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APPMAR 1.0: A Python application for downloading and analyzing of WAVEWATCH III® wave and wind data

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ABSTRACT

This work presents APPMAR 1.0, an application written in the Python programming language that downloads, processes, and analyzes wind and wave data. This application is composed of a graphical user interface (GUI) that contains two main modules: the first module downloads data from WAVEWATCH III® (WW3) production hindcasts by the National Oceanic and Atmospheric Administration (NOAA); the second module applies statistical mathematics for processing and analyzing wave and wind data. This application provides useful graphical results that describe mean and extreme wave and wind climate. APPMAR generates plots of exceedance probability, joint probability distribution, wave direction, Weibull distribution, and storm frequency analysis. Currently, APPMAR only downloads and analyzes wave and wind data from WW3 hindcasts, but it is under development to other datasets and marine climate parameters. This application has been tested in the Magdalena River mouth, Colombia, and Cancún, México, where observational wave and wind data are scarce.

1. Introduction

Coastal engineering projects, geosciences and oceanographic studies often require access to marine climate data in ocean and coastal zones. The fundamental characteristics of the sea states like waves and winds are necessary parameters for the application of numerical wave models. However, there are important constraints for the gathering of these physical parameters in geographical regions such as the Pacific and Caribbean coasts of Latin American countries.

In Colombia, according to Maza Chamorro et al. (2018), wave and wind information has been mainly used for the development of coastal projects which rely on wave propagation models that solve physical processes from deep to shallow water in their decision-making activities. However, the lack of observational wind and wave parameters resolution can cause statistical bias, especially in the long term. Limitations are described by the absence of detailed time and spatial resolution. In Mexico, wave and wind records are only available from local, short-term studies, and the absence of systematic country-wide measurements leads engineers and researchers to rely on marine climate reanalysis and hindcasts (Felix et al., 2018).

In regions with limited data availability, scientists and engineers must analyze datasets from wind and wave model results. Representative sea states drawn from these datasets work as forcing and/or boundary conditions for numerical wave models such as Wave Modelling (WAM), Simulating Waves Nearshore (SWAN), and WAVEWATCH III® (WW3).

Reguero et al. (2013) developed an investigation regarding the analysis of marine climate variability under limited data scenarios. In the research, they used a calibrated and validated global wave reanalysis by Reguero et al. (2012) and performed an analysis of Latin America and

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the Caribbean Sea conditions. The estimations show that wave climate is quite different in both hemispheres, and the southern side of the continent exhibits huge energy potential compared to the northern latitudes.

The requirement of observational wind and wave datasets for countries in the Caribbean Sea basin is evidenced in several studies on wave propagation and wave energy potential under mean and extreme regimes conducted in this region (Appendini et al., 2014; Devis-Morales et al., 2017; Maza Chamorro et al., 2018; Mesa, 2009; Montoya et al., 2018; Ortiz, 2009, 2012; Ortiz et al., 2012, 2015; Ortiz-Royero et al., 2013; Osorio et al., 2016; Torres and Andrade, 2006). Most developed countries have high-quality marine climate monitoring systems where information is easily available. The possibility of open-access data promotes the upgrading of procedures in oceanography, coastal and oceanic engineering, and other fields regarding marine and coastal environments.

In several places around the world, from deep waters to the littoral zone, marine and coastal projects require detailed information regarding wave fields. However, the availability of wind and wave information is incomplete or scarce. It is possible to reproduce sea states from meteo-marine observations through the use of numerical models (Appendini et al., 2014; Ruiz et al., 2009). Yet, this task requires calibration of the models and extensive computing resources. This work aims to manage this information, taking in consideration that for coastal management and engineering, there is a lack of accessible and high-quality marine information.

In the past decades, many user-friendly computer programs and toolboxes have been developed for the processing and analysis of large amounts of data regarding ocean climate, saving engineers and scientists the time-consuming task of coding.

The implementation of numerical models allows to study the marine and littoral dynamics at coastal zones. The analysis of marine climate is very important considering that it offers a detailed knowledge of the characteristics of waves, sea level and circulation from deep to shallow waters, helping in the understanding of the hydrodynamics of the zone of interest. Without this knowledge is not possible to determine the causes of coastal erosion and its possible solutions.

However, the marine climate information in deep waters does not represent adequately the nearshore waves. The wave fronts suffer transformations in energy in their trip towards the shore. And again, the numerical models are the way through which the branches of geoscience and engineering can represent the conditions of interaction of waves with sediment in the beaches.

Once the wave propagation is calculated, it is possible to obtain the mean and extreme regimes in the study area and the statistical characterization of the main wave and wind parameters. This information is relevant for the development and infrastructure projects in the coastal zone.

The wave and wind information are of vital importance for the characterization of geomorphological processes in the short and long term. The long-term analysis is the mechanism that allows to infer the final shape (plane view-profile) of the beach and the temporal evolution of its morphological features in the annual scale, guaranteeing that the functionality of the beach endures along its full life cycle. This analysis requires the detailed knowledge of the hydrodynamic information and sedimentology of the beaches of interest. This implies information about waves and currents, result of numerical modelling under stationary and non-stationary scenarios and sediment data.

From a morphodynamical perspective, with the information of wave time series on the depth of closure and the sediment characteristics, it is possible to evaluate the equilibrium profile in a study area. It is also possible to apply parametric models with wave information, e.g.: Parabolic beach profile (Dean, 1977), or the one proposed by Bernabeu et al. (2002). These techniques make possible to establish if a coastal sector is in equilibrium state and are also very useful for the development of alternatives for beach stabilization.

Bearing this in mind, Capitão and Burrows (1995) developed LTS (Long Term Statistics). LTS is a software package that predicts extreme waves, implements routines for different mathematical descriptions of significant wave height, and extrapolates values based on bivariate probability. LTS requires the user to input field measurements and define the treatment of missing data. However, a program of these specifications might pose a challenge in regions with field measurements limitations.

Another well-known tool is WAFO (Wave Analysis for Fatigue and Oceanography) (Brodtkorb et al., 2000). This software is based on a set of routines for statistical analysis and simulation of waves and loads written in MATLAB®. Users can change the underlying code of these algorithms or mix them with their own code to make relevant calculations for specific coastal engineering purposes. The WAFO algorithms are based on spectral wave description, the Airy Wave Theory, and Gaussian Distribution.

The lack or limited access to information related to marine climate makes it essential to develop open-source tools such as rNOMADS (Bowman and Lees, 2015). This tool gives access to different result datasets from oceanic and atmospheric models. rNOMADS allows users to download marine climate data directly from the National Oceanic and Atmospheric Administration Operational Model Archive and Distribution System (NOMADS) servers in the R programming language. Once downloaded, the information can be analyzed and processed with R code or external tools.

Other tools such as WaveAR and OCEANLYZ —both programmed in MATLAB— are available on the internet. WaveAR estimates wave parameters in a point based on information gotten from neighbour measurement locations to solve the second-order Stokes wave equation and the second-order harmonic waves theory (Landry et al., 2012). OCEANLYZ is a set of functions that estimate wave properties through spectral analysis of time series measured in bodies of water or experiments conducted in laboratories, especially for shallow and intermediate water depths (Karimpour and Chen, 2017).

Recently, a set of Python modules for climate characterization of atmospheric, marine and river forcing has been developed as part of the "Protection of Coastal Urban Fronts against Global Warming" (PROTOCOL) project (https://gdfa.ugr.es/protocol/). PROTOCOL offers three modules for reading, preprocessing, and homogenization of climate data from different sources such as European datasets (e.g. Copernicus) and numerical models results (e.g. WW3), besides three other modules used for the analysis of average and extreme wave climate and generation of result reports in different formats (Magaña et al., 2020).

Now, research literature describes multiple tools to process information regarding the main wave parameters or to access and download information found on international datasets. Yet, a computer program that allows access to data download and analyzes this data from a user-friendly interface (GUI) has not been developed yet.

This work presents an open-source program called APPMAR 1.0. This program, through a GUI, allows the user to download wave and wind datasets from WW3 production hindcasts and perform analysis and visualization of wave and wind climate data for studies on oceanography, coastal and oceanic engineering, and other fields regarding marine and coastal environments. The program integrates and automates the downloading, extraction, processing, and analysis of data for wave and wind climate characterization, and the determination of forcing and boundary conditions for numerical models. These tasks are time-consuming, particularly for people at early academic stages of coastal engineering and oceanography. The application determines mean and extreme conditions of wave and wind, showing results in various statistical plots and directional diagrams (wave roses). APPMAR can be applied in many regions around the world, and it is especially useful in regions of limited data availability where wind and wave variables are not monitored or are not freely available, establishing representative sea states in the study area.

This article is divided into four major sections. Section 1 is an introduction to the subject and a background review on applications and programming toolboxes for marine data downloading and analysis. Section 2 introduces and describes APPMAR. In Section 3, two case studies are proposed to test the capabilities of APPMAR. Finally, Section 4 gives last remarks on the convenience of APPMAR for wave and wind data access and analysis in regions with scarce wave and wind data availability.

2. Design and implementation

APPMAR 1.0 was developed using the Python 3.7 programming language and was tested in Microsoft Windows. Following the structure presented in Fig. 1, the application comprises two main modules. APPMAR includes a user-friendly graphical interface created using the wxWidgets GUI toolkit for Python (wxPython). Its main window displays two buttons, one for the download module and the other one for the analysis module (Fig. 2 (c)).

2.1. Download module

The download module downloads wave or wind data using functions from the Python standard library. Once the type of data is set, the user inputs additional information such as grid ID, the data time span to be downloaded, and the season (users can download whole years if desired), as shown in Fig. 3 (a) and (b) respectively. These inputs are used to determine the hindcast files to download from the NOAA FTP server.

