UNIVERSIDAD NACIONAL DE INGENIERÍA

FACULTAD DE INGENIERÍA MECÁNICA

SECCIÓN DE POSGRADO Y SEGUNDA ESPECIALIZACIÓN

DOCTORAL THESIS

WAVE ENERGY RESOURCE FOR OPEN SEA CONDITIONS OF THE PERU BASIN

TO OBTAIN THE ACADEMIC DEGREE OF DOCTOR IN SCIENCE WITH MENTION IN ENERGY

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LIMA-PERU

2022

DEDICATORY

Dedicated to my wife, Ruth, and my children, Grescia and Lionel, for their support throughout these academical journey. To my parents, for being important in my professional career.

Finally, I dedicate this work to all of who supported me in several ways to achieve this doctoral degree.

ACKNOWLEDGEMENTS

I thank FIM-UNI (Facultad de Ingeniería Mecánica de la Universidad Nacional de Ingeniería) which financed my doctoral studies.

I want to acknowledge my advisor, **Arturo Ortega, PhD** for the invaluable orientation to this thesis.

I would also like to acknowledge to my co-advisor, **Jaime Luyo, PhD**, for his important orientation to the thesis, useful advice and encouragement in academic aspects.

I also thanks to **Luis Lastra PhD**, for promoting Professors to research in FIM-UNI when he was Dean.

Finally, I express my gratitude to all personal of the Doctoral program of UNI for collaboration in the administrative issues at University.

RESUMEN

Las tecnologías para convertir la energía de las olas en electricidad aún no están maduras y es necesario conocer las características ambientales de las olas en el área donde se instalarán. Las investigaciones que se ocupan del estudio de la energía undimotriz disponible pretenden reducir la incertidumbre que aún existe en la estimación de la energía undimotriz y su variabilidad. Esta tesis doctoral tiene como objetivo estudiar el recurso energético de las olas para condiciones de mar abierto en la Cuenca marítima peruana. Los métodos utilizados son el espectral, estadístico y numérico. Se propone un conjunto de criterios para evaluar el rendimiento de la energía de las olas y seleccionar una forma espectral estándar con un período de ola promedio para condiciones de mar abierto. Este estudio se realiza mediante el procesamiento de datos ambientales temporales de oleaje registrados durante 18 años por dos boyas en el Océano Pacífico Sureste específicamente en la cuenca marítima *PERU BASIN*. Los resultados muestran que la energía de las olas es predominantemente alta en el segundo y tercer trimestre. El valor promedio de la potencia de ola es superior a 15 kW/m durante todo el año. La dirección de las olas es principalmente suroeste (225°) la mayor parte del año. La energía anual se concentra en un rango limitado de alturas de olas y períodos de energía. La discrepancia de potencia de las olas es de aproximadamente 46% cuando la forma espectral y el período no se seleccionan de acuerdo con las condiciones de mar abierto. La energía de las olas en los lugares en estudio pasó la evaluación en base a los criterios sugeridos para evaluar su desempeño. Se espera que utilice dispositivos Pelamis, Power buoy y Wave Dragon para la recolección de energía de las olas en la Cuenca del Perú.El espectro marino se considera de banda ancha durante todo el año, por lo que es necesario calcular la altura de las olas en función del parámetro de amplitud espectral. Se propone un nuevo coeficiente para estimar la altura significativa de ola en la cuenca marítima del Perú. La potencia del oleaje direccional se concentra en más de la mitad del total omnidireccional propagado desde el Suroeste en junio, julio y agosto con una dispersión de 30º. La fórmula analítica que mejor estima la potencia de las olas se basa en el espectro de Bretschneider y el período de cruce por cero ascendentes con una subestimación del 8%. Se encontró que el coeficiente de calibración para el período pico converge a 0.8 en estados de mar de alta energía, para el período de cruce por cero ascendente corresponde a 1.25. Por lo tanto, de acuerdo con los resultados y la discusión, el clima de olas en la Cuenca marítima del Perú es estable en el tiempo, con comportamiento estacional, baja variabilidad y muy predecible. Todo esto hace que la instalación de convertidores de energía de las olas sea atractiva o se considere favorable para continuar las investigaciones cerca de la costa de la Cuenca del Perú.

Palabras clave: Energía de ola, Convertidor de energía de ola, Potencia de ola, Altura de ola significativa, Espectro Bretschneider, Espectro JONSWAP, Periodo de energía, Cuenca marítima Perú.

ABSTRACT

Technologies to convert wave energy into electricity are not yet mature, and they need to know the environmental characteristics of the waves in the area where they will be installed. Research dealing with the study of available wave energy aims to reduce the uncertainty that still exists in estimating wave power and its variability. This doctoral thesis aims to study the wave energy resource for open sea conditions in the Eastern South Pacific specifically in Peru Basin. The methods used are the spectral, statistical and numerical methods. A set of criteria is proposed to evaluate wave power performance and select a standard spectral shape with an average wave period for open ocean conditions. This study is carried out by processing temporary environmental data of waves recorded for 18 years by two buoys in the Peru Basin. The results show wave energy is predominantly high in the second and third quarters. The average value of wave power is greater than 15 kW/m throughout the year. The direction of the waves is mainly Southwest (225°) most of the year. Annual energy is concentrated in a limited range of wave heights and energy periods. The wave power discrepancy is approximately 46% when spectral shape and period are not selected according to open sea conditions. Wave energy at the locations under study passed the evaluation based on the criteria suggested for evaluating their performance. It is expected to use Pelamis, Power buoy and Wave Dragon devices for wave energy harvesting in Peru Basin.The sea spectrum is considered broadband all year round, requiring the wave height to be quantified depending on the spectral amplitude parameter. A new coefficient for estimating the significant wave height in Peru Basin is proposed. The directional wave power is concentrated in more than half of the total omnidirectional propagated from the Southwest in June, July and August with a dispersion of 30º. The analytical formula that best estimates the wave power is based on the Bretschneider spectrum and the zero-crossing period with an underestimation of 8%. The calibration coefficient for the peak period was found to converge to 0.8 in the high-energy sea states, for the zero up-crossing period corresponds to 1.25. Therefore, according to the results and discussion, the wave climate in Peru Basin is stable over time with seasonal behaviour, with low variability, and very predictable. All of this makes the installation of wave energy converters attractive or considered favourable for continued investigations near the coast of Peru Basin.

Keywords: Wave energy, Wave energy converter, Wave power, Energy period, Significant wave height, Bretschneider spectrum, JONSWAP spectrum, Peru Basin.

CONTENTS

FIGURES

SYMBOLS

H_s	Significant wave height
H_{m0}	Estimated spectral of significant wave height
T_z	Zero up-crossing period
T_p	Peak period
T_e	Energy period
ϵ	Spectral broadness parameter
α	Propagation direction of waves with North as 0°
f	Frequency in Hz
S_ζ	Point spectrum
$S_\zeta(f,\alpha)$	Directional spectrum
$D(f,\alpha)$	Spread function
J_α	Maximum resolved wave power
α_J	Direction of maximum resolved wave power
d_α	Wave power directionality coefficient
$J_{spectral}$	Omnidirectional wave power calculated from spectral data
$J_{parametric}$	Omnidirectional Wave power from integral wave parameters
J	Omnidirectional wave power

ABBREVIATIONS

NDBC	National Data Buoy Center
IEC	International Electrotechnical Commission
JONSWAP	Joint North Sea Wave Project
WEC	Wave energy converter
SWAN	Third-generation wave model
CV	Coefficient of variability

CHAPTER 1. INTRODUCTION

In this work, the wave energy resource at two closely spaced locations offshore the Peru Basin was estimated using buoy data. A mean zero up-crossing period and a Bretschneider spectral shape, both the most suitable for open sea conditions, were used to quantify the mean wave power, its variability and directionality, and the amount of potential energy. Based on previous research, a set of proposed criteria was used to assess wave power performance.

Behaviour over time and the relationship between wave parameters such as wave power, significant wave height, energy period, spectral broadness parameter, maximum directional wave power, directionality coefficient and direction of directional wave power have also been analyzed. In addition, the wave power estimations based on standard sea spectra to approximate the energy period have been compared with the wave power quantified from spectral data. Moreover, the relationship between the calibration coefficients with the squared significant height for all sea states was analyzed.

The justification of this thesis is to improve the wave energy resource assessments by studying the resource attributes of south-east pacific for their potential wave energy, conducting a comprehensive evaluation of wave energy resources for the open ocean, and utilizing the Peruvian sea basin as a case study, implementing programming codes for data processing.

1.1 MOTIVATION OF THE THESIS

With the constant development of technology for the conversion of wave energy into electrical energy [1], currently the union of the sectors is being developed: wind and wave to replace systems based on fossil fuels [2], [3], [4]. Wave energy will be usable once the technology is within reach and the detailed behaviour of the wave climate is known where wave energy converters (WEC) are to be installed.

One of the problems in the wave energy sector is the level of uncertainty in assessing the wave energy resource, like the accuracy of historical data [5] and variability and predictability of the wave climate [6]. So far, wave energy resource characterization was mainly carried out based on a relatively small number of sea states propagated towards the shore employing spectral wave models [7]. Examples of these characterizations are possible to find all over the world. In Europe, Wave energy potential in Galicia (NW Spain) [8]; Wave energy assessment in Sicily (Italy) [9]; Wave energy extraction in Scotland through an improved nearshore wave atlas [10]. In America, wave energy potential assessment in the Caribbean Low-Level Jet using wave hindcast information [11]; Nearshore assessment of wave energy resources in central Chile (2009-2010) [12].

A first estimation of the wave energy resource in Peru has been done. Based on one-wave buoy measurements, a general picture of the resource has been drawn, and the most representative offshore sea states were propagated towards the coast utilizing a numerical model to map the wave energy distribution on the nearshore. [13]. This last reference presents among other important things the monthly distribution in % of the total annual energy: offshore wave resource and Peruvian electric demand, according to the monthly variation, namely, there is a large variability for wave throughout the year than the variability of Peruvian electric demand (See Fig. 1). And, the mean wave energy flux has uniform spatial distribution with values of the mean wave power over 17 kW/m because large water depth and the absence of obstacles (implying low energy losses during propagation), (See Fig. 2).

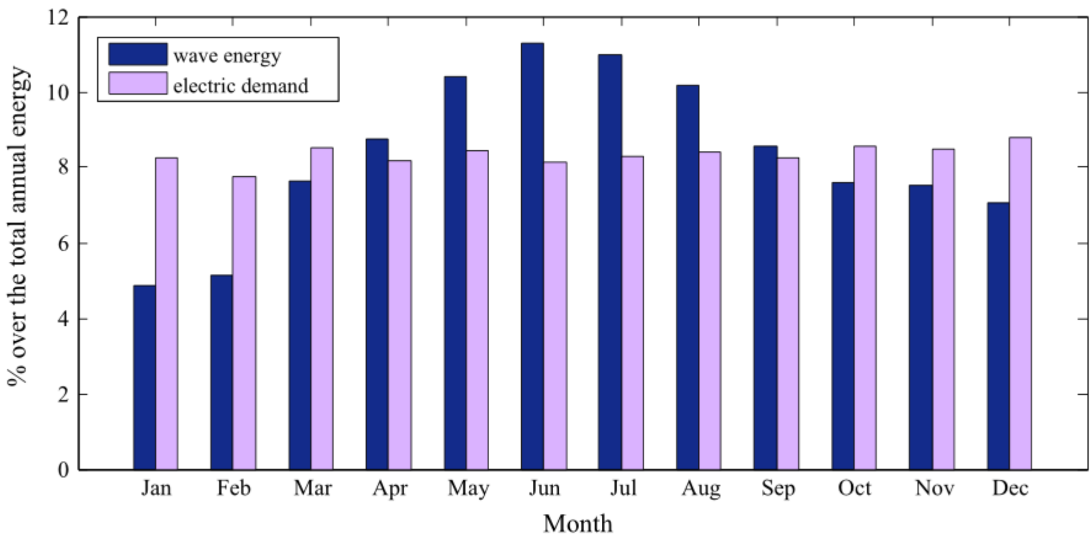

Fig. 1. Monthly distribution in % of the total annual energy: offshore wave resource and Peruvian electric demand [13].

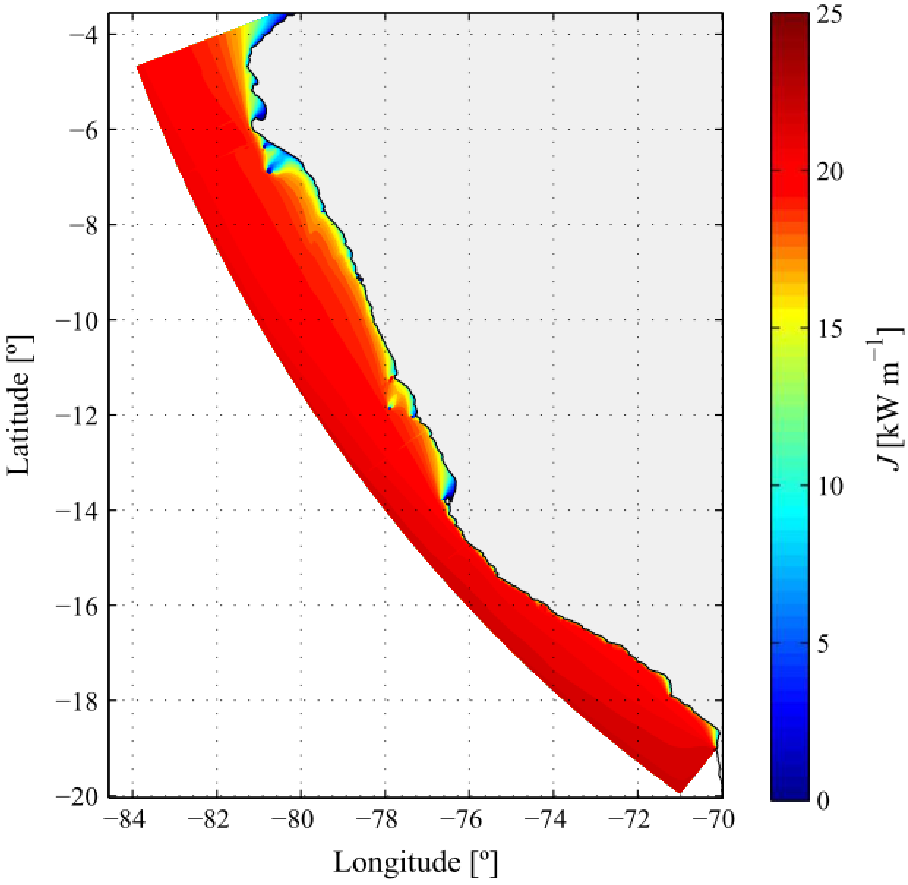

Fig. 2. Mean wave energy flux [13]

While, West coast of South America is recognized as Classes 3 and 4 [14]. These classes are moderate wave energy classes. Significant wave height distributions are similar for classes 3 and 4 and the variability in significant wave height is again similar each other and the lowest for all classes. Correspondingly, the risk factors are also lowest for these two classes. These classes are primarily found on the western coast of continents but away from direct storm impact; these areas are well exposed to long swell waves from distant storms, and such conditions generate the majority of their resources.

Nowadays, there is a standard for wave energy resource assessment and characterization -IEC-TS 62600-101-2015, which recommends six wave parameters and at least 90% of sea states to characterize and assess the magnitude and quality of a wave energy resource [15].

As highlighted above and from the literature review, most works have been done for North Hemisphere and Asia, mainly for confined water or nearshore, [16], [17], [18], but not for the open ocean as in Peru Sea Basin.

For South-East Pacific (See Fig. 3 for location) there is a lack of information about the behaviour of wave climate to make reliable the deployment of wave energy converters, specifically in Peru Basin (Historical data in Peru Basin, see Fig. 4).

