

Article

Characterization of Wave Power Resources off the Coast of Guangdong

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Abstract: A wave energy resource characterization for China's Guangdong Coast is carried out utilizing 1-year (2020) wave data from four buoy sites. The wave heights, wave periods, wave directions, and effective wave height occurrence were analyzed using statistical methods. The wave energy spectrum methodology is used to calculate the wave power density. The wave energy level frequency and effective storage of wave energy are presented. The seasons and month variation indices are used to assess the wave power stability. The contribution of sea conditions to wave power is examined. The results indicate that the waters off Guangdong are rich in wave-related energy resources. The average wave energy density is (8.55–13.1) kW/m, and the maximum wave energy density is (94.6–624.2) kW/m. The effective reserves in winter are the largest at 1.0×10^6 kW·h/m. The biggest share of wave energy is found in the sea state, with significant wave heights of 0.5–1.0 m and significant wave periods of 5–6 s. Typhoons contribute very little to yearly wave energy, yet they are significant when evaluating the dependability and durability of ocean wave energy converters.

Keywords: Guangdong coast; wave energy density; wave energy resource; EWHO (effective wave height occurrence)



Citation: Liu, T.; Yu, J.; Yu, Y.;

Zhang, X.; Zhou, B.; Yin, L.

Characterization of Wave Power

Resources off the Coast of

Guangdong. *Processes* **2023**, *11*, 2221.

<https://doi.org/10.3390/pr11072221>

Academic Editor: Davide Papurello

Received: 6 June 2023

Revised: 7 July 2023

Accepted: 19 July 2023

Published: 24 July 2023



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1. Introduction

Countries have boosted the production and consumption of renewable energy in response to the increasingly severe global energy scarcity and degradation of the environment [1]. Among all kinds of renewable energy, the most effective and undeveloped energy is ocean energy, among which wave energy, tidal energy, and temperature gradient are the most valuable and potential [2]. With the goal of achieving the long-term development of electric power in the coastal regions, China strongly supports the development strategy of marine energy and develops wind energy, wave energy, tidal energy, and other resources in coastal areas. As a natural green energy, wave energy has the benefit of being renewable, clean, environmental, rich reserves, wide distribution, and all-weather, which is of great significance to relief from the power and ecological crises, and creates good economic and environmental benefits. Therefore, it is widely valued by countries all over the world [3–5].

The global wave energy resources are abundant, with a total available amount of 2 TW [6]. China has a vast coastline and abundant wave energy resources, with a theoretical storage capacity of about 7×10^8 kW, with huge development potential [7,8]. Guangdong's coastline is relatively lengthy, with regular land and sea economic operations. It is an important area for industrial production and energy consumption, as well as a natural area for renewable energy. Among them, Guangdong Province ranks among the top in terms of total marine energy reserves in the country, while wave energy reserves rank first in the country. One of the key avenues for the creation of new energy is the development of

ocean energy, such as wave energy, and conducting a scientific resource assessment is a requirement for producing and using the power of waves.

Researchers have recently used techniques like numerical simulation, satellite remote sensing, reanalysis data, and observed data to study wave power resources. The popular wave numerical simulation models are WAVEWATCH-III (WW3), Simulated Waves Nearshore (SWAN), etc. Zheng et al. [9,10] and Xi et al. [11] apply the WW3 numerical model along with the Cross Calibrated Multi-Platform (CCMP) wind data to analyze wave power resources. And Zong et al. [12] use the Simulated Waves Nearshore (SWAN) numerical model. They discovered that northern South China Sea waters are rich in wave power potential. These numerical simulation methods, although low cost and large in scope, require precise bathymetric topography, wind fields, etc., as boundary conditions. Therefore, the simulation accuracy needs to be further improved. Reanalysis data are a data set that uses data assimilation to re-fuse observations of various types and sources with numerical forecast products. The European Centre for Medium-Range Weather Forecasts (ECMWF) is one of the world's leading reanalysis data centers. The ERA-Interim reanalysis wave data is utilized to assess wave energy resources [13–15]. Jiang et al. [14] concluded that the spatial resolution of ERA-Interim reanalysis wave data is not high enough to accurately characterize the key areas along the Guangdong coast, especially along the east Guangdong-Pearl River Estuary-western Guangdong coast. Wan et al. [16] studied the wave energy features in Chinese waters using AVISO satellite data from 2009 to 2013 and discovered that wave energy was predominantly influenced by the contribution of sea state of $0.5 \text{ m} \leq H_s \leq 4 \text{ m}$, $4 \text{ s} \leq T_e \leq 10 \text{ s}$. Reanalysis data generally have the disadvantage of low resolution and poor accuracy. In the use of on-site actual measurement data, Defne et al. [17] and Ozkan and Mayo [18] used wave data from National Data Buoy Center (NDBC) stations to evaluate available wave power for the southeast Atlantic coast of the United States and the Florida peninsula. Wu et al. [19] conducted an analysis of wave resources in the East China Sea using measured wave data from six buoys. In addition, Yang et al. [20] also used on-site observed data for wave energy evaluation. At present, the methods for evaluating wave resources mainly rely on numerical simulation, satellite remote sensing, and reanalysis data, with few on-site measurements. Numerical simulation has the advantages of low cost, high resolution, and a wide spatiotemporal range for monitoring the marine environment, but it also requires measured data to verify and correct [21]. The on-site measurement cost is high, the risk is high, and the data is difficult to obtain. However, on-site measurement data are the most accurate and particularly precious [22]. And they provide significant data for characterizing errors in wave power formulations, offering additional insights into the calibration coefficients between the energy and peak or mean periods. It can serve as a basis for refined wave energy site selection, as well as a calibration verification and supplement for satellite and numerical simulation, which is of great significance for wave energy resource assessment.

Due to the fact that the coast of Guangdong is constantly influenced by monsoon climate and tropical cyclones, it has complex wave characteristics. For example, wave refraction, wave diffraction, and wave fragmentation [23]. At the same time, the Pearl River Estuary in Guangdong Province is also an important area with frequent disasters and serious disasters in the sea area [24,25]. Wave energy devices have poor survivability in extremely high waves and are at high risk of damage. After selecting specific sea areas for wave energy development and utilization, previous research work has the disadvantages of large scope and low spatial and temporal resolution of the simulation. It is difficult to provide finer and more accurate results of wave energy resource analysis for wave energy development activities. In situ buoy observations are the most accurate and suitable for fine-grained assessment of wave energy.

