719 °N	19.9 km	1.4 km	Cape San Antonio
Point 2	85.221 °W; 21.595 °N	39.9 km	1.6 km	Cape San Antonio
Point 3	85.356 °W; 21.467 °N	59.9 km	2.2 km	Cape San Antonio
Point 4	74.023 °W; 20.267 °N	12.7 km	1.1 km	Punta de Maisí
Point 5	73.842 °W; 20.332 °N	32.9 km	1.3 km	Punta de Maisí
Point 6	73.620 °W; 20.355 °N	55.9 km	2.5 km	Punta de Maisí

**Figure 3.** Wave power density (kW/m) at grid points 1, 2 and 3 in the 2000-2018 period (Tables I S, II S, III S and IV S). A) Annual average. B) Average in the dry periods. C) Average in the rainy periods. D) Monthly average.

is approximately 20 km, and that there is a greater difference between the depths at which they are, compared with points 1 and 2, that is relatively little. This could be because of the influence exerted on the waves by the characteristic marine currents of the study area (Pérez-Santos *et al.* 2015).

It is noteworthy to stand out that in 2004 and 2005 a large number of tropical cyclones affected the western part of the island, mostly high intensity hurricanes such as Charley, Ivan, Dennis, Rita and

Wilma; hence, in these years the values in the graph have suffered a dramatic leap.

The mean value of wave energy flux for each of the points studied throughout the period was:

Point #1 (19.9 km) —————> 5.35 kW/m

Point #2 (39.9 km) —————> 6.52 kW/m

Point #3 (59.9 km) —————> 6.99 kW/m

As can be seen, these values show that the wave energy flow in this area has the necessary power density to be used (> 2 kW/m) (Kamranzad &

Hadadpour, 2020). In this study area, the highest annual averages were observed in the years 2004 (Figure 4) and 2005 (Figure 5), with values between 5.76-7.61 kW/m and 7.21-10.39 kW/m, respectively; and the lowest, in 2000 (Figure 6), with values in the interval between 3.68-5.52 kW/m.

To make a more thorough analysis the power density is compared in the dry and rainy periods. It is conveyed that in the dry period (Figure 3B), the highest power densities were observed in the years 2008-2009 (7.93 -10.23 kW/m) and 2009-2010 (8.51-10.19 kW/m), while the lowest ones, in the 2004-2005 period (4.74-7.03 kW/m), with average values for each point in this period of:

Point #1 (19.9 km) —————> 6.55 kW/m
 Point #2 (39.9 km) —————> 7.96 kW/m
 Point #3 (59.9 km) —————> 8.59 kW/m

However, in the rainy season (Figure 3C), the highest power densities occurred in 2005 and the lowest in 2003, with values of 9.98-14.21 kW/m and 2.60-3.89 kW/m, respectively. It must be noted that the 2005 hurricane season was the most active of all the years analyzed, which justifies the maximum observed in the graph. On the contrary, the seasons 2014 (4.64-6.04 kW/m) and 2015 (3.78-4.83 kW/m) were totally inactive, which illustrates the influence

on power density that these meteorological phenomena can cause. The mean power density values at each of the points for this period were:

Point #1 (19.9 km) —————> 4.23 kW/m
 Point #2 (39.9 km) —————> 5.20 kW/m
 Point #3 (59.9 km) —————> 5.52 kW/m

From the above data, it can be concluded that the energy flow is in the dry season higher than in the rainy season, which is in correspondence with the determinations made by Guillou *et al.* (2020). The months of the years analyzed with the highest wave power density were January (8.25-10.81 kW/m) and December (7.41-9.68 kW/m); and the one with the lowest August (2.72-3.65 kW/m). The graph shown in Figure 3D corroborates what has been stated. Furthermore, if the monthly average values are observed for each of the points studied in the western region of Cuba, it can be seen that the months with the greatest wave potential are those corresponding to the winter season.