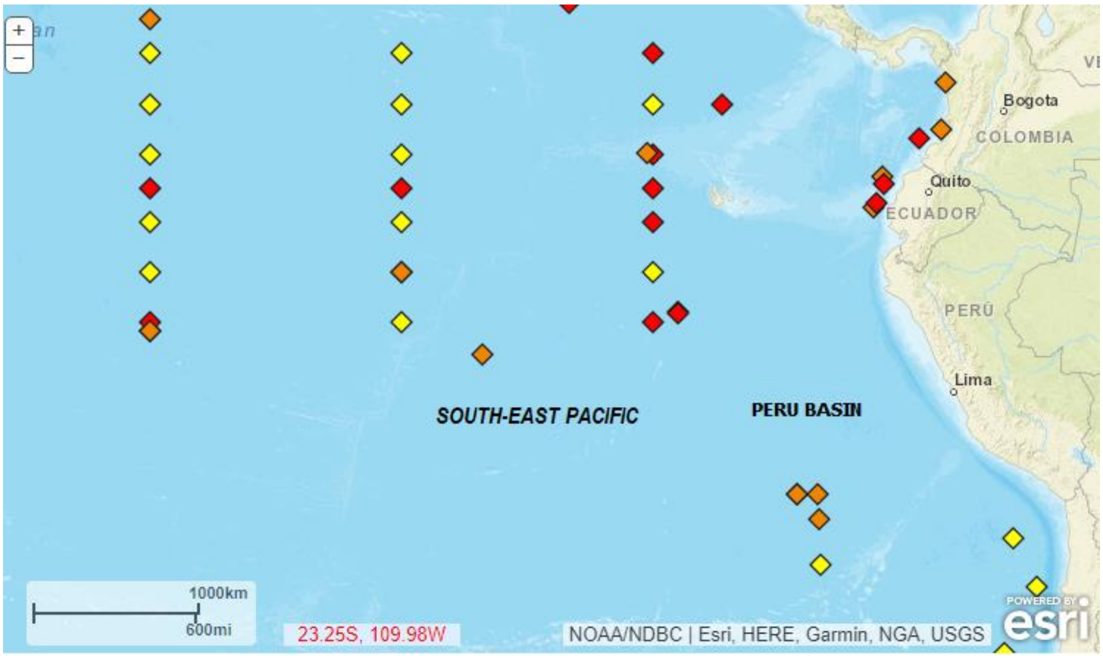

Fig. 3. Location of South-East Pacific area in particular the Peru Basin.

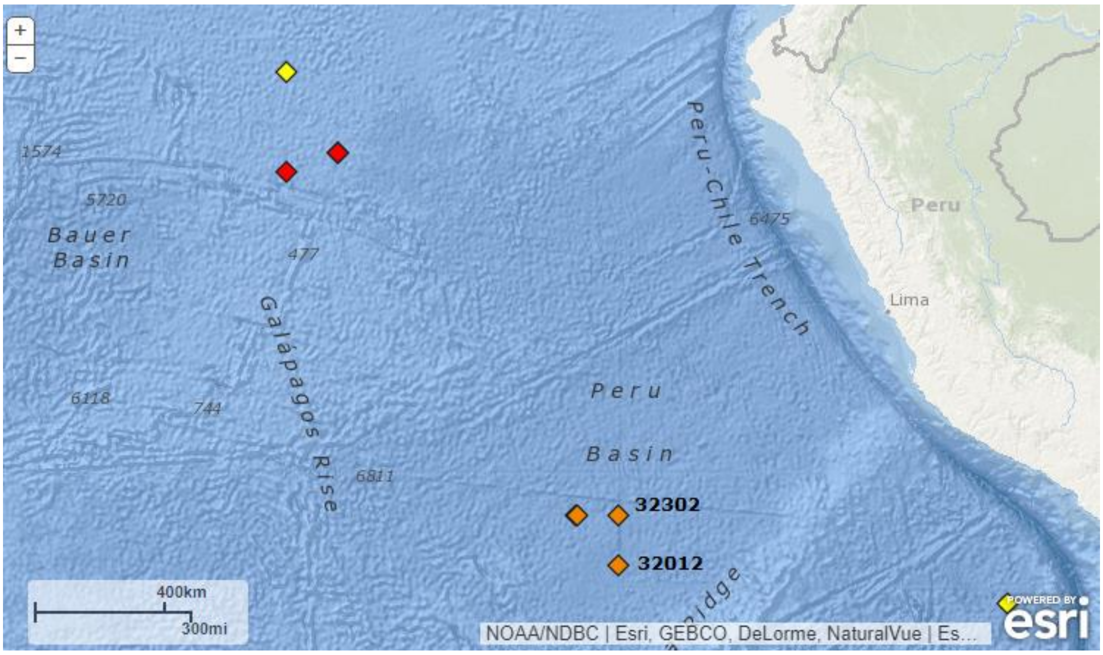

Fig. 4. Ubication of buoys. Buoy 32302 contains integral wave parameter data and 32012 provides integral wave data and spectral data.

1.2 LITERATURE REVIEW

i. The PhD. Thesis, by Curtis Rusch (2021) "Scaling of Point-Absorber Wave Energy Converter Hydrodynamics" [19] stablishes that harnessing power from the marine environment is an active area of research and development, with a growing emphasis on blue economy applications where the global presence of wave energy provides compelling opportunities, and designs a wave energy converter based on the most up to date information of wave energy resource.

ii. The PhD. thesis, by Seongho Ahn (2019), "Wave energy resource characterization and classification for the United States" [20] improved the wave energy resource assessments by characterizing the resource attributes and classifying the US coastal waters for their potential wave energy. It also investigated and mapped the wave resource attributes parameterized by simple indices of the variability, or constancy, of the resource, which can affect the capacity factor and annual energy production of a wave energy generation project.

iii. The PhD. thesis, by Pilar Fernandez (2017), "Estudio del potencial de aprovechamiento energético del océano en la costa Andaluza" [21] studied the potential of ocean energy for Andalucia-Spain, including suitable wave energy converters, sea conditions like currents, tides and waves and restraints for installing and operating wave energy converters.

iv. The research paper, by Rezvan Alamian (2017) "Wave energy potential along the southern coast of the Caspian sea" [18]. Their main goal was to find a suitable location for installing wave energy conversion systems along the southern coast of the Caspian Sea, within Iran's territorial waters, based on the data obtained from ECMWF2 between 1999 and 2013. The authors plotted annual and seasonal diagrams of wave height, period, and energy at 17 different locations. Based on the analyzed data, they suggested that two cities are suitable locations for installing wave energy conversion systems.

v. The research paper, by V. Ramos et al (2016), "Exploring the utility and effectiveness of the IEC (International Electrotechnical Commission) wave energy resource assessment and characterization standard: A case study" [7] explored the methodology of Wave energy resource assessment and characterization (IEC-62600-101) standard using the Irish West Coast as a case study. Overall, they found that the methodology proposed performs well, offering a detailed characterization of the resource; however, to make the technical specification more manageable, the authors recommended revisiting the procedures related to the seasonality of the wave resource for future editions.

vi. The research paper, by Joao Morim et al (2016), "Wave energy resource assessment along the Southeast coast of Australia" [22], a long-term assessment of the wave energy resource potential for the Australian southeast shelf, was performed from deep to shallow water, based on a 31-year wave hindcast. The hindcast, which covers the period from 1979 to 2010, has been performed at high Spatio-temporal resolution with the wave energy transformation model, SWAN, using calibrated source-term parameters. The high-resolution model allowed them to perform an in-depth analysis of wave power characteristics, providing resource knowledge on seasonal and longer-term variability necessary for wave technology's reliable and optimal design.

vii. The research paper, by Shuping Wu et al (2015), "Offshore wave energy resource assessment in the East China Sea" [16]. In this paper, the offshore wave energy resource in the East China Sea (ECS) off the coast of southern

East China is assessed by the authors using wave buoy data covering the period of 2011-2013. They found that the average offshore wave power was approximately 13 kW/m in the region of interest.

viii. The PhD Thesis, by Brendan Cahill (2013), "Characteristics of the wave energy resource at the Atlantic marine energy test site" [23] assessed and characterized the wave energy resource that has been measured and modelled at the Atlantic Marine Energy Test Site, a facility for conducting sea trials of floating wave energy converters being developed near Belmullet, on the west coast of Ireland.

ix. The PhD Thesis, Ian Ashton (2011), "Spatial variability of wave fields over the scale of a wave energy test site" [24] established the magnitude of the random error term for verification of theoretical variability, identified the underlying processes contributing to deterministic differences and quantified their effect.

As a summary of the literature review, there is a wide and increasing interest in the study of the energy source of waves and efforts are aimed at reducing the uncertainty of the evaluation of the energy potential of sea waves.

1.3 OUTLINE OF THE WORK

The thesis is organized as follows:

Chapter 1: This chapter presents the thesis's introduction, including the justification, thesis's motivation, literature review and outline of the work.

Chapter 2: This chapter describes the theorical framework of the thesis.

Chapter 3: This chapter describes problem statement, research questions, objectives and hypothesis.

Chapter 4: This chapter describes the methodology for data processing, through algorithms and pseudo codes.

Chapter 3: This chapter summarises the scientific articles that constitute this doctoral thesis; scientific articles as a product of the research carried out.

Chapter 4: This chapter details the contribution to the state of the art of scientific articles of the doctoral thesis.

Chapter 5: This chapter makes a summary and the results of the scientific articles..

Chapter 6: This chapter answers the research questions.

Chapter 7: This chapter recommends carrying out various investigations in the area of energetics.

CHAPTER 2. WAVE ENERGY RESOURCE FOR OPEN SEA CONDITIONS

The theoretical framework of this thesis is that composed of the relationship between wave parameters and wave power, mainly in open sea conditions characterized by a standard Bretschneider spectrum and in contrast to confined sea conditions characterized by a JONSWAP spectrum.

This theoretical framework begins by detailing wave parameters. The methodology to approximate the energy period Then, the different approximations of the wave power based on the wave parameters is detailed. Next, the method to quantify the directional wave power is presented. Finally, the indicators of variability and discrepancy are explained.

2.1 WAVE PARAMETERS

The representative wave height is the significant wave height calculated from the wave elevation variance of an omnidirectional wave spectrum. The estimated expression for significant wave height, considering narrowband assumption, is written as [25]:

$$H_{m0} = 4\sqrt{m_0}, \qquad \textit{Equation 1}$$

where m_0 is calculated through numerical methods from

$$m_0 = \sum_{i=1}^{n-1} 0.5(S_i + S_{i+1})(f_{i+1} - f_i), \qquad \textit{Equation 2}$$

$$m_2 = \sum_{i=1}^{n-1} 0.5(S_i f_i^2 + S_{i+1} f_{i+1}^2)(f_{i+1} - f_i), \qquad \textit{Equation 3}$$

$$m_4 = \sum_{i=1}^{n-1} 0.5(S_i f_i^4 + S_{i+1} f_{i+1}^4)(f_{i+1} - f_i). \qquad \textit{Equation 4}$$

Wave spectral data consist of a finite number of components (n) of observed spectral energy density ($S_i = S_\zeta(f_i)$, with $i \in [1, n]$).

In general, the moment of order n of the variance spectrum (m_n) or spectral moment of order n is calculated as:

$$m_n = \int_0^\infty f^n S_\zeta(f) df, \qquad \textit{Equation 5}$$

The zero-crossing period of the waves, regarding to a reference level on the sea surface, is calculated as [26]:

$$T_z = \sqrt{\frac{m_0}{m_2}}. \qquad \textit{Equation 6}$$

The peak period T_p is calculated as the inverse of the frequency corresponding to the peak of the wave spectrum.

The spectral broadness parameter ϵ is calculated by means of the spectral moments:

$$\epsilon = \sqrt{1 - \frac{m_2^2}{m_0 m_4}}, \qquad \textit{Equation 7}$$

or ϵ can be expressed as [27]:

$$\epsilon = \sqrt{1 - \left(\frac{T_c}{T_Z}\right)^2}, \qquad \textit{Equation 8}$$

where T_c is the peak-to peak period, calculated as:

$$T_c = \sqrt{\frac{m_2}{m_4}}. \qquad \textit{Equation 9}$$

2.2 APPROXIMATION OF ENERGY PERIOD

The average period of the component waves or wave energy period T_e is calculated as:

$$T_e = \frac{m_{-1}}{m_0}. \qquad \textit{Equation 10}$$

However, to date wave climate databases are commonly restricted to providing parameters that do not include T_e. The wave energy period is defined as that of a sinusoidal wave containing the same amount of energy as an actual wave. Climate databases normally only provide T_p and T_z.. Commonly T_p has been used instead of T_z since the former is more widely available. Both are approximated to T_e using a calibration coefficient λ:

$$T_e = \lambda T_k, \qquad \textit{Equation 11}$$

where λ can take several values depending on standard point spectrum chosen. where *k* refers to *p* (peak) or *z* (zero-crossing) as explained in the PAPER 4.

2.3 MODELLING THE POWER AND ENERGY OF WAVES.

The group velocity or speed that the wave energy propagates c_g (m/s) can be calculated for deep waters, like in the case of the Peru Sea Basin, by:

$$c_g = \frac{g}{4\pi f}, \qquad \textit{Equation 12}$$

where g is the gravitational acceleration (9.81 m/s^2) and f is the wave frequency (Hz).

According to the principle of linear superposition of waves, the omnidirectional wave power (potential wave energy per unit wavelength) J (kW/m) can be calculated by integrating the c_g multiplied by S_ζ (m^2/s):

$$J_{spectral} = \rho g \int_0^\infty c_g(f) S_\zeta(f) df, \qquad \textit{Equation 13}$$

where ρ is the seawater density (1025 kg/m^3).

The wave power spectral ($J_{spectral}$) is approximated in a parametric relationship for the omnidirectional wave power ($J_{parametric}$) as a function of H_{m0}, and T_e [28]:

$$J_{parametric} = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e, \qquad \textit{Equation 14}$$

The omnidirectional wave power can be calculated in a discrete way by numerical methods of integration. The formulation of $J_{spectral}$ is thus expressed as:

$$J_{spectral} = \rho g \sum_{i=1}^{n-1} 0.5\left(c_{g,i} S_i + c_{g,i+1} S_{i+1}\right)(f_{i+1} - f_i), \qquad \textit{Equation 15}$$

with $c_{g,i} = c_g(f_i)$ obtained for a frequency f_i.

The wave energy per unit crest length per average year *E*, in W·h/m/year, is obtained from:

$$E = \sum_{i=1}^{n} h_i J_i, \qquad \textit{Equation 16}$$

where *n* is the number of sea states, and h_i are hours that a given sea state *i* lasts in an average year. J_i is the wave power for the given sea state *i*.

The mean wave direction θº is a reference direction. This mean wave direction considers the most representative wave direction.

2.4 ESTIMATION OF THE DIRECTIONAL WAVE SPECTRUM

The directional wave spectrum can be calculated with the following expression:

$$S_\zeta(f,\alpha) = S_\zeta(f) D(f,\alpha), \qquad \textit{Equation 17}$$

where $S_\zeta(f,\alpha)$ is the directional wave spectrum. It is a function of the wave frequency *f* and the wave propagation angle α which is measured clockwise relative to the geographic North, direction from which the waves are assumed to be approaching. $D(f,\alpha)$ is a spread function, which can be expressed using the Fourier series :

$$D(f,\alpha) = \frac{\left[\frac{1}{2} + r_1 \cos(\alpha - \alpha_1) + r_2 \cos\big(2(\alpha - \alpha_2)\big)\right]}{\pi}, \qquad \textit{Equation 18}$$

where r_1 and r_2 are the first and second normalized polar coordinates of the Fourier coefficients. α_1 and α_2 are the main and mean wave direction, respectively.

The characteristics of the directionality of sea state are the maximum directional wave power (J_{α_J}) and the wave power directionality coefficient (d_α). The directional wave power can be calculated as [29]:

$$J(f,\alpha) = \rho g c_g(f) S_\zeta(f,\alpha). \qquad \textit{Equation 19}$$

Thus, the directional wave power propagating to a particular direction α (J_α) can be calculated by summing the power of all waves traveling in that direction α according to their given frequency:

$$J_\alpha = \sum_i J(f_i,\alpha)\Delta f_i \Delta\alpha. \qquad \textit{Equation 20}$$

The wave power directionality coefficient is the ratio of the maximum directional wave power to the omnidirectional wave power:

$$d_\alpha = \frac{J_{\alpha_J}}{J}. \qquad \textit{Equation 21}$$

this directional coefficient tells us how concentrated the wave power is. Knowing the direction of J_{α_J} (α_J) is important because wave power is predominant in a particular direction, direction in which wave energy converters must be oriented to harvest maximum power.