In this paper, the characteristics of effective wave height and period, wave energy density, and the contribution ratio of sea state to wave power are analyzed by using the measured data from buoys at four observation stations along the Guangdong coast in 2020. The results of the study not only provide a scientific basis and auxiliary decision for wave

power generation along the coast of Guangdong but also provide some reference for wave forecasting and warning.

2. Materials and Methods

2.1. Materials

The data come from four large-scale marine data buoys in the waters of Guangdong province (Table 1). The buoy is a 10 m diameter disc-shaped metal hull with a Catenary Anchor Leg Mooring. A wave and meteorological measurement system is installed on the buoy. The uncertainty in buoy wave measurements lies mainly in the wave-following nature of the buoy. Such buoys may have difficulty measuring smaller wave heights but are accurate for large wave heights. Wave power generators generally operate at larger wave heights, so these measurement data are suitable for evaluating wave energy generation. The SBY1-1 wave sensor is developed by Institute of Oceanographic Instrumentation China Shandong Academy of Sciences, with the principle of gravity acceleration measurement and the wave height ranging from 0.2 to 25 m. The wave sampling frequency is 4 Hz. The wave surface was recorded every hour for 1024 s. The wave characteristic value is transmitted back to receiving station on land through Beidou satellite system on an hourly basis. The analysis data of wave spectrum in this study were the retrieved original data of wave surface obtained through fast Fourier transformation (FFT) analysis. Figure 1 depicts the spread of observation sites with a water depth of approximately 60 m. Data are available from 1 January 2020 through 31 December 2020. The wave meter operates on the gravity acceleration concept and collects a set of wave data every hour, including wave parameters such as significant wave heights (H_s) and periods (T_s) [26].

Table 1. Coordinates of observation stations.

No.	Longitude	Latitude	Depth/m
P1	112.63 E	21.12 N	60
P2	113.99 E	21.49 N	62
P3	115.59 E	22.27 N	58
P4	117.10 E	22.86 N	61

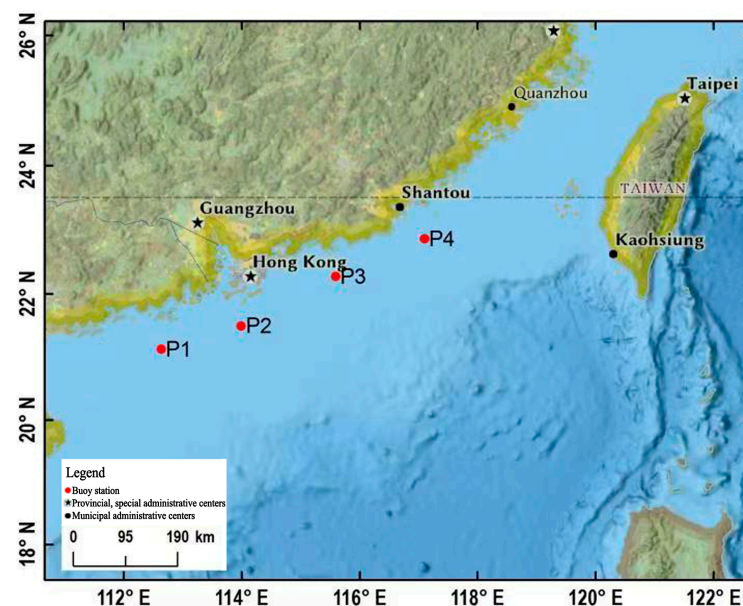


Figure 1. Location map of wave buoy stations.

2.2. Methods

Real sea waves are made up of random waves with varying frequencies, amplitudes, and orientations. One of two formulae can be used to calculate available wave power. The

first necessitates spectral wave data for various wave frequencies. The second equation, which is a simplified form of the first, is the most commonly utilized. We predict that the spectral wave equation will provide a more accurate assessment of available wave power. The wave energy level is proportional to the wave energy spectrum E , and the wave energy density P_w is commonly employed to assess the wave energy level. It denotes the wave energy transfer per unit crest length, which is written as [27]:

$$P_w = \rho g \int_0^{2\pi} \int_0^{\infty} C_g(f) S(f, \theta) df d\theta \quad (1)$$

where P_w is wave energy density, ρ is density of seawater, g is the acceleration of gravity, C_g is the group velocity, $S(f, \theta)$ is the directional wave energy spectrum, f is the individual wave frequency, and θ is the wave propagation direction.

According to linear wave theory, the wave group celerity in Equation (1) is as follows:

$$C_g(f) = \frac{f}{2k} \left(1 + \frac{2kh}{\sinh(2kh)} \right) \quad (2)$$

where $k = 2\pi/L$ represents the wave number, and L represents the wavelength. In deep water, the wave energy density can be reduced to References [28,29]:

$$P_w = \frac{\rho g^2}{64\pi} T_e H_s^2 \quad (3)$$

H_s is significant wave heights, T_e and is wave energy periods. In addition, T_e it is related to the n -order moment of the wave spectrum m_n , and the calculation formula is as follows:

$$m_n = \int_0^{2\pi} \int_0^{\infty} f^n S(f, \theta) df d\theta \quad (4)$$

The effective wave height H_s and energy period T_e can be expressed as

$$\begin{aligned} H_s &= 4\sqrt{m_0} \\ T_e &= \frac{m_{-1}}{m_0} \end{aligned} \quad (5)$$

Because there is a corresponding conversion relationship between wave periods, the energy period T_e can be converted from the spectral peak period T_p or the effective wave period T_s for the convenience of calculation. This paper adopts the following conversion formula:

$$T_e = 0.9T_p = 1.035T_s \quad (6)$$

3. Results

3.1. Wave Heights and Periods

Figure 2 shows the change curve of H_s and T_s for the four buoy stations. Some data were missing for a few months, and the data gaps for the P4 station are shown in Figure 2. It is obvious that H_s is mainly in the range of 1–2 m, and T_s is mainly in the range of 6–8 s. In August through December, when typhoons are most active, extreme sea conditions with H_s over 4 m are most common. The maximum effective wave heights of the four buoy stations P1, P2, P3, and P4 were 9.8 m, 5.6 m, 5.1 m, and 4.6 m, respectively, while the average wave heights were 1.5 m, 1.4 m, 1.4 m, and 1.6 m, respectively. The average effective wave periods were 6.3 s, 6.6 s, 6.4 s, and 6.3 s, respectively. Among the four stations, P1 has the largest maximum wave height, which may be related to the typhoon's landfall location. In winter, the wave heights at stations P3 and P4 are slightly higher than those at stations P1

and P2, which are associated with cold air. The difference between the wave periods of the four stations is small.