The NOAA's production hindcast provides spectral parameters stored in GRIB (General Regularly-distributed Information in Binary) format, and it is split into two groups: NWW3 and Multigrid. The NWW3 hindcast was computed with an early single-grid WW3 model from July 1999 to November 2007. The Multigrid hindcast uses the current multigrid WW3 model and comprises data computed from February 2005 to May 2019. Since the two groups use different IDs for the same grids, the download module requires the input of the corresponding two IDs for the study area separated by a comma as shown in Fig. 3 (b). Table 1 shows the grid IDs that users can input in APPMAR.

APPMAR downloads data from both NWW3 and Multigrid groups, prioritizing Multigrid files in case the data is available in both groups. The top priority is set by first downloading all the required data available from Multigrid and the rest from NWW3. The download routine deals with the directory structure, group priority, and different naming conventions in the FTP server, and places all the downloaded GRIB files in a local subdirectory. In addition, the download routine checks for downloaded files and only overwrites them in case of size incompatibility with the files in the FTP server. The downloading process can be resumed in case of connectivity issues, minimizing potential errors caused by corrupted or partially downloaded files. For example, the Northwest Atlantic dataset from 1999 to 2019 requires about 12 GB of available space, and it would take about 3 h to download over a stable 10 Mb/s LAN connection. However, download times are dependent on geographic location and bandwidth stability on both client and NOAA's server.

2.2. Analysis module

The analysis button displayed on APPMAR window provides two categories of analysis: mean climate and extreme climate of wave and wind parameters. Each type of analysis is shown in different windows (Fig. 4), and its routines require additional inputs such as season and coordinates. APPMAR makes use of the Xarray library with the CFGRIB engine to read GRIB files and extract point time series from them. The first time an analysis is performed in a set of coordinates, APPMAR extracts the time series and store them on a cache file to speed up subsequent analyses. Then, the first analysis takes about 25 min, and the following analyses are performed in few seconds. During runtime, time series are stored on Pandas dataframes for efficient temporal filtering and indexing, yet they are converted to NumPy arrays for further mathematical and statistical manipulation using NumPy and SciPy routines.

Mean climate analysis in APPMAR comprises exceedance probability plots of significant wave height and peak period, a joint probability plot of significant wave height and average direction, and a wave rose diagram of significant wave height. Besides, the extreme climate analysis comprises a Weibull probability plot, regional quantile maps of significant wave height and wind velocity, and storm occurrence analyses.

All analyses except for the regional quantile maps are performed from a single point in the study area. These single-point analyses take data from the cell to which the coordinates belong. Thus, to get values of the study area, APPMAR requires a routine to iterate over all the GRIBs of the specified climate variable (wave and wind) and extract the time series for the selected cell in each one of them. After that, the time series from different GRIBs of a variable are merged and then filtered for

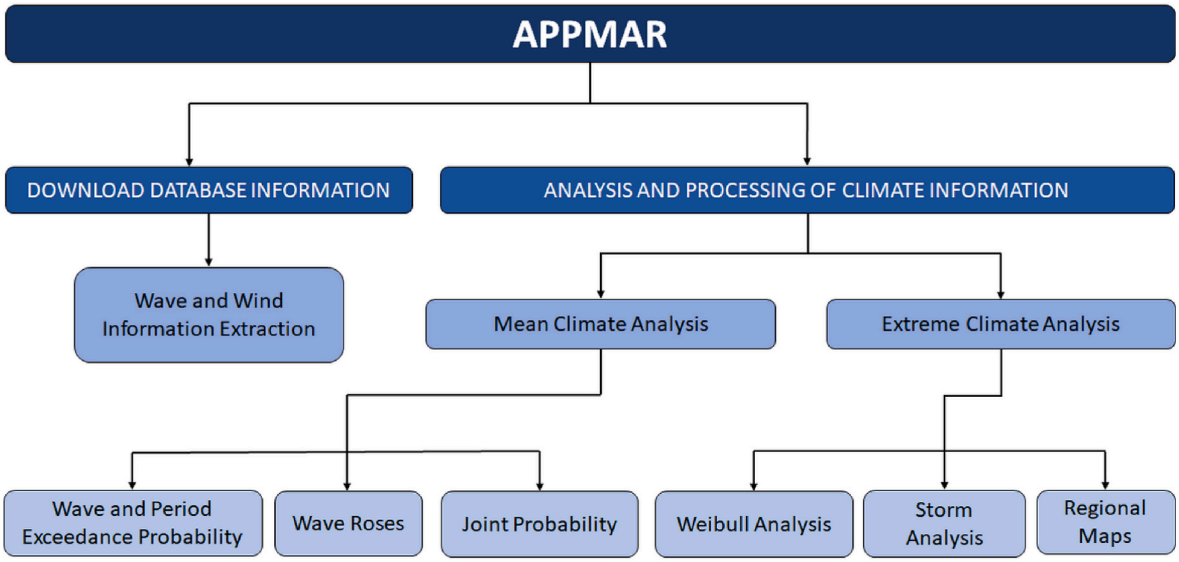
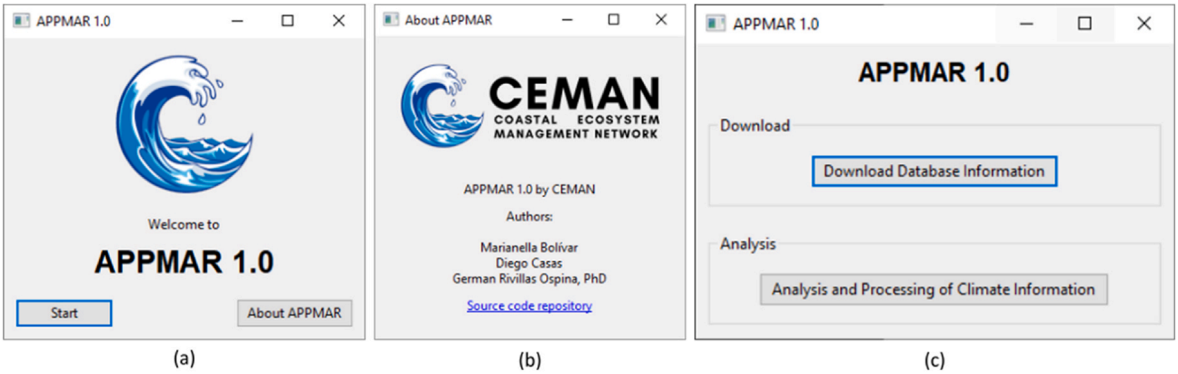


Fig. 1. APPMAR's structure.



APPMAR 1.0 by CEMAN
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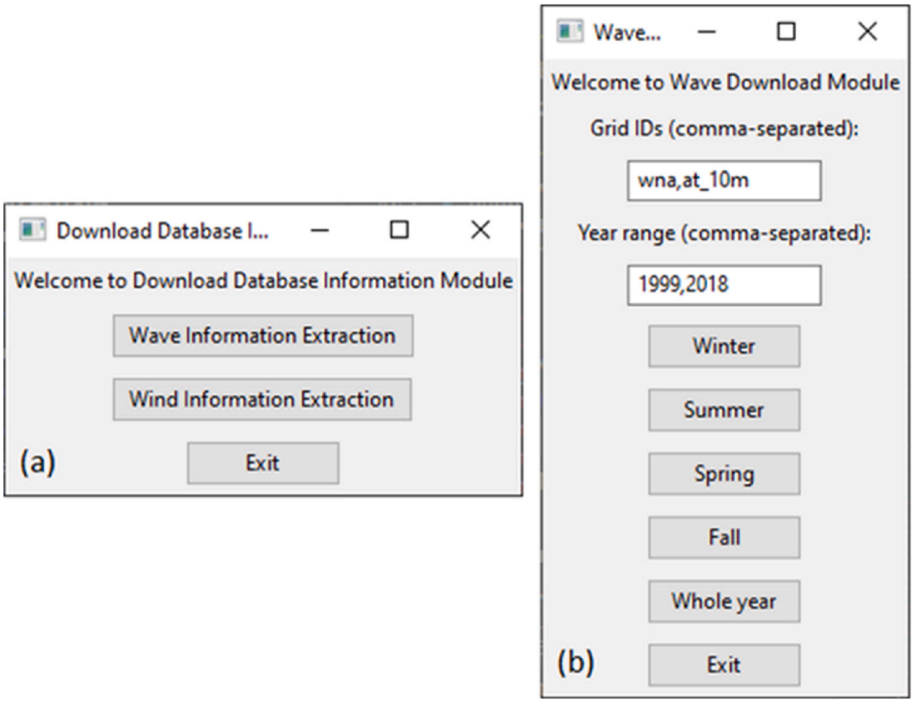
Source code repository

Fig. 2. APPMAR welcome window (a); "About APPMAR" window (b); and APPMAR main window (c).



Grid IDs (comma-separated): wna,at_10m
Year range (comma-separated): 1999,2018

Fig. 3. Windows for the selection of dataset (a) and input parameters (b).

Table 1
Grid IDs to use in APPMAR.

Name	Grid ID	
	NWW3	Multigrid[a]
Global	nww3	glo_30m
Northwest Atlantic	wna	at_10m
Alaska	akw	ak_10m

[a] Detailed model description at https://polar.ncep.noaa.gov/waves/hindcasts/prod-multi_1.php.

missing data. Finally, the data is used to generate the required plots and diagrams.