Analysis of wave energy potential in the most prospective area of the eastern region of Cuba: There must be highlighted that for this analysis was taken into account that the boundaries of Cuba's Exclusive Economic Zone are closer to the coast than in the western region; so, the study points are

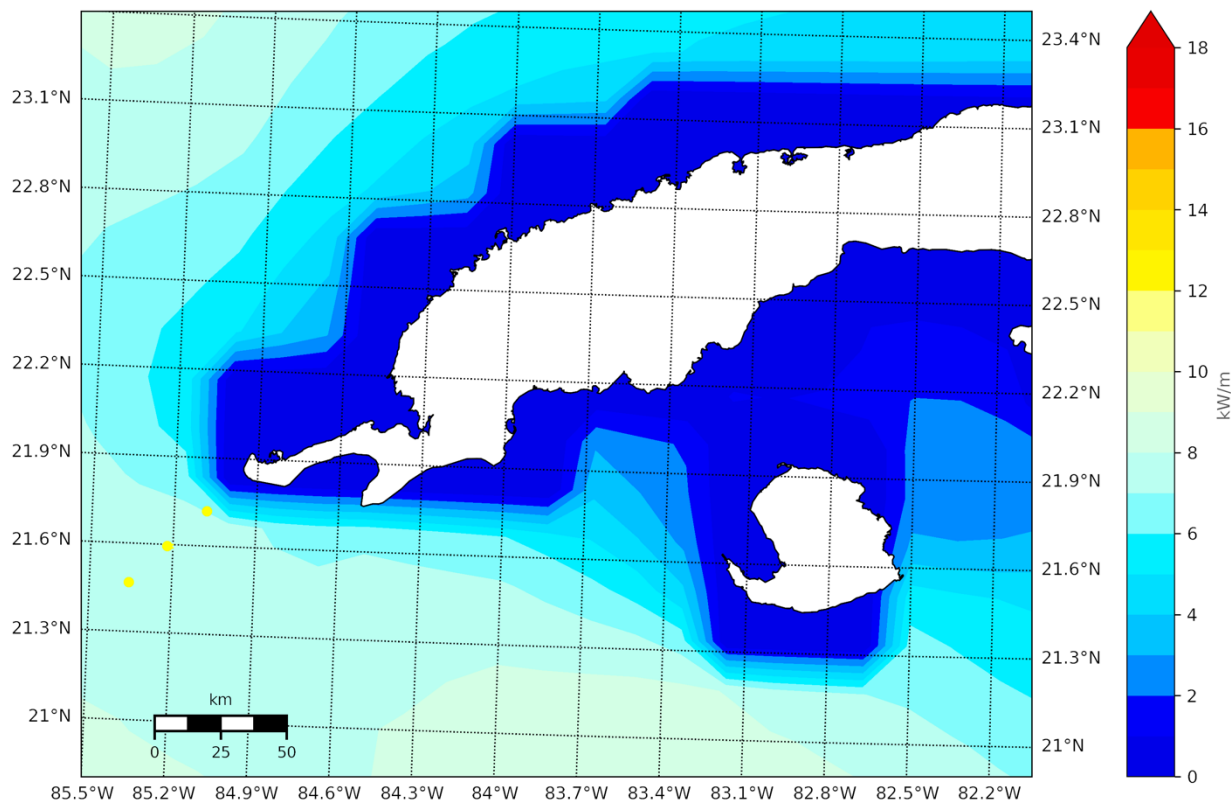


Figure 4. Spatial distribution of wave power density (kW/m) on the western coast of Cuba in 2004.

