https://revistas.ucr.ac.cr/index.php/ingenieria/index
www.ucr.ac.cr / ISSN: 2215-2652

Ingeniería

Revista de la Universidad de Costa Rica

JULIO/DICIEMBRE 2023 - VOLUMEN 33 (2)

DOI: 10.15517/ri.v33i2.54492
Ingeniería 33(2): 116-133, Julio-Diciembre, 2023. ISSN: 2215-2652. San José, Costa Rica

Waves Data in Costa Rica: Validating the WAVERYS Reanalysis using Waves Data

Datos de Oleaje en Costa Rica: Validando el Reanálisis WAVERYS con Mediciones de Campo

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Recibido: *14 de marzo de 2023* **Aceptado:** *16 de abril de 2023*

Abstract

Field wave data are a relevant source of information with high impact for marine sciences and engineering. The present work compiled, in a single database, the different wave data records found in Costa Rica. Such wave data were compared with the WAVERYS reanalysis from the Copernicus Marine Environment Monitoring Service with the purpose of examining this information and its possible use in future research at both the country and regional levels. The historical wave data compilation considered records documented in different projects carried out on behalf of several governmental institutions. Statistical methods were used to analyze and compare, spatially and temporally, the information contained both in the field wave data and in the WAVERYS reanalysis. Results showed that, in the Caribbean, there are wave records between 2015 and 2017. In the Pacific, there are measurements made during the construction of Puerto Caldera between 1978 and 1985. There are also wave data obtained in different sites between 2009 to 2011 and by a recently established wave gauge network from 2014 onwards. It was verified that the reanalysis database has a high potential for applications in marine sciences and coastal engineering in this region of the Earth.

Keywords:
Costa Rica, field measurements, reanalysis, wave data, WAVERYS.

Resumen

Las bases de datos de oleaje, a partir de mediciones de campo, son información relevante y de alto impacto para las ciencias marinas y la ingeniería. Este trabajo compiló las diferentes bases de datos de oleaje medidas en campo en Costa Rica con el fin de preservar en una única fuente de consulta dicha información; a su vez, se compararon dichos datos con los ofrecidos por el reanálisis WAVERYS del Copernicus Marine Enviroment Monitoring Service, con el propósito de analizar esta información y su posible utilización en futuras investigaciones en el país y en la región. Se recopilaron los datos históricos empleados en distintos proyectos y registrados por diferentes instituciones del Estado. Los datos fueron analizados espacial y temporalmente por métodos estadísticos, se realizaron comparaciones entre los distintos registros y la base de datos de reanálisis de oleaje WAVERYS. Los resultados mostraron que en el Caribe se tienen registros de oleaje entre los años 2015 y 2017. En el Pacífico, se cuenta con datos que se midieron durante la construcción de Puerto Caldera (1978-1985); además, existen datos de campañas de campo realizadas en distintos lugares entre los años 2009 y 2011, y los datos medidos por una red de equipos de oleaje colocados en zonas costeras desde el 2014 hasta la actualidad. Finalmente, se verificó que los datos del reanálisis tienen un alto potencial de aplicación en las ciencias marinas y la ingeniería de costas en esta región del globo.

Palabras Clave:
Costa Rica, mediciones de campo, reanálisis, datos de oleaje, WAVERYS

1. INTRODUCTION

Waves affect natural processes and human activities in the coastal zone, such as coastal erosion and accumulation [1], marine ecosystems and their dynamics [2], marine aquaculture [3], the design of maritime structures [4], such as breakwaters [5], and the behavior of floating structures [6].

Wave data measured *in situ* are one of the most important sources of information to characterize this variable. However, due to their investment and operation costs, these data are usually measured in strategic areas and mostly during short periods, which can be representative of a large spatial extension. Countries with developed coastal and port engineering have networks of equipment distributed along their coasts on a permanent basis (*i.e*: Buoy Network of Puertos del Estado, España; National Data Buoy Center-National Oceanic and Atmospheric Administration's (NDBC-NOAA), USA; Ocean Data Buoy Observations-Japan Meteorological Agency, Japan).

Nevertheless, in other oceanic regions such as along the Latin American coast, wave data measured on the field are usually scarce. Costa Rica is no exception, and the available data catalogs, until the last decade, were few and present temporal and spatial limitations since they have solved specific needs for particular projects [7], [8] and [9]. However, as of 2014, Costa Rica has a network of gauge wave placed in coastal areas, formed by the research groups: Unidad de Ingeniería Marítima, de Ríos y de Estuarios (IMARES) and Módulo de Información Oceanográfica del Centro de Investigación en Ciencias del Mar y Limnología (MIO-CIMAR), both from the University of Costa Rica (UCR). The purpose of the network is to measure waves on both coasts of the country continuously and through equipment distributed in sites of scientific interest.

Other sources of wave data, which have gained relevance over the last two decades, are global wave reanalysis based on spectral wave model —*i.e*: Production Hindcast [10]; GOW2 [11]; WAVERYS [12]. These databases are characterized by having historical information, homogeneous in space and continuous in time, which is important to understand the dynamic behavior of waves. Nevertheless, despite the continuous improvement in the models used, the resolution and quantity of their forcings, they need to be calibrated and validated with information measured in field or from satellites [13].

The WAVERYS database of the Copernicus Marine Environment Monitoring Service (CMEMS) is used in this work due to the high spatial resolution, which is important for our regional application. WAVERYS is a global reanalysis of wave surface conditions, generated with the operational model MFWAM (Meteo France WAve Model) version 4 [14]. It is forced from the ice and wind fields coming from the ERA5 atmospheric reanalysis [15], an initiative developed by European Centre for Medium-Range Weather Forecasts [16].

WAVERYS has a spatial resolution of 1/5°, currently covers the period between 1993 and 2021, and has information on wave parameters with a resolution of every three hours. The WAVERYS information was validated for deep water areas with data from satellite altimeter (HY-2A satellite, not included in the assimilation) and for coastal areas with information from buoys along the globe between the years 1994 and 2015 [12]. However, the buoys used for validation are mainly located in the high latitudes of the northern hemisphere, because there is more equipment installed. For the South American region, five buoys are used for validation, three in the Pacific Ocean (one in Colombia and two in Chile) and two in the Atlantic (one in Florianopolis, Brazil and one in Cayenne, French Guiana) [17].

The present work has two main objectives: i) to show the historical wave databases recorded in the field on both coasts of Costa Rica and ii) to compare the wave data provided by the WAVERYS reanalysis with the information measured in the field at different sites and times, in order to analyze the information provided by this reanalysis and its possible use in future research in the country and in the region.

