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Study on wave energy resource assessing method based on altimeter data—A case study in Northwest Pacific

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Abstract

Wave energy resource is a very important ocean renewable energy. A reliable assessment of wave energy resources must be performed before they can be exploited. Compared with wave model, altimeter can provide more accurate *in situ* observations for ocean wave which can be as a novel method for wave energy assessment. The advantage of altimeter data is to provide accurate significant wave height observations for wave. In order to develop characteristic and advantage of altimeter data and apply altimeter data to wave energy assessment, in this study, we established an assessing method for wave energy in local sea area which is dedicated to altimeter data. This method includes three parts including data selection and processing, establishment of evaluation indexes system and criterion of regional division. Then a case study of Northwest Pacific was performed to discuss specific application for this method. The results show that assessing method in this paper can assess reserves and temporal and spatial distribution effectively and provide scientific references for the siting of wave power plants and the design of wave energy convertors.

Key words: altimeter data, wave energy resources assessment, assessing method, Northwest Pacific, wave power density

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1 Introduction

The ongoing development of human society is increasing the demand for energy. Conventional fossil energy will be rapidly exhausted in the coming decades. In addition, use of these conventional energy will lead to serious environmental pollutions. In order to effectively relieve energy crisis caused by shortage of conventional fossil energy sources and the influence on climate, developing renewable energy has been general concerned by many countries all over the world. Reasonable development for renewable energy will decrease greenhouse effect and local air pollution effectively. There are several abundant renewable energy sources, including ocean wind energy, tidal energy, wave energy, current energy, thermal gradient energy and ocean salinity energy, in the oceans, which cover approximately 71% of the earth's surface in which wave energy is a most widely studied ocean energy all over the world (Wan et al., 2014). Reserve of wave energy is enormous in the oceans. Previous work has estimated that the theoretical wave energy in the oceans is approximately 10^9 kW, which is hundreds of times larger than the power generated around the world. In addition, wave energy has the greatest potential and is the most valuable type of ocean energy because it will only slightly affect the environment and it is a form of mechanical energy (Li et al., 2010). Before exploitation and utilization, a reliable assessment of wave energy resources, including the temporal and spatial distribution and potential, must be performed, which can give some valuable information for decision makers to site wave power plants. This work is called wave energy assessment. Early wave energy assessment primarily depended on limited *in situ* observation material. Quayle and Changery (1982) assessed deep water wave energy around the world based on *in situ* observations from American ships. Wang (1984), Wang and Lu (1989) analyzed the distribution and variation for wave energy in coastal waters in China's seas by wave observation materials from some Chinese ocean stations and carried out division for coastal wave energy in the project of Chinese Coastal Country Ocean Energy Division. In studies above, long-term and wide-range observations are difficult to be obtained because of restrict of observation range. With the development of wave numerical models, some wave energy assessments for different sea areas had been carried out successfully based on wave models by researchers from various countries. Cornett (2008) investigated global wave energy resources based on a third-generation model WAVEWATCH-III. Folley and Whittaker (2009) investigated wave energy in coastal and nearshore waters in Atlantic north of Scotland by using third-generation nearshore wave model SWAN. Rusu and Soares (2009) studied wave energy in nearshore waters of Portugal based on buoy data and WAMSWAN simulated data and determined the most potential areas. Soares et al. (2014) assessed wave energy in Atlantic European coast in detail by WAVEWATCH-III and SWAN simu-

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*Corresponding author, E-mail: upcwanyong@163.com, wanyong@upc.edu.cn lated data. Based on SWAN model, Iglesias and Carballo (2010), Iglesias and Carballo (2011) assessed temporal and spatial distributions for nearshore wave energy in detail in Estaca de Bares and Calician Southwest in Spain. Stopa et al. (2011) provided a quantitative assessment of the regional wind and wave patterns as well as the wave energy along the Hawaiian Island chain based on two hindcast case using wave model WAVEWATCH-III. Arinaga and Cheung (2012) employed 10 years wave field data from WAVEWATCH-III to evaluate global wave energy. Zheng et al. (2013a), Zheng et al. (2014) analyzed reserves and temporal and spatial distributions in global ocean in detail by using ERA-40 reanalysis data from European Center for Medium-Range Weather Forecasts (ECMWF). Zheng et al. (2012, 2013b) assessed wave energy resources for the China's seas based on high resolution wave fields from WAVEWATCH-III wave model. Liang et al. (2013) investigated wave energy for Shandong Peninsula, China based on SWAN model. Liang et al. (2014) assessed wave energy for two important areas in the China east adjacent seas based on 22 years wave data by SWAN model. Wu et al. (2015) evaluated wave energy for offshore areas in East China Sea based on buoy data in 2011–2013. It can be seen that wave numerical model is a primary method for acquiring long-term and wide-range wave materials and assessing wave energy. But wave data provided by wave model is a simulated data which accuracy is conditioned by many factors such as the accuracy of wind fields which can drive wave model, various initial conditions and assimilation with observation data. In addition, wave data from wave model are not *in situ* observations and simulated ability of wave model is limited for complicated wave fields. The accuracy of simulated wave fields by wave model is lower than that of *in situ* observation. So we need to find a novel and more suitable method to measure wave data and assess wave energy resources.

Microwave remote sensing technology is a novel method for wave observation and wave energy assessment. Altimeter is an important sensor in microwave remote sensing and can realize long period and large scale wave observation which is *in situ* observation result. Altimeter could provide accurate observation about ocean surface including significant wave height (H_s, unit: m) and wind speed (unit: m/s). ECMWF and the French Research Institute for Exploitation of the Sea (Ifremer) compared the measurements from several altimeters, such as Jason-1, ENVISAT, Jason-2 and Cryosat-2, with buoy data and wave model data and found that measurements from altimeters are accurate; the root mean square errors (RMSEs) were less than 0.5 m for H_s and less than 2 m/s for wind speed (Abdalla et al., 2008; Queffeulou et al., 2010). H_s from altimeter data have been widely used in ocean wave research field. There are two aspects: the first one is accuracy verification for wave model. Li et al. (2011) verified simulated results from WAM model by using T/P, ERS-2 altimeter H_s and buoy H_s under tropical cyclones. Stopa et al. (2011) implemented verification for WW3 simulated results with altimeter H_s around Hawaiian Islands and assessed wave energy based on model results. Zheng et al. (2012) verified WW3 results for a typhoon progress and a cold air progress in China's seas based on T/P and Jason-1 H_s data and evaluated wave energy in the East China Sea and the South China Sea. Zhang et al. (2011) verified SWAN results for a wind sea progress in the Bohai Sea based on T/P and Jason H_s data. The second one is altimeter data assimilation for wave model to improve forecast accuracy. ECMWF provides an atmospheric reanalysis dataset ERA-Interim for global users. During generating wave dataset synchronous altimeter data were assimilated into wave model to improve forecast accuracy. Hsu et al. (2010) studied influence of wave data assimilation to simulated results by using optimal interpolation assimilation method under the condition of typhoon. In this study, altimeter data were assimilated into wave model and were used to verify the accuracy of model. The results showed that altimeter data assimilation can improve forecast accuracy effectively. Thus it can be seen that the accuracy of H_s from altimeter is higher than that from wave model. So we can obtain more accurate wave parameter from altimeter data. Altimeter is a novel method for wave energy assessment which can provide more accurate assessment than wave model. Based on analysis of 2 years' T/P satellite altimeter data, Barstow et al. (1998) obtained wave energy evaluation in several hundred discrete points along global coastline deep water. So far, studies for wave energy assessment by altimeter data are scarce.