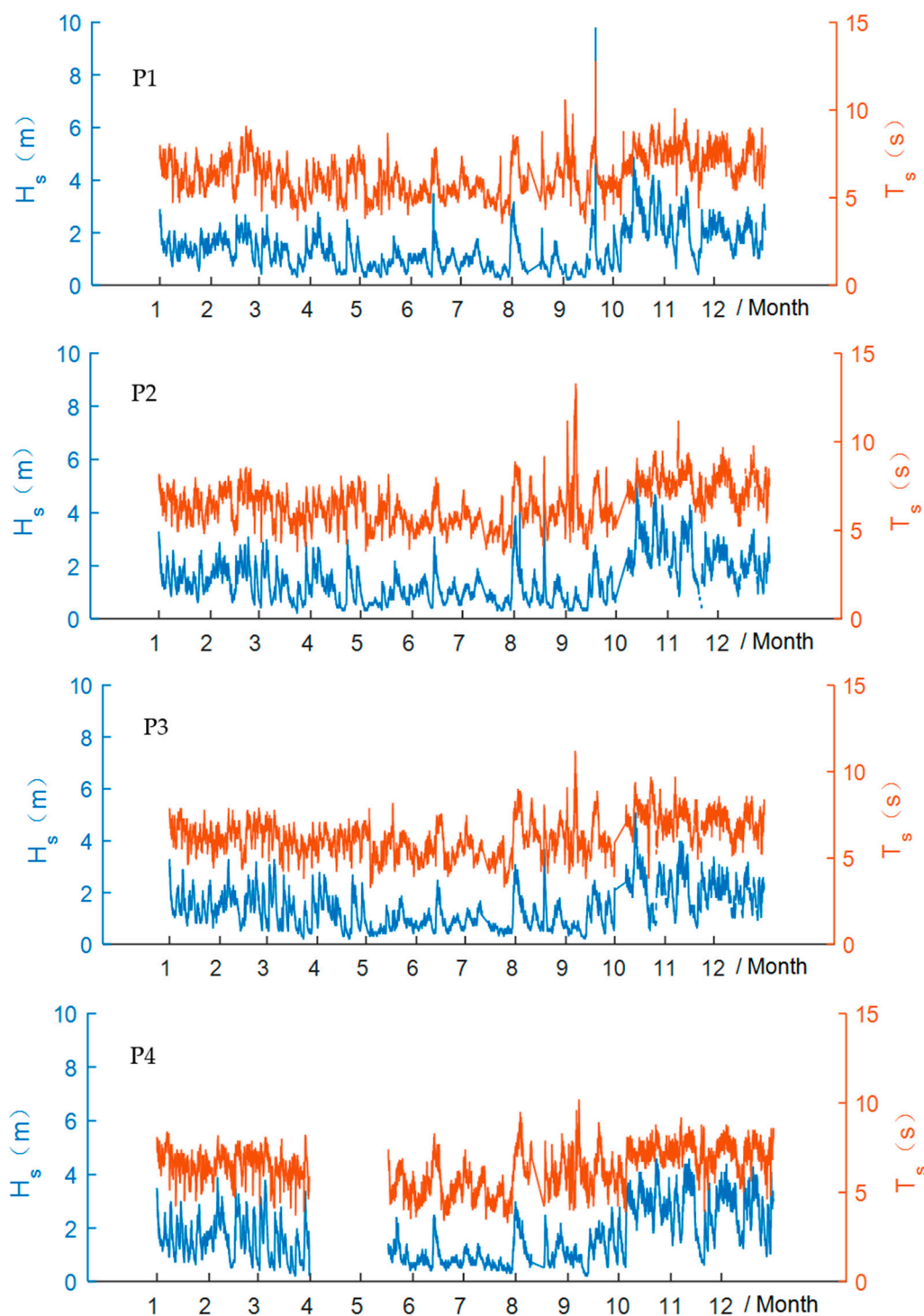


Figure 2. Time changes of H_s and T_s .

3.2. Wave Directions

Wave direction is a crucial characteristic of the wave climate, as well as for WEC design. Figure 3 provides the wave roses for the four stations. As can be seen from Figure 3, the wave direction at each of the four buoy stations is different. The predominant wave direction at station P1 is north, whereas it is east at station P2, northwest at buoy P3, and northeast at buoy P4. The powerful wave direction is aligned with the dominant wave

direction. The difference in wave direction of buoy stations is mainly caused by the different surrounding geography. Therefore, the design of wave energy devices in different locations should take full account of the specificity of wave direction. On the other hand, it can also be seen from the figure that the proportion of wave height above 1 m is higher in the sea near the four buoy stations. This indicates that the sea area is rich in wave resources, and at the same time, the sea conditions are also relatively harsh.