2. MATERIALS AND METHODS

This research used historical and available wave data measured by different public institutions in the Pacific and Caribbean coasts of Costa Rica. Moreover, information recently measured in the field by IMARES and MIO-CIMAR of the UCR was used. All the wave databases used were measured by different types of wave gauges, placed in different places and at different times.

In addition, the study included data from the WAVERYS wave reanalysis [12] of the Copernicus Marine Environment Monitoring Service (CMEMS). The numerical nodes of the reanalysis were selected close to the sites where the equipment was placed in the field, in order to validate the trend over time of the WAVERYS information, based on the measured data.

The wave data measured in field and those from the reanalysis were standardized by means of the main wave parameters, such as zero-order moment wave height (H_{mo}), peak period (T_p) and mean direction (θ). Both databases were analyzed using descriptive statistical tools; these were compared using graphical control tools and quality indicators.

2.1 Study zone

The databases and numerical nodes of the WAVERYS model used in this study are located in the northern and central zone of the Pacific coast of Costa Rica; on Coco Island, located approximately 500 km from the national territory, between the country and the Galapagos Islands, and on the Caribbean coast (Fig. 1).

The data sites present natural and social conditions that have favored the measurement of wave data in their vicinity. For example, they include the most important ports of the country (*i.e.*, Caldera and Moín in Fig. 1), natural parks and conservation areas of important ecological interest (*e.g.*, Coco Island, Cabo Blanco in Fig. 1), and exposed sites that allow accurate characterization of incident waves (*e.g.*, Cabo Velas, Sámara, Playa Grande and Quepos). In addition, they present shallow depths where it has been feasible to install measurement equipment (50 m or less).

The study area also includes six numerical nodes of the WAVERYS model (Fig. 1), located in the vicinity of the wave measurement points, which makes it possible to compare both sources of information.

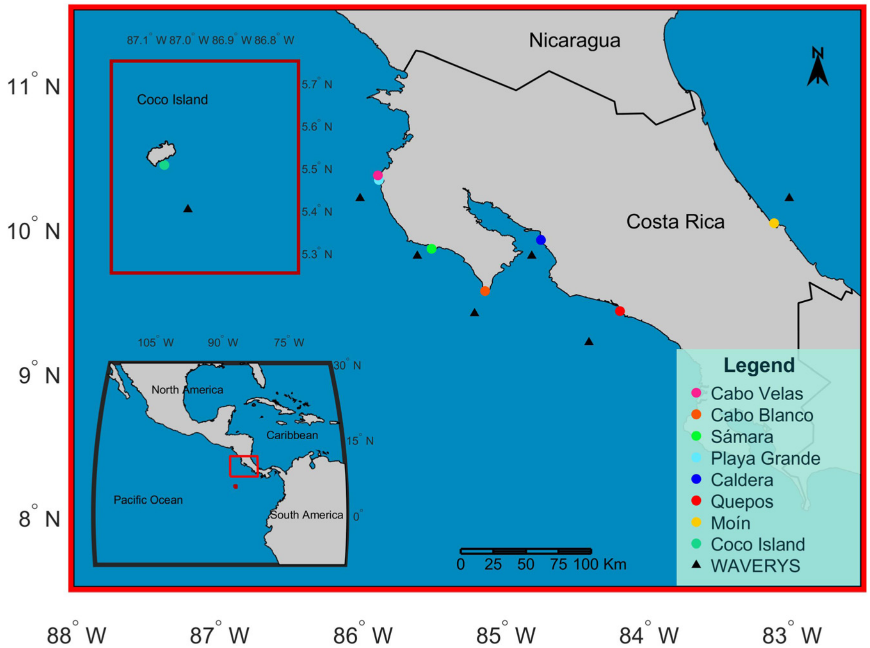

Fig. 1. Spatial distribution of gauges and nodes of reanalysis WAVERYS.

2.2 Field measured data and WAVERYS reanalysis

The wave data were collected by public institutions in different time periods and were not centralized in any general database or public access system. Therefore, the collection of the measured data, as well as the details associated with the recording process (*i.e.*, dates, coordinates, types of gauges), were done through direct contact with the institutions in charge of the information. The original data and measurement details were requested; in cases where the information was printed on paper, it was digitized manually.

Numerical nodes from the WAVERYS reanalysis [12] (Fig 1) had the wave parameters zero-order moment height, peak period and wave direction (H_{mo}, T_p and θ) extracted together with the associated time variable. Subsequently, time periods were selected when both databases coincided temporally. In this way, the spatial and temporal comparison of both sources of information was achieved.

2.3 Data analysis

The wave data and the reanalysis were analyzed by means of graphical tools of descriptive statistics such as time series and wave rose. Also, the H_{mo} and T_p parameters of both data sources were compared using scatter plots; in addition, statistical descriptors such as *BIAS* in equation (1), root mean square error (*RMSE*) in equation (2), Pearson's correlation coefficient (ρ) in equation (3) and dispersion index (*SI*) in equation (4) were calculated.

$$BIAS = \bar{x} - \bar{y} \tag{1}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \tag{2}$$

$$\rho = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}} \tag{3}$$

$$SI = \frac{RMSE}{\bar{x}} \tag{4}$$

where x_i is the reference data, y_i is the reanalysis data and n is the number of observations.

3. RESULTS

3.1 Field measured data

Field data were measured by public institutions such as the Ministerio de Obras Públicas y Transportes (MOPT), the Comisión de Marinas y Atracaderos Turísticos (CIMAT), the Consejo Nacional de Concesiones (CNC), and the UCR through the IMARES and MIO-CIMAR research groups. Data were recorded at eight different sites (Fig. 1): Cabo Velas, Cabo Blanco, Sámara, Playa Grande, Caldera, Quepos, Moín, and Coco Island.

The MOPT wave data were measured as part of field studies during the design and construction of Puerto Caldera. The equipment used was an ultrasonic wavemeter model USW-2000A (brand: Kaijo Denki Corporation/SONIC, Japan), which was placed 1.8 km offshore, at a depth of 15.5 m and measured for a period of 7.3 years, between 1978 and 1985; however, it presented interruptions, and the effective period of measurement was 3.3 years [7]. The available information corresponds to the main wave parameters, represented by various statistics of forty-eight storms with significant wave height greater than 1.5 m.