2.5 INDICATORS TO EVALUATE VARIABILITY AND DISCREPANCY

2.5.1 Calculation of the Coefficient of Variability

The coefficient of variability (*CV*) is a statistical parameter used to assess whether a “statistical characteristic” is consistent or variable. *CV* is calculated as:

$$CV = \frac{standard\ desviation\ \ of\ the\ feature}{average\ value\ of\ the\ feature}. \qquad \textit{Equation 22}$$

If *CV* is less than 0.2, we state that the statistical characteristic or feature under study is consistent or quasi-constant.

2.5.2 Temporal variability

The Variability Index characterizes the temporal differentiations of the resource; there are annual, seasonal and monthly and it is defined as:

$$AV = \frac{J_{y1} - J_{y2}}{J_{year}}, \qquad \textit{Equation 23}$$

where J_{year} is the annual average wave power. J_{y1} and J_{y2} are the average wave powers available for the years with the highest and lowest energy, respectively. This formulation is adapted to estimate the Seasonal Variability Index *SV(J)* and Monthly Variability Index *MV(J)* of the wave power.

$$SV = \frac{J_{S1} - J_{S2}}{J_{year}}, \qquad \textit{Equation 24}$$

$$MV = \frac{J_{M1} - J_{M2}}{J_{year}}, \qquad \textit{Equation 25}$$

2.5.3 Discrepancies formulations

Discrepancy in the Calculation of the Averages Wave Power or the underestimates or overestimates of *J*, calculated according to the approximation of T_e for the parametric formulation are obtained by:

$$\%Discrepancy = \frac{\bar{J}_{parametric} - \bar{J}_{spectral}}{\bar{J}_{spectral}} x\ 100, \qquad \textit{Equation 26}$$

the superscript “-“ indicates averages of the values calculated from the time series of the ocean wave data.

Discrepancy of Averages Values or the underestimates or overestimates of *J* based on integral wave parameters and calculated according point spectrum selected is:

$$\%Discrepancy = \frac{\bar{J}_{JONSWAP} - \bar{J}_{Bretschneider}}{\bar{J}_{Bretschneider}} x100, \qquad \textit{Equation 27}$$

where the superscript “-” indicates averages of the values calculated.

The discrepancy in the calculation of the significant wave height calculated according to the approximation of the factor that estimates H_{m0} is obtained by:

$$\%Discrepancy == \frac{Factor_{narrowband} - Factor_{broadband}}{Factor_{broadband}} x\ 100. \qquad \textit{Equation 28}$$

CHAPTER 3. RESEARCH DESIGN

This doctoral thesis has the purpose of producing knowledge and theories or basic research. This thesis has a quantitative approach.

3.1 PROBLEM STATEMENT

In a previous study on the offshore wave energy resource off the coast of Peru [13], the wave energy resource was first characterized, and its temporal variability was analyzed. A wave propagation numerical model (*SWAN*) was then used to determine the spatial distribution of near-shore wave energy. The authors presented the first estimation of the wave energy resource of the Peruvian sea waters using data taken over six years (2007-2012). However, the work assumed a Joint North Sea Wave Project (JONSWAP) spectrum for Peruvian sea wave conditions. The work reported that the average wave power and the maximum power near the Peruvian coast are 32 kW/m and 260 kW/m, respectively, which coincides with the results obtained for the Southeast Pacific from a global evaluation of wave energy resources [30] which is also based on the use of a JONSWAP spectrum, a standardized spectrum not designed to represent open ocean conditions. Additionally, the peak period was used to quantify wave power; however, this dominant period is not representative of open ocean conditions, as sea waves and swell waves dominate offshore wave environmental conditions.

Additionally, there is little exhaustive data on wave climates and investigations of wave energy potential in open ocean conditions in the southern hemisphere, especially in the South Pacific. Recent studies of wave power and sea states have been carried out in the Southeast Pacific, such as those developed in the evaluation of wave energy on the central-south coast of Chile [31], [12] and Peru [13]. Likewise, there is concern about the still existing uncertainties when estimating the wave power of integral wave parameters provided in historical records by mainly oceanic buoys. Several assumptions of standardized sea spectra have been made to approximate the energy period, a vital wave parameter when estimating wave power. In [32], it is appreciated that wave power is generally estimated assuming standard forms of the wave energy spectrum and that it can present more significant differences in the combined sea states, including swell waves (or long crest waves or two-dimensional wave) and waves generated by local winds (three-dimensional wave) with two energy maxima, at low and high frequencies, respectively. This multiplicity of wave systems results in a wide range of values for wave energy resource evaluation according to calibration coefficient values estimated by different methods, resulting in incorrect wave energy values.

3.2 RESEARCH QUESTIONS

The research questions corresponding to the papers presented respectively are the following:

i. Do wave energy resources in Peru Basin have potential, based on integral wave parameters in open ocean conditions?

ii. Is the wave power concentrated in a small range of propagation directions?

iii. What is the variability of wave power over time-based on integral parameters under open ocean conditions in the Peru Basin?

iv. What is the accuracy in evaluating omnidirectional wave power based on integral wave parameters using wave periods characteristic of open sea conditions and not also?

v. Is there a significant discrepancy between wave power calculated in confined ocean conditions and wave power in open ocean conditions?

vi. How do multiple wave systems influence significant wave height and omnidirectional wave power in the Peru Basin sea states?

vii. What criteria evaluate the performance of wave power so that the installation of energy converters is feasible?

3.3 OBJECTIVES OF THE THESIS

The main objective of this doctoral thesis is to study wave energy resources for open sea conditions utilizing the Peru Basin as analysis unit, in which future wave farms will operate. This investigation will be also used to further research near coasts.

The specific research objectives corresponding to the papers presented respectively are the following:

i. To assess wave energy resources in Peru Basin based on integral wave parameters. This assessment includes a scatter diagram of relative frequencies, wave energy distribution and quantification for each sea state. It also includes wave power direction and its relationship to wave height and energy period. This research complements the global wave energy assessment, carried out mainly in the northern hemisphere.

ii. To evaluate the wave climate in open sea conditions (unlimited fetch) using directional spectral data from Peru Basin as the unit of analysis to provide exhaustive information on the prevailing wave climate in the region under study.

iii. To analyse the wave power average variability in the Peru Basin based on integral wave parameters, considering its open sea wave conditions and contrasting its results with previous work.

iv. To determine the overestimates and underestimates when calculating the parametric omnidirectional wave power through peak period or zero up-crossing period and propose new calibration coefficients under the Peru Sea Basin conditions. These coefficients will allow predicting more exact wave power values for the region under study.

v. To assess the wave power average in the Peru Basin in a different location into the Peru Basin, considering its open sea wave conditions based on integral wave parameters and contrasting its results with previous work.

vi. To determine the presence of multiple wave systems and its influence in the significant wave height and omnidirectional wave power and quantify the spectral broadness parameter, its time series, averages and variability.

vii. To propose a complete set of criteria to evaluate the performance of the wave energy resource or wave power and thereby justify or not the installation of a wave conversion farm.

3.4 HYPOTHESIS OF THE THESIS

The hypothesis of the thesis doctoral corresponding to the papers presented respectively are the following:

i. Wave energy resources in Peru Basin has potential based on integral wave parameters in open ocean conditions.

ii. Wave climate in open sea conditions (unlimited fetch) using directional spectral data from Peru Basin has seasonal behaviour, no longitudinal trend and the maximum resolved wave power has low directional spread.

iii. The wave power has low temporal variability.

iv. Exist overestimates and underestimates when calculating the parametric omnidirectional wave power through peak period or zero up-crossing period.

v. Wave energy resource in other buoy in Peru Basin has potential to be harvested, considering its open sea wave conditions.

vi. There are multiple wave systems in sea states of Peru Basin that influence in the significant wave height and omnidirectional wave power.

vii. Criteria to evaluate the performance of the wave energy resource or wave power can assess installation feasibility of wave energy converters.

CHAPTER 4. DATA PROCESSING

This chapter explains the data processing of the doctoral thesis. The quantitative method calculates the energy potential, directionality and temporality, their characteristic parameters and the variability of these characteristics for the open sea conditions. These calculations will be carried out using measured data from the temporary wave elevation records obtained by the oceanographic buoys installed by NOAA, published on its website and located in the Peruvian sea basin. Subsequently, various analyses are carried out, among them the spectral one and calculations according to the wave energy theory to determine the characteristics of the energy potential of the wave energy resource in the open sea, taking the Peruvian sea as the subject of analysis.

The data consists of more than 75,000 records and has been tabulated as a single database. From this database, several of the wave weather characteristics have been processed through numerical methods. Which, in turn, has allowed to quantify other characteristics of the wave climate, which normally are not determined.

These characteristics of the wave climate were processed to obtain important findings in its behaviour using pivot tables, reports, and diagrams.

In determining the directional spectrum of the sea and the directional characteristics, a computer program was implemented to obtain the results and make the graphs. The algorithm consists of calculating the directional spectrum, making sure that it is positive for each of the frequencies and selecting the largest directional spectrum in each iteration. Then, this iterative operation is performed for each of the wave propagation directions. This loop selects the higher wave power and records its direction. In the last direction, the loop returns the maximum directional wave power and also its direction. This loop is made for all the temporal records of the oceanic data.

The algorithm for processing maximum wave power and its direction is described in Fig. 5. The pseudocode for processing maximum wave power and its direction is described in Fig. 6.

The algorithm for processing the peak period from the oceanic data consists in selecting the higher spectrum data and convert its frequency into period. This procedure is repetitive for all data. The algorithm and pseudocode for processing peak period is described in Fig. 7 and Fig. 8.

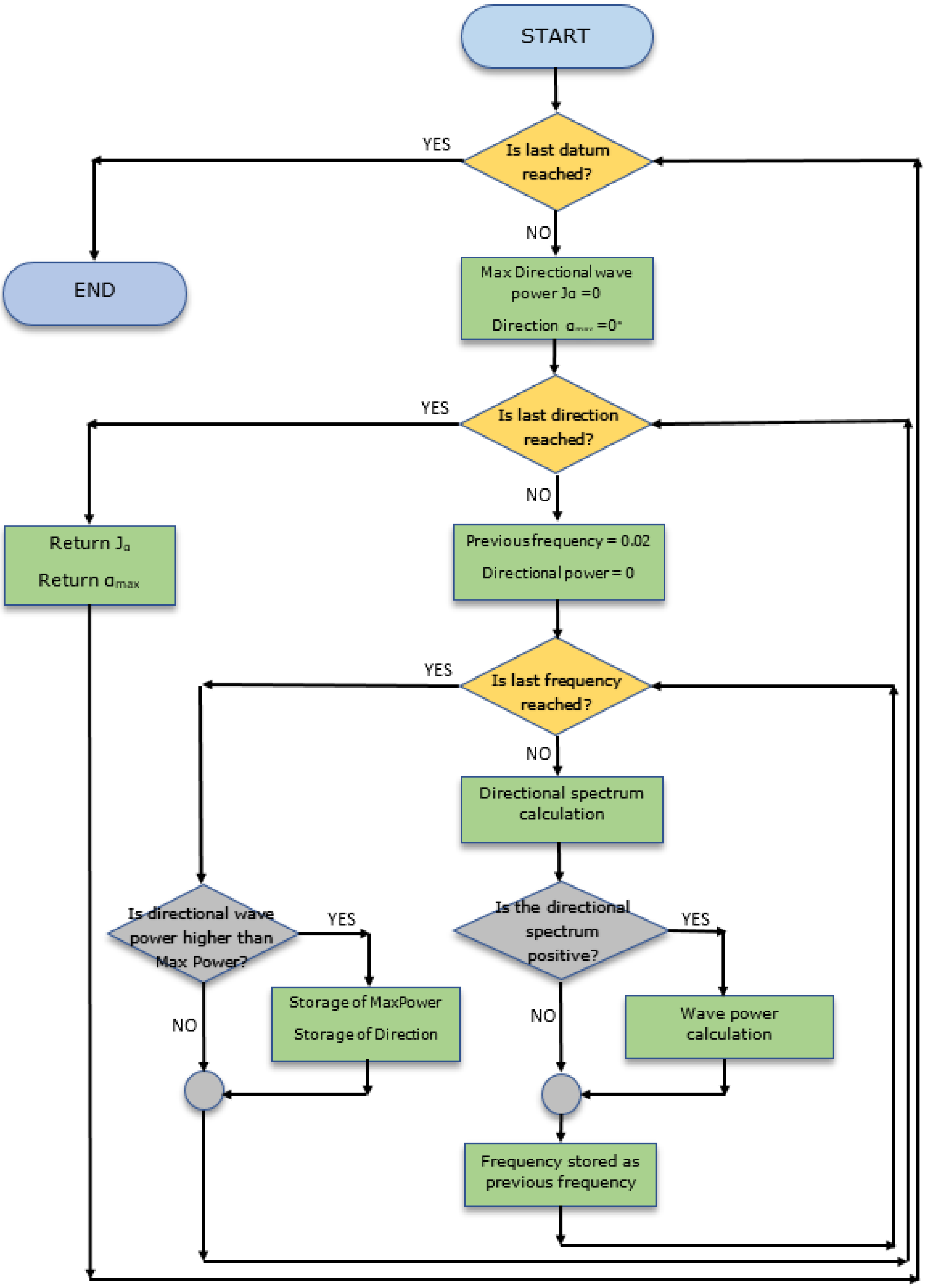

Fig. 5. Algorithm for the maximum directional power and its direction.