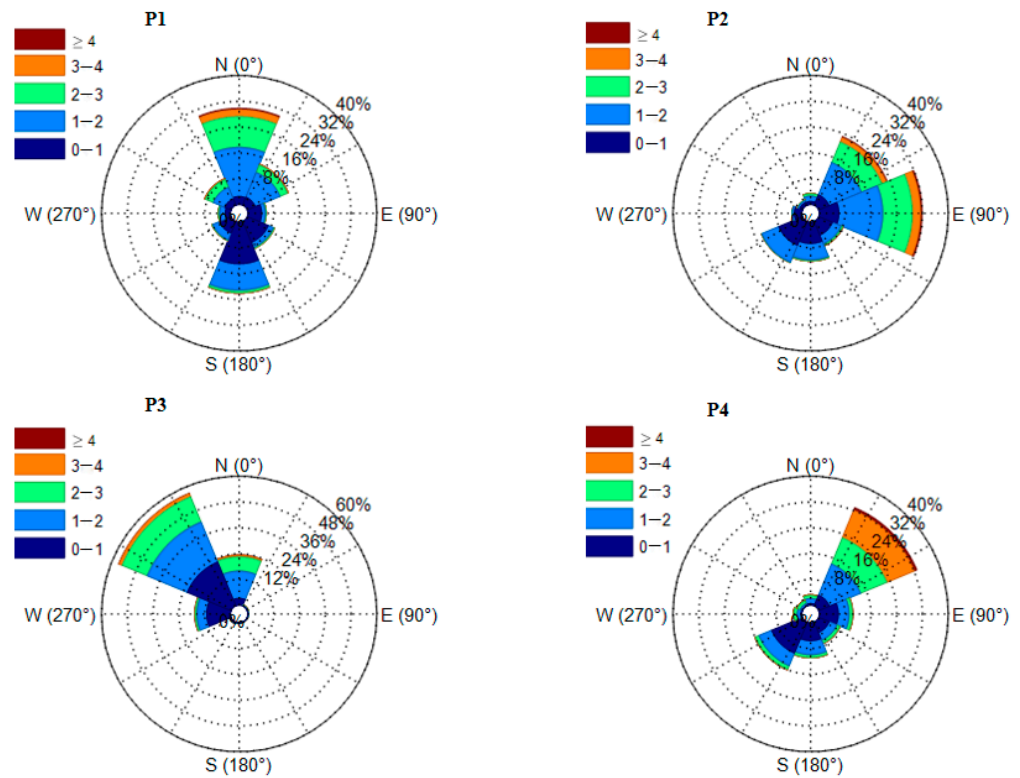


Figure 3. Wave rose of the buoys.

3.3. Effective Wave Height Occurrence (EWHO)

Significant wave heights (SWH) of more than 1.3 m can be used for wave energy generation, but excessive SWH can cause certain damage to the device [30,31]. Zheng and Li et al. [32] defined SWH ranging from 1.3 m to 4.0 m as EWHO (effective wave height occurrence), and this parameter reflects the degree to which wave energy can be exploited. The definitions of EWHO are as follows:

$$EWHO = \frac{N_{power}}{N_{all}} \times 100\% \quad (7)$$

where N_{power} is the number of times SWH occurred between 1.3 m and 4.0 m during the observation period, and N_{all} is the number of times all waves were observed. For example, if all wave heights during the observation period are between 1.3 m and 4.0 m, the value of EWHO is 100%.

Figure 4 shows the monthly variation characteristics of the occurrence frequency of EWHO. It can be seen that, except that the frequency of available wave height is relatively low from May to September, the frequency of available wave height in other months is more than 35%, of which the frequency from October to December is the highest, all of which are more than 70%. The inter-monthly trends of EWHO were generally consistent across the four stations. In winter, the P4 station has the highest EWHO value.

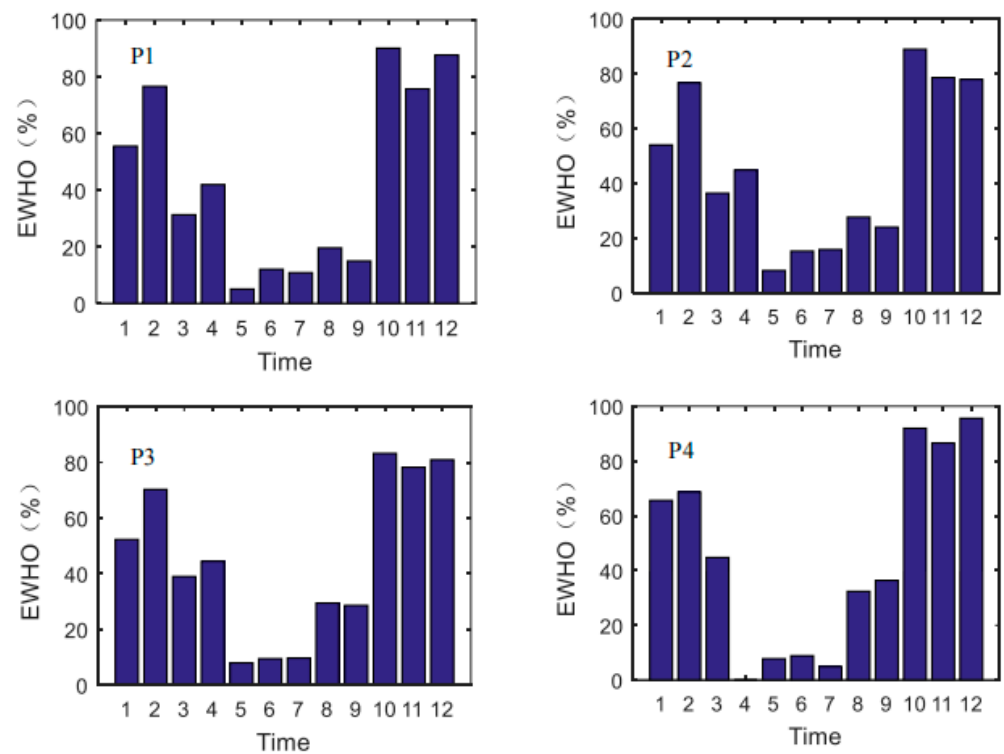


Figure 4. Time changes of effective wave height occurrence (EWHO).

3.4. Wave Energy Density

Figure 5 depicts a time history of the computed wave energy density (P_w) at the four buoy stations using Equation (2). The wave energy density can be found to have substantial seasonal variation, with higher levels in autumn and winter and lower ones in spring and summer. The average wave energy density is about 10 kW/m, and the maximum is below 130 kW/m. According to the national wave energy zoning classification [14], the sea area with wave energy current density greater than 4 kW/m is a wave energy-rich area. The marine area near the four buoy stations in Guangdong waters can be determined to be a wave-rich area [33].

Table 2 lists the statistical characteristics of wave heights, wave periods, and energy density of the four buoy stations. The significant wave height H_S is (1.34 ± 0.75) m – (1.63 ± 0.98) m, the smallest in western Guangdong and the largest in eastern Guangdong. The maximum wave height is between 4.6 m and 9.8 m, which may be related to the landing path of the typhoon. The average significant wave period is about 6.3 s. The average wave energy density is (8.55–13.1) kW/m. The maximum wave energy density is (94.6–624.2) kW/m. The extreme value appears during the typhoon.

3.5. Wave Energy Level Frequency

The frequency of occurrence of different levels of WPD visually reflects the abundance of wave energy, and two indicators, *ALO* (Available level occurrence) and *RLO* (Rich level occurrence) are defined with the threshold values of 2 kW/m and 20 kW/m.

$$ALO = N_2/N_{all} \times 100\% \quad (8)$$

$$RLO = N_{20}/N_{all} \times 100\% \quad (9)$$

where N_2 is the number of times the wave energy density is greater than 2 kW/m, N_{20} is the number of times the wave energy density is greater than 20 kW/m, and N_{all} is the number of all statistics.