The CIMAT wave data were measured as part of a consultancy, whose purpose was to calibrate the NOAA wave forecast with data measured in field. The equipment used was a pressure sensor model TWR-2050 (brand: RBR Ltd., Canada), which was placed in front of Sámara at 22 m depth and maintained collecting data between 2009 and 2010. Subsequently, the equipment was moved in front of Playa Grande, where it was placed at 22 m depth during 2011. The sensor sampled at 2 Hz, so that it would take data for 20 minutes every hour; however, it only took measurements when NOAA predicted that the waves in deep water and in front of these beaches would exceed approximately 2 m wave height [8].

The CNC wave data were measured during the construction process of the Terminal de Contenedores de Moín (TCM). The equipment placed was a directional buoy model Waverider (brand: Datawell, Netherlands), which was located in front of Moín at 14 m depth and measured for 2 years, between 2015 and 2017 [9].

The MIO-CIMAR group reported wave data during the months between March and November 2020, measured by a directional oceanographic buoy model SB-138P (brand: Tideland, USA), located about 8 km northwest of Quepos, on the isobath of approximately 50 m and with real-time transmission. The buoy measured the main wave parameters, current profile and meteorological variables with a reporting interval of 15 minutes. Directional waves were measured with a MOTUS sensor (movement in Latin, brand: Aanderaa, Norway), which measures the motion of the buoy by integrating accelerometers, magnetometers, gyroscopes in its inertial motion unit (IMU) and in conjunction with an external compass for correction. The sampling rate of the free surface elevations of the MOTUS sensor was 4 Hz.

The IMARES group has measured waves at different sites along the Pacific coast with two types of equipment: an ADCP (Acoustic Doppler Current Profiler) model AWAC (Acoustic Wave and Current Profiler, brand: Nortek, Norway) and a scalar buoy model BARES (brand: HCTech, Spain). The first site where IMARES measured waves was in front of Cabo Blanco, at 15 m depth, in 2014 with an AWAC. In 2015, this equipment was moved approximately 2.5 km to the northwest at 1 m depth and currently remains at that location. The second site was in Puerto Caldera with the BARES buoy, anchored at 15 m depth, where it recorded data between 2015 and 2018. The third site was at Coco Island, where another AWAC was placed at 20 m depth, between the months of March and October 2018 and during April 2019. The fourth site was Cabo Velas, where another AWAC was placed at 18 m depth in October 2019 and continues measuring nowadays.

The AWAC equipment was set to collect data at 2 Hz for approximately 17 minutes every 3 hours. The data collected free surface records, which were then analyzed in the time and frequency domain to determine the main wave parameters. The buoy made inertial measurements in all three-axis using a gyroscope, accelerometer and a compass, and it was controlled by a low-power microcontroller. The buoy was set up to take data for approximately 17 minutes on an hourly basis and transmitted in real time. TABLE I summarizes the main information from the historical and available wave databases.

TABLE I
MAIN INFORMATION OF HISTORICAL AND AVAILABLE WAVES DATA

Location	Equipment	Recording period	Geographic Coordinates	Depth (m)	Source
Cabo Velas	AWAC	2019-present	10.36°N 85.88°W	18.0	IMARES
Playa Grande	TWR-2050	2011	10.20°N 86.00°W	22.0	CIMAT
Sámara	TWR-2050	2009-2010	9.85°N 85.50°W	22.0	CIMAT
Cabo Blanco	AWAC	2014-present	9.56°N 85.13°W	18.0	IMARES
Puerto Caldera	USW/BARES	1978-1985 2015-2018	9.91°N 84.74°W	15.5	MOPT IMARES
Quepos	MOTUS	2020-present	9.39°N 84.23°W	50.0	MIO-CIMAR
Coco Island	AWAC	2018-2019	5.50°N 87.06°W	20.0	IMARES
Moín	Waverider	2015-2017	10.03°N 83.11°W	14.0	CNC

3.2 Comparison of measured and modeled data by WAVERYS

The wave data measured for the Puerto Caldera project do not temporally overlap with the reanalysis data, so a comparison is not possible; however, this information was included as supplementary material in order to preserve the only existing wave data record from that project. The data correspond to the wave parameters of the forty-eight storms greater than 1.5 m significant wave height, which were recorded during the 7.3 years that the equipment was in place.

Fig. 2A and C show the time series of the wave parameters H_{mo} and T_p, respectively, corresponding to the data measured in front of Moín and the WAVERYS node near that site. Both sources of information follow the same pattern of behavior over time; in addition, it was found that the series of measured data shows continuity in the first year and a half of measurement and then there are periods of time with missing information. Fig. 2B shows a linear correlation of the H_{mo} data with a coefficient ρ of 95 %, a *BIAS* of 17 cm, an *SI* of 0.14 and a *RMSE* of 24 cm. Fig. 2D, corresponding to the variable T_p, shows a correlation ρ of 76 %, a *SI* of 0.11, a *BIAS* and *RMSE* of less than 1 s.

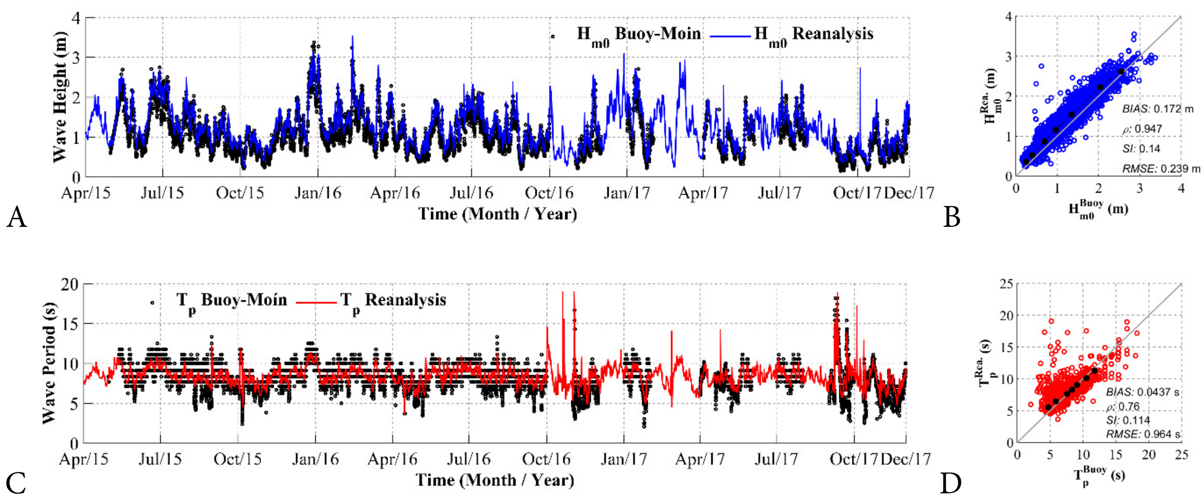

Fig. 2. Moín, A) Time series of H_{mo} parameter, B) scatter plot of H_{mo}, C) time series of T_p parameter and D) scatter plot of T_p.