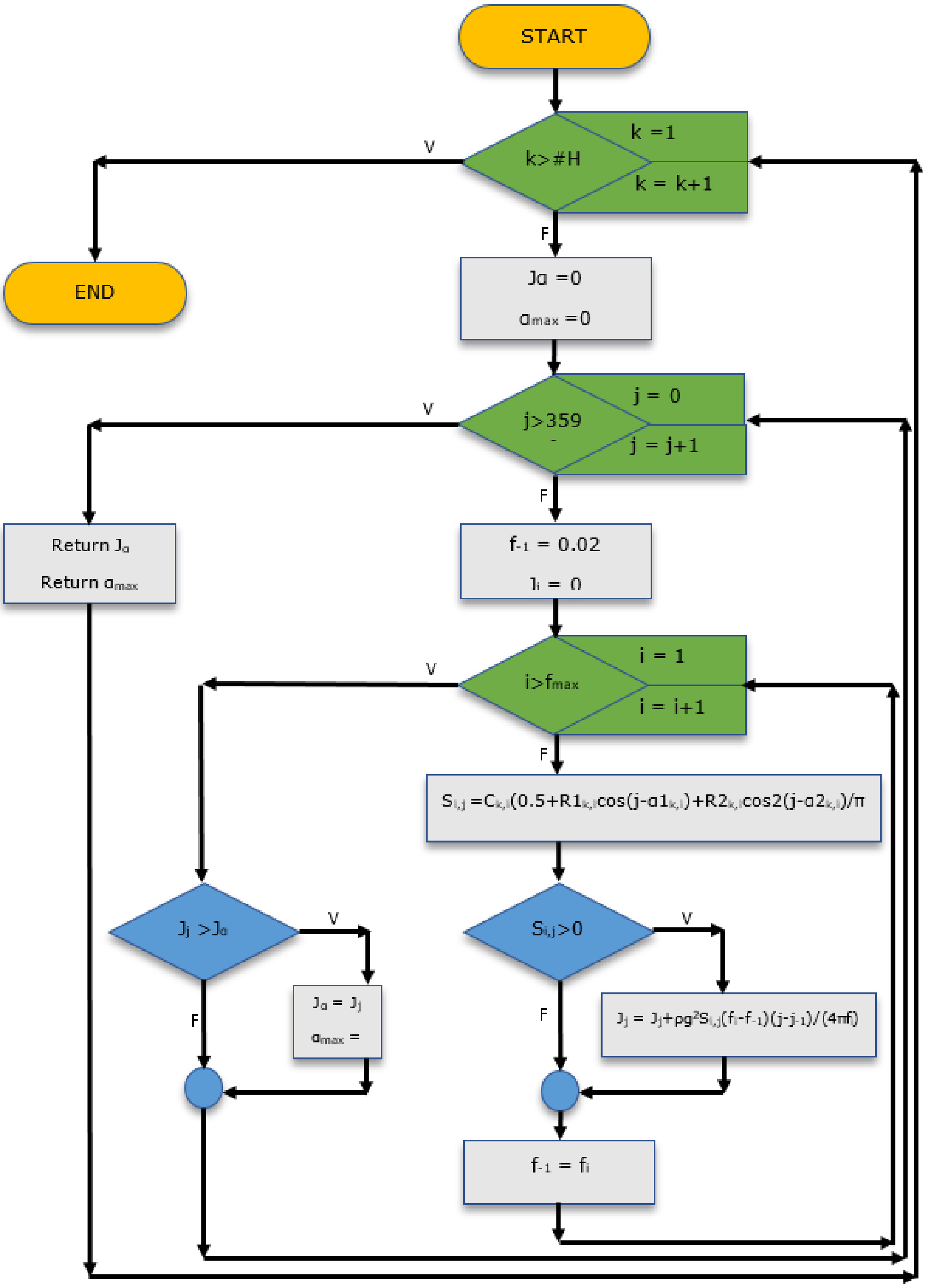

Fig. 6. Pseudocode for the maximum directional power and its direction

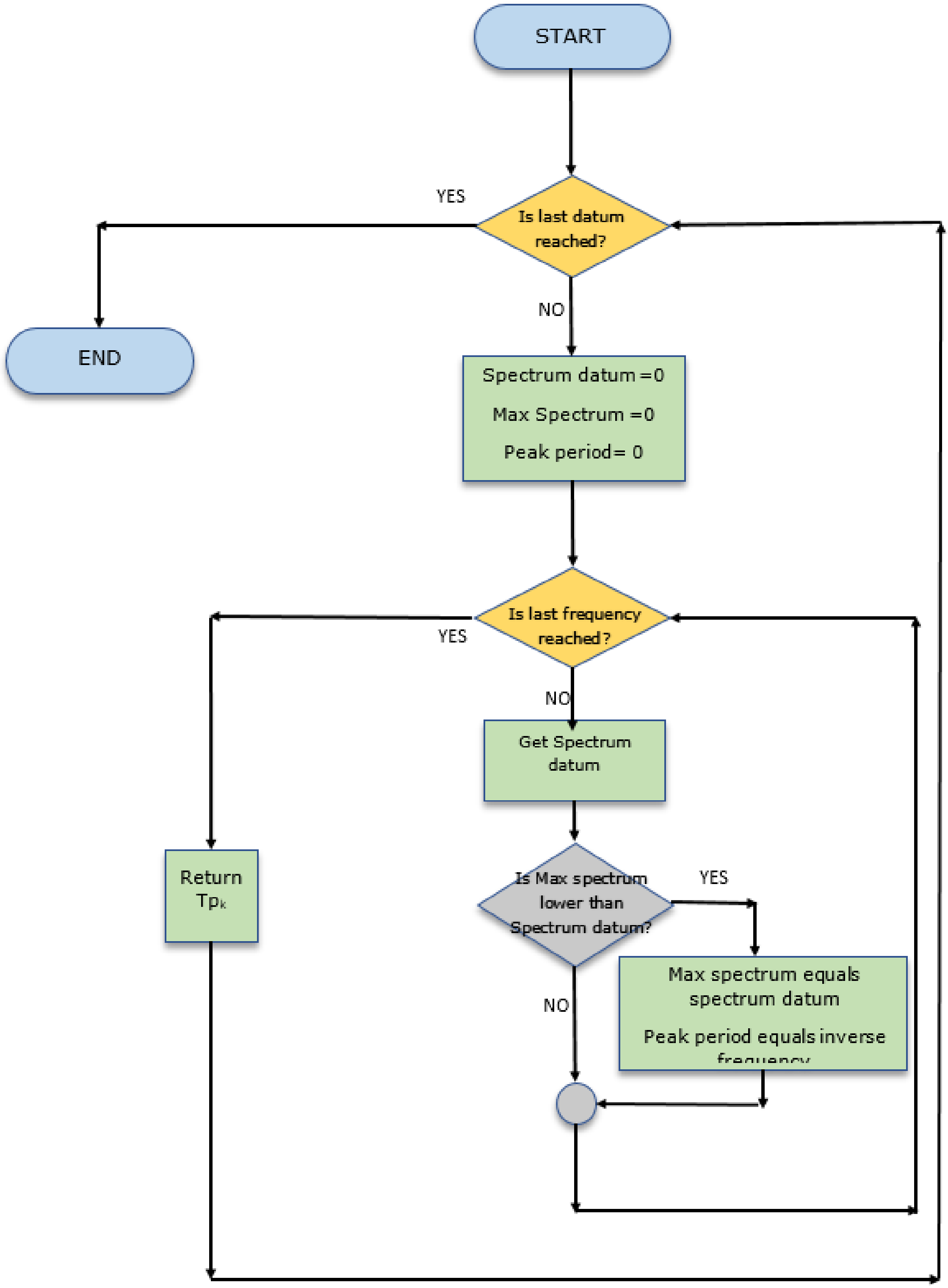

Fig. 7. Algorithm for peak period calculation

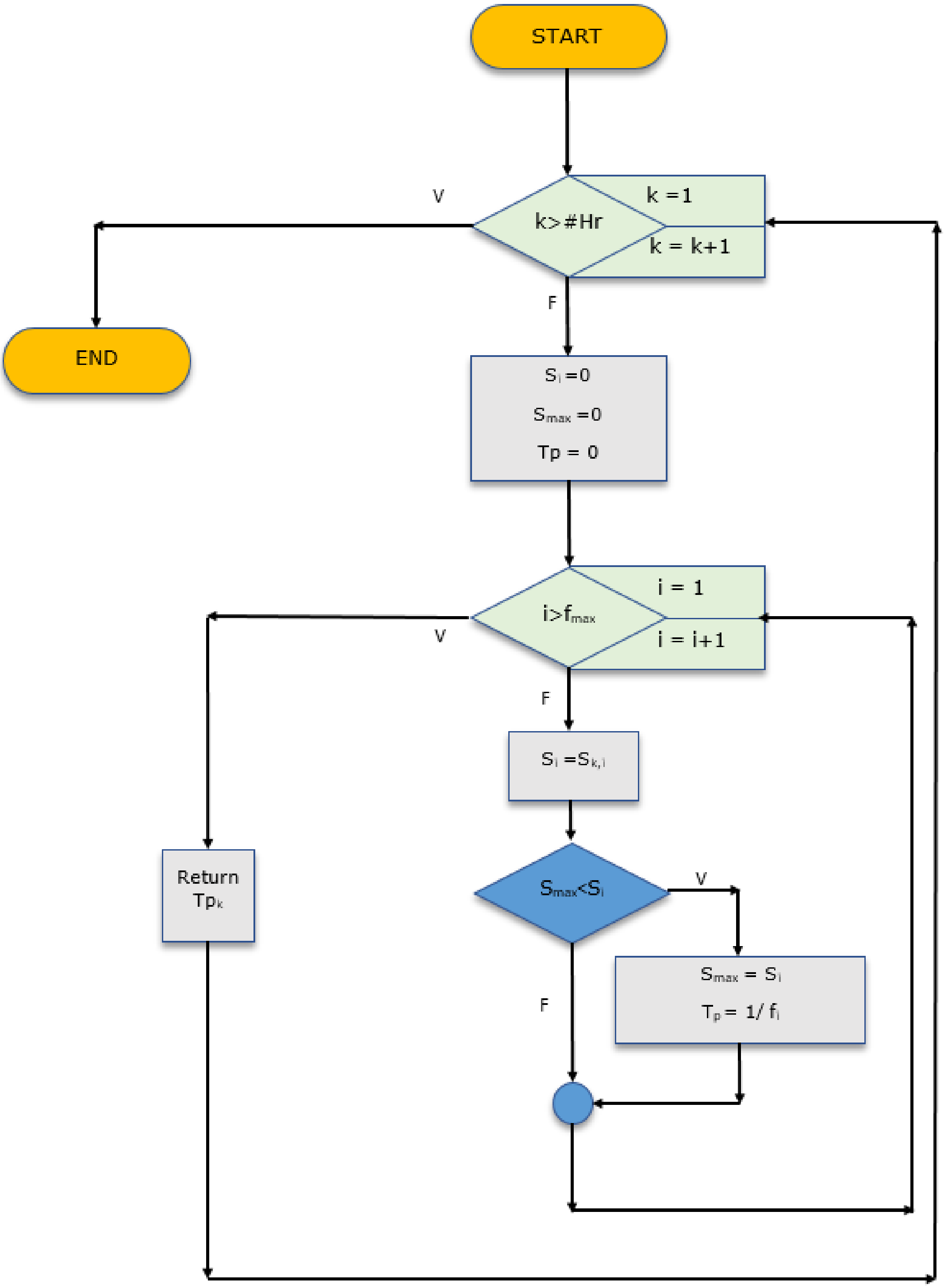

Fig. 8. Pseudocode for peak period calculation.

Moreover, the computer codes in VBA are detailed in the ANNEX.

CHAPTER 5. SUMMARY AND THE RESULTS OF THE PUBLICATIONS

5.1 Wave energy distribution and direction assessment in the Peru Basin

This paper was presented in “Proceedings of the 2022 IEEE 29th International Conference on Electronics, Electrical Engineering and Computing, INTERCON 2022” and published in IEEE Xplore Scopus indexed journal. This paper is accessible on the next DOI:

10.1109/INTERCON55795.2022.9870153

This scientific article evaluates the wave energy resource by calculating the wave power through the significant wave height corresponding to narrow band spectra and also approximating the energy period through another characteristic period and a calibration coefficient linked to a standard sea point spectrum.

The data is provided by the ocean buoy 32012. The spectral data of 10 years, recorded every hour, were tabulated and processed through a spreadsheet. This resulting database allowed the production of rectangular and polar graphs.

This work utilizes a parametric estimation of wave power based on the estimated significant wave height for narrow band spectra, $H_{m0} = 4\sqrt{m_0}$, and the energy period. The energy period was approximated following open sea conditions by using the zero up-crossing period using a calibration coefficient corresponding to the Bretschneider standard spectrum.

The most important results are the wave energy distribution and direction assessment, considering the characteristic of open ocean conditions in the southern hemisphere, specifically in the southeast pacific. The paper also analyses frequency diagrams of the sea states concerning significant wave height and the period of energy, the distribution of the energy of the sea states, the direction of the wave power and the direction of the significant wave height.

5.2 Wave Climate Analysis on The South-East Pacific

This paper was presented in "Proceedings of the 2022 IEEE 29th International Conference on Electronics, Electrical Engineering and Computing, INTERCON 2022" and published in IEEE Xplore Scopus indexed journal. This paper is accessible on the next DOI:

10.1109/INTERCON55795.2022.9870142

In this paper, a wave climate study in a Peruvian Basin region is carried out using wave directional spectral data. Unlike the previous scientific article, the wave parameters were quantified directly from directional spectral data.

The data is provided by the ocean buoy 32012. The spectral data of 10 years, recorded every hour, were tabulated and processed through a spreadsheet. Programming codes to calculate the maximum directional wave power and the direction of the maximum directional power were developed and are attached in the annexe. The resulting database allowed the production of rectangular graphs. Time series and monthly means of 10-year buoy ocean data are processed.

This work has no approximations of wave power based on integral wave parameters. The significant wave height was quantified using its dependence on the spectral broadness parameter or for broadband spectra.

This paper results are time series and monthly averages of the essential characteristics of a wave climate, both in magnitude, concentration and direction. Also, it considers the open sea conditions of the study area. These results conclude those essential aspects of the behaviour of the wave climate in the South East Pacific.

5.3 Variability and Wave Power for Open Ocean Wave Conditions of the Peru Basin.

This paper was accepted in “2022 IEEE EIRCON: 2022 IEEE Engineering International Research Conference” and published in IEEE Xplore Scopus indexed journal. This paper is accessible on the next DOI:

10.1109/EIRCON56026.2022.9934093

This work aims to approximate the wave power average in the Peru Basin, considering its open sea wave conditions through statistical and spectral analysis and contrasting its results with previous research.

This analysis was made based on integral wave parameters like the significant wave height and the zero up-crossing period. This data is provided by the buoy 32302. The spectral data of 7 years, recorded every hour, were tabulated and processed through a spreadsheet. The resulting database allowed the production of rectangular graphs. Time series and monthly means of ocean data are processed.

The main results of this paper are to analyse temporal variability like annual, seasonal and monthly. Furthermore, it is also relevant that the assessment of the wave power in Peru Basin is expanded for another place and in other time contrasted to information of buoy 32012. Finally, the wave power average result is contrasted with the minimum value profitable for deploying wave energy converters.

5.4 Applicability of the Standard Sea Spectrums and New Calibration Coefficients for the Wave Energy Period Calculation of the Peru Sea Basin

This paper was accepted in “2022 IEEE EIRCON: 2022 IEEE Engineering International Research Conference” and published in IEEE Xplore Scopus indexed journal. This paper is accessible on the next DOI:

10.1109/EIRCON56026.2022.9934825

The spectral data of 10 years, recorded every hour, were tabulated and processed through a spreadsheet. This resulting database allowed the production of scatter diagrams showing of $J_{spectral}$ versus $J_{spectrum\text{-}Tk}$ at Peru Sea Basin showing underestimates and overestimates of the parametric wave power.

Calculating accurate ocean wave energy values is crucial for evaluating the feasibility of installing wave energy converters. Wave power can be quantified using a spectral parametric formulation. This parametric formulation is a function of the significant wave height and the wave energy period. The energy period is usually estimated using ad-hoc formulations based on characteristic wave periods modified by a calibration coefficient.

In this paper, an analysis of the suitability of the various calibration coefficients for the wave energy period under the Peru Sea Basin and open sea conditions is carried out.

The significant wave height was quantified using its dependence on the spectral broadness parameter or for broadband spectra.

The main results of this paper consist of new calibration coefficients for approximating the wave power either with the Bretschneider spectrum or with the JONSWAP spectrum.

5.5 Influence of wave conditions on wave power in the South-East Pacific

A wave spectrum is needed to estimate most of the wave parameters. This paper selects the Bretschneider spectrum to represent open ocean wave conditions and quantify the influence of this spectrum shape on wave power. Assessing offshore wave energy resources in many seas has assumed a JONSWAP spectrum. There are also wave energy resource assessments for multimodal sea states based on the Pierson-Moskowitz spectrum because of a suggestion from the International Electrotechnical Commission. This analysis is based on integral wave parameters like the significant wave height, the zero up-crossing period and the peak period.

This data is provided by most ocean buoys like 32302. The spectral data of 7 years, recorded every hour, were tabulated and processed through a spreadsheet. The resulting database allowed the production of rectangular graphs of time series and monthly means.

The main results of this work are to confirm that there is an overestimation based on what was found with open sea conditions. Time series were quantified to verify any longitudinal trend and cyclic behaviour and power averages are quantified for confined and open sea conditions. Finally, the amount of discrepancy between parametric power and spectral power is calculated.

5.6 Influence of multiple wave systems on significant wave height in The South-East Pacific

Regularly for the estimation of wave power, the sea spectrum is considered as narrow band, taking the estimated significant wave height equal to 4 times square root of area under the spectrum, as carried out in the wave energy studies. This is only possible if we are sure that the spectrum is called narrow band. Since the Peru Basin sea is extensive and open, it is possible that many wave systems overlap and that the spectrum of the sea state is considered broadband.