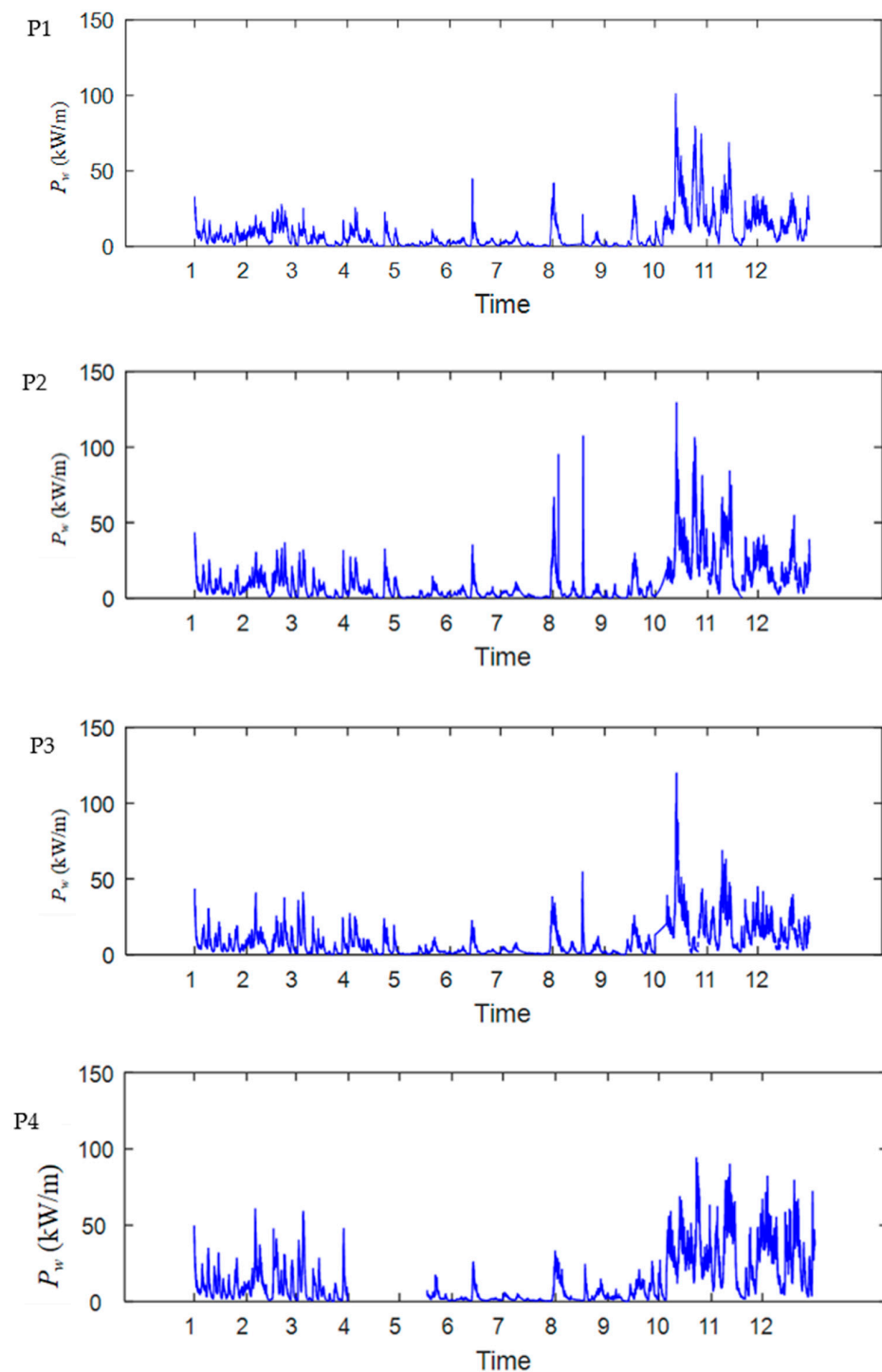


Figure 5. The time history of wave energy density.

The month-by-month *ALO* and *ELO* indices for the waters of the four buoy stations are given in Figure 6. Overall, the *ALO* values were higher in the four winter seas, all above 80%. Spring and summer were relatively low, with *ALO* above 30% for P1, P2, and P3 and around 20% for P4. In terms of *RLO* coefficients, the highest *RLO* values were found near the P4 buoy in winter, reaching over 50%. The other three buoy stations had *RLO* above 20% in winter. The *RLO* values were similar in other months. These differences are mainly due to the fact that the winter waves are mainly caused by the northeast monsoon, and the P4 buoy station is at the easternmost point, which is most affected by the cold air.

Table 2. Statistical parameters of wave energy.

Position	Hs	Max of Hs	Ts	Pmean	Pmax
	(m)	(m)	(s)	(kW m ⁻¹)	(kW m ⁻¹)
P1	1.34 ± 0.75	9.8	6.3	8.6	624.2
P2	1.43 ± 0.82	5.6	6.4	10.1	129.8
P3	1.38 ± 0.76	5.1	6.2	8.6	120.2
P4	1.63 ± 0.98	4.6	6.3	13.1	94.6