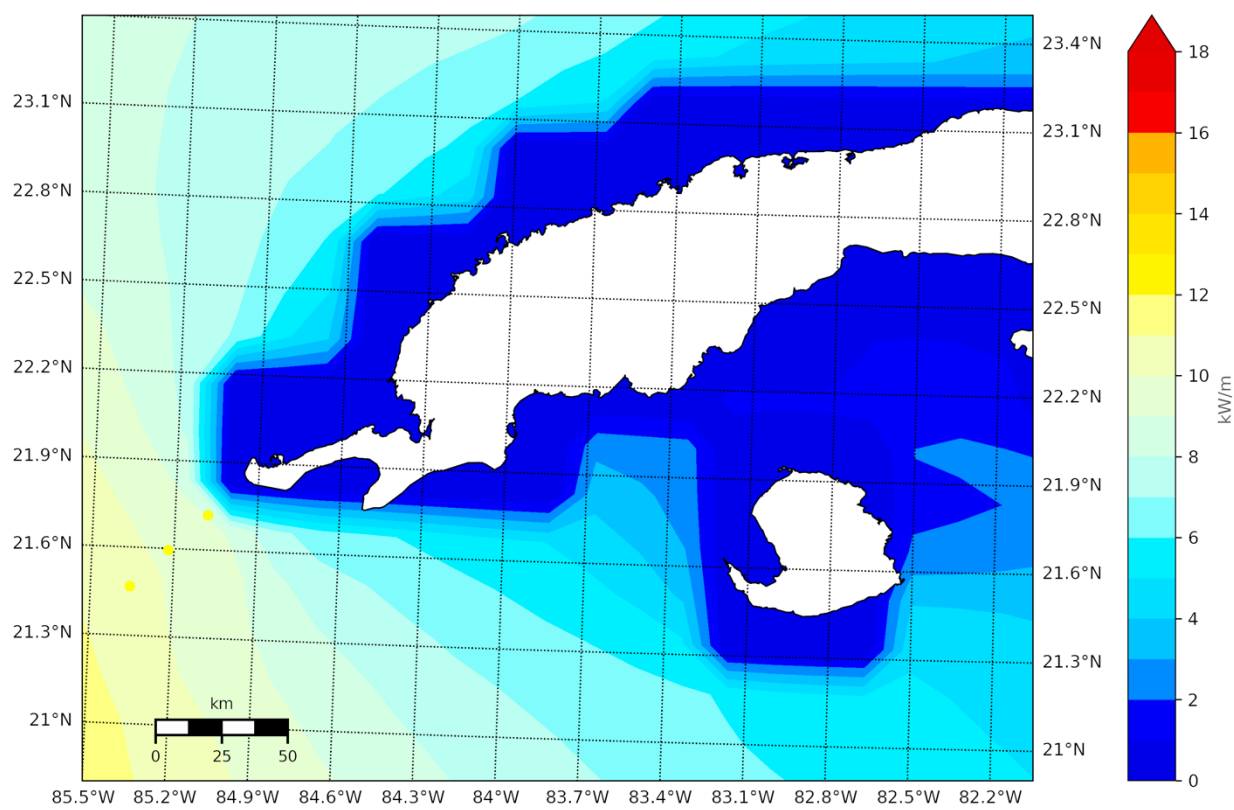


Figure 5. Spatial distribution of wave power density (kW/m) on the western coast of Cuba in 2005.