The objective of this paper is to determine the presence of multiple wave systems and its influence in the significant wave height and omnidirectional wave power and to quantify the spectral broadness parameter, its time series, averages and variability.

The methodology used are inferential statistics and spectral method. The data is provided by the ocean buoy 32012. The spectral data of 10 years, recorded every hour, were tabulated and processed through a spreadsheet. This resulting database allowed the production of rectangular and polar graphs for time series and monthly averages. Also, this paper presents a regression analysis to model the half of factor of estimated significant wave height versus spectral broadness parameter at Peru Sea Basin

The results of this work contribute to define for the Peruvian Maritime Basin a characteristic value for the significant wave height spectral estimate factor and determined the region's wave spectrum as broadband. The paper formulates a new coefficient for the estimated significant wave height in Peru Basin.

5.7 Wave power performance criteria and evaluation in Peru Basin

So far, lots of wave energy resource evaluations have done but they do not affect on profitability regarding the performance of wave power. This research contributes to maritime industry with criteria for evaluating the wave power performance of the wave energy resource when a installation project of wave energy converters is planned. Criteria is proposed to evaluate the wave power performance for open ocean conditions.

This work utilizes a parametric estimation of wave power based on the estimated significant wave height for narrow band spectra, $H_{m0} = 4\sqrt{m_0}$, and the energy period. The energy period was approximated following open sea conditions by using the zero up-crossing period through a calibration coefficient corresponding to the Bretschneider standard spectrum.

This study is done by processing temporal data of wave climate recorded for 18 years by two buoys located in the Peru Basin Pacific Ocean. The spectral data recorded every hour were tabulated and processed through a spreadsheet. The resulting database allowed the calculation of averages, coefficients of variability, indexes of temporal variability, and plotting of wave power roses and wave energy distribution charts.

The first criterion points out the lower value of wave power to make feasible the installation of WEC's. The second criterion stablishes the upper value of wave power variability. The third criterion evaluates the concentration of wave energy based on wave height and energy period classes. The last criterion sets up the upper value of direction spread of the wave power.

CHAPTER 6. DISCUSSION AND CONCLUSIONS

This chapter checks whether the research questions have been answered. The conclusions are the following:

i. Wave energy resources in Peru Basin do has potential based on integral wave parameters in open ocean conditions. Considering that a wave climate property with a variability coefficient of less than 0.2 is statistically constant, we can affirm among many findings that the variability of omnidirectional wave power values is high, corresponding to a variability coefficient equal to 0.7. The significant wave height has a similar variability behaviour, although less marked, obtaining a variability coefficient of 0.3. In contrast, the period of energy experiences a relatively small variation whose variability coefficient reached 0.17, which confirms that the energy period does not influence the variability of the omnidirectional wave power. Therefore, the variability of the significant wave height explains the variability of the omnidirectional wave power. This conclusion explains why the peak values of omnidirectional wave power correspond to the peak values of significant wave height.

   The significant wave height is predominantly constant annually, even considering the high values in the second and third quarters of the year. Its value ranged between 2.14 ± 0.58 m at buoy 32302 and 2.24 ± 0.63 m at buoy 32012. These averages are estimated for a narrow band spectrum.

The estimated average of the energy period has shown consistent behaviour throughout the year. The average value of the energy period has an upward trend in the middle of the year. Its average is around 8.76 s. This average is estimated for open ocean conditions or using the zero up-crossing period and a Bretschneider spectrum.

The available omnidirectional wave power, the significant wave height and the energy period do not show a longitudinal trend over the years, nor do they show a cyclical behaviour constituted by several years. However, they do show seasonal behaviour with accentuated high and minimum values in the middle of the year.

The estimated wave power is predominantly high in June, July, August, and September, providing good conditions to collect the most significant amount of energy in that period. The mean value of the wave power turned out to be 23 kW/m, more significant than the 15 kW/m stipulated as a minimum value by the manufacturers of wave energy converters. The variability of the wave power averages also increases towards the same months where the wave power increase occurs so that we can find average values as high as 58 kW/m and values as low as 10 kW/m. This average is estimated for open ocean conditions or using the zero up-crossing period and a Bretschneider spectrum. The significant wave height is done for narrow band spectrum.

The most significant amount of available wave energy is concentrated in a single small range of energy period and significant wave height. This particularity consisting of having most of the wave energy located in a single area and in the energy dispersion diagram makes this characteristic of the wave climate – wave energy – attractive to continue installation studies of wave converters. This particular range of energy period is located in classes of 7 to 10 s and for the significant wave height of 1.5 to 3.0 m. In these classes of the energy dispersion diagram, energy values about 17 MWh/m/year can be found. This result of wave energy is comparable to another work found offshore Peruvian coasts.

The average direction of all the waves is almost constant all year, with a dispersion of 30º. The direction of most waves is primarily from the southwest to northeast (225°) most of the year, and a smaller number of waves propagate from the southeast throughout the year. The waves from the southeast increase at half a year without being more significant than those from the southwest.

ii. Wave power is concentrated in a small range of directions of propagation. The wave power directionality coefficient does not show cyclical behaviour or a longitudinal trend over the years. Unlike omnidirectional wave power and significant wave height, this coefficient does not show seasonal behaviour either. This directionality coefficient has a stable behaviour throughout the year, which is a consequence of its variability coefficient equal to 0.28, resulting in an average value of 0.5. This result of the directionality coefficient, together with that found for the direction of the maximum directional wave power, means that the power of the waves with the highest power becomes half of the omnidirectional wave power in the predominant direction. The direction of maximum directional wave power is stable throughout the year, without cyclical behaviour or longitudinal trend. Similarly, to what was pointed out by the wave power roses, which concluded that the most significant number of waves propagated from the southwest, this direction of maximum directional wave power demonstrates that the highest power waves, with 50% of the omnidirectional power, propagate from the south, emphasizing the fact that the best direction for the installation of wave converters is between south and southwest or 202º with a spread of 40º, distributed uniformly.

iii. The variability of wave power over time-based on integral parameters under open ocean conditions in the Peru Basin is low The analysis presented that the wave power has a stable behaviour throughout the year and over time. Although there is temporal variability, mainly in the middle of the year, the magnitude of its coefficient of variability is very low and has a value of 0.72. However, intra-annual wave power is usually constant.

iv. The accuracy in evaluating the omnidirectional wave power using both ocean conditions are low. The best approximation to estimate the omnidirectional wave power employing integral wave parameters turned out to be that which consists of approximating the energy period with zero up-crossing period using the Bretschneider spectrum. This best estimate of omnidirectional wave power that effectively corresponds to open ocean conditions such as the Peru Basin yielded an 8% underestimate of the omnidirectional wave power quantified directly from wave spectral data. Regarding the other two estimates, when the energy period is approximated through the peak period and the Bretschneider spectrum, an overestimation of 10% is obtained. When the energy period is approximated with the peak period through the JONSWAP spectrum, an overestimation of 16% is obtained. The cause of the overestimation of the omnidirectional wave power using the JONSWAP spectrum is mainly since this spectrum groups primordially the waves with low frequency. This spectrum gets a very high peak period compared to zero up-crossing period that better averages all the low and high-frequency waves, thus yielding high values of the omnidirectional wave power. The estimate of omnidirectional wave power is discarded by approximating the energy period utilizing the peak period through the JONSWAP spectrum.

In order to reduce these overestimates and underestimates of the estimated values of the omnidirectional wave power, calculations were made of the calibration coefficients for the peak period and the power period for all sea states as a function of the significant wave height, representative of sea state energy. The results showed that the calibration coefficient given by the ratio between the energy period and the peak period converges to 0.8, while the ratio between the energy period and the power period converges to 1.25, now generating errors of less than 5%.

v. There is a significant discrepancy between wave power calculated in confined ocean conditions and wave power in open ocean conditions. Wave energy resource in another buoy in Peru Basin does have the potential to be harvested, considering its open sea wave conditions. If the JONSWAP spectrum and the peak period were selected to calculate the wave power, its average increase would be 46% concerning the value that would be obtained with the Bretschneider spectrum and the zero up-crossing period, considering the first estimate as the maximum attainable value and the second estimate as the minimum obtainable value of wave power, respectively.

vi. Multiple wave systems influence significant wave height and omnidirectional wave power. Its influence consists in the decrease of the value of the significant wave height by 8%. The average of the spectral amplitude parameter turned out to be greater than the maximum critical limit value that considers a spectrum to be narrow band, that is taking the probability density function obtained by Raileigh and consequently estimating the significant wave height as the product of a factor four times the standard deviation of the sea state spectrum. This average resulting from the average of the monthly averages is equal to 0.75; this result rejects the assumption that the sea spectra of the Peru Basin are called narrow band; on the contrary, it is shown that these sea states should be considered broadband. This result has the following consequence: estimating the significant wave height must consider the dependence of the factor of the spectral estimated formula in the spectral method on the value of the resulting spectral amplitude parameter unless historical temporal data is available to quantify $H_{1/3}$. When considering the low variability of the average value of the spectral amplitude parameter whose variability coefficient became equal to 0.08, it is stated that the result of 0.74 is constant. Therefore, it is obtained from the figure "Half of the spectral estimated factor of significant wave height versus spectral broadness parameter at Peru Sea Basin" that the factor of the spectral estimate is equal to 3.7, which leads to the following most accurate formula: $H_{m0} = 3.7\sqrt{m_0}$. The parametric wave power derived from integral wave power for a narrowband assumption and deep waters approximates significantly the integral wave power. This is due because the energy period is actual value and not approximated by other characteristic periods overestimating o underestimating the wave power.

vii. Appropriate criteria are those based on minimum limits of wave power, maximum variability of wave power, concentration of wave energy in a single group of sea states, and maximum directional dispersion of wave power. Wave power performance at both buoy locations has passed evaluation for the Southwest direction based on the criteria proposed to evaluate their performance. The first criterion confirms that the omnidirectional wave power has a value high enough for wave energy converters to be profitable. The second passed criterion establishes that installing these converters will run a minimum risk since there is low variability in the significant wave height. The third passed criterion confirms that the energy harvested by these converters will be maximum since it is concentrated in a small range of energy periods and wave heights. The last criterion states that there is no significant variability in the direction of the waves; therefore, the converters will be able to harvest energy deployed in only one direction. Therefore, according to the results and discussion, the wave climate in Peru Basin is stable over time, with low variability, and very predictable. It is expected to use Pelamis, Power buoy and Wave Dragon devices for wave energy harvesting in Peru Basin.

All of this makes the installation of wave energy converters attractive in the maritime zone or considered favourable for future investigations near the coast of Peru. This research is a contribution for the improvement of Wave energy sector in the phase of exploration of energetic resource.

CHAPTER 7. FUTURE WORKS

In future works the next studies will be done:

i. An analysis of the behaviour of the directional wave spectrum in the Peru Basin. This research will explain the behaviour of the sea states in their respective directions since the presence of multiple wave systems in the area has been demonstrated. In addition, the results will serve the offshore oil exploration sector in the design of marine structures.

ii. A study of the shape of the point spectrum offshore Peruvian coasts. Research has used standard sea spectra developed in the last century and other single ocean areas for its assessments. The adaptation or elaboration of a standard sea spectrum for the area will be essential when quantifying the wave power available for harvesting, the variability of the significant wave height, and other disciplines such as the shipbuilding industry.

iii. To formulate a numerical model that evaluates the potential for harnessing wave energy in the western coast of South America, validated with field data obtained by oceanic buoys in the Peru Basin. In addition, once the sea state model of the maritime basin has been validated, monitor the changes that occur over time and evaluate the wave climate.

iv. To find the optimal installation points for wave energy converters on the coast of South America. Quantifying how much of the wave power reaches the coast and in conjunction with the numerical model is essential to find the best places to install wave converters near the western coast of South America.

v. To design a wave energy converter suitable for harvesting wave energy for open ocean conditions and for particular geography of Peruvian coast.

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ANNEX

Programming code in VBA for quantification maximum directional power:

```
Option Explicit
Sub Jmax()
Const imax As Single = 46
Const pi As Single = 3.141596
Const ro As Integer = 1025
Const g As Single = 9.85
Dim Sdir As Double, Jj As Double, deltafi As Single, fi As Single, Jtheta As Double, Thetamax As Integer
Dim k As Long, j As Integer, i As Integer, fimenos As Single
Dim Ci As Single, R1 As Single, R2 As Single, alfa1 As Integer, alfa2 As Integer

  For k = 1 To 73464
  Jtheta = 0
  Thetamax = 0
    For j = 0 To 359
    fimenos = 0.02
      Jj = 0
      For i = 1 To imax
      fi = Range("G1").Offset(0, i).Value
      deltafi = fi - fimenos
```

```
        Ci = Range("G1").Offset(k, i).Value

        R1 = Range("BL1").Offset(k, i).Value

        R2 = Range("DI1").Offset(k, i).Value

        alfa1 = Range("FF1").Offset(k, i).Value

        alfa2 = Range("HC1").Offset(k, i).Value

        Sdir = Ci * ((0.5 + R1 * Cos((j - alfa1) * pi / 180) + R2 * Cos((j - alfa2) *
        pi / 90)) / pi)


        If Sdir > 0 Then

          Jj = Jj + ro * (g ^ 2) * Sdir * deltafi / (4 * fi * 180)

          End If

        fimenos = fi

        Next i

        If Jj > Jtheta Then
        Jtheta = Jj

        Thetamax = j

        End If

            Next j

    Range("BH1").Offset(k, 0).Value = Jtheta

    Range("BI1").Offset(k, 0).Value = Thetamax

    Next k

End Sub
```

Similarly, a computer code was developed to select the peak period, detailed below.

Programming code in VBA for identification of the peak period for every hourly register:

```
Sub Tdom()
Const imax As Single = 46
Dim Si As Single, Smax As Single, Tp As Single, k As Long, i As Integer
    For k = 1 To 73464
    Si = 0
    Smax = 0
    Tp = 0
      For i = 1 To imax
          Si = Range("G1").Offset(k, i).Value
              If Smax < Si Then
              Smax = Si
              Tp = 1 / Range("G1").Offset(0, i).Value
              End If
       Next i

     Range("MS1").Offset(k, 0).Value = Tp
    Next k

End Sub
```

PAPER 1: WAVE ENERGY DISTRIBUTION AND DIRECTION ASSESSMENT IN THE PERU BASIN.

[33]

PAPER 2: WAVE CLIMATE ANALYSIS ON THE SOUTH-EAST PACIFIC.

[34]

PAPER 3: VARIABILITY AND WAVE POWER FOR OPEN OCEAN WAVE CONDITIONS OF THE PERU BASIN.

[35]

PAPER 4: APPLICABILITY OF THE STANDARD SEA SPECTRUMS AND NEW CALIBRATION COEFFICIENTS FOR THE WAVE ENERGY PERIOD CALCULATION OF THE PERU SEA BASIN.

[36]

PAPER 5: INFLUENCE OF WAVE CONDITIONS ON WAVE POWER IN THE SOUTH-EAST PACIFIC.

PAPER 6: INFLUENCE OF MULTIPLE WAVE SYSTEMS ON SIGNIFICANT WAVE HEIGHT IN THE SOUTH-EAST PACIFIC.

PAPER 7: WAVE POWER PERFORMANCE CRITERIA AND EVALUATION IN PERU BASIN.