Some APPMAR results only require passing data to the Matplotlib plotting library (Hunter, 2007), but other analyses involve some calculations such as the exceedance probability plot and joint probability plot for mean climate, and the Weibull probability plot, regional quantile maps, and storm occurrence analyses for extreme climate.

In the mean climate sub-module, the exceedance probability of significant wave height and peak period is calculated using rank statistics and plotted with a logarithmic scale on the vertical axis. Also, the joint probability plot is generated from a bivariate kernel density estimation using Gaussian kernels, as implemented in the Scipy library, for the datasets of significant wave height and average direction.

For the extreme value analysis, the 3-parameter Weibull maximum distribution is fitted to maximum values of significant wave height. The Weibull cumulative distribution function is

$$F(x,\lambda,\beta,\delta) = \exp\left[-\left(\frac{\lambda - x}{\delta}\right)^{\beta}\right], \tag{1}$$

where λ, β and δ are the location, shape and scale parameters, respectively; and $\lambda \geq x$.

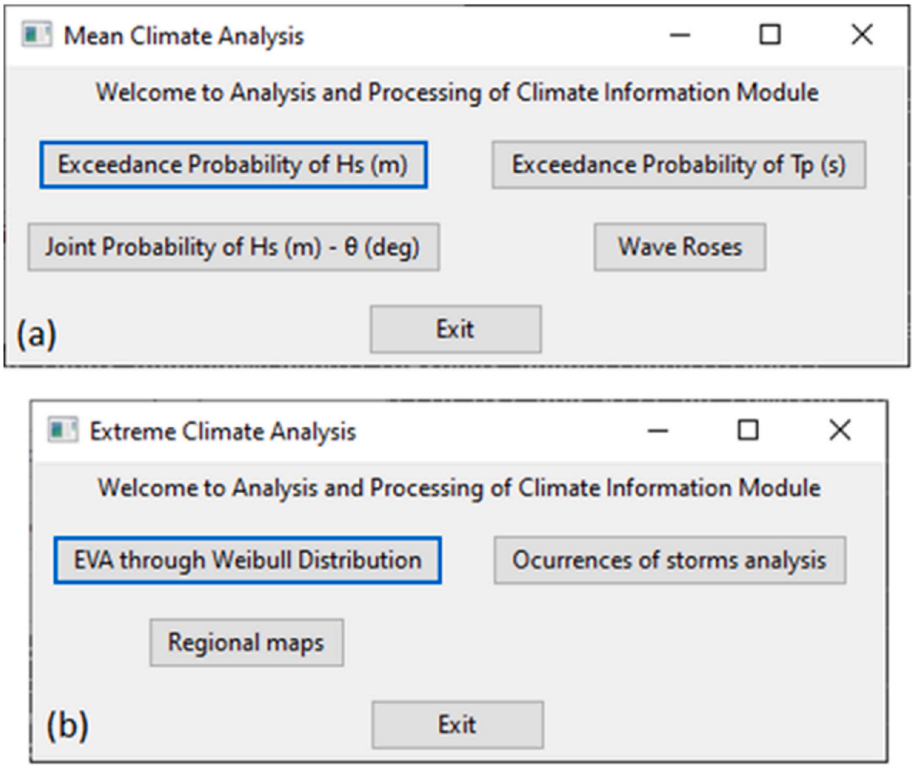
Given $y = F(x,\lambda,\beta,\delta)$, defining the transformations

$$\xi = g(x) = -\log(\lambda - x) \tag{2}$$

and

$$\eta = h(y) = -\log(-\log(y)) \tag{3}$$

results in a linearized form of Eq. (1):



Welcome to Analysis and Processing of Climate Information Module

Welcome to Analysis and Processing of Climate Information Module

Fig. 4. Windows for mean climate analysis (a) and extreme climate analysis (b) for wave and wind parameters.

$$\eta = a\xi + b \tag{4}$$

where $a = \beta$ and $b = \beta \log \delta$.

The empirical non-exceedance probability of significant wave height maximums is computed using the Weibull plotting position:

$$P = \frac{i}{n+1}, \tag{5}$$

where i is the rank (from smallest to largest) and n is the sample size.

Location, shape and scale parameters are estimated using the linear regression method for Eq. (4) (Castillo, 1988; Silva, 2005), and wave height values are plotted with horizontal and vertical scales defined by Eqs. (2) and (3). If data approaches a straight line, the user can visually assess that it comes from a Weibull distribution.

The generation of regional wave and wind quantile maps in the extreme climate submodule requires the user to input a return period and coordinates that define an area of study. Then, for the wave height or wind velocity time series of each cell in the domain specified by the user, the quantile associated with the given return period is calculated. A linear interpolation method is used when the quantile lies between two data points.

The storm occurrence analyses comprise different frequency analysis using 97th and 99th percentiles (P97 and P99, respectively) as storm threshold:

- Directional rose diagrams of wave height and period calculated energetically by storm (wave heights over P97)
- Bar diagrams of annual and monthly storm occurrences over P97 and P99 of significant wave height
- Bar diagrams of annual and monthly storm occurrences over P97 and P99 of normalized wave energy

3. Applications

To test and validate the efficiency of APPMAR, two areas of study were selected: Bocas de Ceniza, Colombia, and Cancún, México. In both zones, wave height, wave period, wave direction, and wind velocity variables for the period from 1999 to 2019 were analyzed (repeated figures for each location can be found in the Appendix). Since the study areas are in the Caribbean Sea, APPMAR covers this region with the mesh “NW Atlantic 10 min”, therefore the user must define the ID pair “wna, at_10m” (see Table 1). Besides, according to Ruiz et al. (2009) and Rivillas-Ospina et al. (2017), both sites show highly energetic marine conditions with seasonal behaviour.

According to Mesa et al. (1997), Ruiz-Ochoa and Bernal Franco (2009), and Osorio et al. (2016), the wave climate in the Caribbean Sea covers four seasons: a dry season from December to February, a wet season from March to May; a second dry season from June to August, and yet again, a more intense wet season from September to November. In the present study, these four seasons will be denoted as winter, spring, summer, and fall, respectively. However, APPMAR considers a configuration file where the user can define the seasons as a function of the study area location. The configuration file is in the INI format and contains key-value pairs defining the months comprising each season and the default coordinates for analysis.

Bocas de Ceniza is the name of the Magdalena River mouth, the most important river in Colombia. To the north, the river discharges fresh water in the Caribbean Sea; to the south, there is the Mallorquín coastal wetland and Barranquilla city (Fig. 5 (a)). The first point selected for this research is located in front of Bocas de Ceniza at the WGS 84 coordinates 11.13°N and 74.85°W. The second point was located in front of Cancún beaches, located in Quintana Roo state, México, at the WGS 84 coordinates 21.10°N and 86.65°W (Fig. 5 (b)). According to Martell et al. (2020) Cancun is located on the Caribbean coast of the Yucatan Peninsula, in Mexico and it is composed by lagoons that supply with fresh water the coastal system, via continental ground water discharge, and with sea water, which arrives with the tides (micro-tidal regime), through two inlets. Moreover, the coastal lagoons are surrounded by a very rich mangrove forest functioning like buffer zone against storms.

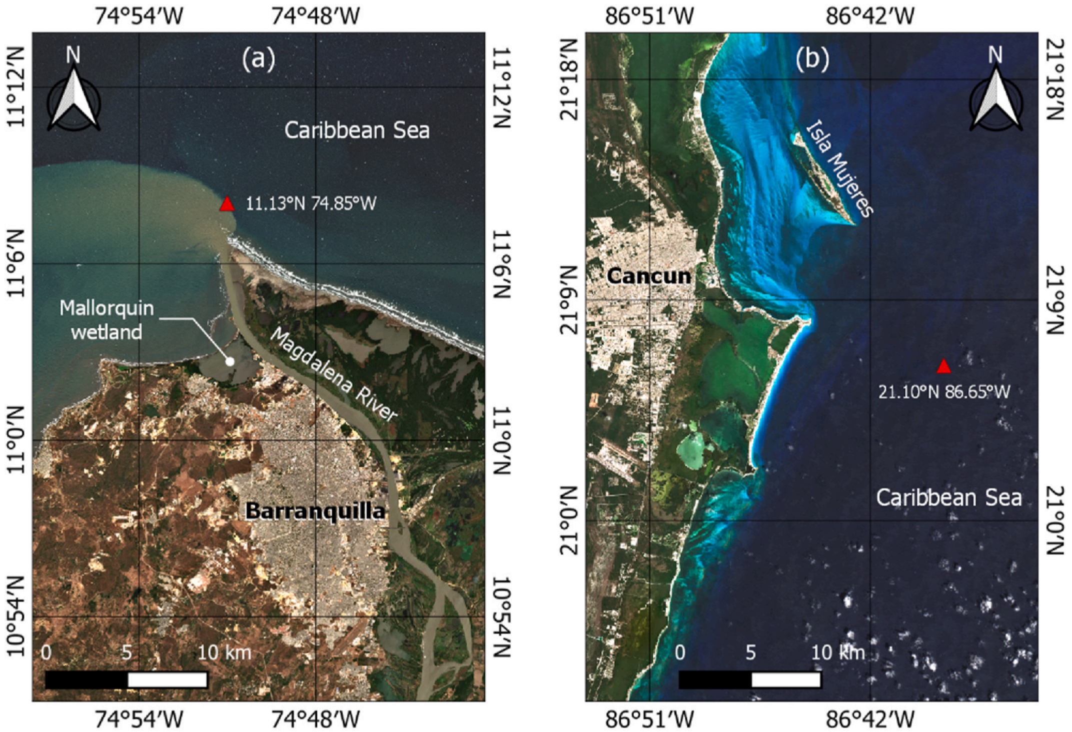


Fig. 5. Location of the analysis points (triangles) at Bocas de Ceniza (a) and Cancun (b).