Application of altimeter data in wave energy resources assessment is scarce. There are two main reasons: firstly, orbital coverage area by single altimeter satellite is limited, so spatial resolution is lower for local sea area observations and cannot satisfy the demand of wave energy assessment. Secondly, accurate H_s and synchronous wind speed can be provided directly from altimeter data. However, when calculating characteristic quantity for wave energy, we also need energy period (T_e, unit: s) except $H_{s.}$ T_e must be obtained by inversion modeling because altimeter data can't provide T_e directly. At present, many inversion models have been developed, including the CS91 model, H98 model, G03 model, Quilfen model, K05 model, Mackay model and quartic polynomial model by Miao (Challenor and Srokosz, 1991; Hwang et al., 1998; Gommenginger et al., 2003; Quilfen et al., 2004; Kshatriya et al., 2005; Mackay et al., 2008; Miao et al., 2012; Zhao et al., 2012). These models are all based on limited buoy data and reanalysis data and are suitable for specific sea areas and sea conditions. And accuracy of T_e from models above rely on the accuracy of H_s, wind speed, buoy data and reanalysis data. Compared with H_s from altimeter, reliability of T_e from inversion models is lower. Therefore, the advantage of altimeter data is to provide accurate significant wave height observations for wave. In order to develop characteristic and advantage of altimeter data, resolve the problem caused by lower spatial resolution and apply altimeter data to wave energy assessment, in this study, we established an assessing method for wave energy in local sea area which is dedicated to altimeter data. Then a case study of Northwest Pacific was performed to discuss specific application for this method. The studies in this paper can provide scientific references for the siting of wave power plants and the design of wave energy convertors.

2 Establishment of assessing method for wave energy

Altimeter has a particular advantage on significant wave height observations. In order to apply altimeter data to wave energy assessment, we must develop an assessing method for wave energy in local sea area which is dedicated to altimeter data. Based on the previous research, a new assessing method was established and includes three parts including data selection and processing, establishment of evaluation indexes system and criterion of regional division.

2.1 *Data selection and processing*

2.1.1 *Data selection*

The purpose of wave energy assessment is mainly to evaluate systematically temporal and spatial distribution statistical property for wave energy in some specific sea areas. Therefore in order to reflect long-term trends, long time series of H_s and T_e for specific sea areas are needed. So firstly wave data selected must be a long time series such as *in situ* data or wave model data at least 5 years. Moreover in order to reflect fully spatial variation of wave energy in interesting area, wave data selected must have high spatial resolution. Because orbital interval is wide for single altimeter satellite, spatial coverage area is limited for local sea area, so spatial resolution cannot satisfy the demand of wave energy assessment. Based on orbital differences among various altimeter satellites, observation data from multi-altimeter-satellites can be merged to improve spatial resolution for local sea areas. For example, AVISO multi-satellites merged altimeter data by Centre National d'Etudes Spatiales (CNES) and Collecte Localisation Satellites (CLS) is a better choice and is a global gridded altimeter dataset product which can provide synchronous accurate significant wave height and wind speed data for global ocean. The AVISO data are merged data by several altimeters, such as Jason-1, ENVISAT, Jason-2 and Cryosat-2 (CNES & CLS). ECMWF and Ifremer compared the measurements from several altimeters with buoy data and wave model data and found that measurements from altimeters are accurate (verification are shown in Section 1). The wave field data from AVISO can meet the demand of wave energy assessment. The characters of the AVISO altimeter data are shown in Table 1. From Table 1, the AVISO altimeter data can cover global ocean with spatial resolution 1°×1° , temporal resolution 24 h and temporal periods from September 2009 to June 2014 for recent 6 a which can meet the demands of spatial resolution, temporal periods and temporal resolution for wave energy assessment for large scale.

2.1.2 *Data processing*

Accurate H_s and wind speed can be provided directly from altimeter data. However, when calculating characteristic quantity for wave energy, we also need T_e. T_e must be obtained by inversion model because altimeter data can't provide T_e directly. So in this section, the main mission is to establish an inversion model for T_e and calculate T_e. Because existing mean wave period inversion models are all established for specific altimeter data and sea areas and are suitable for specific conditions. When altimeter satellite and interesting area change the inversion accuracy is always not obtainable. Therefore we must develop new mean wave period inversion model by altimeter data for different sea areas and altimeter data. Inversion models are always based on the relationship between H_s, wind speed and T_e. H_s and wind speed are provided by altimeter data and collocated T_e is provided by other data sources such as ECMWF reanalysis data which is regarded as true value. Then an empirical mean wave period inversion model is established. This method is relatively simple and the accuracy is higher for local sea areas which will satisfy the demand for wave energy assessment.

2.2 ***Establishment of evaluation indexes system***

Wave energy assessment need to serve for practical engineering application for the siting of wave power plants and the design of wave energy convertors. In this paper, wave energy evaluation indexes system was established based on two aspects described above which will evaluate wave energy generally for each link of wave energy development as far as possible and reflect the feature of altimeter data. Based on this opinion, indexes selected include wave power density (P_w, unit: kW/m) distribution, abundant level, stability, maximum P_w, distribution of total wave energy according to latitude and longitude, distribution of total wave energy according to wave state, exploitable wave energy et al. Next, selection basis and calculation method for various evaluation indexes will be described respectively.

2.2.1 *Conventional indexes*

When siting wave power plants, abundant level and stability of wave energy are most important two factors which are called conventional indexes and as follows:

(1) Wave power density distribution

P_w is the most important characteristic for wave energy resources assessment and is a basic parameter for calculating other evaluative features. P_w is used to indicate abundant level of wave energy and is an important evaluation index for wave energy. P_w is an index which is used in almost all wave energy assessment process. Pontes (1998) and Zheng et al. (2013b) calculated P_w using deep water approximate formula which is defined as:

$$P_{\mathrm{w}} \approx 0.5 H_{\mathrm{s}}^2 T_{\mathrm{e}}. \tag{1}$$

As shown in Eq. (1), P_w is related to H_s and T_e and is proportional with H_s^2, so in calculating P_w the influence of H_s is significant than that of T_e which will meet index selection principle for altimeter data. The distribution of P_w can be as an index for wave energy assessment which is dedicated to altimeter data

In deep water area, the P_w values calculated from Eq. (1) are accurate. But in some nearshore areas such as China's seas and Japan Sea, water depths (generally below 200 m) are shallow. In order to improve the accuracy for P_w, we must consider water depth. For any water depths, P_w can be calculated by Eq. (2) (Wang and Lu, 2009):

$$P_{\mathrm{w}} = \overline{E}\left[\frac{gT_{\mathrm{e}}}{2\pi}\tanh(kd)\right]P_*, \tag{2}$$

where $\overline{E} = \frac{1}{16}\rho H_s^2$ is the wave energy density (J/m^2), ρ is sea-water density (kg/m^3), $k = \frac{2\pi}{\lambda}$ is the wavenumber (m^{-1}), λ is the wavelength (m), d is water depth and $P_* = \frac{1}{2}\left(1+\frac{2kd}{\sinh 2kd}\right)$.