Fig. 3A and C show the time series of the wave parameters H_{mo} and T_p, respectively, corresponding to the data measured in front of Quepos and the WAVERYS node near that site. The same pattern of behavior is observed over time for the two parameters with respect to each source; also, it is highlighted that the measured data is composed of a continuous series and extends from March 2020 to March 2021. Fig. 3B shows a linear correlation of the H_{mo} data with a coefficient ρ of 87 %, a *BIAS* of 20 cm, an *SI* of 0.12 and a *RMSE* of 25 cm. Fig. 3D, corresponding to the variable T_p, shows a correlation ρ of 30 %, a *SI* of 0.24, a *BIAS* and *RMSE* of less than 3 s and 4 s, respectively.

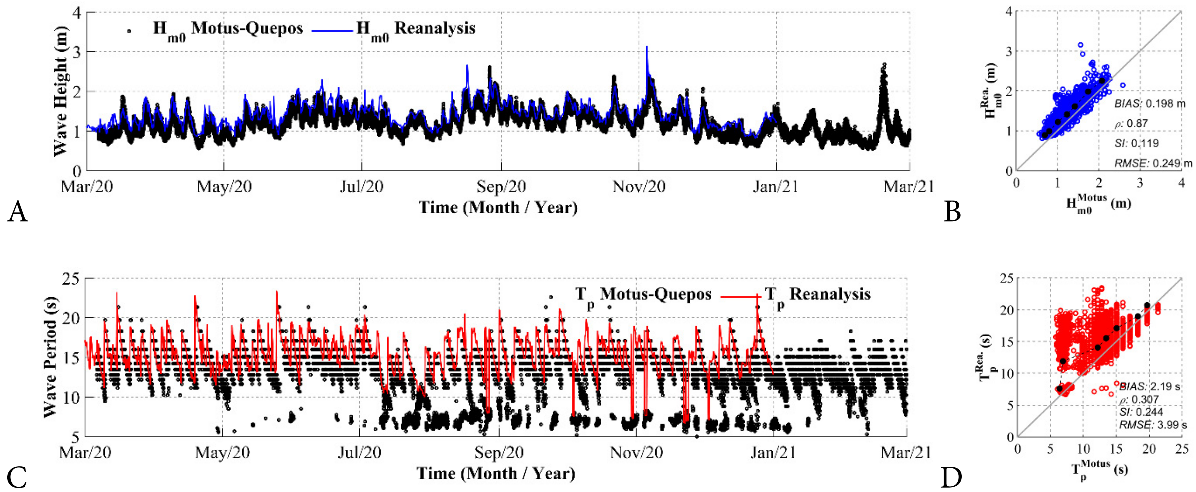

Fig. 3. Quepos, A) Time series of H_{mo} parameter, B) scatter plot of H_{mo}, C) time series of T_p parameter and D) scatter plot of T_p.

Fig. 4A and C show the time series of the wave parameters H_{mo} and T_p, respectively, corresponding to the data measured at Cabo Blanco and the WAVERYS reanalysis node near that site. Both sources of information show the same pattern of behavior over time; Fig. 4A shows that the H_{mo} values measured during 2014, recorded at a different site, are higher compared to the rest of the measured and reanalysis data; also, it is highlighted that the measured data are composed of an almost continuous series that extends to date. Fig. 4B shows a linear correlation of the H_{mo} data with a coefficient ρ of 88 %, a *BIAS* of 12 cm, a *SI* of 0.13 and a *RMSE* of 21 cm. Fig. 4D, corresponding to the T_p parameter, shows a correlation ρ of 55 %, a *BIAS* less than 2 s and *RMSE* less than 3 s.

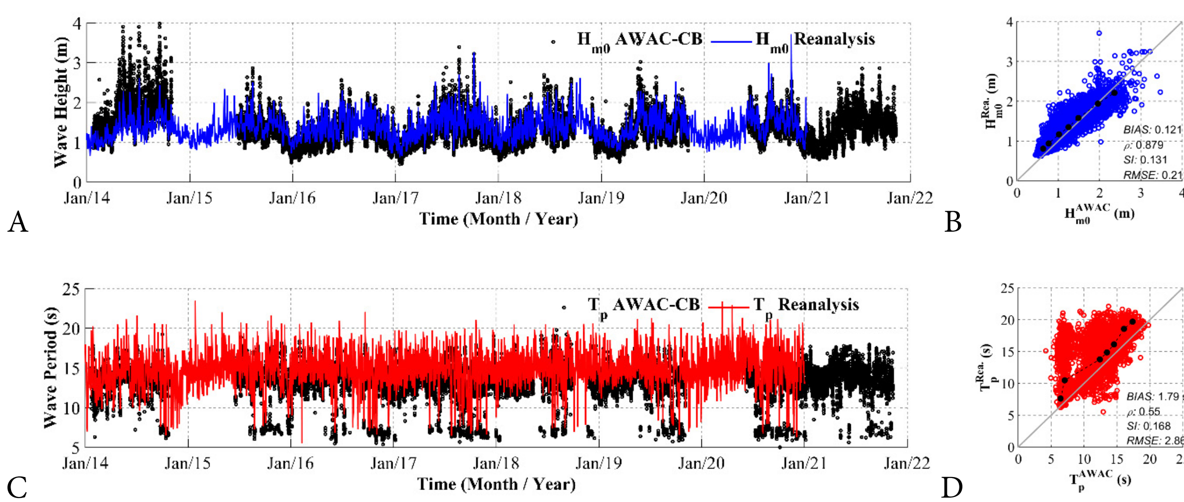

Fig. 4. Cabo Blanco, A) Time series of H_{mo} parameter, B) scatter plot of H_{mo}, C) time series of T_p parameter and D) scatter plot of T_p.

