

Article Assessment of Wave Energy Resources in China

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Abstract: The evolution of renewable energy technologies may surmount fossil fuel disadvantages. Wave energy is considered one of the best alternatives to fossil energy due to its advantages. The 40-year (1979–2018) spatio-temporal distribution of wave energy is presented using European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) datasets. In addition, the common formula used for wave energy evaluation is derived from the linear wave theory in deep water, which is not applicable in shallow water. Therefore, a new equation that is suitable for both shallow and deep water is derived, which improves the accuracy of the wave energy evaluation for various water depths. The main aim is to investigate the spatio-temporal wave energy for offshore China from 1979 to 2018 and combine the new standard of classification to recommend the optimal area. The nearshore zone from Zhejiang province to Guandong province is considered the ideal zone, and the average annual wave energy density in this area is above 10 kW/m.

Keywords: wave energy; ERA5; wave energy assessment; extreme wave height; optimal area; China



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1. Introduction

As the economy grows, the increasing population demands more energy. Having a diverse energy supply is conducive to increasing the resistance of nations to energy crises [1]. Renewable energy development technology is developing rapidly and has become the fastest-growing energy technology [2]. Meanwhile, the share of renewable energy in human electricity supply is also gradually growing, soaring from 26.2 percent in 2018 to nearly 28 percent in 2020 and is expected to rise to 45 percent by 2040 [3]. Renewable energy resources, including solar, hydropower, wind, biomass, geothermal energy and marine energy, have attracted human attention. Wave energy is considered one of the best alternatives to fossil energy due to its obvious advantages [4]. Understanding coastal wave resources is the prerequisite for selecting a suitable place to test and operate wave energy devices [5–8]. In the 1970s, researchers used limited observational data to assess global wave energy resources, such as Mollison [9] and Chiu et al. [10]. Due to the shortcomings of spatial discontinuity and scarcity, it is difficult to use the observed data for large-scale wave energy assessment and site selection. Satellite altimetry has the advantages of wide coverage of the ocean and high measurement accuracy, which provides valuable resources for climate research [11–15]. However, on a global scale, the repeated periods of satellites range from 10 to 35 days. Therefore, the temporal resolution is low, and extreme events such as storm waves are likely to be missed [16]. The innovation and development of computing technology have facilitated the numerical simulation of waves. The availability of reanalysis data makes it easier for scholars to assess wave energy [17–23]. Additionally, reanalysis data have been widely applied in atmospheric and oceanic studies [24–26].

Chinese wave energy has been researched since the 20th century. Wan et al. used ERI reanalysis data [27] and satellite data [28] to analyze the wave energy in the water of China. Zheng et al. [29] and Liang et al. [30] used Wave Watch 3 (WW3) and Simulation WAve

Nearshore (SWAN) wave data to analyze the wave energy around China and obtained wave energy characteristics and storage capacity in the South China Sea (SCS) and Shandong Peninsula, respectively.

In the evaluation of wave energy, the key point is the calculation of wave energy density. At present, the formula commonly used for calculating wave energy density is derived from the linear wave theory in deep water, which has a large error in calculating shallow water and intermediate water. Based on Eckart's work that proposed an explicit relation, Beji [31] proposed a high-precision explicit approximation method of the linear dispersion relation; however, its calculation and derivation process is complicated. You [32] discussed and compared several explicit solutions and proposed a new explicit dispersion calculation method that is applicable to deep, shallow and intermediate water.

At present, there are few studies on wave energy assessment using You's method. For Chinese water, the wave energy assessment results obtained by previous studies are almost based on the common formula that is not accurate in the nearshore area. Therefore, this paper uses You's formula to calculate the wave energy found in China. The datasets of the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) are adopted.

2. Data

2.1. Study Area

The studied area is the sea adjacent to China, located at 105.5° E -127.5° E and 7° N -41° N across 34 latitudes and 22 longitudes (Figure 1). ETOPO1(a 1-arc-minute digital representation of Earth's solid surface that integrates land topography and ocean bathymetry) is adopted as one of the factors to distinguish deep, shallow and intermediate water.



Figure 1. The research area and the depth.

2.2. Data Sources

ERA5 is the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate [33,34]. Compared to the ERA-Interim [33], ERA5 is significantly improved [15,35]. At present, many scholars have adopted this dataset to carry out atmospheric and oceanic research [35–37].