In deep water (i.e., $d/\lambda \geqslant 1/2$, $P_* = \frac{1}{2}$ and $\tanh(kd) \approx 1$ were included in Eq. (2) and rearranged), P_w can be calculated as

$$P_{\mathrm{w}} = \frac{\rho g^2}{64\pi} H_{\mathrm{s}}^2 T_{\mathrm{e}} \approx 0.5 H_{\mathrm{s}}^2 T_{\mathrm{e}}. \tag{3}$$

In shallow water (i.e., $d/\lambda < 1/20$, $P_* = 1$ and $\tanh(kd) \approx 2\pi d/\lambda$ were included in Eq. (2) and rearranged), P_w can be calculated as

$$P_{\mathrm{w}} = \frac{\rho g}{16} H_{\mathrm{s}}^2 \sqrt{gd}. \tag{4}$$

For medium water depths (i.e., $1/20 \leqslant d/\lambda < 1/2$), we must consider the shallow water correction. P_w can be calculated as

$$P_{\mathrm{w}} = \overline{E}\left[\frac{gT_{\mathrm{e}}}{2\pi}\tanh(kd)\right]\left[\frac{1}{2}\left(1+\frac{2kd}{\sinh 2kd}\right)\right], \tag{5}$$

Table 1. Characters of AVISO altimeter data

Temporal periods	Spatial range	Spatial resolution	Temporal resolution/h	Parameters
2009. 9–2014. 6	global ocean	1°×1°	24	significant wave height wind speed

when calculating P_w, the water depth data were obtained from NOAA ETOPO2 and have a spatial resolution of 2′×2′. The wavelength can be estimated using the mean wave period; Wen and Yu indicated that to obtain more accurate results, λ cannot be directly calculated from the relationship according to sine wave theory. Instead, we must adopt the relationship from experiment (Wen and Yu, 1984). Thus, λ can be calculated using

$$\lambda = 0.87\frac{g}{2\pi}T_e^2. \tag{6}$$

Temporal and spatial distribution of wave energy can be expressed effectively by annual average and seasonal average P_w from a long-term series P_w.

(2) Abundant level of wave energy

Abundant level for wave energy is a major concern by decision-makers when siting wave power plants and is an important factor for wave energy assessment. Abundant wave energy has crucial significance for wave energy development and utilization. Zheng et al. (2013b) and Ren et al. (2009) indicated that wave energy is available when $P_w \geqslant 2$ kW/m and is rich when $P_w \geqslant 20$ kW/m. Abundant level for wave energy can be calculated by P_w which is mainly related to H_s and will meet index selection principle for altimeter data and can be as an index for wave energy assessment which is dedicated to altimeter data to express rich level. In this study, the frequencies of $P_w \geqslant 2$ kW/m and $P_w \geqslant 20$ kW/m, which are called the usable level frequency (*ULF*, unit: %) and the rich level frequency (*RLF*, unit: %), respectively, are defined to express usable wave energy and rich wave energy.

(3) Stability of wave energy

Cornett indicated that the wave energy stability is an important factor that affects the feasibility of wave power plants projects. The wave energy stability is more important than the wave energy reserves, and stable energy is advantageous for energy conversion and development (Cornett, 2008). The wave energy stability can be expressed by coefficient of variation (*COV*) which can be calculated as follows:

$$COV = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(P_w - \bar{P}_w\right)^2}}{\bar{P}_w}, \tag{7}$$

where P_w is sample value, $\overline{P}_w$ is the mean wave power density, N is number of samples. It can be seen that stability of wave energy is mainly related to P_w and will meet index selection principle for altimeter data also and can be as an index for wave energy assessment which is dedicated to altimeter data to express stability.

2.2.2 *Novel indexes*

For siting wave power plants, except abundant level and stability of wave energy, we also must consider safety of wave power plants and spatial distribution of total wave energy. In addition, for wave energy convertors, we also must obtain wave state range in which energy is prominent to total wave energy which will provide references for the design of wave energy convertors. For this reason, three novel indexes were designed which are as follows:

(1) Maximum wave power density

Some wave energy conversion systems may have difficulty operating successfully in locations that experience extremely large waves on a frequent or even infrequent basis because of the severe technical challenges and/or high costs associated with surviving highly energetic wave conditions (Cornett, 2008). The viewpoint above show that some areas are unfit for siting wave power plants even though wave energy are rich if extreme wave state is severe and regular which will possibly destroy wave power plants or increase cost for maintenance. Therefore, for siting wave power plants, we also must consider severe level of extreme wave state in some potential areas. In this paper, we define maximum wave power density (max P_w, unit: kW/m) to express severe level of extreme wave state. Maximum wave power density is defined as maximum value for wave power density in each spatial position. The larger the maximum wave power density is, the higher the defensive demand of wave power plant and wave energy convertor is and the cost is higher.

(2) Distributions of total wave energy according to latitude and longitude

It is very meaningful to study spatial distributions of total wave energy for siting wave power plants. In this paper, distributions of total wave energy according to latitude and longitude were studied which can express spatial distributions of total wave energy and determine abundant energy areas. This index can be as a basis for siting wave power plants.

This index can be calculated as follows:

First, annual average total wave energy is defined and can be calculated by

$$E_t = \overline{P}_w \cdot T \cdot L, \tag{8}$$

where E_t is annual average total wave energy (unit: MWh/a); $\overline{P}_w$ is annual average wave power density (unit: kW/m); T is annual total wave hour ($T = 365 \times 24$, unit: h); L is width of wave front (unit: m).

Then annual average total wave energy for each latitude and longitude were calculated according to latitude and longitude with interval 0.2° and the distributions of total wave energy according to latitude and longitude are obtained. In detail, for a same latitude, an annual total wave energy is calculated with 0.2° interval along longitude direction. And then we can add all results to get annual average total wave energy. For a same longitude, the calculation method is similar.

(3) Distributions of total wave energy according to wave state

Several studies have shown that the wave height and the wave period are two important parameters for determining the component dimensions in pneumatic WECs, Isaacs wave energy pumps and Kayser wave energy generators (Ma and Yu, 1983). In order to provide a uniform standard for the design of wave energy convertors, the distribution of the total wave energy density (the mean of the sum of P_w multiplied by the number of hours in a year (MWh/(m·a)) according to the wave state which can be used to design the WECs (Wan et al., 2015). In this paper, based on wave energy safe utilization, we studied and determined wave state range in which energy is prominent to total wave energy where the range of significant wave height is 1 m$\leqslant H_s \leqslant$4 m (the reason is shown in Section 2.2.3) and the range of energy period should be determined according to practical condition for specific areas.

2.2.3 *Exploitable wave energy*

The purpose of wave energy assessment is to provide scientific decision basis for development and utilization of wave energy and the siting of wave power plants. With respect to theoretical wave energy resource, decision makers of wave energy project care more about the condition of exploitable wave energy. When studying the distributions of exploitable wave energy, we must establish a division criterion between theoretical wave energy and exploitable wave energy and then select suitable indexes to analyze exploitable wave energy.

(1) Division criterion for exploitable wave energy

The establishment of division criterion is based on practical application need of WECs, so we mainly consider two aspects including operational safety and running requirement. On the one hand, in high sea condition, wave is rough and disruptive which will seriously threaten safety of wave power plants and WECs or destroy WECs. Therefore, in this situation, WECs must be closed although wave energy are abundant but are un-exploitable because the energy can not be collected by WECs. In international sea condition table, ocean wave in level 6 sea condition and level 7 wind is defined as rough wave. The destructive power of rough wave is higher. Wave energy above level 6 sea condition is un-exploitable. According to international sea condition table, minimum H_s is 4 m for level 6 sea condition which will be a criterion for deciding high sea condition. For exploitable wave energy, we must eliminate the influence by high sea condition from theoretical wave energy. On the other hand, in order to determine minimum running condition of WECs, Chinese National Ocean Technology Center have organized several experts who are specialized in WECs and are from some research institutes including Guangzhou Institute of Energy Conversion Chinese Academy of Sciences, Ocean University of China, Chinese National Ocean Technology Center etc. who are interesting in WECs. Through investigation on experts, at present the minimum running condition of various WECs built by various institutes generally is $H_s \geqslant 1$ m. In other word, wave energy are un-exploitable when $H_s<1$ m which had been used in Ocean Renewable Energy Special Fund Project of the State Oceanic Administration China (GHME)①. In this paper, the criterion $H_s=1$ m is used as an exploitable minimum H_s. For exploitable wave energy, we must eliminate the energy which can't be utilized effectively from theoretical wave energy. Overall, theoretical wave energy denotes wave energy including all parts of wave and exploitable wave energy denotes wave energy including the part of 1 m$\leqslant H_s \leqslant$4 m wave.