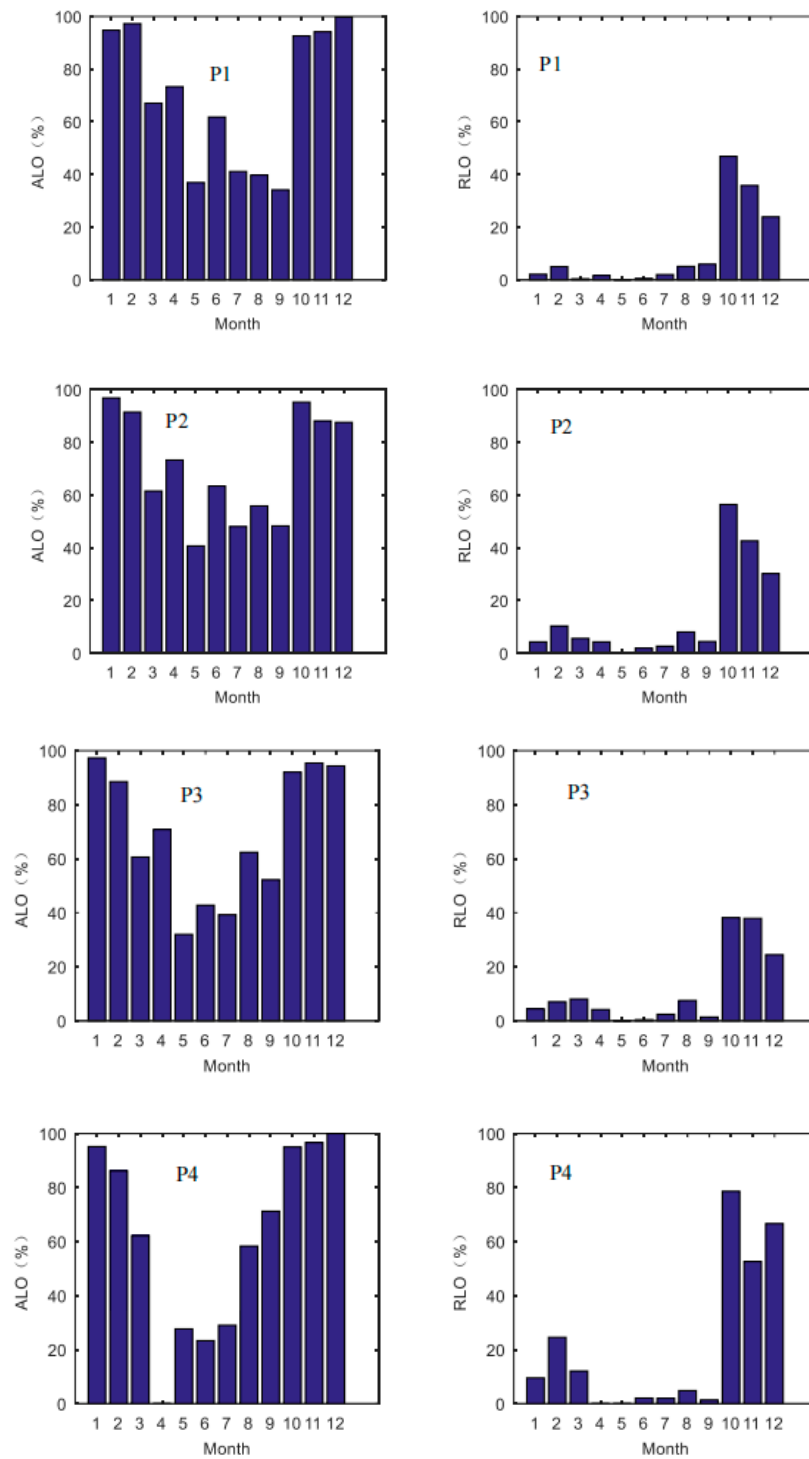


Figure 6. Monthly characteristics of wave energy level frequency.

3.6. Effective Storage of Wave Energy

The effective storage of wave energy is a technical indicator related to wave production capacity, which has practical guiding significance for wave energy development. Zheng [34] proposed the calculation formula for the monthly effective stock of waves as follows:

$$E = \bar{P} \times H \times fw \quad (10)$$

where E is effective storage, \bar{P} is the average wave energy density (WPD) of the month, H is the hours of the month, and fw is the available effective wave height frequency (EWHO) of the month. The effective wave reserves of the four observation stations calculated according to the above method are shown in Figure 7. The figure shows that Guangdong's coast region has comparatively large effective storage facilities of wave resources throughout the year, ranging from $(4.8\sim 7.7) \times 10^6$ kW·h/m; from the perspective of geographical location, the wave energy along the coast of West Guangdong—Pearl River Estuary—East Guangdong shows a “low-high-low-high” distribution feature. The effective reserves of wave resources have obvious seasonal variation characteristics. The effective reserves are the largest in October, November, and December at 1.0×10^6 kW·h/m. During the period from January to April, the effective reserves of waves took second place, with an average of 3.0×10^5 kW·h/m. The average effective wave reserve between the months of May through September is 1.0×10^5 kW·h/m. The P4 station has the highest wave energy storage. It may be related to the maximum wave height in autumn and winter.

3.7. Wave Power Stability Analysis

Waves are random in nature, and therefore, wave energy resources are unstable. This instability is related to the efficiency of the conversion of wave energy to electrical energy and the safety of the equipment. The stability of the wave energy density is usually assessed using annual, seasonal, and monthly coefficients of variation. In this paper, the seasonal (Sv) and monthly (Mv) variation indices proposed by Cornett will be used to analyze the stability of wave energy resources along the Guangdong coast [14]. The smaller the value of the monthly variation index and seasonal variation index, the better the stability. The calculation formula is as follows:

$$Sv = (P_{smax} - P_{smin}) / P_{mean} \quad (11)$$

$$Mv = (P_{Mmax} - P_{Mmin}) / P_{mean} \quad (12)$$

where P_{mean} is the average wave energy density throughout the year; P_{smax} and P_{smin} are the maximum and minimum seasons, respectively; P_{Mmax} , P_{Mmin} is the maximum and minimum energy months, respectively.

The variation indices of wave energy are shown in Table 3. In terms of seasonal variation, the wave energy variability index for the Guangdong coast ranged from 1.71 to 1.93. The variation in the four sites was not significant. The inter-monthly variation results are similar, with the inter-monthly variation index ranging from 2.22 to 2.85. It can be seen that the stability of wave resources along the Guangdong coast is good.

Table 3. Monthly and seasonal variation index.