3. Methods

Wave Energy Estimation

According to the dispersion relation and the definition of wave energy flux (P_w), P_w can be expressed in the following form [38] with the unit of kW/m:

$$P_w = \frac{1}{64\pi} \left[1 + \frac{2kh}{\sinh(2kh)} \right] \rho g^2 H_s^2 T tanh(kh), \tag{1}$$

where k, h, ρ , g, H_S and T are the wave number, water depth, seawater density, gravity acceleration, significant wave height and mean wave period, respectively. For waves, the significant wave height (H_S) is the average of the 1/3 large wave height during the observation time, and the period (T) is the time interval between two cross-zero points. According to Equation (1), if we know the value of kh, we can accurately calculate the wave energy. However, in general, according to the dispersion equation, the value of kh can be obtained through multiple iterations. This would waste a lot of time and computing power. In order to reduce the workload, we introduce the calculation method of kh proposed by You [32]. The equation of kh can be expressed as:

$$kh = \frac{k_0 h}{\tanh(kh)} = \frac{k_0 h}{\tanh(x_0)},$$
(2)

where the description of k_0h , x_0 can be expressed as follows:

$$k_0 h = \frac{\omega^2 h}{g} = \frac{4\pi^2 h}{gT^2},$$
(3)

$$x_0 \approx \sqrt{k_0 h} [1 + \frac{1}{6} (k_0 h) + \frac{1}{30} (k_0 h)^2],$$
 (4)

where T_e is the energy wave period. Combining Equations (2)–(4), *kh* can be easily calculated with a maximum relative error of 0.1% [32].

4. Result

4.1. The Annual Wave Energy Distribution

This paper adopts the formulas proposed in Section 2 for calculating wave energy in the study area. The 40-year annual mean H_s and P_w are shown in Figure 2. As shown in Figure 2a, the annual mean H_s is gradually decreased from deeper water to shallower water, and the annual mean H_s is the highest (over 1.8 m) in eastern Taiwan and northeastern SCS, which is generated by high wind in these regions. However, due to the sheltering effect of Taiwan, there are no huge waves in western Taiwan. The annual mean H_s is the lowest in the Bohai Sea (BS) (below 0.8 m) and Gulf of Tonkin (below 1.0 m) due to these semi-enclosed water bodies. As for P_w , the annual mean P_w shows the same distribution characteristics as H_s . The average annual P_w in the East China Sea (ECS) and SCS is larger than that in the BS and Yellow Sea (YS). The annual mean P_w can exceed 16 kW/m in eastern Taiwan. On the other side, the annual mean P_w in BS is the lowest, with a value of less than 2 kW/m; that in the Gulf of Tonkin is also very low, with a value of less than 4 kW/m.



Figure 2. The annual mean significant wave height (a) (H_s) and wave energy density (b) (P_w) .

4.2. The Seasonal Wave Energy Distribution

Figure 3 shows the seasonal mean P_w distribution of 40 years in the study area. Figure 3a shows that P_w along the mainland coast is very low in spring, with the value less than 2 kW/m in most nearshore areas. In summer, P_w is less than 2 kW/m in the whole BS and can reach 8 kW/m in the nearshore area of the southeastern mainland and around Taiwan (Figure 3b). According to Figure 3c,d, wave energy resources in winter and autumn are more abundant than those in spring and summer. The most abundant wave energy resources are concentrated on the southeast side of Taiwan Island and the northeast side of the SCS. The area with P_w over 20 kW/m in autumn is lower than that in winter, and the area with abundant wave energy density in winter moves southward. Furthermore, the offshore area with P_w of more than 10 kW/s is mainly concentrated on the southeast coast, such as Zhejiang and Fujian provinces. Therefore, it is convenient for wave energy collecting and utilizing due to the short distance to the mainland and the lower cost of cable laying.



Figure 3. Seasonal mean P_w .

4.3. The Monthly Wave Energy Distribution

The monthly P_w distribution is shown in Figure 4. The P_w reaches its maximum value in December and decreases month by month from December to June. After reaching the lowest value in June, the rich area of P_w moves from the northeast of the ECS to the southwest of the SCS month by month from July to December. Additionally, the wave energy peak is concentrated in the Bass Strait and the Philippines strait from January to June. The peak center of P_w gradually moves to the northeast since June. Additionally, the peak region of the P_w changes from the Bass Strait to the Miyako Strait and Tokala Strait from June to September. Until October, the peak area of P_w completely returns to the Bass Strait. From October to December, the peak area of P_w moves southwest of the Bass Strait, and the maximum mean P_w in the three months is approximately 25 kW/m.