(2) Evaluation indexes

Two indexes such as exploitable wave power density and wave energy exploitable ratio (*WEER*, unit: %) are used to assess exploitable wave energy. Exploitable wave power density denotes annual average wave power density except un-exploitable part. And *WEER* is defined as

$$WEER = \frac{\text{annual average exploitable } P_w}{\text{annual average theoretical } P_w} \times 100\%, \qquad (9)$$

which is used to express the ratio of exploitable wave energy.

2.3 *Regional division for wave energy*

Ultimate purpose for wave energy assessment research is to provide decision basis for siting wave farm and to determine key development areas. After acquired reliable wave energy assessment, we also need to perform regional level division for wave energy in interesting areas. Zheng et al. (2012, 2013b) developed a criterion of regional division for wave energy followed criterion of regional division for wind energy and carried out regional division for wave energy for the China's seas. In this paper, studies from Zheng et al. (2012, 2013b) was referenced and a criterion of regional division which is suitable for local sea areas and altimeter data was established. In Section 2.2.1, we presented that wave energy is available when $P_w \geqslant 2$ kW/m and is rich when $P_w \geqslant 20$ kW/m which will be as a main basis, then we divided wave energy into 5 level according to annual average P_w and annual average effective time (T_E, unit: h) which is annual average duration for wave with 1 m$\leqslant H_s \leqslant$4 m (the destructive power of rough wave is higher and wave energy from slight wave are lower valuable, in these situation, wave energy is un-exploitable). Criterion of regional division is shown in Table 2 in which P_w and H_s were selected which will embody the superiority of altimeter data.

Table 2. Division criterion for wave energy resource for altimeter data

Grade	Annual average P_w/kW·m^{-1}	Annual average effective time (T_E)/h	Rich level
1	<2	<1 500	poor area
2	2–8	1 500–3 000	available area
3	8–14	3 000–5 000	medium area
4	14–20	>5 000	subrich area
5	>20	>5 000	rich area

3 A case study for wave energy assessment in Northwest Pacific

In Section 2, we established an assessing method for wave energy which is dedicated to altimeter data. In this section, a case study of Northwest Pacific was performed to discuss specific application for this method. The Northwest Pacific is a new geographical and political hub all over the world which has important strategic shipping line including Malacca Strait, Bass Strait, Taiwan Strait and North Korea Strait and is the fastest economic growth area from the 1950s . In addition, four forces in global five main strategic forces including America, Russia, Europe, China and Japan are located in or adjoined with Northwest Pacific which has a significant strategic position (Wang, 2002). In Northwest Pacific, wave energy resources are abundant. It is of great significance to develop wave energy reasonably for the development of various countries in this area.

3.1 *Data selection and processing*

3.1.1 *Data selection*

In assessing wave energy in Northwest Pacific, AVISO data selected for this study were from September 2009 to June 2014 and encompassed 0°–60°N and 100°–180°E; the spatial and temporal resolutions were 1°×1° and one day, respectively. In addition, a new mean wave period inversion model by altimeter data must be developed for Northwest Pacific. T_e from ECMWF ERA-Interim had been used as true value of mean wave period in modeling. ERA-Interim is the latest global atmosphere numerical reanalysis dataset that has been provided by the ECMWF for global users. ERA-Interim data can provide high resolution and high accuracy wave field data including H_s and T_e. In order to acquire reliable altimeter mean wave period inversion model, verification for the accuracy of ERA-Interim T_e must be carried out in

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①The First Institute of Oceanography, State Oceanic Administration. 2013. Wave energy resource prospection and division in key exploitable areas (OE-W01 Block) assessment report.

Northwest Pacific. Based on shallow water buoy Buoy_006 T_e observation (30.717 0°N, 123.070 0°E, water depth: 46 m) which is located in nearshore water of the China's seas during GHME project and deep water buoy Buoy_46070 T_e observation (55.083 0°N, 175.270 0°E, water depth: 3 804 m) which is maintained by NDBC in 2012, comparisons between T_e from ERA-Interim data and T_e from buoy data were performed. The results are shown in Fig. 1. From Fig. 1, RMSE between T_e from ERA-Interim and T_e from Buoy_006 is 0.56 s; correlation coefficient (CC) is 0.78. RMSE between T_e from ERA-Interim and T_e from Buoy_46070 is 0.70 s; CC is 0.93. It can be seen that in offshore and nearshore water of the Northwest Pacific T_e from ERA-Interim are considerably accurate. ERA-Interim T_e data selected in this paper are at the same period and same resolution with AVISO data.

3.1.2 *Data processing*

In order to calculate T_e from altimeter data, mean wave period inversion BP neural network model for Northwest Pacific was established. The process is as follows: Wang (2006) presented the following relationship between the nondimensional wave height and wave age:

$$1.44\,\frac{gT_z}{2\pi U_{10}}=\alpha\left(\frac{gH_s}{U_{10}^2}\right)^{\beta},\tag{12}$$

where the nondimensional wave height is in the parentheses, the left hand side is the wave age, T_z is the zero-crossing mean wave period (s), U_{10} is the wind speed (m/s), g is gravity acceleration (m/s^2). The modeling dataset was created using the AVISO data and ERA-Interim data from 2011, then according to H_s, subsection mean wave period inversion BP neural network model (denoted by MWP_NN_model) was established with nondimensional wave height input, with wave age output. Network was trained by Levenberg-Marquardt feedback training method to adjust weight of the network. Pay special attention to, mean wave period retrieved by inversion models are T_z which can be converted to T_e by the relationship below (Li, 2007):

$$T_e = 1.247\,3T_z.\tag{13}$$

In order to illustrate advantage of the model established in this study, H98 model by Hwang et al. (denoted by H98_model) is selected to compare with MWP_NN_model. The validation dataset was created from the AVISO altimeter data and ERA-Interim data in 2012. T_z had been retrieved based on MWP_NN_model and H98_model respectively. Then quality control had been carried out including removing inversion data with bias>3×RMSE. Comparisons between T_z from models and T_z from ERA-Interim are shown in Fig. 2. The results show that RMSE of T_z from MWP_NN_model is 0.91s; bias is –0.32 s; CC is 0.72. RMSE of T_z from H98_model is 1.85 s; bias is –1.41 s; CC is 0.78. The inversion accuracy by MWP_NN_model is obviously superior to that by H98_model.

3.2 *Wave energy assessment*

In this paper, based on recent 6 years' AVISO data and evaluation indexes system in Section 2.2, various evaluation indexes were calculated and wave energy were assessed in detail for Northwest Pacific.