TABLES II and III show the *BIAS*, *RMSE*, ρ and *SI* results for the H_{mo} and T_p parameters for each of the sites analyzed; the respective figures were included as supplementary material. TABLE II shows that there is linear correlation of the H_{mo} parameter between both sources of information, with Puerto Caldera being the site with the lowest value of 76 %, but with the smallest BIAS of 7.7 cm towards the measured data. The rest of the sites show linear correlation values greater than 80 % and dispersion less than 0.2. TABLE III shows the periods are biased towards the WAVERYS data, the errors are less than 5 s and the correlation does not exceed 64 %.

TABLE II
STATISTICAL DESCRIPTORS OF H_{mo} PARAMETER

Location	*BIAS* (cm)	*RMSE* (cm)	ρ	*SI*
Sámara	11	24	0.81	0.16
Playa Grande	53	55	0.94	0.15
Puerto Caldera	-7.7	23	0.76	0.21
Coco Island	32	37	0.83	0.13
Cabo Velas	44	48	0.80	0.19

TABLE III
STATISTICAL DESCRIPTORS OF T_p PARAMETER

Location	*BIAS* (s)	*RMSE* (s)	ρ	*SI*
Sámara	-	-	-	-
Playa Grande	0.45	2.9	0.62	0.22
Puerto Caldera	1.1	2.5	0.64	0.16
Coco Island	2.7	3.7	0.55	0.20
Cabo Velas	2.9	4.5	0.26	0.27

Fig. 5 shows the wave roses corresponding to the H_{mo} parameter; row 1 corresponds to the data measured in the field and row 2 to the reanalysis nodes near each measurement site; columns A, B, C and D correspond to the measurement sites Cabo Velas, Cabo Blanco, Quepos, and Moín, respectively. The sites located in the Pacific show that the swell comes from the SW sector; Fig. 5A1 shows that the direction S67.5°W corresponds to 50 % of the time, followed by 25 % of the time with SW swells. However, Fig. 5B1 and C1 show that the main swell direction is S22.5°W for about 60 % of the time and 25 % of the time there are S45°W directions. Fig. 5A2, B2 and C2 coincide with the distributions of the directions reported by the measured data. In the central part of the Pacific coast, the swell concentrates the directions with a greater southern component (Fig. 5B1, B2, C1 and C2), while the northern most sector of the coast presents swells with directions with a greater western component (Fig. 5A1 and A2).

Fig. 5D1 and D2 show the same distribution of directions, with the main direction being N67.5°E with about 50 % of the time, followed by N45°E with about 30 % of the time; the rest of the time the swell direction is distributed between N and N22.5°E.

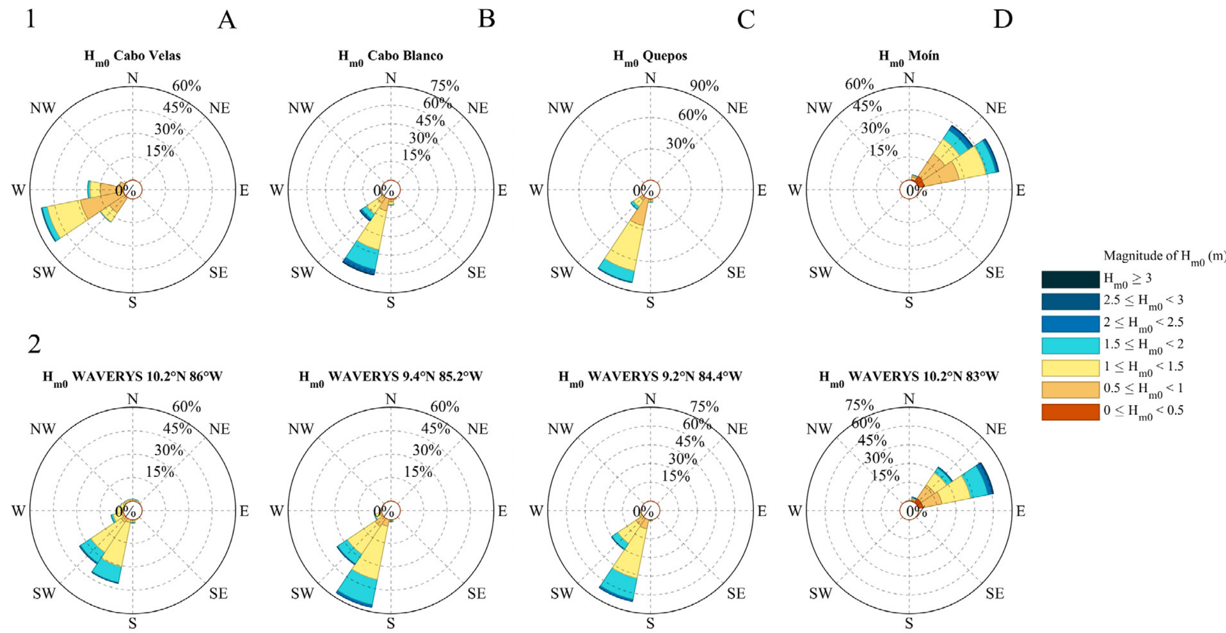

Fig. 5. H_{mo} parameter roses, 1) field data, 2) nodes of WAVERYS near to, A) Cabo Velas, B) Cabo Blanco, C) Quepos y D) Moín.

4. DISCUSSION

The analysis of the field measured data shows a swell climate that varies in time and space, and that corresponds, for example, to the Pacific coast, with the weather patterns of other latitudes. The most extensive wave database, corresponding to Cabo Blanco, shows an oscillatory annual behavior of the H_{mo} variable. Between the months of November and March, the H_{mo} magnitudes are, on average less than 1 m with a T_p of approximately 15 s; between the months of April and October, the magnitudes of H_{mo} and T_p increase and are of the order of 1.5 m and 17 s, respectively; while during the months between June and August, some waves exceed 3 m height and 20 s of peak period.

This behavior coincides temporally with the climatology of the southern hemisphere, where the summer and winter months coincide with the months of lowest and highest wave energy in the Costa Rican Pacific, respectively. Thus, it is found that the swell originates in the southwestern Pacific Ocean, it travels approximately 9000 km to cross the ocean and reach the coast of Central America [18]-[19].

On the other hand, wave data measured in the Caribbean show that months with the highest wave energy occur between December and March, with H_{mo} and T_p magnitudes of about 2 m and 10 s, respectively; the lowest energy months occur between September and October, with H_{mo} magnitudes of approximately 1m and T_p of 8 s. Between the months of July and August, wave events occur with high H_{mo} magnitudes, but normally lower than those occurring between months of December and March.