Wave power performance criteria and evaluation in Peru Basin

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***Abstract*— Wave energy converters are to be deployed in sea zones where the harvest of energy is profitable. So far, lots of wave energy resource evaluations have done but they do not affect on profitability regarding the performance of wave power. This investigation aims to assess the wave power performance of an offshore water zone of the sea of the Peru Basin through statistical and spectral analysis. A set of criteria is proposed to evaluate the wave power for open ocean conditions. This study is done by processing temporal data of wave climate recorded during 18 years by two buoys located in the South-East Pacific Ocean. According to our results, wave power is predominant high in the second and third quarters. Its value is greater than 15 kW/m throughout the year. The annual energy is not spread all over the range of energy period and wave height values in both locations. The wave power passed the proposed criteria for its performance evaluation for the predominant wave direction.**

Keywords—Wave power evaluation, Wave energy resource, Wave energy variability, Annual contribution of wave energy, Peru Sea Basin

I. INTRODUCTION

The evaluation of wave energy resources has become an essential research topic worldwide as the demand for energy increases more and more. In addition, greenhouse gas emissions increase due to burning fossil fuels, leading to an acceleration of climate change. It is crucial to change the energy matrix generally based on fossil fuels to renewable energy sources, to sustainable, inexhaustible and widely available energy sources, such as energy from marine waves. According to a preliminary study, the qualitative value of the world's wave energy resource is theoretically estimated to be 2.11 ± 0.05 TW at 95% confidence, with similar proportions in the northern and southern hemispheres [1]. Similarly, mean monthly wave power above 30° N ranges from 17 to 130 kW/m, while wave power below 30° S is persistent throughout the year with a range from 50 to 100 kW/m [2].

Only a single criterion is known for the profitability of the wave energy resource or the wave power harvested by a wave converter. This criterion refers to the minimum amount of wave power to make the wave energy conversion operation profitable. The critical value is 15 kW/m [3].

This research aims to propose a complete set of criteria to evaluate the performance of the wave energy resource or wave power and thereby justify or not the installation of a wave conversion farm.

The method used to quantify the wave climate is the spectral method and the method used for the selection of criteria is statistical.

II. METHODOLOGY

A. *Ocean Wave Information*

The analysis carried out for this study is based on field measurements of the conditions/behaviour of the waves, which have been taken in an area of the Peru Basin maritime basin.. These data under analysis were obtained from the website of the National Data Buoy Center (NDBC - www.ndbc.noaa.com), which operates and maintains a network of wave measurement buoys. Two buoys with historical data available in the region of interest were taken; their measurement dates, geographical location, depths of the seabed in that area and other characteristics are shown in Table 1.

The measurements belonging to buoy number 32012 consist of parameters such as significant wave height H_{m0}, and wave periods such as zero crossing period T_{zero}, peak or dominant period T_p, as well as average wave directions $\theta°$. On the other hand, the measurement of buoy number 32302 consists of wave parameters such as H_{m0}, T_{zero} and T_p. These data were provided hourly, thus representing the mean values of a set of measurements taken within that range. More than 91% of the data is available for buoy 32012, and more than 95% of the data is also available for buoy 32302. This database covers measurements over 18 years—ten years for buoy 32302 and eight years for buoy 32012.

Table 1. List of wave buoys in the Peru Basin providing historical data

Buoy	Owner	Latitude (° S)	Longitude (° O)	Depth (m)	Time
32012	Woods Hole Oceanographic	19,425	85,078	4524	2007-2018
32302	National Data Buoy Center	18	85,1	4929	1986-1995

B. *Wave power and wave parameters models*

The following parameters characterize the wave conditions of a sea state per hour: significant wave height H_s, energy period T_e, omnidirectional wave power J, wave energy per unit length of average crest per year E and mean wave direction $\theta°$. In the wave energy study, the reference representative wave height H_{m0} is the significant wave height calculated from the wave elevation variance m_0 of a non-directional wave spectrum, according to Earle [4].

$$H_{m0} = 4\sqrt{m_0} \quad (1)$$

The moment of order n of the variance spectrum (m_n) or spectral moment is calculated as:

$$m_n = \int_0^\infty f^n S_\zeta(f)df \quad (2)$$

The energy period or average period of component waves [5], T_e, which corresponds to the period of a single sinusoidal wave with the same energy as the sea state, is given by:

$$T_e = \frac{m_{-1}}{m_0} \quad (3)$$

Assuming linear superposition, the omnidirectional wave power J [6], in terms of H_{m0} and T_e, can be defined for deep water as:

$$J = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e \quad (4)$$

where ρ is the sea water density and g is the gravity acceleration.

Wave energy per crest unit is in Wh/m/year

$$E = \sum_{i=1}^{n} h_i J_i \quad (5)$$

where n is the quantity of the various sea states, and h_i are hours that a given sea state i lasts in an average year.

T_e is approximated by T_z considering a Bretschneider spectrum for open sea conditions using the following expression:

$$T_e = 1.2 \cdot T_z \quad (6)$$

The zero up-crossing period T_z represents the average period when the waves cross an average sea surface level, it is calculated as:

$$T_{zero} = \sqrt{\left(\frac{m_0}{m_2}\right)} \quad (7)$$

The mean wave direction θ° is a reference direction that considers the most representative wave direction. This direction is the average direction of waves located in the frequency band of the non-directional spectrum with maximum spectral density.

C. Variability

The Coefficient of variability *COV* calculates the amount of variability concerning an average value; this is obtained by dividing the standard deviation σ by the average μ:

$$COV(J) = \frac{\sigma[J(t)]}{\mu[J(t)]} \quad (8)$$

The Variability Index characterizes the temporal differentiations of the resource; there are annual, seasonal and monthly and it is defined as:

$$AV = \frac{J_{A1} - J_{A2}}{J_{year}} \quad (9)$$

$$SV = \frac{J_{S1} - J_{S2}}{J_{year}} \quad (10)$$

$$MV = \frac{J_{M1} - J_{M2}}{J_{year}} \quad (11)$$

D. Wave energy performance evaluation criteria.

To assess wave energy performance in a region, the authors propose the following set of criteria:

i. **Feasibility of installing the energy converter (WEC):** J values greater than 15 kW/m allow the feasibility of installing WEC [3].

ii. **Wave energy variability**: J can vary depending on H_{m0} and T_e. An acceptable statistical value of variability is 0.2 for each variable. Thus, the maximum variability limit for J is (1 + 0.2)^3 = 1.728, according to the evaluation of the monthly averages.

iii. **Annual wave energy contribution:** It is possible to select more than one range of classes in the bivariate relative frequency distributions, where the annual wave energy contribution is significant. The selected range of classes of H_{m0} and T_e should contribute annually to wave energy above 50%. The lower range of H_{m0} should be considered to minimize risk during the operation and survival of WECs.

iv. **Wave energy directionality:** WECs must be installed to capture the most significant amount of wave energy in the predominant direction. The percentage of waves in the installation direction of the WECs must be above 50%.

Table 2 summarizes these criteria and their threshold values.

Table 2. Wave power performance criteria and threshold values.

Criterium	Description	Treshold value
1	Viabilidad de instalación de WEC	> 15 kW/m
2	Variabilidad de la energía de olas	< 1,728
3	Contribución anual de la energía de olas	> 50 %
4	Direccionalidad de la energía de olas	> 50 %

III. Results and Discussion

A. Estimated wave climate characteristics.

Table 3 and Table 4 summarizes the key characteristics of wave energy resources: Significant wave height (annual average and standard deviation), Maximum significant wave height, Energy period (annual average and standard deviation), Wave power (annual average and standard deviation) and the coefficients of variation for both buoys.

These tables show that the significant wave height varies from 2.14 ± 0.58 m at buoy 32302 to 2.24 ± 0.63 m at buoy 32012. H_{m0} averages around 2.2m. The COV of H_{m0} has a value of 0.2, which is statistically low. Therefore, H_{m0} has a highly consistent value. T_e varies from 8.72 ± 1.52 s at buoy 32302 to 8.79 ± 1.52 s at buoy 32012. The energy period averages about 8.76 s. The COV of T_e turned out to be less than 0.2, representing marked stability over time. J has, on average, for both buoys, values between 21.92 kW m-1 and 24.10 kW m-1, which are values higher than the minimum profitable limit of 15 kW/m according to Fairley and co-authors [3]; J has an overall COV of about 0.7; which is also a low value.

Table 3. Main characteristics of wave at each buoy station

Boya	H_{m0} ± SD (m)	H_{m0} (max) (m)	T_e ± SD (m)	J ± SD (kW/m)
32032	2.14 ± 0.58	5.60	8.72 ± 1.52	21.92 ± 15.76
32012	2.24 ± 0.63	5.93	8.79 ± 1.52	24.10 ±17.71

Table 4. coefficients of variability for main characteristics of wave climate at Peru Basin

Boya	COV(H_{m0})	COV(T_e)	COV(J)
32032	0.27	0.17	0.72
32012	0.28	0.17	0.73

The wave energy variability increases from the annual rate to the monthly rate. The values presented are relatively low, considering that the data recorded is offshore (Table 5).

Table 5. Temporal variability indices for wave power, both buoys

Periodo	AV(J)	SV(J)	MV(J)
1986-1989	0.21	0.76	1.11
1991-1994	0.18	0.68	1.12
2008-2009	0.03	0.58	1.21
2012-2017	0.21	0.96	1.58

B. Wave energy performance evaluation

The considerations made for this evaluation are the following: for the first criterion, the average J value of both buoys has been taken (Table 3); for the second criterion, the monthly variability of wave energy has been taken (Table 5); for the third criterion, the sum of the relative frequencies of the classes has been taken from Fig. 1, where H_{m0} is within the range of its average value plus its standard deviation, the same happens for T_e. Finally, in the fourth criterion, wave direction equal to 225° was selected as the predominant one, with a range of ± 30°, and a sum of relative frequencies was performed for each season (Fig. 2). Table 6 summarizes the wave energy performance evaluation for buoys 32032 and 32012. According to our analysis, the wave energy performance has passed the evaluation in the 225° direction.

Table 6. Results of wave power performance evaluation at buoys 32032 and 32012 of the sea of Peru Basin

Criterio	Valor estimado	Evaluación
1	23 kW/m (Table 3)	Aprobado
2	1,255 (Table 5)	Aprobado
3	62% (Fig. 1)	Aprobado
4	Verano: 70%	Aprobado
	Otoño: 75%	Aprobado
	Invierno: 50%	Aprobado
	Primavera:58% (Fig. 2)	Aprobado

IV. Conclusions

In this work, the wave energy resource at two closely spaced offshore locations in the Peru Basin was estimated using buoy data. A mean zero-crossing period and a Bretschneider spectral shape, both the most suitable for open sea conditions, were used to quantify the mean wave power, its variability and directionality, and the amount of potential energy. Based on previous research, a set of proposed criteria was used to assess wave power performance.

Wave energy at the locations under study passed the evaluation based on the criteria suggested for evaluating their performance.

Therefore, according to the results and discussion, the wave climate in Peru Basin is stable over time, with low variability, and very predictable.

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1994

Significant wave height (m) \ Energy period (s)	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5
5,75	0	0	0	0	0	0	0	203	219	0
5,25	0	0	0	0	0	0	0	507	365	0
4,75	0	0	0	0	0	116	764	830	0	0
4,25	0	0	0	0	253	465	2650	554	0	128
3,75	0	0	0	1466	2163	4781	4443	604	373	1000
3,25	0	0	350	8193	5711	7128	5602	2008	1609	526
2,75	0	0	4647	12772	6908	8337	4224	2644	1903	323
2,25	0	1017	14362	15791	10453	5477	2856	1863	268	0
1,75	0	1475	12260	12975	4582	2777	1918	995	223	22
1,25	0	713	1955	2300	1282	829	300	163	0	0

2017

Significant wave height (m) \ Energy period (s)	5,5	6,5	7,5	8,5	9,5	10,5	11,5	12,5	13,5	14,5
5,75	0	0	0	0	0	0	0	0	657	470
5,25	0	0	0	0	128	0	156	338	548	0
4,75	0	0	0	0	2524	1162	1400	2075	299	0
4,25	0	0	0	1732	6314	4838	2853	1108	0	0
3,75	0	0	0	3694	3998	4781	3412	1466	186	200
3,25	0	0	4703	8809	7631	5931	4112	1555	630	150
2,75	0	24	16000	19427	12090	5883	4053	1391	551	0
2,25	0	1033	17976	17121	8895	4486	2542	1304	436	36
1,75	33	3252	10209	8429	4767	2161	1279	207	0	0
1,25	30	1330	1046	645	517	201	0	0	0	0

Fig. 1. Wave energy distribution in classes of Hs and Te for years 1994 and 2017.

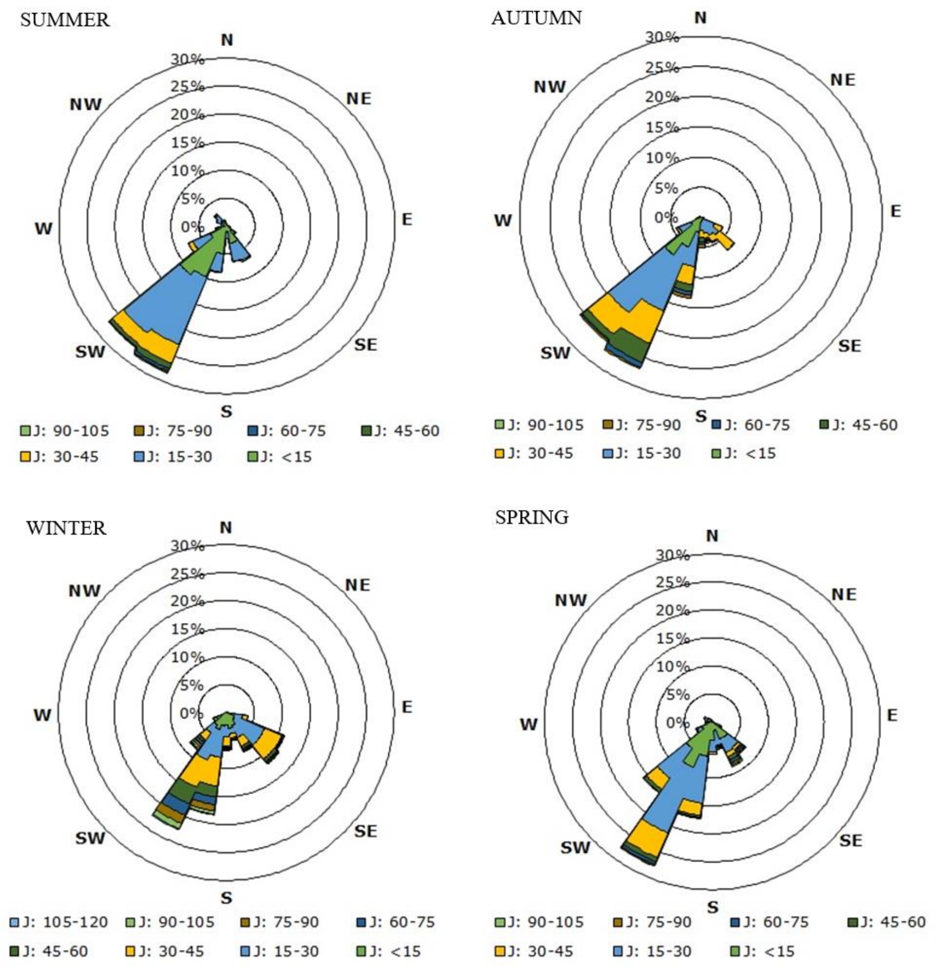

Fig. 2. Seasonal wave power roses based on measurements from buoy 32012

Influence of multiple wave systems on significant wave height in The South-East Pacific

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***Abstract*— Regularly for the estimation of wave power, the sea spectrum is considered as narrow band, taking the estimated significant wave height equal to 4 times square root of area under the spectrum, as carried out in the wave energy studies. This is only possible if we are sure that the spectrum is called narrow band. Since the Peru Basin sea is extensive and open, it is possible that many wave systems overlap and that the spectrum of the sea state is considered broadband. The objective of this paper is to determine the presence of multiple wave systems and its influence in the significant wave height and omnidirectional wave power and to quantify the spectral broadness parameter, its time series, averages and variability. The methodology used are inferential statistics and spectral method. This work defined for the Peruvian Maritime Basin a characteristic value for the significant wave height spectral estimate factor and determined the region's wave spectrum as broadband. The influence of multiple wave systems on wave power is not significant.**

Keywords—Wave power, significant wave height, spectral estimate factor, spectral broadness parameter, Peru Basin

I. Introduction

The emission of greenhouse gases is mainly caused by the use of fuels with a high carbon content in power generation. Expanding the energy matrix to renewable energy sources such as wind, solar, tidal, and wave energy has become a global interest in recent decades. The adverse effects of climate change arouse this interest.