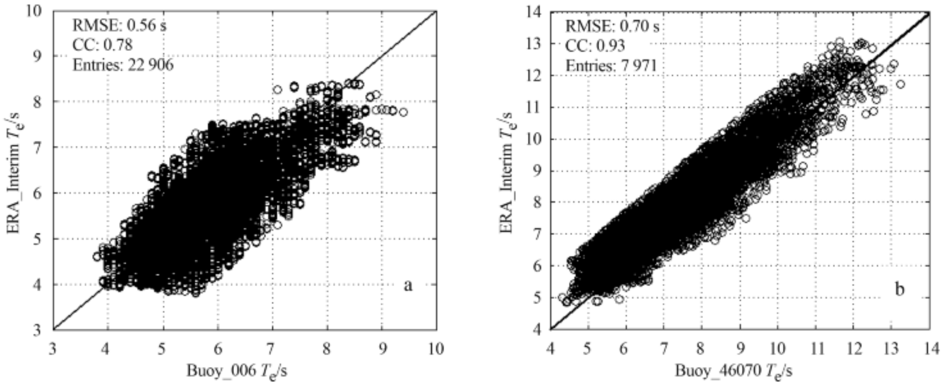

Fig. 1. Scatter plots of T_e from Buoy_006 (a), Buoy_46070 (b) versus T_e from ECMWF ERA-Interim.

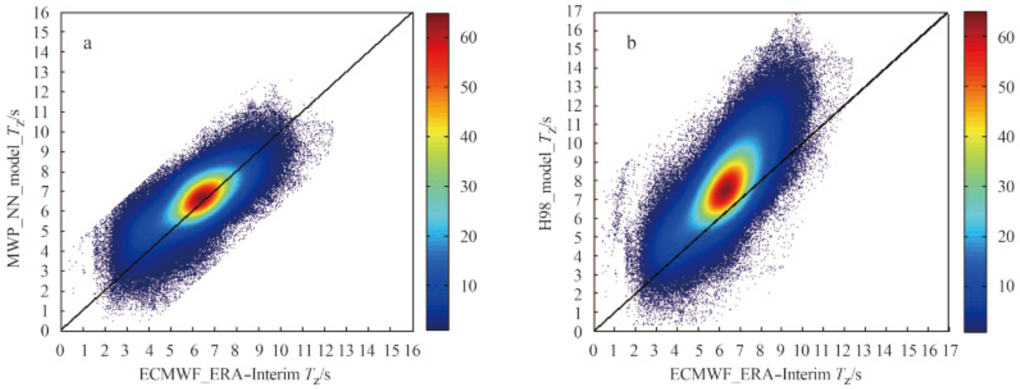

Fig. 2. Scatter plots of T_z from MWP_NN_model (a), H98_model (b) versus T_z from the ECMWF ERA-Interim (colors denote density of data).

3.2.1 *Conventional indexes*

(1) Temporal and spatial distributions of P_w

Based on 2009–2014 AVISO altimeter data annual average and seasonal average of P_w were calculated for Northwest Pacific. The results are shown in Fig. 3. From annual average, P_w are gradually increasing from nearshore waters to offshore waters, from low latitude areas to middle latitude areas and present stripped distribution with P_w equal 2–60 kW/m. Areas with large P_w values (approximately 35–60 kW/m) are primarily located in westerlies in north of Northwest Pacific where wave energy are abundant and present cricoid distribution. Areas with small P_w values (below 25 kW/m) are primarily located in China's seas, Japan Sea, Okhotsk Sea and south waters of 30°N in Northwest Pacific. From seasonal average, seasonal spatial distributions of P_w are similar to annual average distributions. P_w present obvious seasonal variation. In winter, spring and autumn, areas with large P_w values are all located in westerlies areas because of strong wind where P_w are largest (approximately 70–120 kW/m) in winter and are similar (approximately 30–60 kW/m which are obviously less than P_w in winter) in spring and autumn. But in summer, wind power obviously decrease in westerlies and areas with large P_w values (approximately 14–16 kW/m which are obviously less than P_w in other seasons in large value areas) are located in east waters of Taiwan, surrounding waters of Ryukyu Islands,

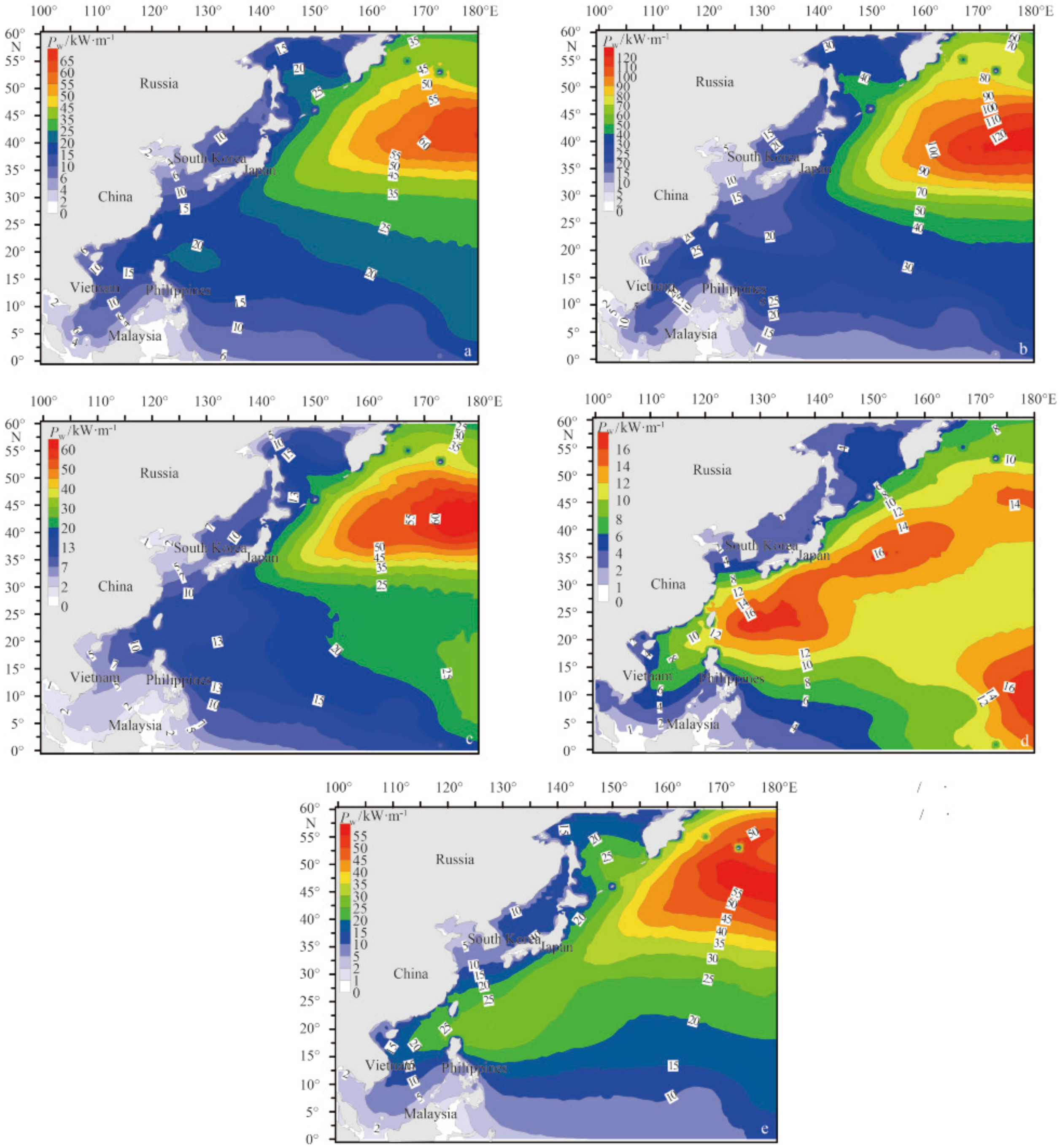

Fig. 3. Distributions of multi-year P_w (kW/m): annual average (a), winter average (b), spring average (c), summer average (d), and autumn average (e).