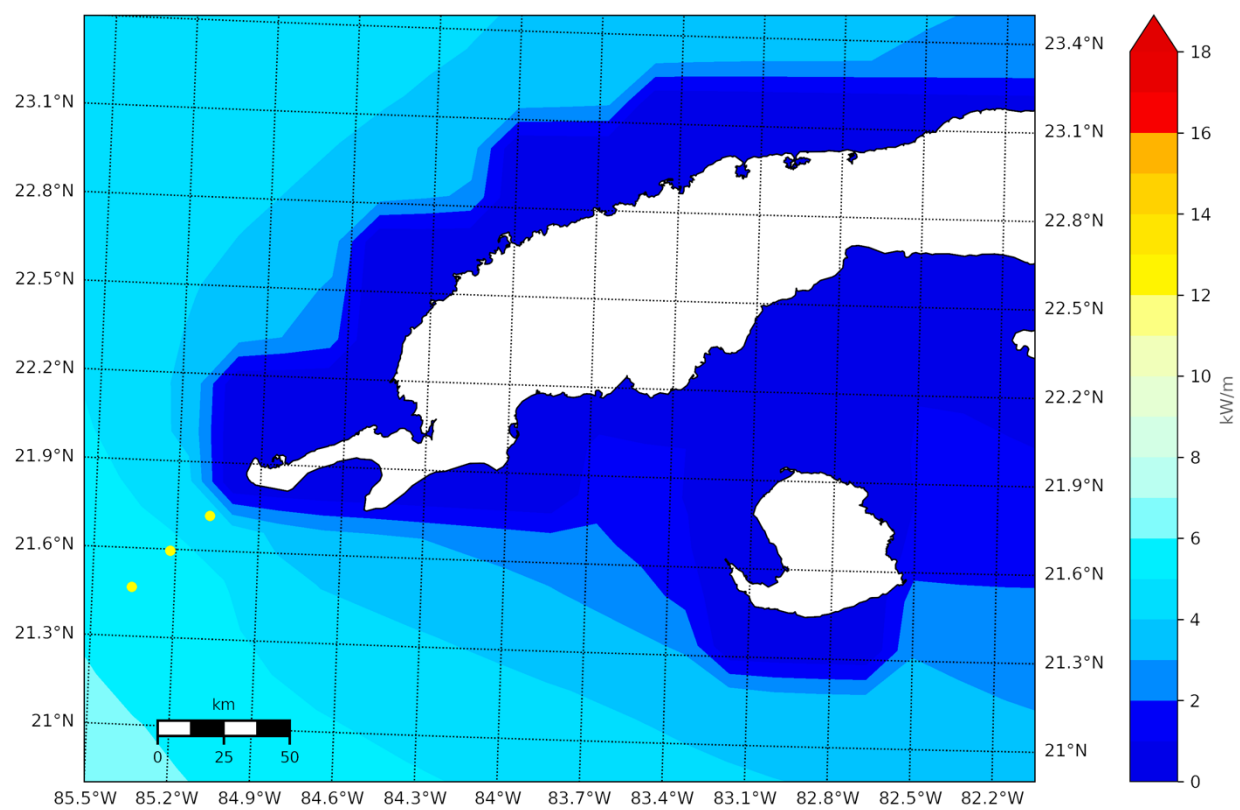


Figure 6. Spatial distribution of power density (kW/m) on the western coast of Cuba in 2000.

also located closer to the coast. In this region, the spatial distribution of wave energy shows the maximum values towards the easternmost end of the northeastern coast. Figure 7A displays the annual average wave energy flow, in the 2000-2018 period, for grid points 4, 5 and 6.

The mean wave power density for each of the points in the period studied were:

Point #4 (12.7 km) —→ 4.95 kW/m

Point #5 (32.9 km) —→ 6.46 kW/m

Point #6 (55.9 km) —→ 6.78 kW/m

As was observed in the western region, at points 5 and 6 the wave power density values are greater than at point 4, and with little difference between them, despite the difference between the depths at which points 5 and 6 are located is much higher than the difference between points 4 and 5. In this case, there must be taken into account that in such area there is also a current, which can influence

the wave structure at the entrance of the Windward Passage (Mitrani & Cabrales, 2020). It is worth noting that a rise in wave energy flow is observed in the last eight years of the period studied (2011-2018), since its average ranges between 6.1-7.5 kW/m for the three points studied.

The years with the highest wave power density values were 2018 (7.20-7.53 kW/m) (Figure 8) and 2013 (6.25-8.32 kW/m); and the lowest, 2003 (Figure 9), with values between 3.12-5.51 kW/m. It is valid to point out that in these years there was no impact by tropical cyclones.

In the dry season (Figure 7B), the highest wave energy flows occurred in the 2011-2012 and 2013-2014 periods, with values between 8.17-10.2 kW/m and 8.38-11.13 kW/m, and the lowest in 2002-2003 (3.08-5.3 kW/m). On the other hand, the mean wave power density values at each of the points were:

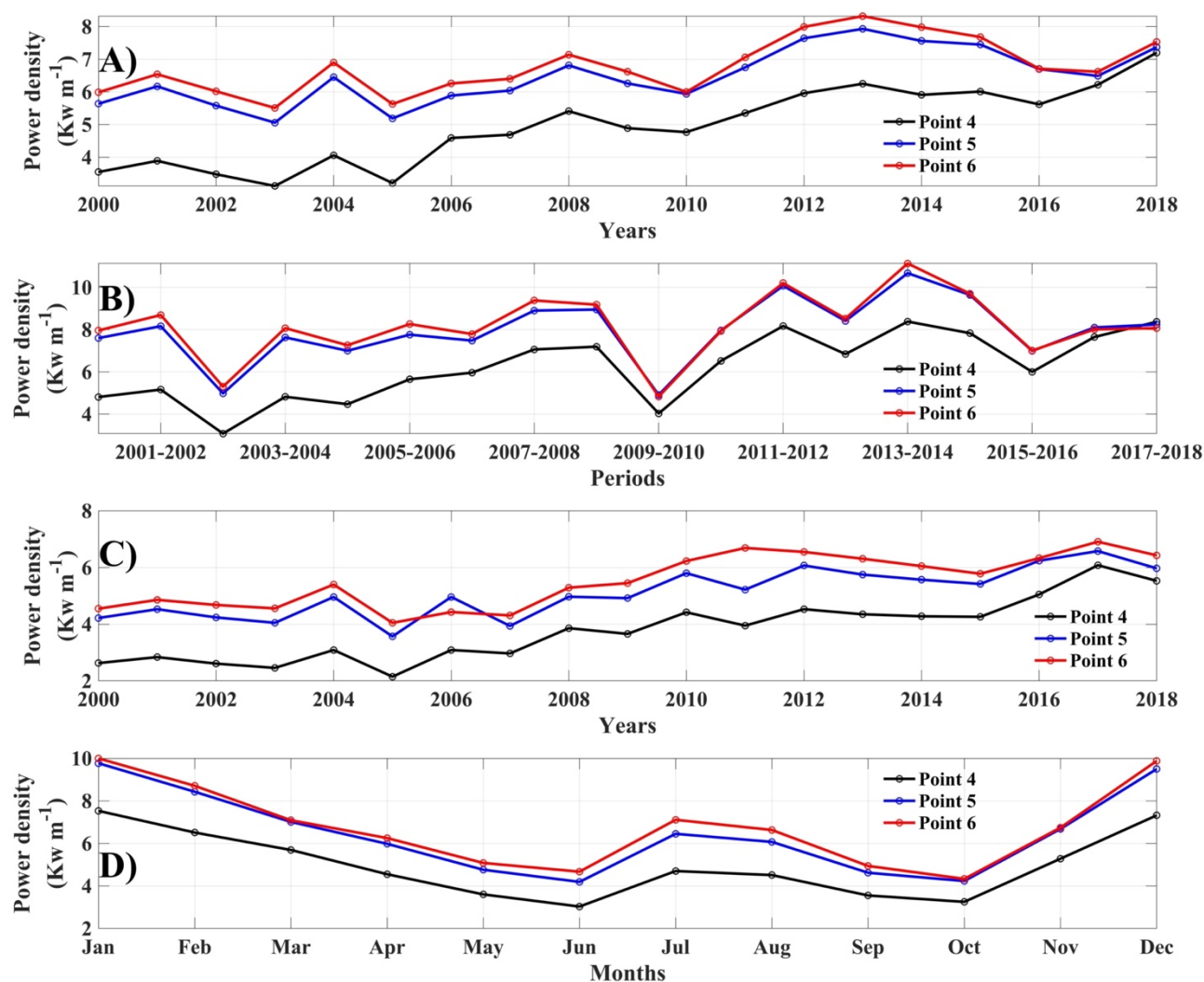


Figure 7. Wave power density (kW/m) at grid points 4, 5 and 6 in the 2000-2018 period (Tables I S, II S, III S and IV S). A) Annual average. B) Average in the dry periods. C) Average in the rainy periods. D) Monthly average.