3.1. *Magdalena River mouth – "Bocas de Ceniza"*

The joint probability of significant wave height and mean direction (Fig. 6), as well as the wave roses (Fig. 7) generated by APPMAR, show that waves reach the Bocas de Ceniza sector from the northeast (NE) throughout the year. With the use of this toolbox it is possible to observe significant waves during different seasons like winter and the effect of pressure gradients on wind components in the Caribbean basin, and the

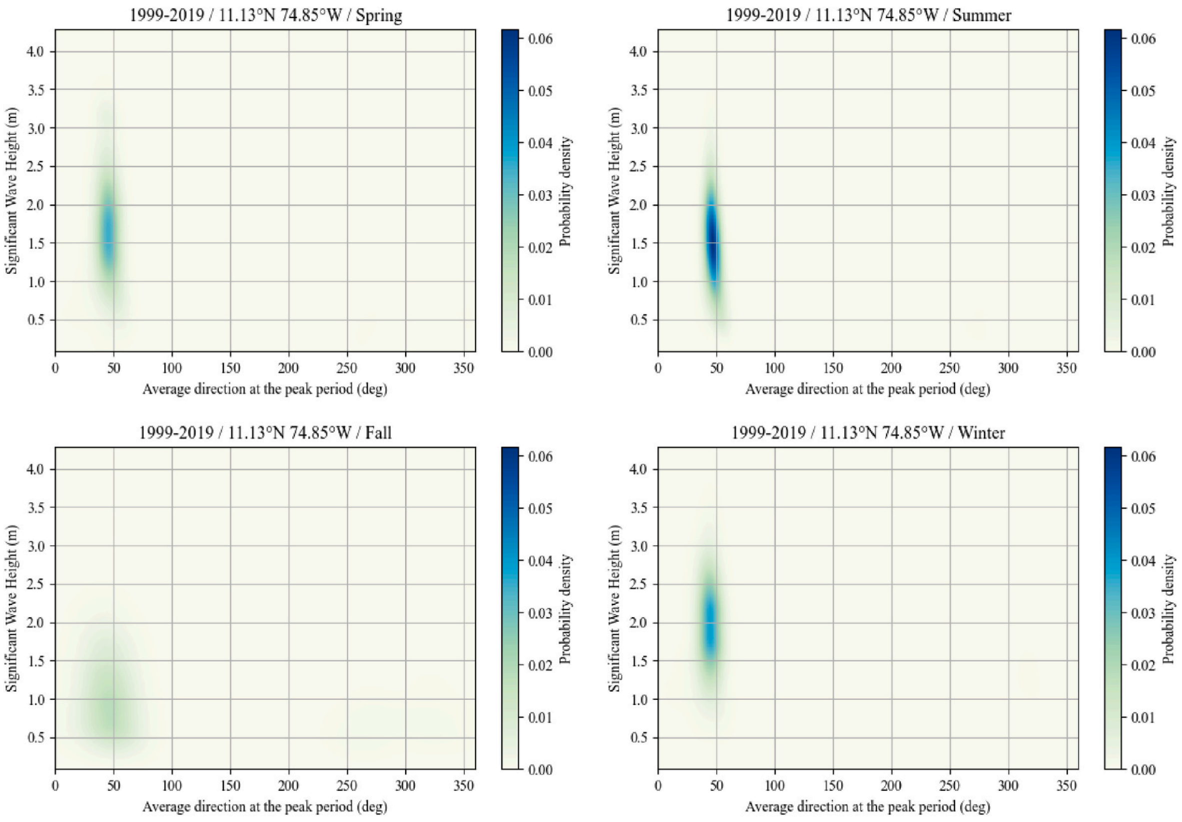


Fig. 6. Seasonal joint probability distribution of wave mean direction and significant wave height at Bocas de Ceniza.

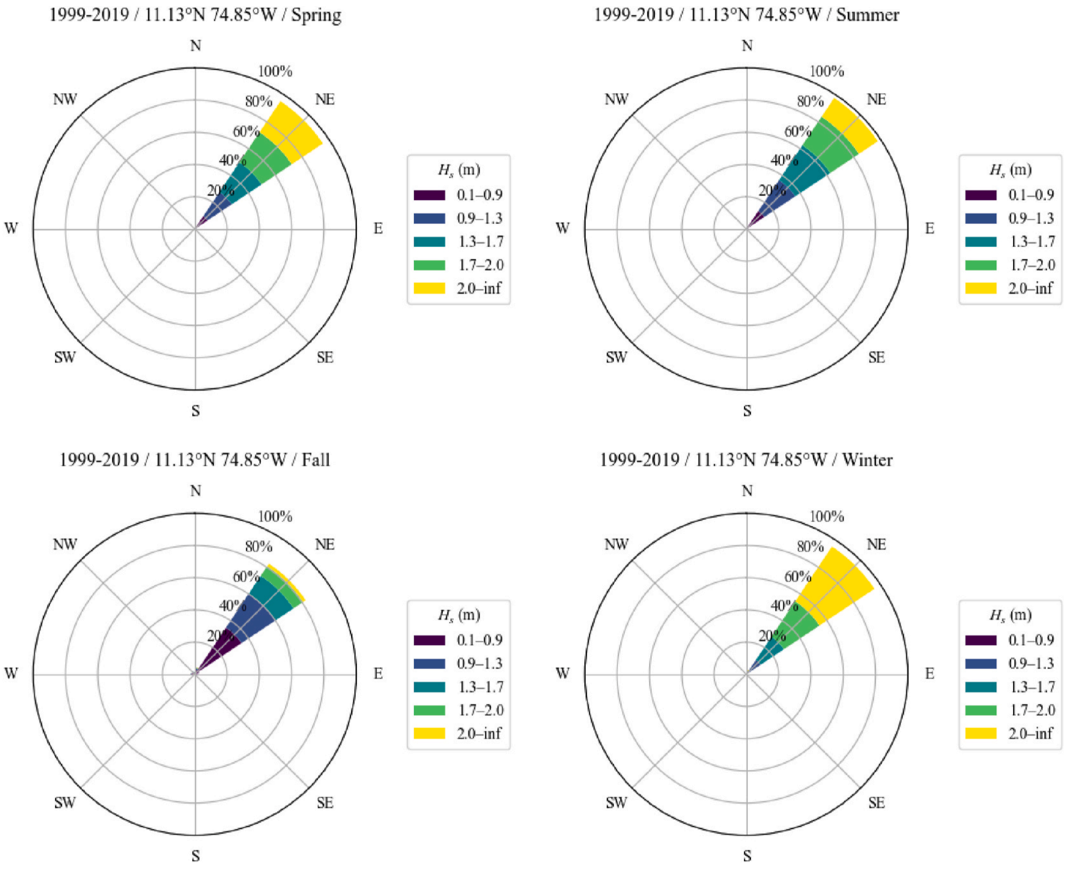


Fig. 7. Seasonal wave roses at Bocas de Ceniza.

occurrence of cold fronts (Ortiz-Royero et al., 2013). The highest waves occur in winter; they can be up to 2 m high, traveling from NE. In contrast, fall shows very few events of this magnitude, where significant wave heights of 1 m from NE have the highest relative frequency.

Fig. 7 shows that waves in this area come predominantly from NE, with slight variations throughout the year. However, the recurrence percentage shows changes in magnitude. Spring and winter display records of significant wave heights of 3.0–3.8 m (up to 5%), and heights of 2.6–3.4 m (up to 20%), respectively. Fall consistently presents the lowest wave heights, and during this period of the year only the effects of a hurricane could change this condition.

The long-term analysis illustrated in Fig. 8 was generated by APPMAR by extrapolating data at Bocas de Ceniza retrieved from WW3 hindcasts. According to the Weibull probability plot, the highest wave height registered was of 4.27 m high, with a return period of 25 years, approximately. These results from APPMAR show how intense wave trains generated by the effects of hurricanes, cold fronts, and storm activity can affect the Magdalena River mouth, affecting the coastal infrastructure or the operational activities in the inland Barranquilla port.

Another feature of APPMAR is that it provides wind speed and significant wave height maps (Fig. 9) considering the range variation of these parameters, and they show the areas that are most exposed to the action of waves and winds. The coastal boundary presents lower values of wind and wavefronts because of the interaction with the inner shelf. Fig. 9 exhibits the results of wind and wave variables for a return period of 100 years on a multiannual scale. These maps illustrate the more energetic zones in terms of wave values of significant wave height near “Bocas de Ceniza”, with the highest wave height values in deep waters and lowest wave height values near the shore, due to wave transformation processes. Since the wave’s behaviour is a response to the sustained action of the wind and the processes related to their propagation and the evolution, the areas with the highest wave heights will be related to strong wind fields and also swell propagation. Locations to the north of the littoral cell show wind component values up to 22 m/s, and also wave trains over 5.0 m of significant wave heigh. Besides, these maps describe the potential effects of intense waves throughout the year, with variations in wave climate. The area with lower wavefronts, because of the presence of the headlands, are located near the Ciénaga municipality and Ciénaga Grande de Santa Marta (CGSM), in the Magdalena Department.