Index	P1	P2	P3	P4
Sv	1.83	1.89	1.71	1.93
Mv	2.85	2.76	2.36	2.22

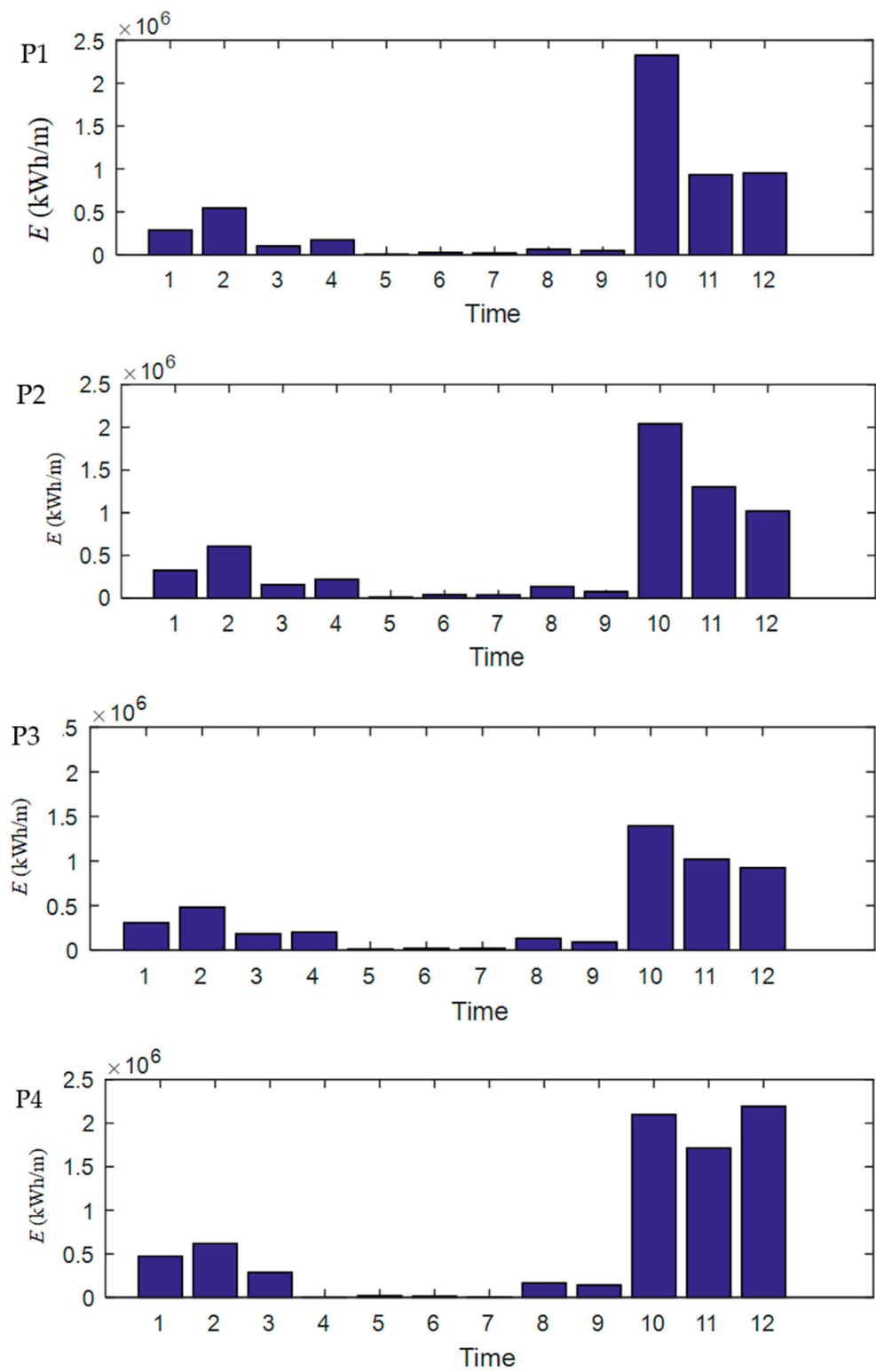


Figure 7. The wave energy's effective storage.

3.8. The Effect of Ocean Conditions

In the design of wave energy conversion devices, wave height and period are important parameters for determining the scale of the components, so it is necessary to study the distribution of wave energy according to the effective wave height and period and to determine the wave conditions that make a prominent contribution to the total energy as an important basis for the design of wave energy devices. In order to analyze the contribution of wave power under different sea states, Figure 8 shows the joint distribution of wave energy in the annual ratio corresponding to specific sea conditions. The sea condition is separated into wave heights at 0.5 m intervals and periods 1 s intervals. The number in the figure indicates the number of times the sea state occurs in the whole year, and the filled color indicates the ratio of wave energy in the whole year under the sea state. It can be concluded that the annual wave energy mainly contributes to the sea state in the range of 0.5–2 m wave heights and 5–8 s periods. Among them, the probability of the occurrence of effective wave height 0.5–1 m and effective wave period 5–6 s sea state is the largest, while the contribution ratio of wave energy to the whole year is the largest, accounting for about 7–12%. Although the wave height of extreme sea conditions such as typhoons is large, its contribution to the annual wave energy is relatively small.

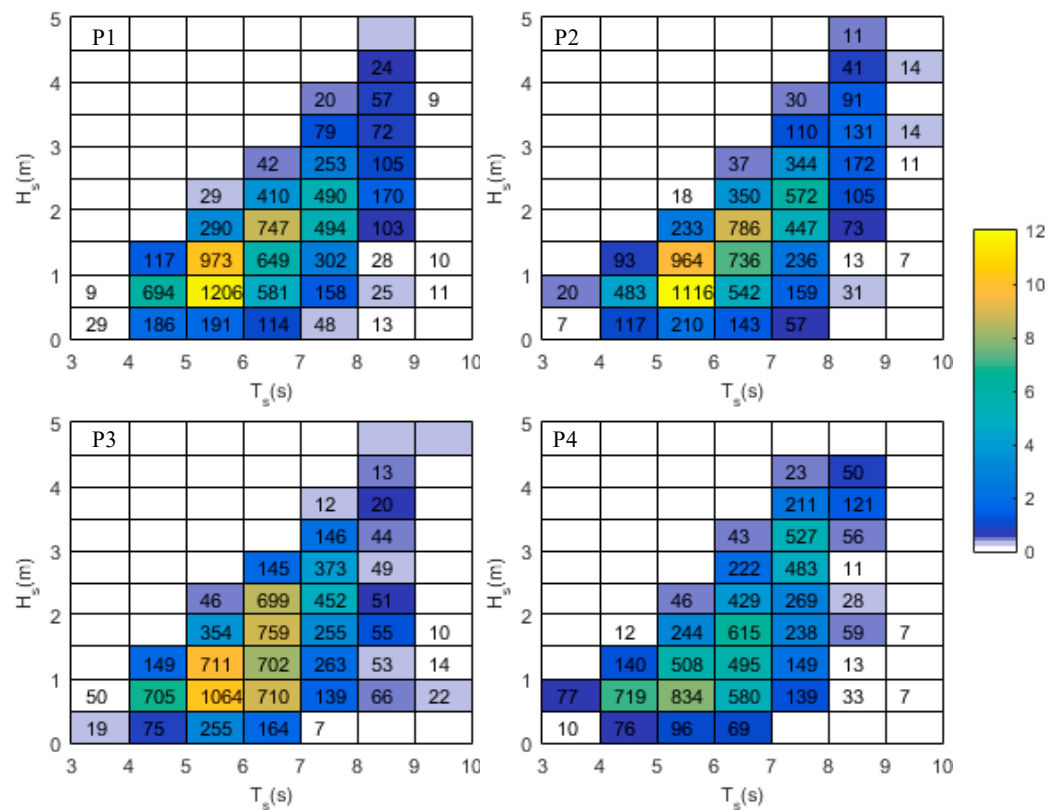


Figure 8. Joint distribution of sea state (H_s, T_s) and annual contribution ratio of wave energy.