Figure 4. Monthly mean P_w .

5. The Long-Term Tendency of Wave Energy

5.1. The Decade Distribution of Wave Energy Density

In this paper, every decade's distributions of P_w are shown in Figure 5. According to Figure 5, the mean P_w between 1979 and 1988 in the study area was the lowest in 40 years. The rich area was concentrated to the west of the Bass Strait and the east of the Philippine Strait, where P_w could be reached at over 16 kW/m. P_w during 1989–1998 was basically the same as that in 1999–2008, but the total wave resource was more abundant in the latter decade. The rich area was mainly distributed in the east of Taiwan Island and the SCS, with a value of 18–20 kW/m. It can be seen that P_w increased in the south of the ECS and the north of the SCS during 2009–2018. According to the distribution of every decade, P_w in the study area is generally increasing, especially in the east of Taiwan Island and the northeast of the SCS.



Figure 5. Decade distribution of P_w .

In general, the long-term tendency of P_w in the study area is to be increased at present. According to Figure 5, P_w in the west of the Bass Strait, north of the Philippine Strait and east of Taiwan Island is abundant.

5.2. The Decade Distribution of Seasonal Wave Energy

The decade distribution of seasonal P_w in the study area is shown in Figures 6–9. For the whole study area, the wave energy resources in the BS, YS and the Gulf of Tonkin are basically unchanged, and the average P_w is the lowest in the study area.



Figure 6. The decade distribution of wave energy density (P_w) in spring.

24°N

18°N

12°N

20

110°E 115°E 120°E

24°N

18°N

125°E



Figure 8. The decade distribution of P_w in autumn.

110°E 115°E 120°E 125°E

24°N

18°N

12°N

20 15

110°E 115°E 120°E 125°E



Figure 9. The decade distribution of P_w in winter.

For spring (Figure 6), the P_w with the high value was concentrated southeast and south of Taiwan Island, and the value reached over 8kW/m. Additionally, Pw showed an increasing trend in these areas during the past 40 years, and the increase of wave

24°N

18°N

12°N

5

110°E 115°E 120°E 125°E

energy resources in 1999–2008 was the largest, approximately 0.12 kW/m/a, compared with other decades.

For summer (Figure 7), the P_w with the high value was concentrated southeast and south of Taiwan Island, and the value reached over 16 kW/m. Additionally, the wave energy resources showed an increasing trend in these areas in the periods 1979–1988 and 1989–1998; the increase of P_w in the two periods was approximately 0.22 kW/m/a. P_w over the last 20 years remained basically unchanged.

For autumn (Figure 8), the P_w with the high value was concentrated southeast and south of Taiwan Island, and the value reached over 25 kW/m. Additionally, the wave energy resources in the four periods showed a trend of fluctuation. It was the most abundant in the period of 1989–1998, and the following one is the period of 2009–2018. Such distribution characteristics may be related to the impact of typhoons, which needs to be analyzed in combination with typhoon information.

As can be seen from Figure 9, P_w in winter are more abundant than in other seasons, and the most significant change in P_w also occurred in winter in the past 40 years. P_w in the whole study area presents an upward trend, and the value can reach up to 0.5 kW/m/a from 1989–1998 to 1999–2008. The mean wave energy in the southwest of the Bass Strait exceeded 30kW/m in the period of 2009–2018.

6. The Extreme Wave Height

Extreme waves have great influence on the device for wave energy utilization. Under the action of large waves, the device is damaged, which affects its energy capture and safety. Therefore, the study of the characteristics of extreme waves is conducive to screening out the suitable area for wave energy utilization.