This behavior coincides with the climatology of the trade winds, which present their greatest magnitudes between months of December and March; then their speeds decrease, increase again between months of July and August, and decrease again between September and October [20].

The wave height roses generated from the data measured in field and from the reanalysis confirm that the swell has a greater variability of directions in the northern sector of the Pacific coast; that is, the swell directions are distributed between south and west. Nevertheless, in the central sector of the Pacific coast the swell shows less variability with mainly south-southwest directions. This could be because the Galapagos Islands, located about 1300 km away, alter the propagation process of the swell coming from the southern hemisphere.

The H_{mo} parameter measured in Cabo Blanco during 2014 shows higher magnitudes than those reported in the rest of the record but follows the same annual behavior. This difference could be attributed to the fact that the equipment, starting in 2015 and up to the present, was relocated 2.5 km northwest of the site where it was originally placed in 2014.

In Caldera, the H_{mo} magnitudes are biased towards the measured data; that is, the data measured in the field are higher than those reported by the WAVERYS. It is possibly because the equipment was placed in front of the breakwater and close to cliffs that are reflective, which could influence the measurements and be evidenced as an increase in the energy measured by the equipment. In the rest of the sites, being coastal sites and directly exposed to waves, the reanalysis shows higher magnitudes of the H_{mo} parameter than the data measured in the field.

As for the T_p parameter, the results at all sites show that there is a temporal correlation with the database. However, the peak period is an imprecise parameter to compare, as it is the maximum frequency associated with the spectrum; being the measured spectra of a higher sampling resolution than the theoretical wave spectra, which generally have programmed wave reanalysis.

The comparison of the H_{mo} parameter between the measured and WAVERYS wave data reveals that there is a temporal and linear correlation between the databases, even though they do not match spatially. This demonstrates that, despite not being a calibration, WAVERYS reanalysis is able to adequately follow trends in space and time. The wave parameter H_{mo}, which, added to its spatial and temporal homogeneity, gives it a great value and usefulness to undertake, as a first approximation, different projects of maritime engineering, environmental, mariculture, wave energy and risk mitigation product of extreme events. Likewise, the magnitudes of the statistical descriptors related to the period and direction obtained coincide in order of magnitude with those estimated by [12] in their validations.

5. CONCLUSIONS

This work compiled, in a single source of consultation, the wave information that has been measured in the country in order to preserve the data, make them available to the scientific community and the corresponding decision-making authorities, upon request to the authors. Among them, the wave data measured by IMARES and MIO-CIMAR groups stands out, being an unpublished source of information of great value for the country and for the region, since it is an area of the globe where primary information is scarce.

The measured data were used to validate the WAVERYS wave reanalysis information; an adequate temporal and spatial coincidence was verified in the sites analyzed, so it is concluded that the reanalysis is suitable for various marine science and marine engineering projects in this region. However, this source of information is considered complementary to the measured data, and for more accurate results it is convenient to calibrate with measured data.

ACKNOWLEDGMENTS

We would like to thank the Ministerio de Obras Públicas y Transportes for financing the wave measurements at Cabo Blanco, the Comisión de Marinas y Atracaderos Turísticos, the Consejo Nacional de Concesiones and APM Terminals for providing the wave data. We would also like to thank the technical staff of IMARES, who made an exceptional contribution to the fieldwork.

ROLES

Henry Alfaro-Chavarría: Conceptualización, Análisis formal, Adquisición de fondos, Investigación, Metodología, Administración del proyecto, Validación, Redacción – borrador original – Preparación

Javier Zumbado-González: Curación de datos, Análisis formal, Recursos, Software, Visualización

Rodney Mora-Escalante: Curación de datos, Recursos, Software, Redacción – revisión y edición – Preparación

Felipe Calleja-Apéstegui: Conceptualización, Redacción – revisión y edición – Preparación

Georges Govaere-Vicarioli: Conceptualización, Adquisición de fondos, Metodología, Recursos, Supervisión, Redacción – revisión y edición – Preparación

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COMPLEMENTARY MATERIAL

TABLE A1
FORTY-EIGHT HIGHEST WAVES SURVEYED DURING THE CONSTRUCTION OF PUERTO CALDERA

Ranking	Date				Hmax (m)	Tmax (s)	H1/10 (m)	T1/10 (s)	H1/3 (m)	T1/3 (m)	Hmean (m)	Tmean (s)
	Year	Month	Day	Time								
1	1981	5	21	16	5.44	16.90	4.17	17.80	3.55	17.90	2.19	15.10
2	1983	7	18	4	4.44	16.80	4.09	17.20	3.47	17.10	2.31	16.10
3	1978	6	18	8	4.10	18.00	3.90	17.80	3.30	17.50	1.90	15.00
4	1985	5	28	17	4.17	16.30	3.74	17.70	2.94	17.80	1.85	15.50
5	1982	3	18	12	3.83	15.70	3.10	16.10	2.86	15.90	1.33	12.30
6	1985	9	13	17	3.66	19.80	3.47	17.70	2.77	17.60	1.73	13.00
7	1981	5	6	18	3.98	20.00	3.43	16.70	2.74	17.40	1.58	12.00
8	1983	8	7	24	3.80	16.90	3.27	17.30	2.66	17.50	1.71	16.00
9	1980	11	5	8	3.36	17.70	2.95	17.60	2.53	17.10	1.55	12.50
10	1985	10	2	23	3.22	17.60	2.83	17.30	2.49	17.00	1.54	12.30
11	1981	11	29	2	3.14	17.50	2.93	16.40	2.44	16.40	1.50	13.90
12	1980	10	16	22	3.55	18.10	3.11	17.30	2.22	17.10	1.30	12.40
13	1985	10	27	7	2.92	17.50	2.75	17.10	2.20	17.30	1.33	14.50
14	1982	6	12	4	2.75	13.90	2.53	14.50	2.13	15.70	1.38	12.80
15	1978	9	18	4	3.20	9.00	2.70	8.60	2.10	8.90	-	-
16	1985	5	17	18	3.05	16.90	2.55	17.30	2.10	16.10	1.26	10.70
17	1981	11	20	24	3.10	16.10	2.37	15.50	2.06	15.90	1.41	13.90
18	1985	8	18	8	2.88	14.20	2.56	15.60	2.06	15.60	1.26	12.90
19	1981	7	10	20	2.69	17.60	2.30	14.60	2.02	15.40	1.21	11.00
20	1978	10	3	16	3.00	15.00	2.50	16.00	2.00	16.00	-	-
21	1979	8	7	16	2.50	20.00	2.30	19.00	2.00	18.20	1.40	16.20
22	1981	3	21	18	2.48	14.30	2.29	15.50	2.00	15.70	1.21	13.00
23	1981	11	1	20	2.99	16.30	2.40	16.40	1.99	16.10	1.23	18.30
24	1978	8	6	4	3.20	14.00	2.40	14.50	1.90	14.50	-	-
25	1979	5	20	24	2.50	17.00	2.30	16.00	1.90	16.00	1.30	15.00
26	1985	4	17	15	3.00	12.90	2.41	9.60	1.88	12.30	1.08	8.50