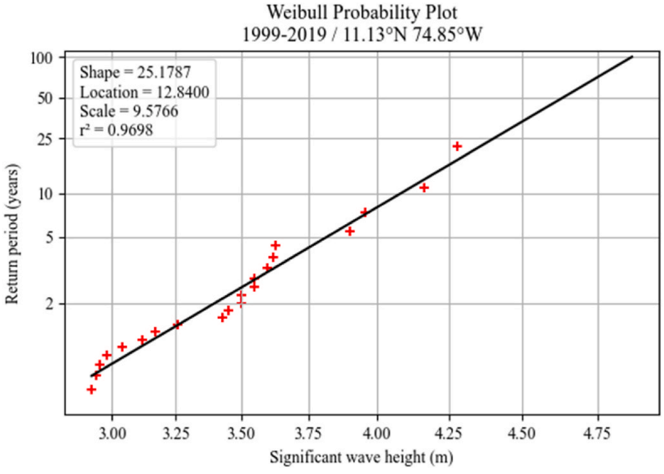


Fig. 8. Weibull distribution for significant wave height at Bocas de Ceniza.

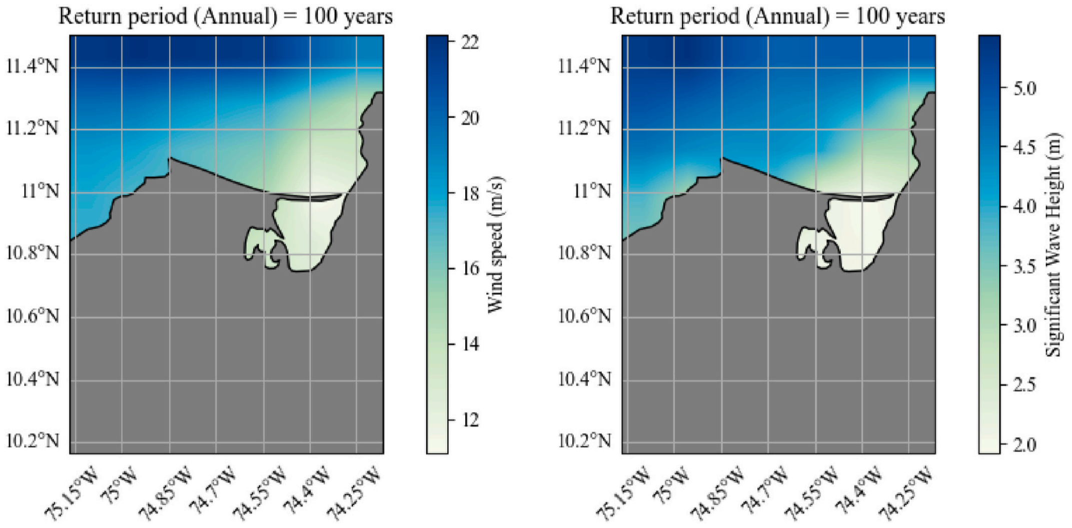


Fig. 9. Wind speed (left) and significant wave height (right) maps at Bocas de Ceniza.

3.2. *Cancún, México*

In order to validate the efficiency of APPMAR in other region, different statistical plots were generated for Cancún, México. Fig. 10 shows the exceedance probability of significant wave height in front of Cancún for each season of the year. The figure shows that the highest wavefronts with a low probability of exceedance occur during summer and fall. In contrast, in spring and winter wave trains do not exceed 3.5 m, and mean ranges of wave height show high probabilities of exceedance. Similarly, Fig. 11 illustrates the exceedance probability of the peak period which shows the same seasonal behaviour as the wave trains, with high values during the summer and fall seasons.

Wave roses (Fig. 12) show that the predominant wave direction is east-southeast (ESE) in every season. However, during spring, fall and winter there is a greater variation regarding the directions compared to summer. In Summer, up to 79.1% of the wave records come from ESE.

APPMAR shows a directional analysis of wave heights in front of Cancun. According to Fig. 12, wavefronts are more intense, reaching the coast with heights up to 2.8 m in winter, at percentages up to 47.7%. However, the direction of propagation may vary from ESE keeping equal wave heights, but with percentages up to 9.5% traveling from the NE. Autumn shows to be the season with more outstanding variations, as the range goes from the northeast to the ESE. However, the wave heights are low most of the time (up to 1.9 m high).

Fig. 13 exhibits the analysis of the monthly occurrence of storms, which shows most events occur between fall and winter. This analysis generated by APPMAR helps the user to determine that the highest number of storms associated with the P97 quartile (2.18 m) corresponds to January, whereas those associated with P99 (2.62 m) correspond to November. Similarly, the analysis of the annual occurrence of storms (Fig. 14) shows a declining trend in the number of events above the P97 threshold since 2008.

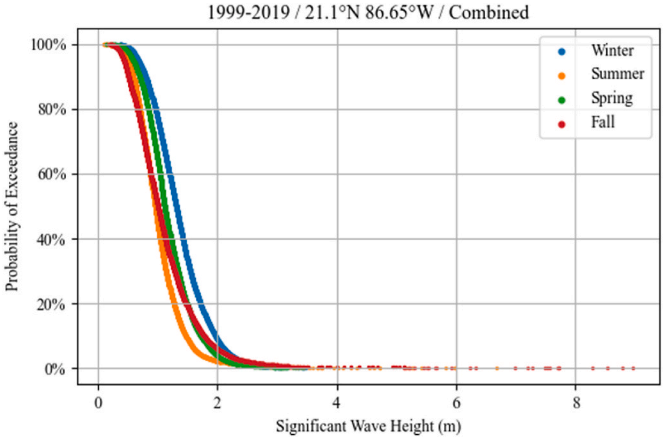


Fig. 10. Seasonal exceedance probability of significant wave height at Cancún.

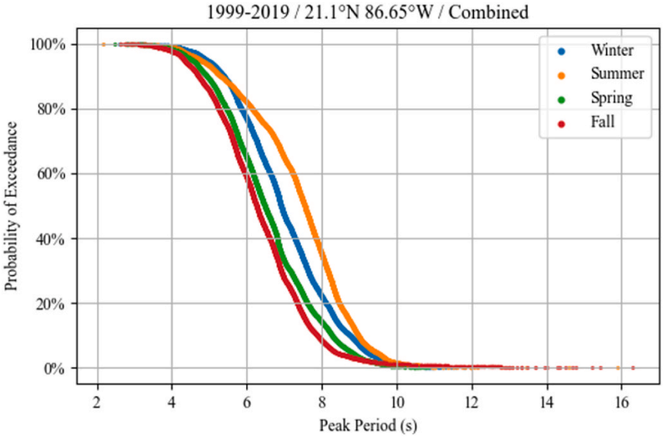


Fig. 11. Seasonal exceedance probability of wave peak period at Cancún.

Finally, APPMAR presents different ways to analyze parameters associated with storms. The wave rose presented in Fig. 15 offers a directional analysis of wave height events identified as a storm with significant wave heights greater than the 2.18 m (P97) threshold. It can be seen that, although the primary direction for mean conditions is ESE (Fig. 12), storm waves reaching the coast come from a wider range of directions between NE and ESE.

4. Conclusions

An application called APPMAR 1.0 with a GUI for downloading, processing analysis, and visualization of wave and wind climate data was developed using computational tools applied to marine sciences to perform mean and extreme climate analysis. The program accesses wave and wind datasets from NOAA's WW3 production hindcasts. The major contribution and innovation of APPMAR software is the automatic download of wave and wind data from the NOAA's WW3 hindcast and performance of statistical data analysis using standardized

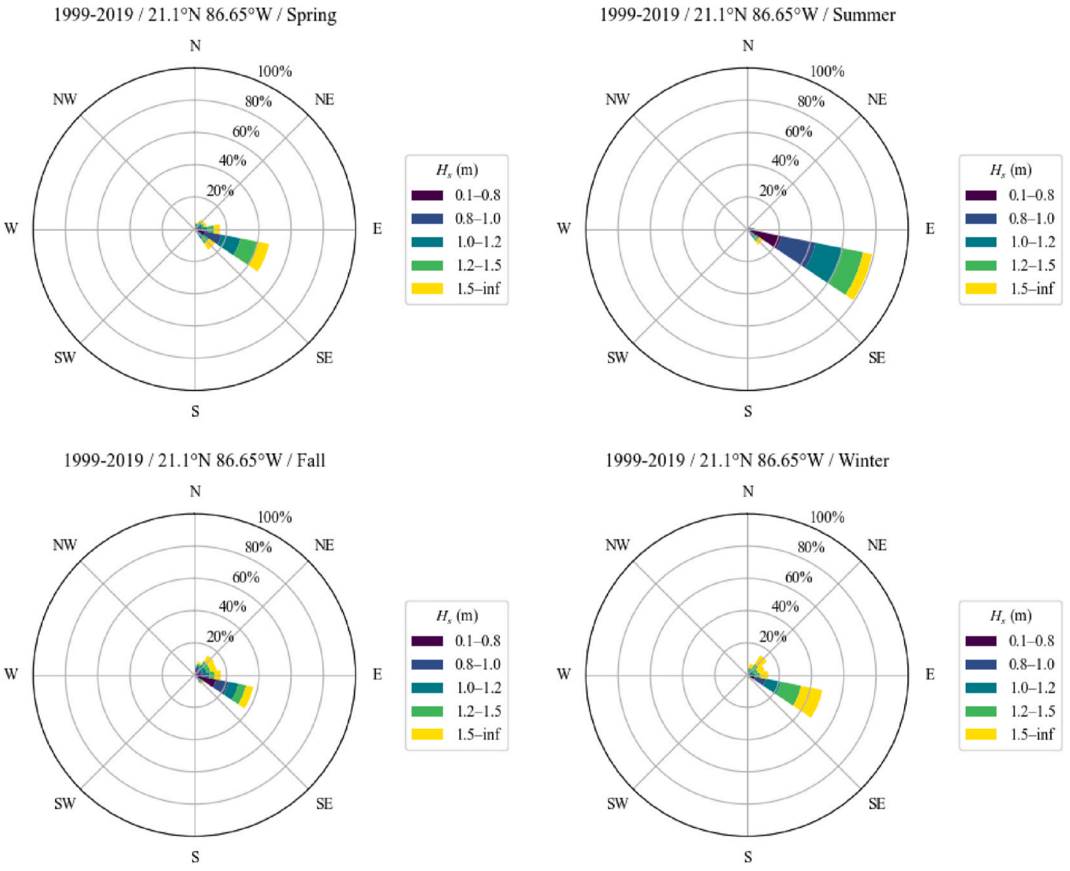


Fig. 12. Seasonal significant wave height roses at Cancún.