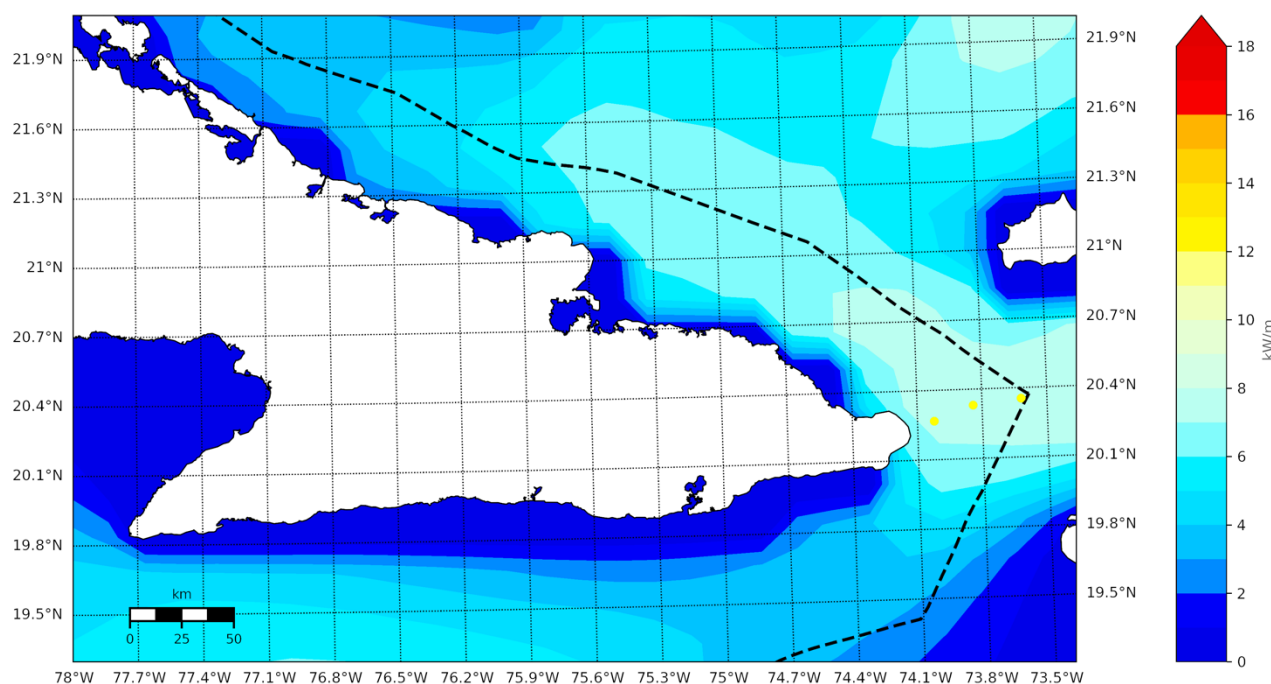


Figure 8. Spatial distribution of wave power density (kW/m) on the eastern coast of Cuba in 2018.