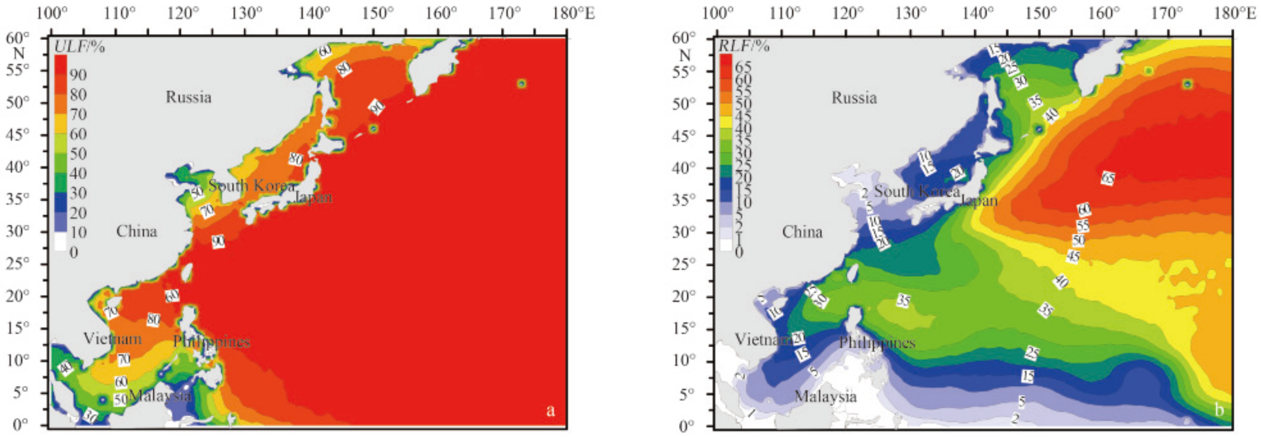

Fig. 4. Distributions of energy level frequency *ULF* (a) and *RLF* (b).

southeast waters of Japan and surrounding waters of Marshall Islands. In addition, influenced by monsoon climate, P_w present obvious seasonal variation in China's seas, Japan Sea, Okhotsk Sea and some south waters of 30°N in Northwest Pacific where P_w are gradually decreasing from winter and autumn to spring and summer. Thus it can be seen except summer, wave energy are abundant in winter, spring and autumn which are key periods for wave energy utilization. Zheng et al. (2014) assessed spatial distributions of annual average and seasonal average of P_w for global ocean based on ECMWF ERA-40 reanalysis data. We carried out a detailed comparison between the results of spatial distributions of annual average and seasonal average of P_w for Northwest Pacific by our method with those of Zheng et al. (2014). The results in this paper are consistent with those of Zheng et al. (2014). But the values still have a little difference which is probably because of the differences of data source and interpolation method. Thus it can be seen that wave energy assessment is reliable by altimeter data.

(2) Abundant level of wave energy

The *ULF* and *RLF* distributions that were calculated from the 2009–2014 AVISO data are shown in Fig. 4. From Fig. 4a, *ULF* are 90% above in most areas of Northwest Pacific and in some nearshore areas such as China's seas, Japan Sea, Okhotsk Sea and a small part of waters in southeast of Philippines *ULF* are 40% above where the value of wave energy is greater. From Fig. 4b, rich level frequency are relatively higher in Northwest Pacific. Except for nearshore waters, *RLF* are 30% above in most areas. Areas with large *RLF* values (approximately 55%–65%) are located in westerlies sea areas. The results are consistent with those of Zheng et al. (2014).

(3) Stability of wave energy

The *COV* for multi-year and *COV* for each season were calculated from 2009–2014 AVISO data. The distributions are shown in Fig. 5. From multi-year's *COV*, stability is relatively poor in nearshore water where *COV* are 1.2 above; stability is relatively good in areas with large P_w values (westerlies sea areas) where *COV* are 1.0–1.2. Wave energy are most stable in low latitude waters south of 30°N where *COV* are 1 below. The trends are consistent with Cornett (2008). From seasons' *COV*, wave energy are not stable in nearshore waters in each season. In winter, stability is relatively good in areas with large P_w values (westerlies sea areas) where *COV* are 1 below. Wave energy are most stable in low latitude waters south of 30°N where *COV* are 0.8 below. In spring, *COV* are 0.9–1.2 in large P_w value areas and are 0.8 below in low latitude waters. In summer, wave energy are not stable in areas with large P_w values (east sea areas of Taiwan and Philippines) where *COV* are 1.2–2.0 and stability is good near equator where *COV* are 0.8 below. In autumn, *COV* are 0.8–1.2 in large P_w value areas and are 1 below in low latitude waters. The results show that in winter, spring and autumn, wave energy are stable in abundant areas in Northwest Pacific which is advantageous factor for wave energy development.

3.2.2 *Novel indexes*

(1) Maximum wave power density

Based on 2009–2014 AVISO altimeter data maximum P_w were calculated and its distributions are shown in Fig. 6. From Fig. 6, maximum P_w are higher in westerlies areas where maximum P_w are above 400 kW/m and extreme value exceed 800 kW/m. Based on present technical level, although wave energy are abundant in westerlies areas, but the development of wave energy is relatively difficult and the maintenance cost is higher for WECs. So westerlies areas are not suitable for siting wave power plants. The maximum P_w are 300–450 kW/m in local sea areas in the south of Japan where it is also difficult to develop wave energy. In addition, in other sea areas including China's seas, Japan Sea, Okhotsk Sea and south waters of 30°N, maximum P_w are generally 300 kW/m below. The defensive demand of wave power plants and WECs is relatively lower which is advantage to energy development in these areas. Furthermore, 300 kW/m can be as a uniform standard for the design of WECs in these areas. The defensive demand of WECs should at least exceed the results in this paper and the defensive demand of wave power plants should be even higher.

(2) Distributions of total wave energy according to latitude and longitude

Based on 2009–2014 AVISO altimeter data, annual average total wave energy for each latitude and longitude were calculated according to latitude and longitude with interval 0.2°. The distributions of total wave energy according to latitude are shown in Fig. 7a. From Fig. 7a, total wave energy are increasing from equator to north latitude and occur peak value nearby 21°N where total wave energy is about 1.3×10^9 MWh/a. And then total wave energy are decreasing until 25°N and then increasing until 38°N where a peak value occurs again with total wave energy about 1.55×10^9 MWh/a. Along latitude direction, there are two peak value of wave energy. One is around 21°N where the typhoon and tropical storm passed frequently; the other is around 38°N which is in westerlies areas. The richest areas of