4. Discussion

A refined assessment of the distribution characteristics and reserves of wave energy resources along the coast of Guangdong is of great significance for the development of clean energy. Jiang et al. [14] concluded that the coastal wave energy density of Guangdong Province is basically above 2 kW/m all year round. In this study, the wave energy distribution characteristics of the Guangdong coast were obtained more accurately. From west to east, the wave energy density in Guangdong waters is 8.6, 10.1, 8.6, and 13.1 kW/m, respectively. In terms of wave energy reserves, the wave energy reserves off the coast of Guangdong are higher than those in the Bohai Sea and the Yellow Sea and slightly lower than those in the East China Sea [19]. Wan et al. [16] showed that the extreme wave

power in the nearshore wave-energy-rich waters of the South China Sea could reach a maximum of 330 kW/m, but this study found a maximum of 624.2 kW/m. This extreme value can be used as a reference basis for the design of wave energy conversion devices. This difference may be due to the fact that this study used measured wave data during typhoons. Typhoons contribute very little to yearly wave energy, yet they are significant when evaluating the dependability and durability of ocean wave energy converters. This conclusion is consistent with the findings of the literature [19,35]. In line with the results of this paper, Wang et al. [36] also found that the seasonal variation of wave energy power density along the Chinese coast is obvious, with a high wave energy bias in the autumn–winter season (October–March) and a relatively weak one in the spring–summer season (April–September). Although this paper has achieved some useful results, there are still shortcomings of insufficient observation time scale and space scale. The subsequent study can be combined with numerical simulation and satellite data.

5. Conclusions

This article uses the wave measurement data of four ocean data buoys in 2020 to study the wave energy resources along the Guangdong coast. Wave height and period variation features, wave directions, wave energy density, energy level frequency, effective storage, wave power stability, and the influence of sea conditions are all explored. The findings are congruent with Jiang and Xi's [11,14] assessment of wave energy characteristics using reanalysis data and numerical simulation approaches. The coast of Guangdong province is rich in wave power resources, making it suitable for growing wave renewable energy sources. Wave energy resource distribution is steadily decreasing from east to west, with high-value locations primarily concentrated in the middle and northern sea areas and exhibiting obvious seasonal variable characteristics. Winter has substantial advantages over other seasons in terms of wave energy flow density and stability. The main conclusions are as follows:

- (1) The waters of the Guangdong coast have abundant wave renewable energy resources, with an average energy density of (8.55–13.1) kW/m.
- (2) The Guangdong's coast region has comparatively large effective storage facilities of wave resources throughout the year, ranging from $(4.8\sim 7.7) \times 10^6$ kW·h/m.
- (3) The primary contribution of wave energy occurs throughout the year in the range of wave heights 0.5–2 m and period 5–8 s. Wave heights of 0.5–1 m and periods of 5–6 s have the highest frequency of occurrence, and the contribution ratio of wave energy to the full year is likewise the largest, accounting for around 7–12%.

In summary, this paper uses the measured buoy data to evaluate and analyze the wave energy off the coast of Guangdong, which improves the accuracy in the nearshore area and makes the calculation results more accurate and provides a reference for the future development and utilization of resources in the sea.

Author Contributions: Conceptualization, T.L.; Methodology, T.L. and J.Y.; Software, J.Y.; Formal analysis, Y.Y. and X.Z.; Resources, B.Z.; Data curation, Y.Y.; Writing—original draft, T.L. and J.Y.; Writing—review & editing, X.Z. and L.Y.; Visualization, B.Z.; Supervision, L.Y. All authors have read and agreed to the published version of the manuscript.

Funding: China National Key R&D Program (2022YFC3104204), Self-established project of the Key Laboratory of Marine Environmental Survey Technology and Application of the Ministry of Natural Resources (No. MESTA-2021-C001).

Data Availability Statement: Data available on request due to restrictions e.g., privacy or ethical.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

Abbreviation	Definition	Units
EWHO	Effective wave height occurrence	%
WPD (Pw)	Wave energy density	kW/m
SWH (Hs)	Significant wave heights	m
ALO	Available level occurrence	%
RLO	Rich level occurrence	%
Te	Wave energy Periods	s
Ts	Significant Wave Periods	s
Tp	the spectral peak period	s
E	Effective storage of wave energy	kW·h/m
WW3	WAVEWATCH-III	/
SWAN	Simulated Waves Nearshore	/
CCMP	Cross Calibrated Multi Platform	/
ECMWF	European Centre for Medium-Range Weather Forecasts	/
Parameters	Definition	Units
ρ	density of seawater	kg/m ³
g	the acceleration of gravity	m/s ²
C_g	the group velocity	m/s
$S(f,\theta)$	the directional wave energy spectrum	m ² /Hz
m_n	the n-order moment of the wave spectrum	m ²
N_{power}	the number of times SWH occurred between 1.3 m and 4.0 m	/
N_{all}	the number of times all waves were observed	/
N2	the number of times the wave energy density is greater than 2 kW/m,	/
N20	the number of times the wave energy density is greater than 20 kW/m	/
\bar{P}	the average wave energy density	kW/m
H	the hours of the month	/
f_w	the available effective wave height frequency	%
S_v	Seasonal variation indices	/
M_v	Monthly variation indices	/
P_{mean}	the average wave energy density throughout the year	kW/m
P_{smax}	the maximum wave energy density seasons	kW/m
P_{smin}	the minimum wave energy density seasons	kW/m
P_{Mmax}	the maximum wave energy density month	kW/m
P_{Mmin}	the minimum wave energy density month	kW/m

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