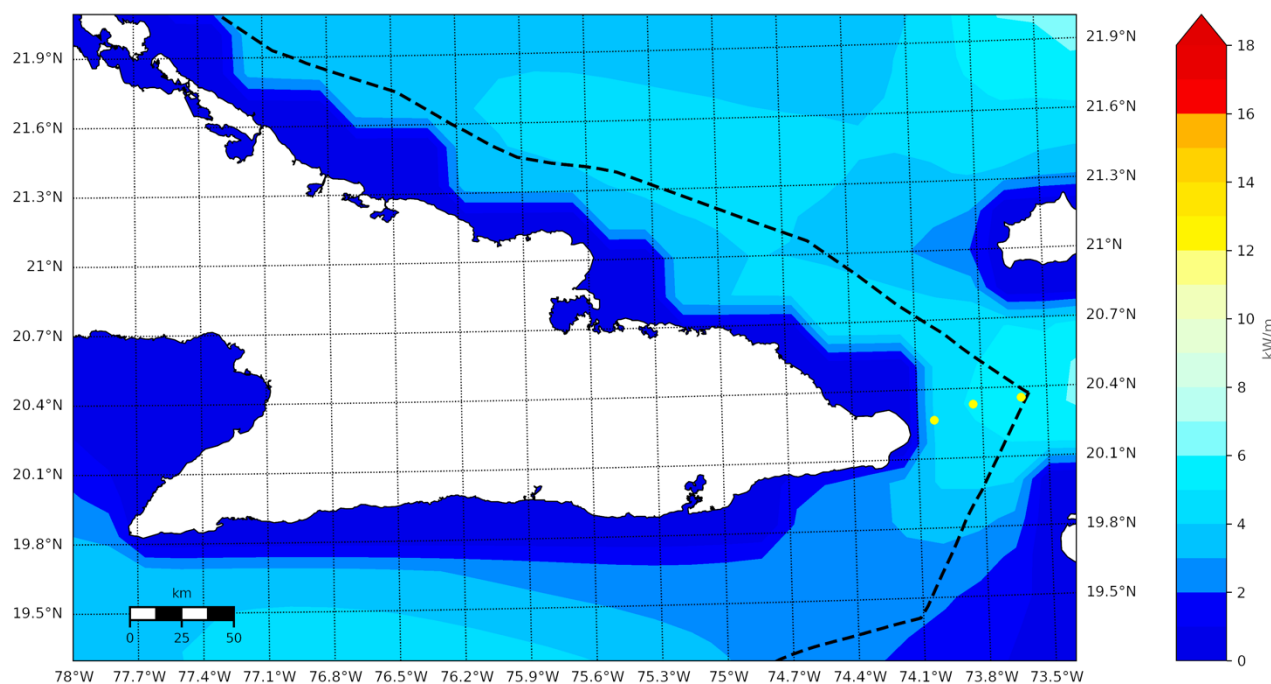


Figure 9. Spatial distribution of wave power density (kW/m) on the eastern coast of Cuba in 2003.

Point #4 (12.7 km) —————> 6.22 kW/m
 Point #5 (32.9 km) —————> 7.97 kW/m
 Point #6 (55.9 km) —————> 8.18 kW/m

In addition, it is outstanding the notable increase in the average for the last 8 years (7.5-8.8 kW/m).

In rainy periods (Figure 7C), the highest wave energy flux values were observed in 2017 (6.08-6.91 kW/m) and the lowest in 2005 (2.15-4.05 kW/m). The year 2017, despite not having a significantly active hurricane season for the eastern region, did have the influence of Hurricane Irma in this region. Therefore, the authors consider more appropriate to

take the year 2018 as a reference, since it was not affected by organisms of this type, the one with the highest average wave power density (5.53-6.43 kW/m). The mean values of wave energy flow for the rainy period, in each of the points were:

Point #4 (12.7 km) —————> 3.77 kW/m
 Point #5 (32.9 km) —————> 5.05 kW/m
 Point #6 (55.9 km) —————> 5.46 kW/m

It is also remarkable that in the last 8 years, a significant growth is observed in this last value (5.0-6.3 kW/m).

Regarding the months with the highest wave potential, it could be concluded that they were January (7.53-10.0 kW/m) and December (7.32-9.88 kW/m); and the one with the lowest value, June (3.03-4.67 kW/m) (Figure 7D).

From the previous results, it can be determined that the same behavior is maintained in terms of the available wave potential between the rainy period and the dry period as in the western region.

Conclusions

In this work, a preliminary assessment of the wave potential in the waters adjacent to Cuba was carried out using the data of the sea states available on the NOAA database. The outcomes show that:

1. In general, wave energy resource availability is limited in the seas adjacent to Cuba with usable wave power densities in the western and eastern extremes of the island.

2. The western region, with the 70 % of cases, is more affected by the cyclonic systems than the eastern region, having a high hazard of flooding coastal areas due to tropical cyclones. Meanwhile, the area with a low hazard is located on the northeastern coast from Punta Lucrecia to Punta Maisi, and the southeastern coast from Cabo Cruz to Punta Maisi.

3. The eastern region-maintained energy flux values between 4-6 kW/m in the deeper waters more than 12 km of distance to the coast, whereas that the western region maintained these values about 20 km of distance.

Recommendations: There were some limitations present in the research due to the restrictions imposed by the resolution of the available grid of 18 x 18 km, which prevented the evaluation of the resource in waters with depths less than 200 m. For this reason:

1. More accurate studies are required, where the sea states to be modeled with a higher resolution grid near the coast of the most promising zones for

exploiting the resource. In that way, wave energy flows are able to be calculated at depths below 200 m, which is the depth where this resource is currently being exploited.

2. It is needed to assess other criteria, such as the resource availability's frequency, and the monthly variability index of the wave power density. So that, a multi-criteria analysis allows to define, with a lower level of uncertainty, if the areas with a usable wave identified potential really meet the conditions that make its use technically possible.

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