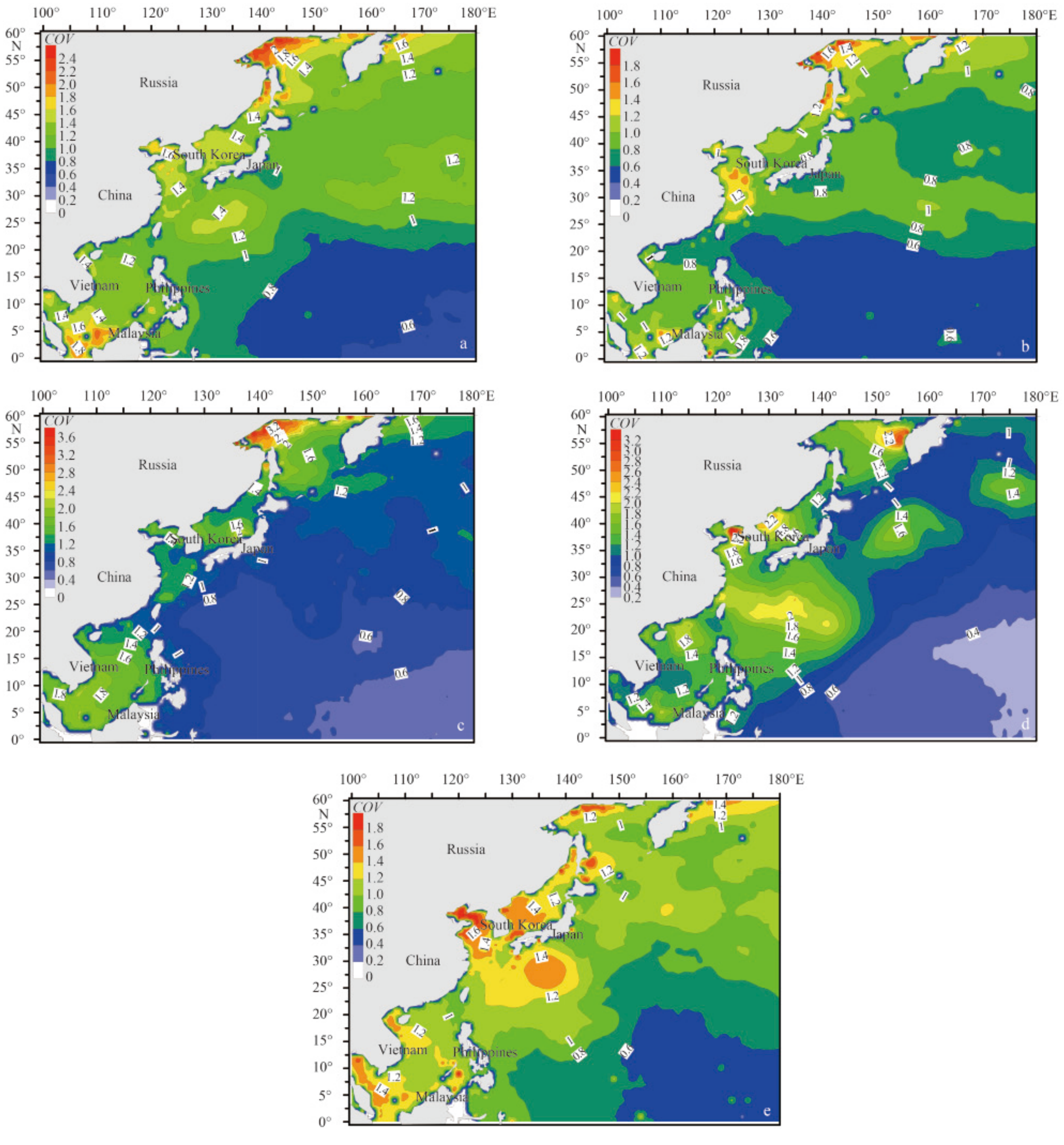

Fig. 5. Distributions of *COV* for annual (a), winter (b), spring (c), summer (d), and autumn (e).

wave energy are located around 21°N and in westerlies areas. The distributions of total wave energy according to longitude are shown in Fig. 7b. From Fig. 7b, total wave energy are increasing from west to east. In the range of 170°–180°E, the influence of westerly is prominent and total wave energy are higher in longitude direction where energy are all 2×10^9 MWh/a above. The reason is land areas are decreasing from west to east and the influence of westerly is prominent from 160°E to east.

(3) Distributions of total wave energy according to wave state

Based on 2009–2014 AVISO altimeter data, wave energy safe utilization and the range of energy period, we calculated the ratio of total wave energy density with 1 m$\leqslant H_s \leqslant$4 m and 4 s $\leqslant T_e \leqslant$10 s to total wave energy density with all wave state. The results are shown in Fig. 8. From Fig. 8, except for westerlies areas and Okhotsk Sea, wave energy in this range is 70% above of total wave energy in other areas in Northwest Pacific. Moreover, wave energy in this range is 80% above of total wave energy in China's seas, Japan Sea and waters from equator to 20°N where we can design WECs according to this wave state range to obtain higher utilization ratio of energy. In westerlies areas, wave energy which can be utilized safely are limited, and it is not suitable for siting wave power plants in this areas.

3.2.3 *Exploitable wave energy*

(1) Annual average P_w for exploitable wave energy

In order to evaluate the distributions of exploitable wave energy for Northwest Pacific, based on 2009–2014 AVISO altimeter data and division criterion in Section 2.2.3, annual average P_w for exploitable wave energy were calculated and shown in Fig. 9. Compared with theoretical wave energy shown in Fig. 3, annual average exploitable P_w are obviously lower than annual average theoretical P_w especially in westerlies areas where the difference is obvious and the decline of P_w will be up to 40 kW/m. While in China's seas, Japan Sea and waters from equator to 20°N, the decline of P_w is lower than 4 kW/m. Thus it can be seen that exploitable wave energy is more close to theoretical wave energy in nearshore waters and equator sea areas which is a good characteristic for wave energy development.

(2) Wave energy exploitable ratio

Based on 2009–2014 AVISO altimeter data, *WEER* were calculated and shown in Fig. 10. From Fig. 10, in China's seas, Japan Sea and the south sea areas of 30°N, the ratio of exploitable wave energy is higher with 70% above; in westerlies areas and Okhotsk Sea, the ratio of exploitable wave energy is lower with 70% below. The more abundant the wave energy are, the lower the *WEER* are. In this case, the difference of the estimations between theoretical and exploitable wave energy will increase and the reference value of estimation of theoretical wave energy for siting wave power plants will decrease. Therefore, the evaluation of exploitable wave energy is very meaningful for siting wave power plants.

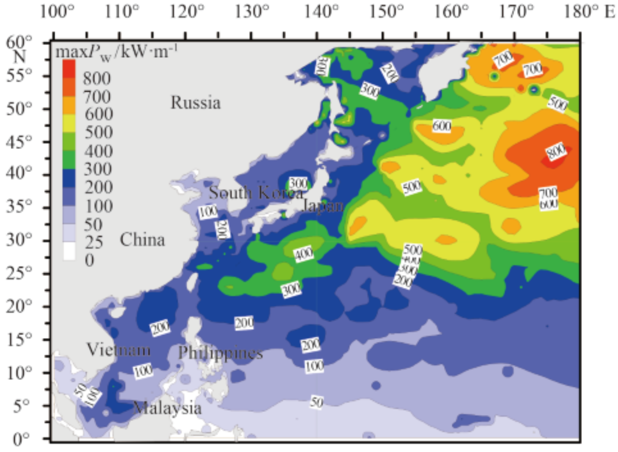

Fig. 6. Distribution of maximum P_w.

3.3 *Regional level division for wave energy*

According to criterion of regional division in Section 2.3, we carried out a regional division for wave energy for Northwest Pacific, the result is shown in Fig. 11. From Fig. 11, poor areas are very small and are only located in the Bohai Sea in China and sea areas around Malaysia. Wave energy are available in most areas and are obvious less in nearshore waters and surrounding waters of equator than those in offshore waters and middle and high latitude sea areas. In Northwest Pacific, rich areas are large and approximately account for 70% of all sea area. For world-wide, Northwest Pacific is a rich region of wave energy where wave energy has a great potential for development and utilization.