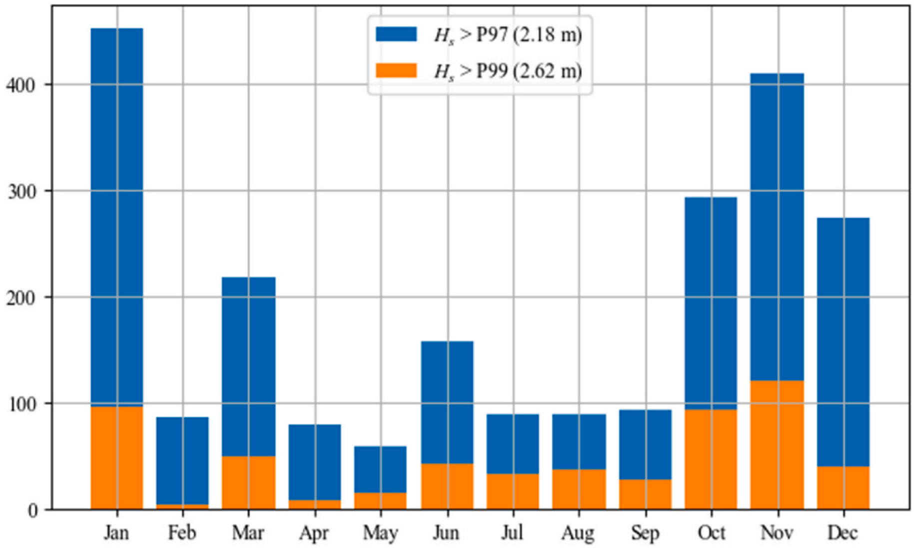


Fig. 13. Monthly occurrences of storm at Cancún.

methodologies implemented as free/open-source code with a user-friendly GUI. The development of a free access application defines an alternative way to improve mechanisms of data sharing for marine projects especially in Latin American countries, where meteorological and marine information are scarce. The analyses can be performed to the entire data series or by season to identify the effects of climatic phenomena like cold fronts or storm seasons as seen in the case studies. Extreme climate analysis considers storm events and the energy potential to determine the long-term behaviour.

APPMAR was designed for wave and wind processing, starting from the analysis of WW3 datasets to have input information that can feed spectral wave numerical models and simulate wave propagation in deep waters. Additional variables concerning marine climate will be considered in an upcoming version.

Authorship contribution statement

German Rivillas-Ospina: Conceptualization, Methodology,

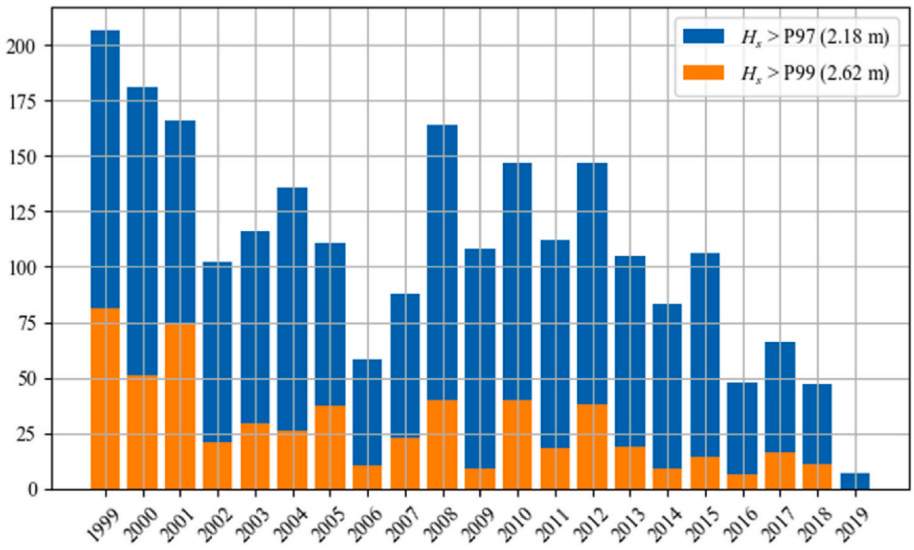


Fig. 14. Annual occurrences of storm at Cancún.

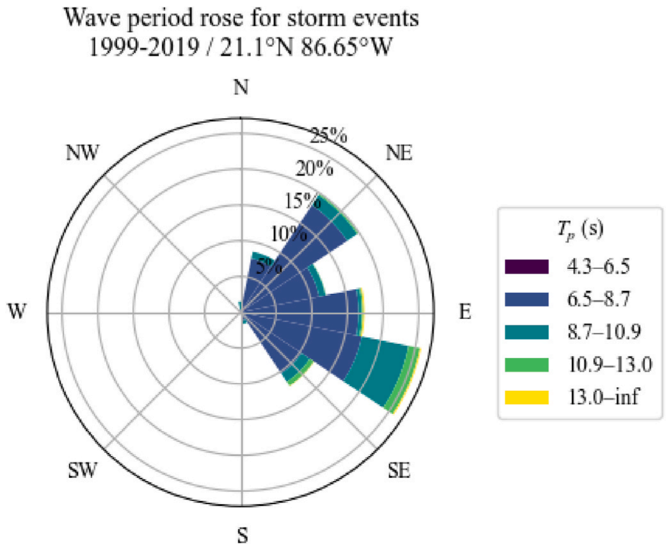


Fig. 15. Wave period rose for storms at Cancún, México, (H_s > P97).

Investigation, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. Diego Casas: Conceptualization, Software, Writing - Original Draft, Supervision. Mauro Antonio Maza-Chamorro: Writing - Review & Editing. Marianella Bolívar: Conceptualization, Validation, Resources. Gabriel Ruiz: Writing - Review & Editing, Supervision. Roberto Guerrero: Writing - Review & Editing. José M. Horrillo-Caraballo: Investigation, Writing - Review & Editing. Milton Guerrero: Writing - Review & Editing. Karina Díaz: Writing - Review & Editing. Roberto del Rio: Writing - Review & Editing. Erick Campos: Writing - Review & Editing.

Code availability section

Name of the code: APPMAR 1.0.

Contact: grivillas@uninorte.edu.co.

Hardware requirements: APPMAR 1.0 was developed and tested on a computer with a 1.6 GHz quad-core CPU and 8 GB of RAM.

Program language: APPMAR 1.0 was written in Python 3.7.

Software required: APPMAR 1.0 requires a Python 3.7 installation with the following packages: cfgrib, windrose, gdal, wxpython, numpy, matplotlib, scipy, xarray, cartopy, scikit-learn, and kneed.

Program size: 105 KB.

The source codes are available for downloading at the link: https://github.com/cemanetwork/appmar.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Magdalena River mouth – "Bocas de Ceniza"

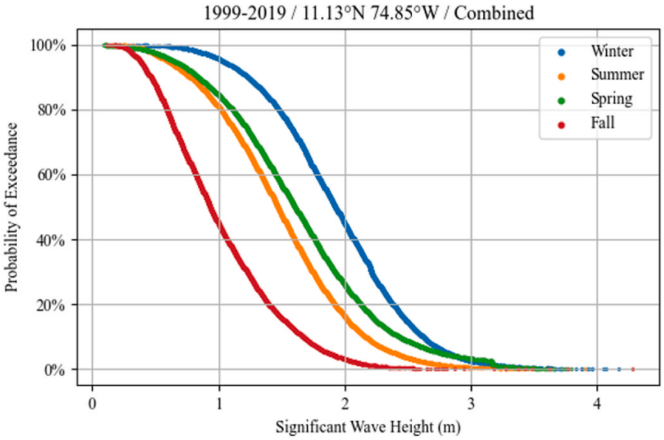

Fig. 16. Seasonal exceedance probability of significant wave height at Bocas de Ceniza.

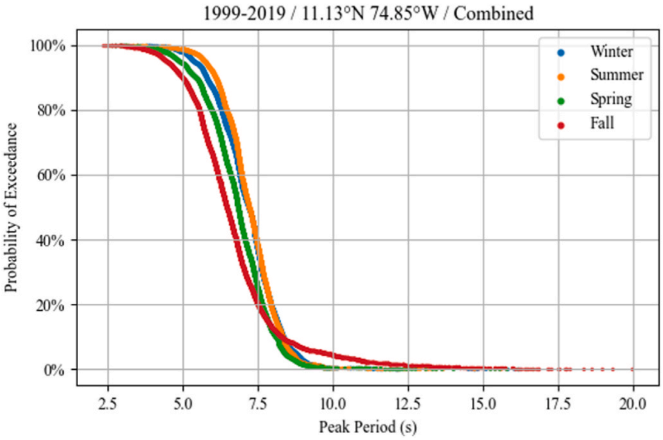

Fig. 17. Seasonal exceedance probability of wave peak period at Bocas de Ceniza.