Ranking	Date				Hmax (m)	Tmax (s)	H1/10 (m)	T1/10 (s)	H1/3 (m)	T1/3 (m)	Hmean (m)	Tmean (s)
	Year	Month	Day	Time								
27	1985	9	26	9	2.48	15.70	2.30	16.30	1.85	16.30	1.13	13.40
28	1985	6	30	13	2.50	14.30	2.18	12.10	1.81	12.70	1.12	8.50
29	1979	9	7	16	2.70	18.00	2.30	16.00	1.80	15.40	1.10	12.20
30	1982	8	7	18	2.62	16.00	2.26	16.20	1.79	16.50	1.06	11.80
31	1985	8	5	11	2.45	17.80	2.17	16.30	1.75	16.50	1.16	13.70
32	1985	3	19	2	2.53	16.00	2.12	17.00	1.74	16.70	1.16	13.70
33	1979	9	25	16	2.50	16.00	2.10	16.00	1.70	15.00	1.20	12.00
34	1985	9	8	15	2.46	15.00	2.04	14.30	1.70	14.50	1.07	12.20
35	1981	1	17	6	2.26	13.80	1.98	13.90	1.67	14.20	1.01	13.00
36	1982	3	9	14	2.35	14.30	2.03	13.70	1.61	13.50	0.96	9.70
37	1978	9	12	20	2.70	14.00	2.00	15.40	1.60	15.00	-	-
38	1983	9	9	6	2.45	15.60	1.98	14.90	1.60	15.00	1.01	11.40
39	1978	7	9	16	2.00	16.00	1.90	15.90	1.60	16.00	-	-
40	1985	7	17	4	1.93	16.00	1.80	15.70	1.58	16.10	1.06	14.00
41	1982	5	19	10	2.42	14.90	1.93	14.90	1.57	14.80	1.00	12.50
42	1981	2	7	22	2.40	14.30	1.96	14.20	1.57	14.30	0.97	13.10
43	1982	8	15	6	2.55	15.80	1.99	15.20	1.56	15.50	1.00	11.90
44	1984	2	26	22	1.89	13.40	1.59	14.70	1.56	11.30	0.90	9.50
45	1985	6	15	7	2.29	13.10	2.04	13.30	1.51	13.30	0.91	11.60
46	1983	8	15	22	2.12	12.80	1.90	13.70	1.51	13.70	0.93	9.90
47	1980	9	11	22	2.06	11.50	1.82	11.80	1.51	11.70	0.97	9.70
48	1978	10	15	4	1.90	16.00	1.70	15.00	1.50	14.00	-	-

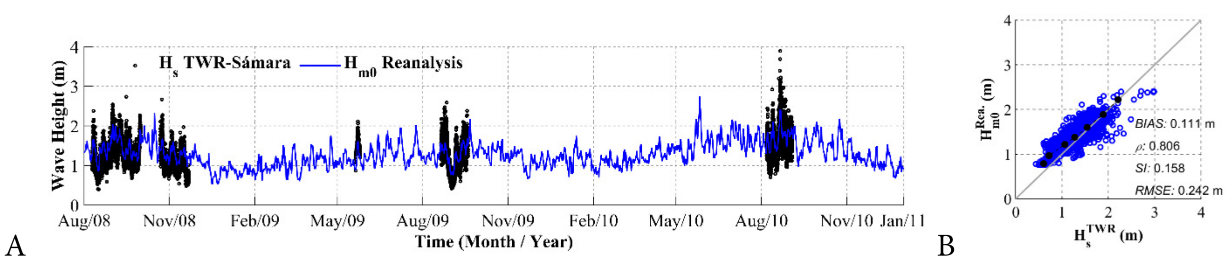

Fig. B1. Sámara Beach, A) Time series of H_{mo} parameter and B) scatter plot of H_{mo}.

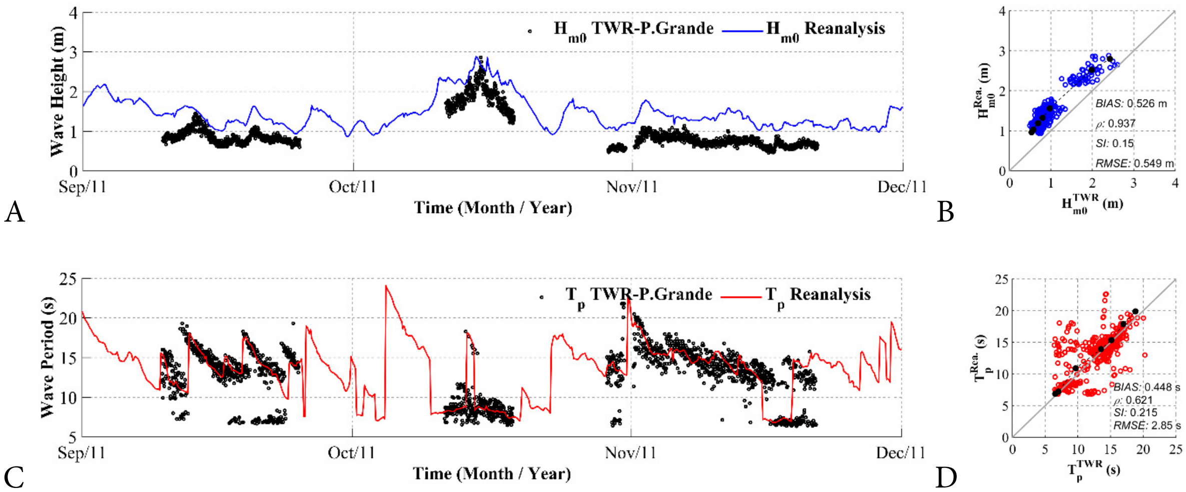

Fig. B2. Playa Grande, A) Time series of H_{mo} parameter, B) scatter plot of H_{mo}, C) time series of T_p parameter and D) scatter plot of T_p.