6.1. The Annual Mean Extreme Wave Height

Figure 10 shows the distribution of annual mean extreme wave height (H_E) at the 99% quintile ($H_{99\%}$) in the study area: in the eastern part of the ECS, especially in the northeastern part of the Bass Strait, the maximum H_E can reach more than 6m. In most areas of the ECS, H_E ranges from 5 to 6 m. In most of the SCS, H_E ranges from 4 to 6 m; in most coastal areas, H_E ranges from 3 to 5 m. In terms of the average annual variation trend of H_E , only the east of Taiwan Island has significant change, with the maximum rate of H_E up to 0.035 m/a. The BS, YS and SCS have no obvious trend in P_w annual distribution, while the ECS generally shows an increasing trend, with an increased rate of 0.01–0.035 m/a.

6.2. The Seasonal Extreme Wave Heights

Figure 11 shows the distribution of seasonal mean H_E at the 99% quintile in the four seasons. It can be seen that H_E in spring is the smallest in the four seasons, while H_E in summer, autumn and winter are larger. Additionally, H_E in summer and autumn is larger than 7 m. In spring, H_E in most proportions of the study area is above 3.5 m, and H_E in the water around the Taiwan Strait and Bass Channel is above 4 m. In summer, H_E in the eastern part of the ECS and the northern part of the SCS is above 4 m, and H_E in the waters near Okinawa Island is above 7 m. In autumn, the maximum wave height in the ECS and most parts of the SCS exceeds 5 m. Moreover, H_E in the water near the Ryukyu Islands. In winter, H_E in the study area occurs in the west of the Bass Channel, and H_E in the study area can reach more than 5.5 m.



Figure 10. The distribution of annual mean H_E at the 99% quintile (H_{99}) and the annual mean growth rate of H_E .



Figure 11. The distribution of seasonal mean extreme wave height at the 99% quintile (H_{99}) .

Figure 12 shows the distribution of the change rate regarding H_E . The change rate of H_E in summer and autumn is significantly higher than that in spring and winter. In spring, H_E of the ECS and most areas of the SCS shows an increasing trend, and the maximum increase rate is up to 0.025 m/a. In summer, there is an obvious growth center in the water near Taiwan Island, and its maximum rate of H_E increases up to 0.05 m/a. H_E in the water near the Bass Channel and the Gulf of Tonkin in the western SCS shows a decreasing trend, and the maximum rate is up to -0.03 m/a. In autumn, H_E in the eastern part of Taiwan Island and the water around the Dongsha Islands shows an increasing trend, with the maximum rate reaching 0.05 m/a, while that in the YS and the central part of the SCS shows a decreasing trend, and the maximum rate in the southwest of SCS can reach -0.03 m/a. In winter, most of the study areas show an increasing trend, and the southwestern SCS has the most significant growth rate, with a value of more than 0.03 m/a.



Figure 12. The distribution of seasonal mean growth rate of extreme wave height.

7. The Key Recommended Area of Wave Energy

The main factors that can affect wave energy utilization are H_s and water depth. Therefore, the area with suitable water depth and available H_s should be analyzed preferentially. Additionally, combined with the development of wave energy technology, the key area for wave energy utilization can be identified.

7.1. The Area with Suitable Significant Wave Height and Water Depth

For the exploitation of wave energy, the distance between wave power generation devices and the mainland should have short distance, and the water depth should be within 100 m to facilitate the collection and utilization of wave energy. In the process of wave power generation, not all wave heights can be absorbed and converted into electricity. If the wave height is too low, the energy is not strong enough to make the power generation device run normally. On the contrary, if the wave height is too high, the power generation device will be damaged, such as typhoon waves and rogue waves. As mentioned above, the regions with a water depth of less than 100 m and H_s between 1 m and 4 m are recognized as suitable areas. In addition, considering the extreme bearing capacity of the wave energy capture equipment, this paper selects the area with extreme wave heights of less than 5 m and no obvious growth trend of extreme wave heights as recommended wave energy utilization zones. In refs. [39,40], they presented a method to determine the best areas for wave energy development that considers three indexes: the annual mean wave power density, the annual effective wave hours, which reflect the duration of exploitable wave energy and are defined as the annual mean temporal duration of ocean waves with $1 \text{ m} \le Hs \le 4 \text{ m}$ and the annual potential installed capacity of wave energy devices. They also described some basic characteristic parameters of the wave energy converters (WECs), and their results showed that the most suitable WECs for China were Sharp Eagle Wanshan, Wave Star and wave dragon, which should be installed in water less than 100 m, except for wave dragon. Considering the distance between WECs and the mainland and the suitable water depth for WECs, we took the wave height range of 1–4 m and the depth of less than 100 m as the optimal parameters.