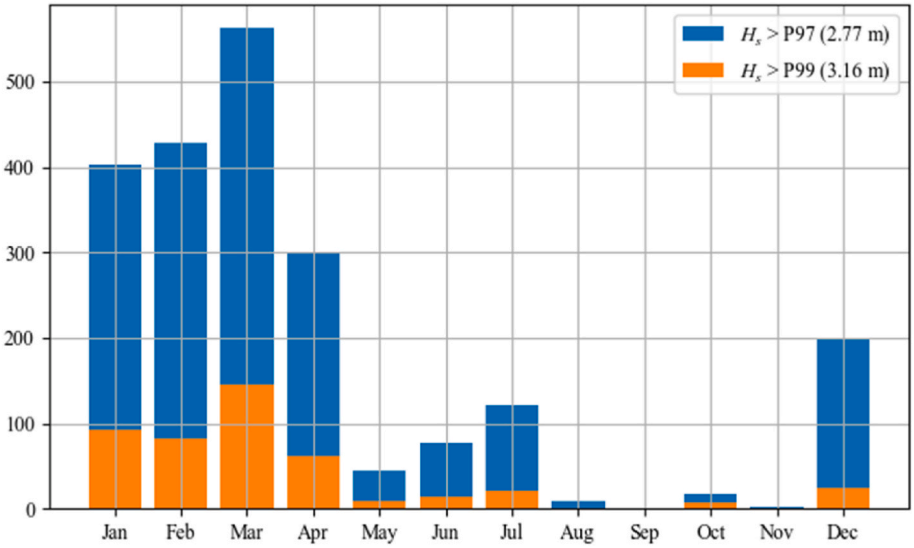

Fig. 18. Monthly occurrences of storm at Bocas de Ceniza.

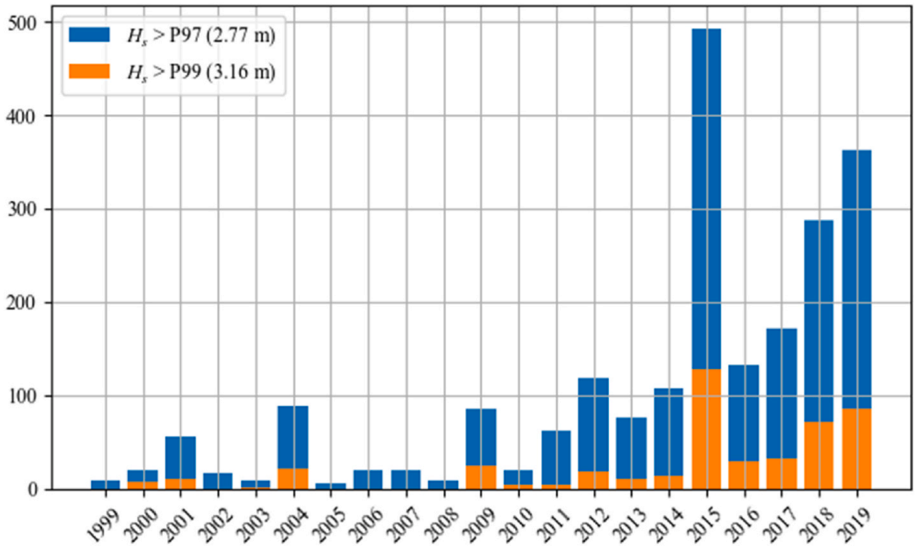

Fig. 19. Annual occurrences of storm at Bocas de Ceniza.

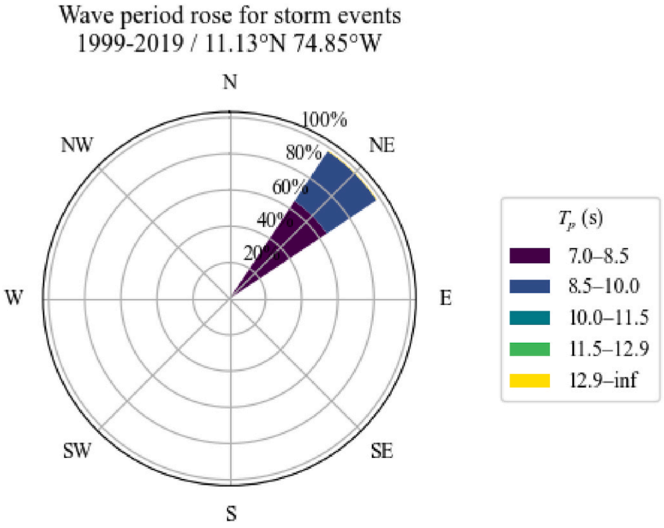

Fig. 20. Wave period rose for storms at Bocas de Ceniza (H_s > P97).

Cancún, México

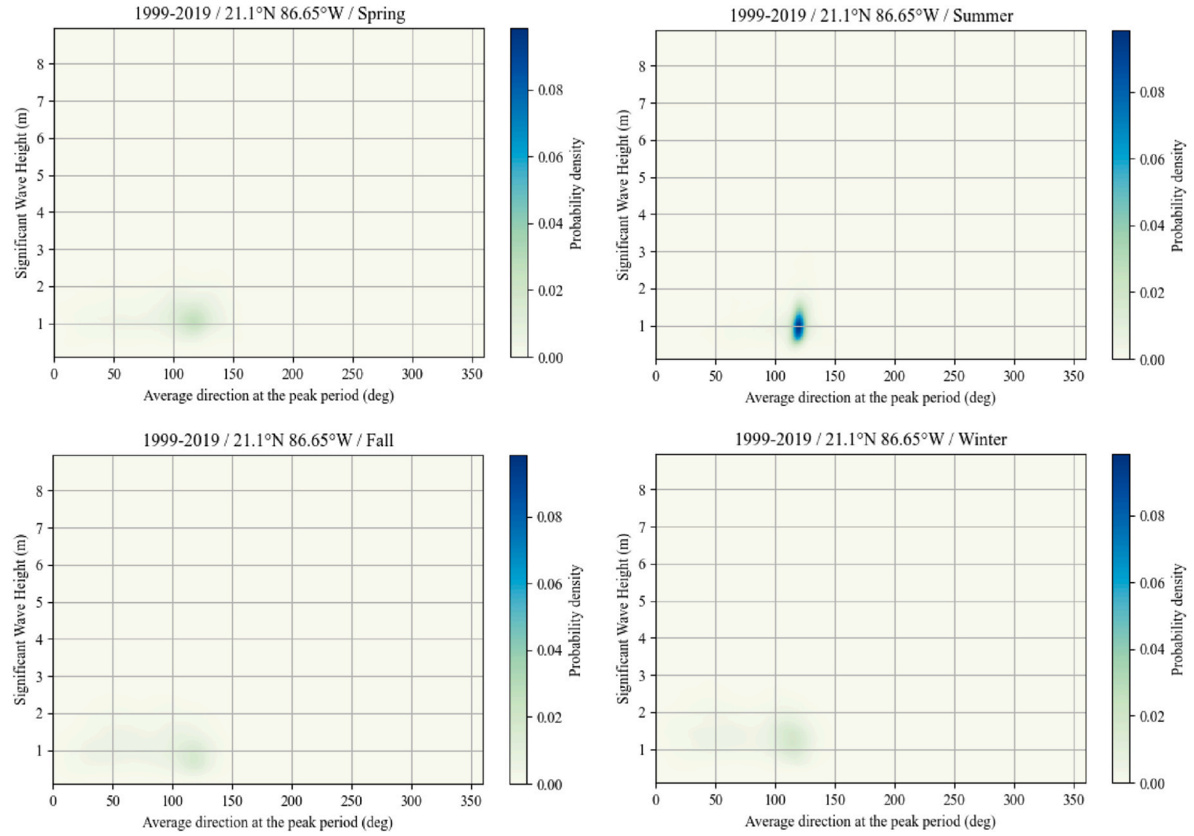

Fig. 21. Seasonal joint probability distribution of wave mean direction and significant wave height at Cancún.

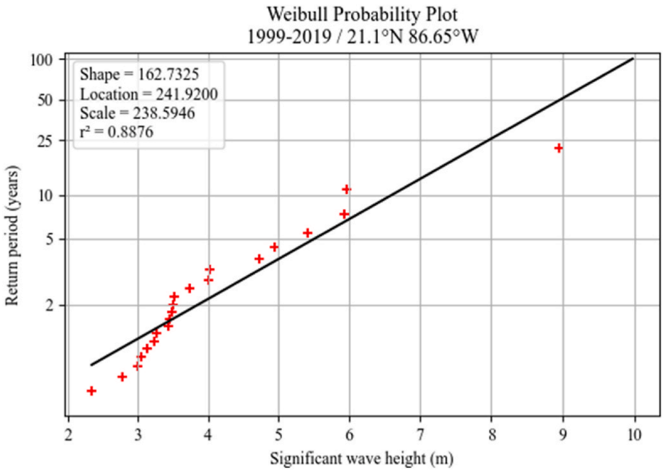

Fig. 22. Weibull distribution for significant wave height at Cancún.