Regularly for the estimation of wave power, the sea spectrum is considered as narrow band, taking the estimated significant wave height equal to 4 times square root of area under the spectrum, as carried out in the wave energy studies in Hawaii [1] and in Spain [2] among others. This is only possible if we are sure that the spectrum is called narrow band. Since the Peru Basin sea is extensive and open, it is possible that many wave systems overlap and that the spectrum of the sea state is considered broadband.

The objective of this paper is to determine the presence of multiple wave systems and its influence in the significant wave height and omnidirectional wave power. To quantify the spectral broadness parameter, its time series, averages and variability.

The methodology used are inferential statistics and spectral method.

II. Methodology

A. Ocean Wave Information

The analysis carried out is based on the measurements of wave conditions taken in the Peru Sea Basin whose position is at latitude 19.425º S and longitude 85.078º W, and whose sea depth is 4524 m. Ocean wave data was recorded over a 10-year period, from the end of 2007 to the beginning of 2018. The data used in this study was taken from the National Data Buoy Center (NDBC – www.ndbc.noaa.gov) website.

Measurements from buoy 32012 consist of the following wave integral spectral parameters: Significant wave height (H_{m0}), ascending zero crossing period (T_z), peak period or dominant period of the spectrum (T_p), and direction average wave propagation ($\theta^{º}$). These parameters were estimated from the spectral energy density, which is not always provided by ocean buoy managers. This ocean buoy also has directional spectral data in its historical records. More than 91% of the data collected during the years mentioned above are available.

B. Wave power and wave parameters models

The significant wave height, estimated based on the zero-order moment of the wave variance spectrum (m_0), is calculated as:

$$H_{m0} = \kappa\sqrt{m_0} \tag{1}$$

where κ is the spectral estimate factor of significant wave height. To determine κ, it is necessary to calculate a parameter that establishes whether the wave spectrum is broadband or narrowband, this parameter is spectral broadness parameter (ϵ). When ϵ is less than 0.5 the spectrum is considered narrowband, otherwise the spectrum is considered broadband (The Society of Naval Architects and Marine Engineers 1989) [3]. If the wave spectrum is narrowband, a factor of 4 is assumed for κ and thus the error in the calculation of H_{m0} typically less than 10 %. Otherwise, κ decreases as ϵ increases, up to a value of 2.2 for ϵ equal to 1.

$\langle E_{1/3}\rangle$ is presented, which depends on ϵ, which is half the factor κ (Korvin-Kroukovsky 1961) [4]. For this work, the behaviour of $\langle E_{1/3}\rangle$ with respect to ϵ was obtained through a regression analysis with a polynomial trend curve of degree 5 using Korvin-Kroukovsky data, Fig. 1.

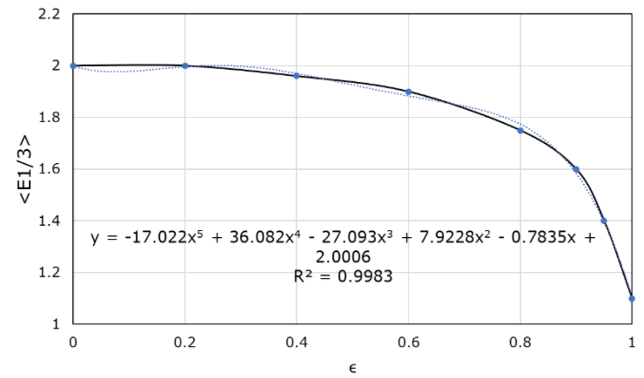

Fig. 1. Half of factor of estimated significant wave height versus spectral broadness parameter at Peru Sea Basin

The spectral amplitude parameter is calculated by means of the spectral moments:

$$\epsilon = \sqrt{1 - \frac{m_2^2}{m_0 m_4}} \qquad (2)$$

In general, the moment of order n of the variance spectrum (m_n) or spectral moment is calculated as:

$$m_n = \int_0^\infty f^n S_\zeta(f) df \qquad (3)$$

ϵ can be expressed as

$$\epsilon = \sqrt{1 - (\frac{T_c}{T_Z})^2} \qquad (4)$$

where T_c is the peak-to peak period, calculated as

$$T_c = \sqrt{\frac{m_2}{m_4}} \qquad (5)$$

and T_z is the zero up-crossing period, calculated as follows

$$T_z = \sqrt{\frac{m_0}{m_2}} \qquad (6)$$

The omnidirectional wave power J (kW/m) is evaluated as the integral of the product between the group speed c_g (m/s), the speed with which the wave energy is transported, and the spectral energy density S_ζ (m^2/s)

$$J_{espectral} = \rho g \int_0^\infty c_g(f) S_\zeta(f) df \qquad (7)$$

where ρ is the density of seawater, g is the acceleration due to gravity, and f is the wave frequency in Hz. In deep waters, such as considered in this work, the group velocity is approximated as:

$$c_g = \frac{g}{4\pi f} \qquad (8)$$

The energy period T_e, which corresponds to the period of a single sinusoidal wave with the same energy as the sea state [5], is given by:

$$T_e = \frac{m_{-1}}{m_0} \qquad (9)$$

The omnidirectional wave power J [6], in terms of H_{m0} and T_e, can be defined for deep water as:

$$J = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e \qquad (10)$$

Significant wave height for a narrow band spectrum is selected for this work. Furthermore, the zero up-crossing period is selected for estimating the energy period using a coefficient of calibration corresponding to open ocean conditions or a Bretschneider spectrum.

$$T_e = 1.2 T_z \qquad (11)$$

C. Discrete calculation of spectral moments

Wave spectral data consist of a finite number of components (n) of observed spectral energy density ($S_i = S_\zeta(f_i)$, with $i \in [1, n]$). Thus, the spectral moments are calculated in a discrete way as:

$$m_0 = \sum_{i=1}^{n-1} 0.5(S_i + S_{i+1})(f_{i+1} - f_i) \qquad (12)$$

$$m_2 = \sum_{i=1}^{n-1} 0.5(S_i f_i^2 + S_{i+1} f_{i+1}^2)(f_{i+1} - f_i) \qquad (13)$$

$$m_4 = \sum_{i=1}^{n-1} 0.5(S_i f_i^4 + S_{i+1} f_{i+1}^4)(f_{i+1} - f_i) \qquad (14)$$

D. Discrepancy in the Calculation of the significant wave height

The overestimate of J, calculated according to the approximation of the factor that estimates H_{m0} is obtained by:

$$\%Discrepancy = \\ = \frac{Factor_{narrowband} - Factor_{broadband}}{Factor_{narrowband}} x\ 100\% \qquad (15)$$

III. Results and Discussion

A. Temporal variability of spectral broadness parameter

The spectral broadness parameter does not show cyclical behaviour or a longitudinal trend over the years. This parameter does not show seasonal behaviour either (Fig. 2). Upper limit is 0.9 and lower limit is 0.6 for almost all data.

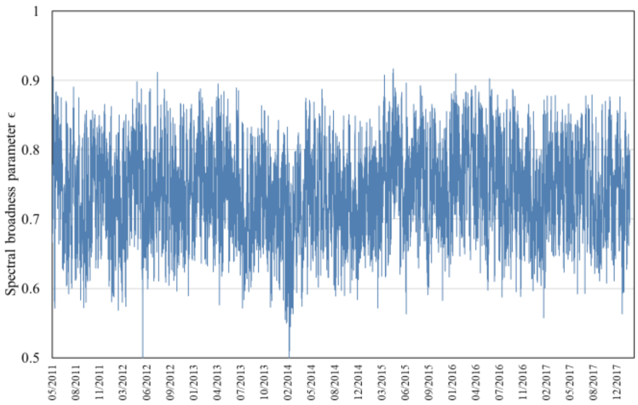

Fig. 2. Time series of spectral broadness parameter at Peru Basin

Based on the spectral data, specifically on monthly averages results, ϵ shows values higher than 0.5, thus calling the wave spectrum of the region under study broadband. Fig. 3 shows that the monthly average of the spectral amplitude parameter is equal to 0.74 on average. The standard deviation is approximately equal to 0.06, resulting in an COV equal to 0.08 (low variability), thus determining that statistically the ϵ average is constant throughout the year. However, it is observed that the monthly average of ϵ increases slightly during the month of May.

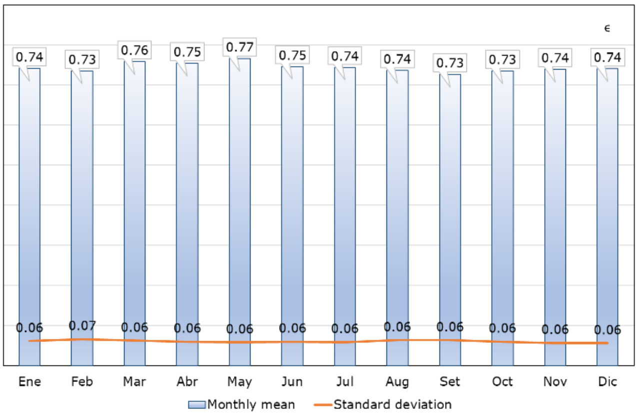

Fig. 3. Monthly mean of spectral broadness amplitude at Peru Sea Basin.

Values of κ are then estimated using the relationship of $\langle E_{1/3} \rangle$ with ϵ, Fig. 1. These κ values were then used to calculate the H_{mo} time series, with equation (1) plotted in Fig. 4.

On average, a value equal to 0.74 corresponds to ϵ, thus estimating an average value of κ equal to 3.6, which can be considered characteristic of the region (Peruvian Sea Basin).

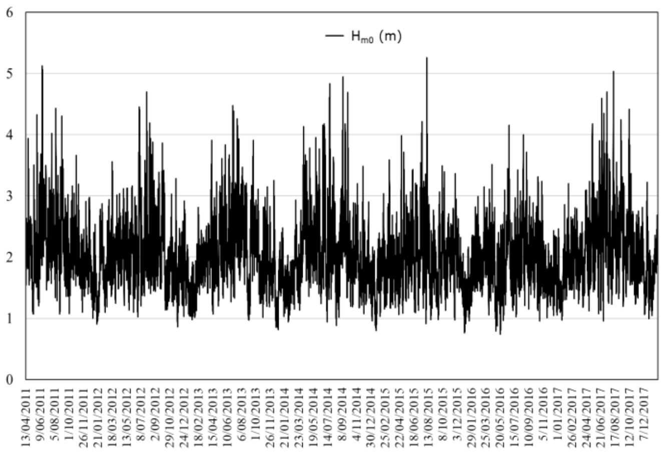

Fig. 4. Time series of significant wave height calculated at Peru Sea Basin based on spectral broadness parameter.

Both time series of significant wave height, one calculated based on ϵ and the other based on $H_{m0} = 4\sqrt{m_0}$ (Fig. 4 and Fig. 5, respectively), have the same behaviour confirming that there is low variability in the values of ϵ. There is only a decrease in the magnitude of H_{m0} equal to

$$\%Decrease\ of\ H_{m0} = \frac{4 - 3.6}{4} x\ 100\% = 10\% \quad (16)$$

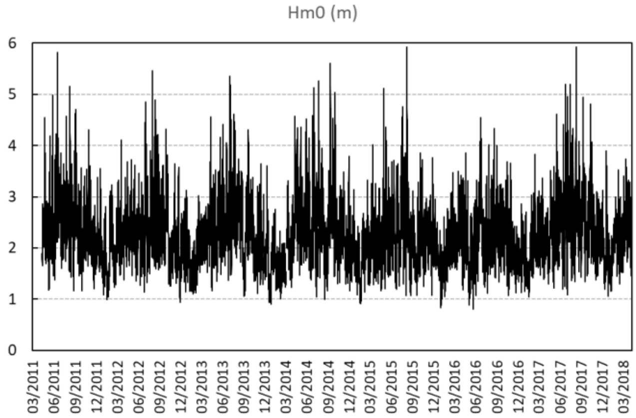

Fig. 5. Time series of significant wave height calculated at Peru Sea Basin based on spectral estimated for narrow band spectrum.

B. *Monthly Averages of wave height.*

The monthly average value of the significant wave height increases progressively from 1.6 m in January to 2.3 m in July and decreases to 1.7 m in December, Fig. 6. The variability also increases towards July, calculating a maximum COV equal to 0.3, which is very close to the statistical critical value of 0.2, thus H_{mo} shows stability throughout the year. Most of the year, from March to October, the average minimum value of H_{mo} is 2 m. Throughout the year, the average value of H_{mo} remains above 1.6 m.

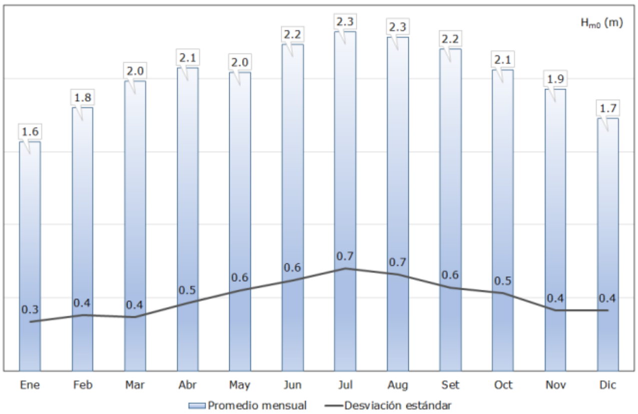

Fig. 6. Monthly mean of significant wave height at Peru Sea Basin.

The influence of multiple wave systems on wave power is insignificant, as shown in Fig. 7 and Fig. 8. The multiple wave systems through the spectral broadness parameter significantly influence the wave height. The magnitude of the wave power also depends on the energy period. The estimated and calculated wave power magnitude are almost identical; that similitude implies that the energy period calculated is bigger than the estimated energy period in The South-East Pacific.

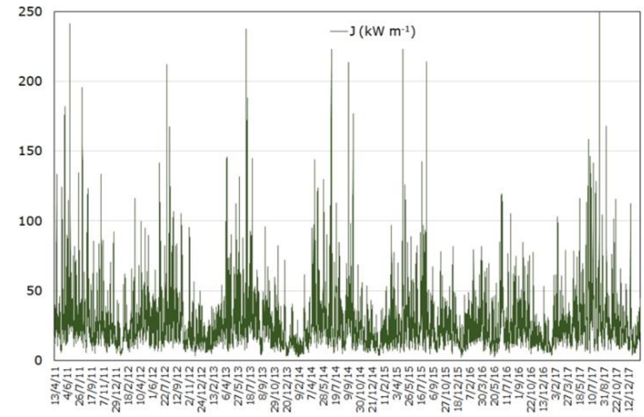

Fig. 7. Time series of wave power calculated at Peru Basin

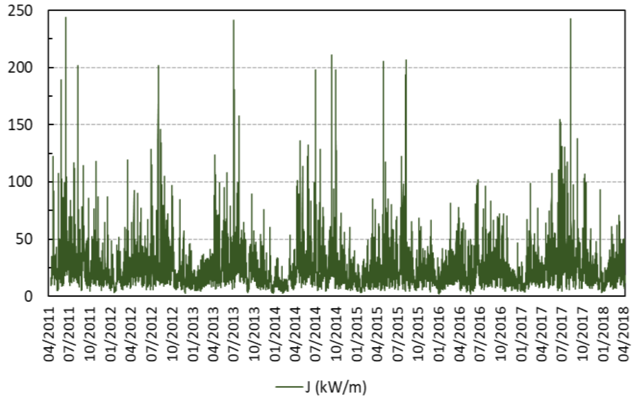

Fig. 8. Time series of wave power estimated at Peru Basin

IV. Conclusions

In this work, the spectral estimate factor of significant wave height, characteristic of the region, was quantified. The average of the spectral amplitude parameter turned out to be greater than the maximum critical limit value that considers a spectrum to be narrow band, taking the probability density function obtained by Raileigh and consequently estimating the significant wave height as the product of a factor four times the standard deviation of the sea state spectrum. This κ factor was found to be equal to 3.6 based on its relationship to the spectral amplitude parameter.