As shown in Figure 13, the probability of annual wave height between 1–4 m in the suitable water depth area is higher from the east side of the Qiongzhou Strait to Zhoushan. It reached 50–70% in the past 40 years. However, the possibilities of the BH and YS are lower, with the range of 20–50%. Regarding the above analysis, the area from the east side of the Qiongzhou Strait to Zhoushan should be the key recommended areas of wave energy utilization.



Figure 13. The probability distribution of wave height between 1 m to 4 m in the water depth less than 100 m.

7.2. Key Recommended Areas of Wave Energy Utilization

In this paper, the area that meets the conditions of suitable wave height and water depth is selected. Figure 14 shows the distribution of annual mean P_w . The mean annual P_w in this area could be reached more than 10 kW/m. According to the previous definition of a wave energy zone, the area with P_w less than 1 kW/m belongs to the indigent area, the area with a value between 1 and 6 kW/m belongs to the available area, and the area with a value between 6 and 15 kW/m belongs to the sub-rich area. In the case of the available frequency ($P_w \ge 2kW/m$), if this area is more than 80%, the energy is easily collected and utilized.

Figure 15 shows the seasonal mean wave energy distribution of 40 years in the selected area. It shows that P_w is very small in the BS and most areas of the YS during spring and summer, with a value less than 6 kW/m in those areas. However, the wave energy resources in winter and autumn are more abundant than those in spring and summer. The most abundant wave energy resources are concentrated on the southeast side of Taiwan Island and the northeast side of the SCS. The area with P_w over 15 kW/m in autumn is smaller than that in winter. Furthermore, the offshore area with P_w of more than 10 kW/s is mainly concentrated on the southeast coast, such as Zhejiang and Fujian provinces. Therefore, it is convenient for wave energy collecting and utilizing due to the short distance to the mainland and the lower cost of cable laying. The frequency of available waves is more than 40% and even more than 80% in winter. Above all, it is still an ideal area for increasing WECs efficiency in the future.



Figure 14. The distribution of annual mean P_w in the selected area.



Figure 15. The distribution of seasonal mean P_w in the selected area.

According to ref. [40], for the Zhoushan Islands, it is suitable for the layout of the oscillating body (Sharp Eagle Wanshan) and overtopping (wave dragon) power generation devices. For the middle sea of Zhejiang province, it is suitable for the layout of a multipoint absorber (wave star) power generation device. For the Fujian area, it is more suitable for multipoint absorber (wave star) power generation installation. For the surrounding areas of Guangdong, an oscillating body (Sharp Eagle Wanshan) power generation device is suitable. The east sea of Hainan Island is suitable for oscillating body (Sharp Eagle Wanshan) and overtopping (wave dragon) power generation.

8. Conclusions

This study investigated wave power potential along the eastern coasts of China. For the characterization of the wave energy, a reanalysis dataset of ERA5 covering 40 years (1979–2018) was adopted. A new formula for assessing wave energy at any depth proposed by You [35] was introduced in this paper, and it effectively improved the evaluation accuracy of wave energy density in shallow water areas. The wave energy resource was discussed in terms of the annual and seasonal variation of wave characterization and wave power. According to the analysis, it can be seen that the spatial and temporal distribution characteristics of H_s and P_w are similar, and their values are decreasing gradually from offshore to nearshore. In other words, values of H_s and P_w are inversely proportional to water depth. Most waves have mean H_s between 0.2 and 1.4 m in the research area. The highest mean H_s exceeding 1.5 m occurs on the east and south of Taiwan Island. The highest wave energy flux located in a similar location is greater than 16 kW/m, respectively.

As for the seasonal characteristics of wave energy, wave energy reaches its maximum in winter and decreases continuously from winter to spring to reach its minimum in spring and then increases again in the summer and autumn. During the nearly 40a, the wave energy flux in all the research areas showed an increasing trend. The zones with a strong increasing tendency are located to the east of Taiwan Island (approximately 0.12 kW/(m·a)). The nearshore area showed decreasing tendency.

In the study area, the nearshore area from Zhejiang province to Guandong province is considered the wave energy hotspot, which provides a regional reference for subsequent wave energy development. Additionally, considering water depth, geological conditions and wave density, different sea areas are suitable for different wave energy conversion devices.

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