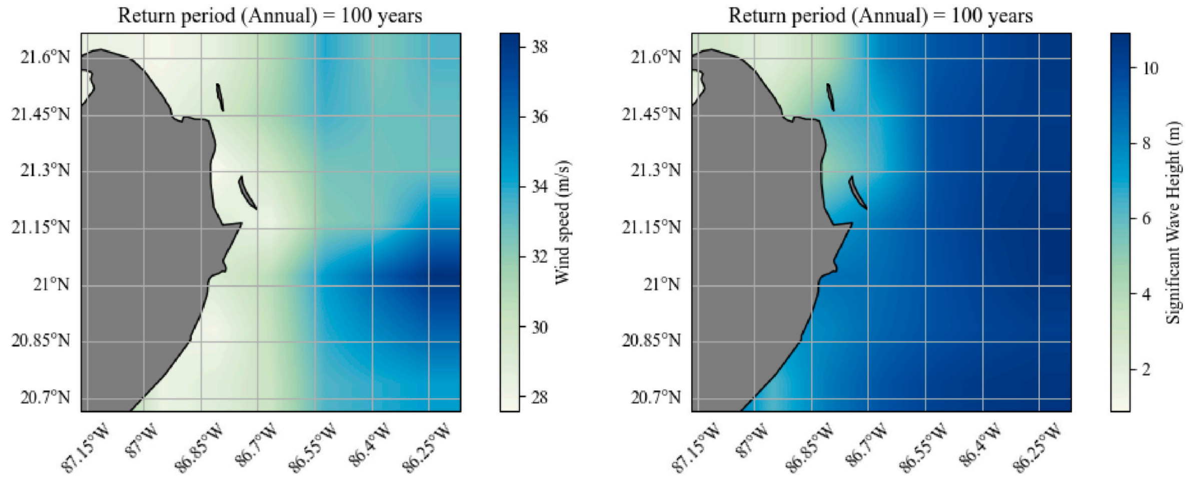

Fig. 23. Wind speed (left) and significant wave height (right) maps at Cancún.

References

Appendini, C.M., Torres-Freyermuth, A., Salles, P., López-González, J., Mendoza, E.T., 2014. Wave climate and trends for the Gulf of Mexico: a 30-yr wave hindcast. J. Clim. 27, 1619–1632. https://doi.org/10.1175/JCLI-D-13-00206.1.

Bernabeu, A.M., Medina, R., Vidal, C., 2002. An equilibrium profile model for tidal environments. Sci. Mar. 66, 325–335. https://doi.org/10.3989/scimar.2002.66n4325.

Bowman, D.C., Lees, J.M., 2015. Near real time weather and ocean model data access with rNOMADS. Comput. Geosci. 78, 88–95. https://doi.org/10.1016/j.cageo.2015.02.013.

Brodtkorb, P., Johannesson, P., Lindgren, G., Rychlik, I., Ryden, J., Sjo, E., 2000. WAFO - a Matlab toolbox for analysis of random waves and loads. Proc. Int. Offshore Polar Eng. Conf. 3, 343–350.

Capitão, R., Burrows, R., 1995. Wave predictions based on scatter diagram data. A computer program package. Adv. Eng. Software 23, 49–59. https://doi.org/10.1016/0965-9978(95)00019-N.

Castillo, E., 1988. Extreme Value Theory in Engineering, Statistical Modeling and Decision Science. Academic Press, San Diego, California. https://doi.org/10.1016/C2009-0-22169-6.

Dean, R.G., 1977. Equilibrium Beach Profiles, U.S. Atlantic and Gulf Coasts (Technical Report No. 12). University of Delaware, Newark.

Devis-Morales, A., Montoya-Sánchez, R.A., Bernal, G., Osorio, A.F., 2017. Assessment of extreme wind and waves in the Colombian Caribbean Sea for offshore applications. Appl. Ocean Res. 69, 10–26. https://doi.org/10.1016/j.apor.2017.09.012.

Felix, A., Mendoza, E., Chávez, V., Silva, R., Rivillas-Ospina, G., 2018. Wave and wind energy potential including extreme events: a case study of Mexico. J. Coast Res. 85, 1336–1340. https://doi.org/10.2112/SI85-268.1.

Hunter, J.D., 2007. Matplotlib: a 2D graphics environment. Comput. Sci. Eng. 9, 90–95. https://doi.org/10.1109/MCSE.2007.55.

Karimpour, A., Chen, Q., 2017. Wind wave analysis in depth limited water using OCEANLYZ, A MATLAB toolbox. Comput. Geosci. 106, 181–189. https://doi.org/10.1016/j.cageo.2017.06.010.

Landry, B.J., Hancock, M.J., Mei, C.C., García, M.H., 2012. WaveAR: a software tool for calculating parameters for water waves with incident and reflected components. Comput. Geosci. 46, 38–43. https://doi.org/10.1016/j.cageo.2012.04.001.

Magaña, P., Del-Rosal-Salido, J., Cobos, M., Lira-Loarca, A., Ortega-Sánchez, M., 2020. Approaching software engineering for marine sciences: a single development process for multiple end-user applications. J. Mar. Sci. Eng. 8, 350. https://doi.org/10.3390/jmse8050350.

Martell, R., Mendoza, E., Mariño-Tapia, I., Odériz, I., Silva, R., 2020. How effective were the beach nourishments at Cancun? J. Mar. Sci. Eng. 8, 388. https://doi.org/10.3390/jmse8060388.

Maza Chamorro, M., Del Río Colón, R., Campo Rojas, E., 2018. Uso de información de viento y oleaje en el Caribe. In: Diocean, C.T.N. (Ed.), Manual de Referencia En Mejores Prácticas de Gestión de Datos Oceánicos. DIMAR, Bogotá. , D.C., Colombia, pp. 32–36.

Mesa, J.C., 2009. Metodología para el reanálisis de series de oleaje para el caribe colombiano.

Mesa, O.J., Poveda, G., Carvajal, L.F., 1997. Introducción al clima de Colombia. Universidad Nacional de Colombia, Medellín.

Montoya, R.D., Menendez, M., Osorio, A.F., 2018. Exploring changes in Caribbean hurricane-induced wave heights. Ocean Eng. 163, 126–135. https://doi.org/10.1016/j.oceaneng.2018.05.032.

Ortiz, J.C., 2012. Exposure of the Colombian Caribbean coast, including San Andrés Island, to tropical storms and hurricanes, 1900–2010. Nat. Hazards 61, 815–827. https://doi.org/10.1007/s11069-011-0069-1.

Ortiz, J.C., 2009. Aplicación de un modelo paramétrico de vientos y un modelo de oleaje espectral para el estudio del oleaje máximo generado por el huracán Lenny en las costas del Caribe colombiano en 1999. Boletín Científico CIOH, pp. 29–36.

Ortiz, J.C., Moreno, J.M.P., Lizano, O., 2015. Evaluation of extreme waves associated with cyclonic activity on san Andrés Island in the Caribbean Sea since 1900. Coast. Res. 31, 557–568. https://doi.org/10.2112/JCOASTRES-D-14-00072.1.

Ortiz, J.C., Salcedo, B., Otero, L.J., 2012. Investigating the collapse of the Puerto Colombia Pier (Colombian Caribbean coast) in March 2009: methodology for the reconstruction of extreme events and the evaluation of their impact on the coastal infrastructure. J. Coast Res. 30, 291–300. https://doi.org/10.2112/JCOASTRES-D-12-00062.1.

Ortiz-Royero, J.C., Otero, L.J., Restrepo, J.C., Ruiz, J., Cadena, M., 2013. Cold fronts in the Colombian Caribbean Sea and their relationship to extreme wave events. Nat. Hazards Earth Syst. Sci. 13, 2797–2804. https://doi.org/10.5194/nhess-13-2797-2013.

Osorio, A.F., Montoya, R.D., Ortiz, J.C., Peláez, D., 2016. Construction of synthetic ocean wave series along the Colombian Caribbean Coast: a wave climate analysis. Appl. Ocean Res. 56, 119–131. https://doi.org/10.1016/j.apor.2016.01.004.

Reguero, B.G., Méndez, F.J., Losada, I.J., 2013. Variability of multivariate wave climate in Latin America and the Caribbean. Global Planet. Change 100, 70–84. https://doi.org/10.1016/j.gloplacha.2012.09.005.

Reguero, B.G., Menéndez, M., Méndez, F.J., Mínguez, R., Losada, I.J., 2012. A Global Ocean Wave (GOW) calibrated reanalysis from 1948 onwards. Coast. Eng. 65, 38–55. https://doi.org/10.1016/j.coastaleng.2012.03.003.

Rivillas-Ospina, G.D., Ruiz-Martinez, G., Silva, R., Mendoza, E., Pacheco, C., Acuña, G., Rueda, J., Felix, A., Pérez, J., Pinilla, C., 2017. Physical and morphological changes to wetlands induced by coastal structures. In: Finkl, C.W., Makowski, C. (Eds.), Coastal Wetlands: Alteration and Remediation, Coastal Research Library. Springer International Publishing, Cham, pp. 275–315. https://doi.org/10.1007/978-3-319-56179-0_9.

Ruiz, G., Mendoza, E., Silva, R., Posada, G., Pérez, D., Rivillas, G., Escalante, E., Ruiz, F., 2009. Caracterización del régimen del oleaje y viento de 1948-2007 en el litoral mexicano. Ingeniería del agua 16, 51–64. https://doi.org/10.4995/ia.2009.2944.

Ruiz-Ochoa, M.A., Bernal Franco, G., 2009. Variabilidad estacional e interanual del viento en los datos del reanálisis NCEP/NCAR en la cuenca Colombia, mar Caribe. Av. Recur. Hidraul.

Silva, R., 2005. Análisis y descripción estadística del oleaje, Serie Docencia. Universidad Nacional Autónoma de México, México, D.F.

Torres, R.R., Andrade, C.A., 2006. Potential en Colombia para el Aprovechamiento de la Energía No Convencional de los Océanos. Boletín Científico CIOH, pp. 11–25. https://doi.org/10.26640/22159045.145.