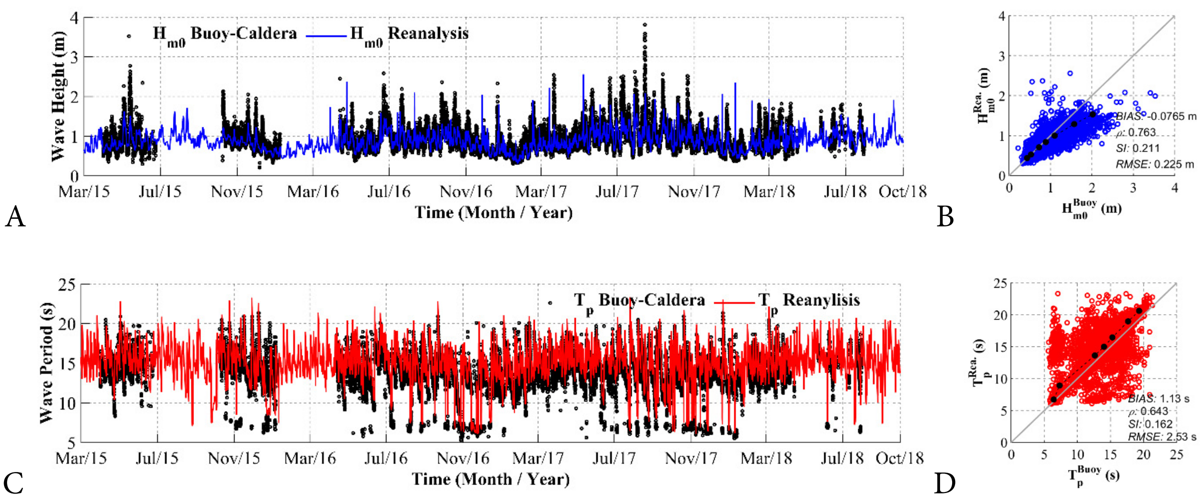

Fig. B3. Puerto Caldera, A) Time series of H_{mo} parameter, B) scatter plot of H_{mo}, C) time series of T_p parameter and D) scatter plot of T_p.

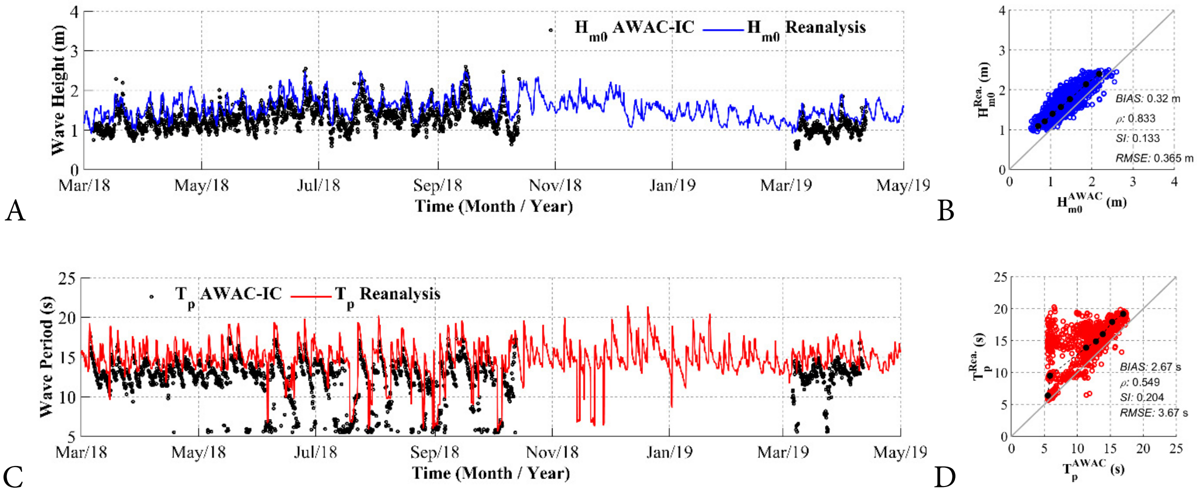

Fig. B4. Coco Island, A) Time series of H_{mo} parameter, B) scatter plot of H_{mo}, C) time series of T_p parameter and D) scatter plot of T_p.

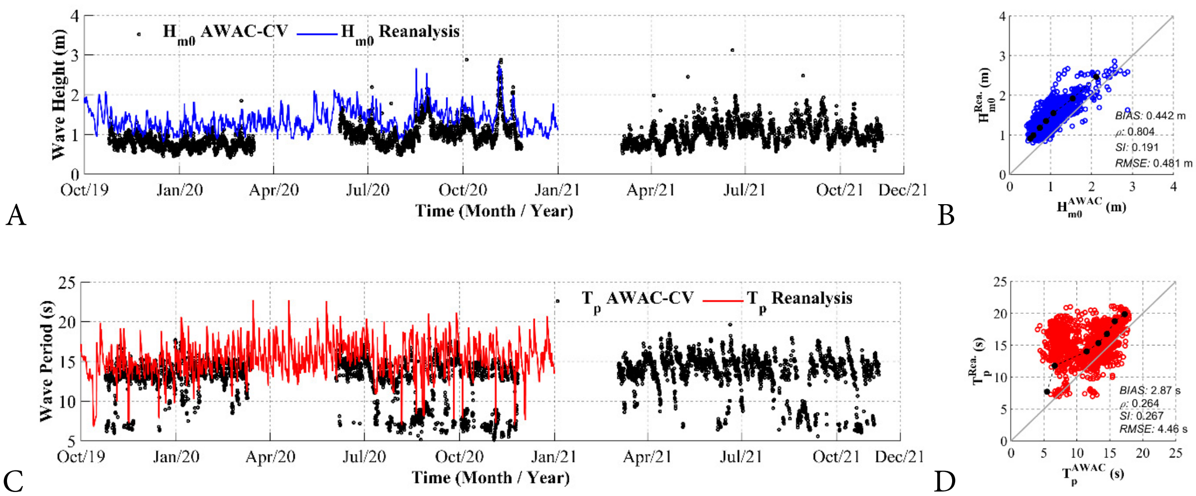

Fig. B5. Cabo Velas, A) Time series of H_{mo} parameter, B) scatter plot of H_{mo}, C) time series of T_p parameter and D) scatter plot of T_p.