This average resulting from the average of the monthly averages is equal to 0.74; this result rejects the assumption that the sea spectra of the Peru Basin are called narrow band; on the contrary, it is shown that these sea states should be considered broadband.

Thus, when estimating the significant wave height must consider the dependence of the factor of the spectral estimated formula in the spectral method on the value of the resulting spectral amplitude parameter.

When considering the low variability of the average value of the spectral amplitude parameter whose variability coefficient became equal to 0.08, it is stated that the result of 0.74 is constant.

Therefore it is obtained from the figure "Half of the spectral estimated factor of significant wave height versus spectral broadness parameter at Peru Sea Basin" that the factor of the spectral estimate leads to the following most accurate formula: $H_{m0} = 3.6\sqrt{m_0}$.

The estimated and calculated wave power magnitude are almost identical; that similitude implies that the energy period calculated is bigger than the estimated energy period in Peru Basin. This hypothesis will be investigated in a future work.

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Influence of wave conditions on wave power in the South-East Pacific

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***Abstract*— In wave energy conversion field, the wave conditions of a sea state, per hour, are characterized by the following parameters: significant wave height, energy period, omnidirectional power, wave energy per unit crest length per average year, and average wave direction. In order to estimate grand part of wave parameters, a wave spectrum is needed. The Pierson-Moskowitz standard wave spectrum has often been used for fully developed sea states, while the JONSWAP spectrum has been used for partially developed sea states. The assessment of offshore wave energy resources in many seas have assumed a JONSWAP spectrum only because that assumption was also used to assess wave energy resources in other places. There are also wave energy resource assessments for multimodal sea states based on the Pierson-Moskowitz spectrum because of a suggestion of the International Electrotechnical Commission. We point out that working with a standard spectral shape without considering wave conditions overestimates the amount of wave power for open ocean wave conditions. For the present paper, we selected a Bretschneider spectrum to represent open ocean wave conditions and quantify the influence of spectrum shape on wave power. We conclude that energy period is constant. Although it is true that there is temporal variability, this variability is nearly zero. Confined ocean wave conditions analysis yields high averages of wave power, that is, there is overestimation. It is recommendable to use a spectrum for multimodal wave system, like the Bretschneider spectrum. We calculated an overestimation on wave power about 46%.**

Keywords—energy period, wave power overestimation, significant wave height, open ocean conditions, Peru Basin

I. Introduction

In a spectral analysis it is assumed that the wave spectrum can represent the sea surface as the superposition of sinusoidal waves with defined ranges of frequencies, amplitudes and directions. The variation of wave energy with frequency and direction is called the wave spectrum. In wave energy conversion field, the wave conditions of a sea state, per hour, are characterized by the following parameters: significant wave height H_{m0}, energy period T_e, omnidirectional power J, wave energy per unit crest length per average year E, and average wave direction θº.

The Pierson-Moskowitz standard wave spectrum has often been used for fully developed sea states, while the JONSWAP spectrum has been used for partially developed sea states [1]. According to the literature, several wave energy estimates have been made for the open sea using the Pierson-Moskowitz or JONSWAP spectrum, for example, off the coast of Galicia [2], along the northwest coast of the Iberian Peninsula [3], off the coasts of the United States [4], in the evaluation of the wave energy resources of the Peruvian sea [5].

The assessment of offshore wave energy resources in the East China Sea assumed a JONSWAP spectrum only because that assumption was also used to assess wave energy resources off the Canada's coasts and in the north sea as well as for a global study of the oceans [6]. The wave energy resource assessment for the Hawaii multimodal sea state was based on the Pierson-Moskowitz spectrum because of the International Electrotechnical Commission (IEC) - Technical Committee 114 suggests that approach to calculate wave energy when energy period is not available.

In contrast, the spectrum measured by the Atlantic Marine Energy Test Site (AMETS), Ireland, were found to fit relatively well with what we would expect from an open water site, as shown by the similarity of the shape spectral average with the Bretschneider spectrum [7].

According to the papers presented, when there is no spectral data, a predefined form is selected; in most cases the JONSWAP spectrum has been used. We point out that working with a standard spectral shape without considering wave conditions overestimates the amount of wave power for open ocean wave conditions. For the present paper, we selected a Bretschneider standard spectrum to represent the influence of spectrum shape on wave power.

We have used spectral analysis and statistics techniques to investigate the behavior of the energy period as a function of time, too. From our results, we conclude that it is recommendable to select in advance a spectrum for open ocean wave conditions when sea state has both swell and sea waves or there are no boundaries which confine the sea.

II. Data and Methodology

A. Measurements

The measurements were obtained from the National Data Buoy Center NDBC (*www.ndbc.noaa.com*). These data are based on field measurements taken in Peru Basin. The measurements taken by buoy 32302 consist only of the following wave parameters: the significant wave height H_{m0}, the average period between zero upcrossings T_z, and the peak period T_p. Fig. 1 shows the location of buoy 32302 and the sea of Peru Basin in South-East Pacific. TABLE I shows the measurement period, geographic location, sea depth, and period of measurements. These data were provided hourly, thus data points represent mean values of measurements taken within range. More than 95% of the data is available within the period. The registration time spans 10 years.

TABLE I. Location of Buoy 32302

Buoy	Buoy characteristics			
	Latitude (º S)	*Longitude (º W)*	*Sea depth (m)*	*Period*
32302	18º	85.1º	4929	1986-1995

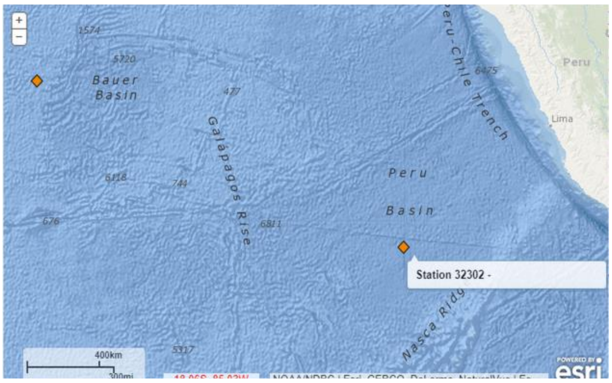

Fig. 1. Location of buoy 32302 in the Peru Basin.

B. *Wave Parameters*

In wave energy conversion field, the reference representative wave height is the significant wave height calculated from the wave elevation variance of an omnidirectional wave spectrum [8]. The estimated expression for significant wave height is written as

$$H_{m0} = 4\sqrt{m_0}, \tag{1}$$

The spectral moments (m_0, m_{-1} and m_2) are calculated from

$$m_i = \sum_{n=1}^{n_b} f_n^i S_\zeta(f_n) df_n \quad i = 0, 1, 2 \tag{2}$$

where df_n is the bandwidth of the n*th* band, S_ζ is the omnidirectional wave spectrum as a function of the wave frequency f in hertz.

The energy period or average period of component waves T_e, [9], is calculated by

$$T_e = \frac{m_{-1}}{m_0}. \tag{3}$$

The omnidirectional wave power J [10], in terms of H_{m0} and T_e, can be defined for deep water as

$$J = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e, \tag{4}$$

where ρ is the average sea water density and g is the gravity acceleration.

The peak or dominant period is the period corresponding to the central frequency of the spectral frequency band which has the maximum spectral density. The peak period is the reciprocal of the peak frequency f_p, for which the spectral wave energy density is maximum. The peak period represents the period of the highest waves that occurred during the wave monitoring using the buoys. In contrast, T_z represents the average period when waves cross a mean sea surface level, and this period is calculated as

$$T_z = \sqrt{\frac{m_0}{m_2}}. \tag{5}$$

The energy period is estimated based on the data of the available periods, such as T_p as well as T_z. Thus, when T_e is estimated based on T_p, the relationship is written as

$$T_e = 0.9 T_p \tag{6}$$

for the JONSWAP standard spectrum.

By utilizing a Bretschneider standard spectrum and T_z [9], the relationship is written as

$$T_e = 1.2 T_z. \tag{7}$$

C. *Coefficient of Variability*

The Coefficient of Variability *CV* calculates the amount of variability with respect to an average value..

$$CV = \frac{\sigma(T_e)}{\mu(T_e)}, \tag{8}$$

We define energy period standard deviation $\sigma(T_e)$ and average value $\mu(T_e)$. We consider that a *CV* value of 0.2 is low, and therefore the characteristic that *CV* represents is stable.

D. *Discrepancy of Averages Values*

The underestimates or overestimates of J calculated according to the estimation of T_e are obtained by:

$$\%Discrepancy = \frac{\bar{J}_{JONSWAP} - \bar{J}_{Bretschneider}}{\bar{J}_{Bretschneider}}, \tag{9}$$

where the superscript "-" indicates averages of the values calculated.

III. Results and Discussion

A. *Time Series Analysis*

Fig. 2 presents the time series of energy period which shows no trend only a slight seasonal behavior. Energy period has high extraordinary values about 16 s and low

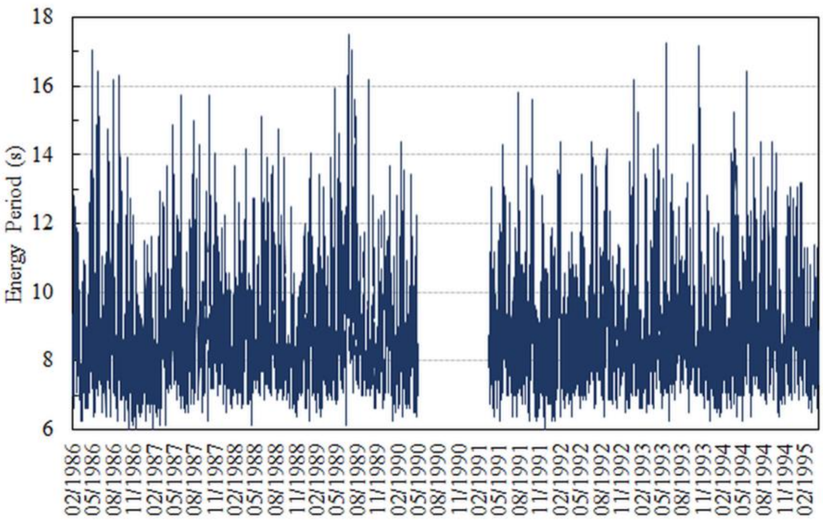

Fig. 2. Time series of energy period from 1986 to 1995 for buoy 32302 in the Peru Basin.

extraordinary values around 6 s. Energy period varies between 7 and 11 s. As Fig. 2 shows, there is a data gap from May 1990 to May 1991. Outside data gap that spans a year the database is complete.

Fig. 3 presents the time series of wave power and significant wave height which shows no trend, only a marked seasonal behavior for both. The wave power shows some high extraordinary values around 200 kW/m but it is concentrated about 20 kW/m. Significant wave height shows concentrated data between 1.5 and 3 m. There are few high extraordinary values for H_{mo} time series.

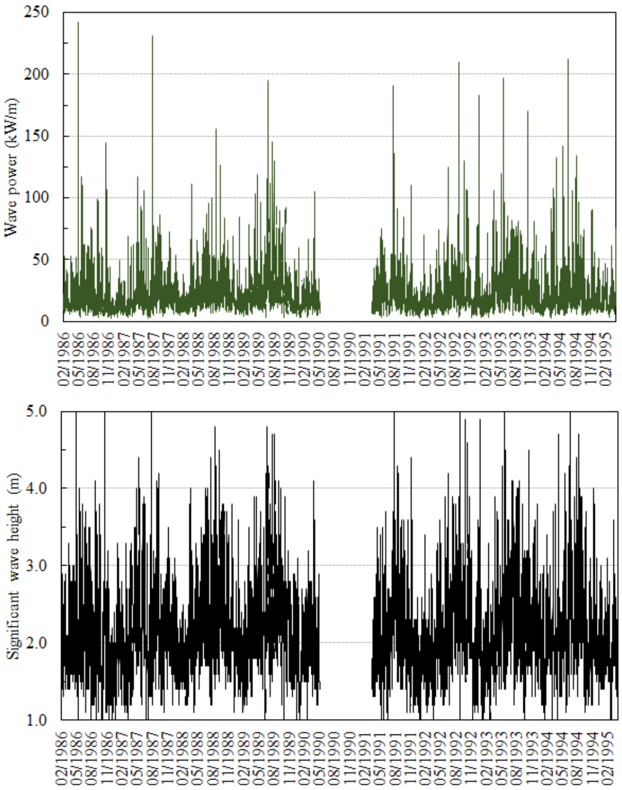

Fig. 3. Time series of wave power and significant wave height from 1986 to 1995 for buoy 32302 in the Peru Basin.

Fig. 4 shows no cyclical component of T_e in the four-period moving average of quarterly time series. Energy period does not have a long-term trend.

TABLE II summarizes the statistical characteristics of T_e, H_{m0} and J. As TABLE II shows, T_e has an average of 8.72 s and a standard deviation of 1.52 s, these preceding values yields a *CV* of 0.17. Also, H_{m0} has an average of 2.14 m and a standard deviation of 0.58 m that yields a CV equals to 0.27. Finally, J has a *CV* equals to 0.72. Particularly, T_e is considered to be constant because of its *CV* is nearly zero.

TABLE II. WAVE CLIMATE STATISTICS FOR BUOY 32302 IN PERU BASIN

Buoy	Wave Climate Statistics			
	$H_{m0} \pm SD$ (m)	$J \pm SD$ (kW/m)	$T_e \pm SD$ (s)	$CV(T_e)$
32302	2.14 ± 0.58	21.92 ± 15.76	8.72 ± 1.52	0.17

B. Wave Power Variation

Our results for wave power contrast what López, Veigas and Iglesias reported about wave power with a value of 32 kW/m, the mean annual energy flux in the offshore of Peru. They used JONSWAP spectrum and T_p to characterize by first time the wave energy resource off Peru's coasts [5]. Since we used a suitable spectrum for open ocean conditions like in Peru Basin rather than confined sea wave conditions we get wave power low than the reference work. The discrepancy is

$$\%Discrepancy\ of\ J = \frac{32-21.92}{21.92} \cdot 100 = 46\% \qquad .$$

IV. CONCLUSIONS

We quantified the energy period for open ocean wave conditions through spectral analysis to calculate the variation of wave power compared to what is found in confined ocean wave conditions. We used reliable wave data to get the behavior of energy period and statistics characteristics of the sea of Peru Basin.

We conclude that energy period is constant. Although it is true that there is temporal variability, this variability is nearly zero. Energy period does not have long-term trend. Seasonal behavior is negligible.

Confined ocean wave conditions analysis yields to high averages of wave power, that is, there is overestimation. It is recommendable to use a spectrum like Bretschneider when coast is open to the ocean or sea has both swell and sea waves. In that sense, by considering 21.92 kW/m as actual value and 32 kW/m as first estimation, the overestimation is about 46%.

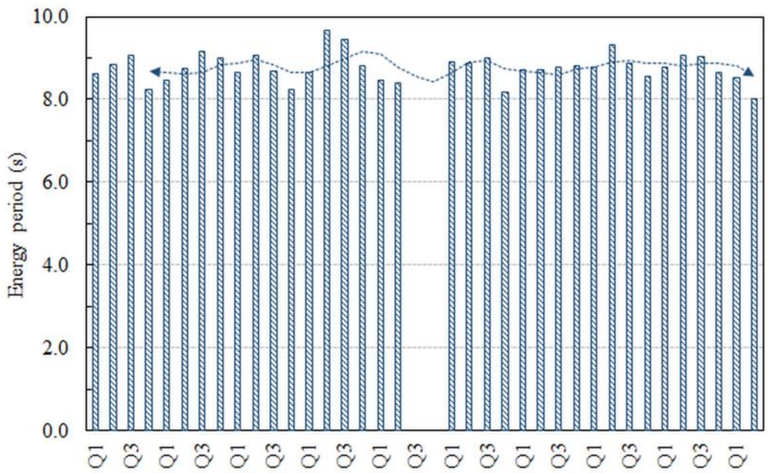

Fig. 4. Quarterly time series of energy period from 1986 to 1995 for buoy 32302 in the Peru Basin.

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