Next, based on the results above and present technological level for wave energy development (the development of wave energy is mainly located in nearshore waters), 5 potential sites in nearshore waters for siting wave power plants and experiments of WECs were selected which are shown in Fig. 11, A–E including the nearshore waters of the southeast of Petopavlovsk Kamchatskiy in Russia (A), the nearshore waters of the southeast of Japan (B and C), the surrounding waters of Taiwan (D) and the nearshore waters of the northeast of Philippines (E). In all potential sites, wave energy are abundant with annual average P_w >14 kW/m and annual average effective time T_E>5 000 h where wave energy have great potential in future. These potential sites are all located in the nearshore waters of adjacent countries which is

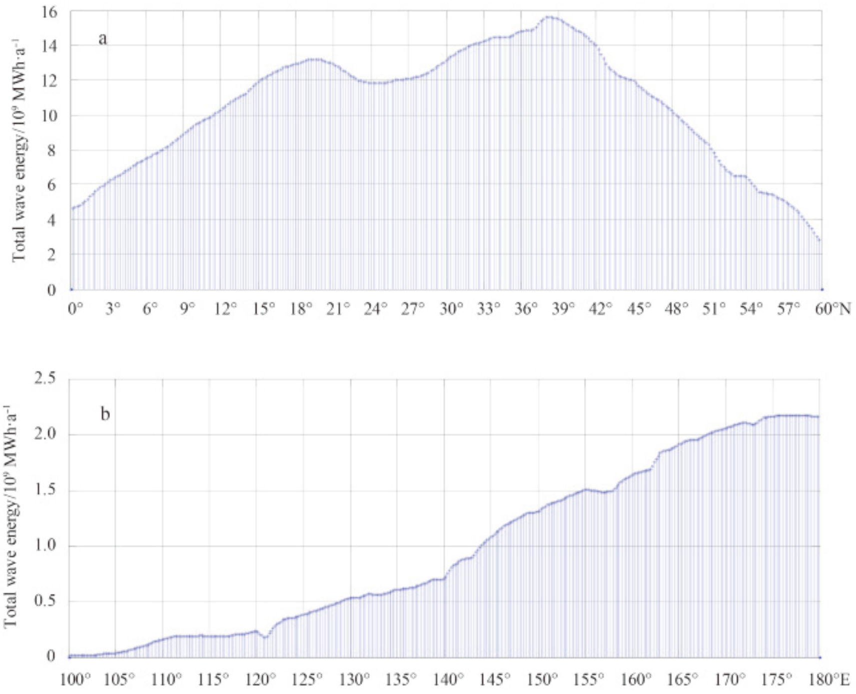

Fig. 7. Distributions of total wave energy according to latitude (a) and longitude (b).

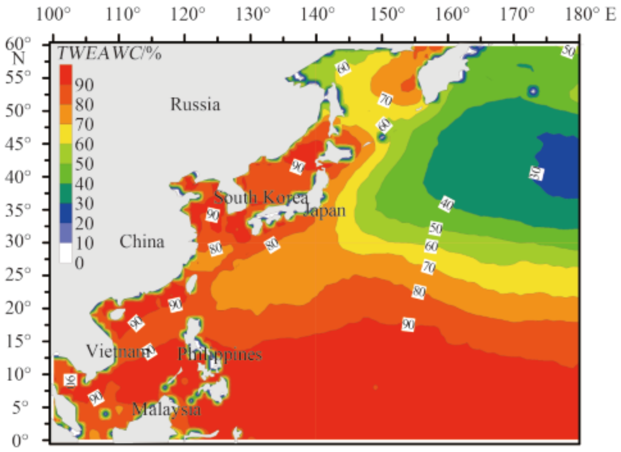

Fig. 8. Distribution of total wave energy according to wave state.

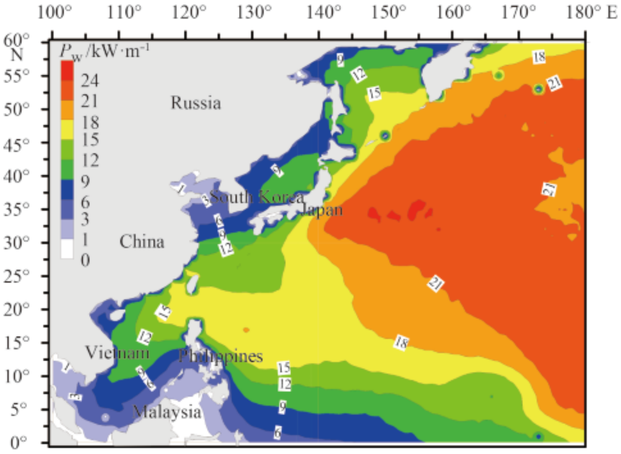

Fig. 9. Distribution of annual P_w for exploitable wave energy.

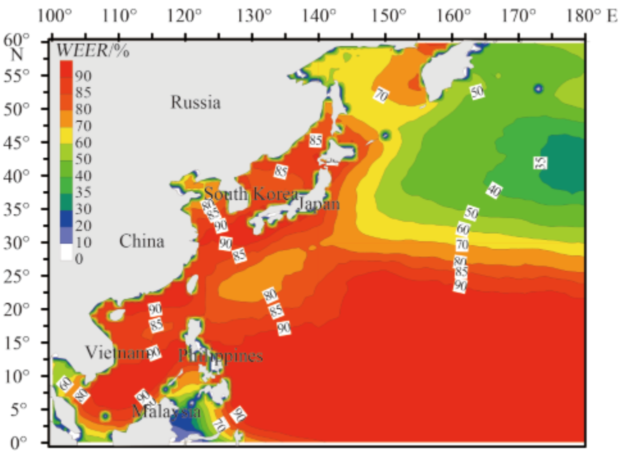

Fig. 10. Distribution of *WEER*.

very advantage to utilization because the power can transfer to the mainland easily. In all potential sites, wave energy are abundant which is a huge energy sources for adjacent countries.

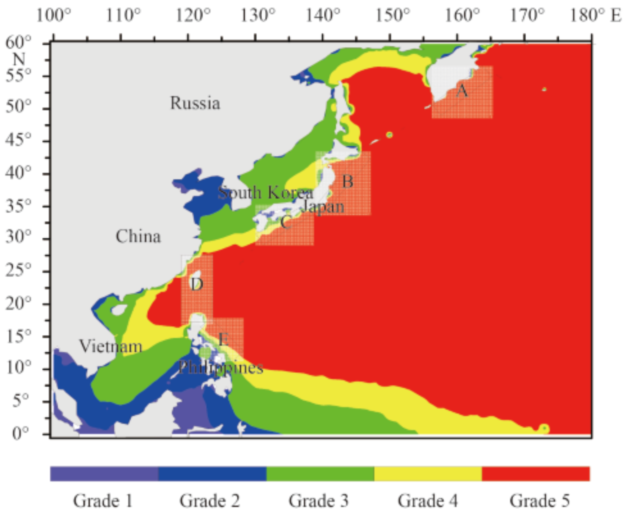

Fig. 11. Wave energy regional division.

4 Conclusions

In this study, we established an assessing method for wave energy in local sea area which is dedicated to altimeter data. Then a case study of Northwest Pacific was performed to discuss specific application for this method. The conclusions are as follows:

(1) In order to realize application of altimeter data in wave energy assessment, we established an assessing method for wave energy. In altimeter data selection, multi-satellites merged altimeter data is a better choice which can improve spatial coverage area. In order to obtain T_e, mean wave period inversion model has been developed for Northwest Pacific. Some evaluation indexes were selected which are suitable for the siting of wave power plants and the design of WECs including wave power density distribution, abundant level, stability, maximum P_w, distribution of total wave energy according to latitude and longitude, distribution of total wave energy according to wave state, exploitable wave energy et al. And then a criterion of regional division with regional characteristic including various indexes was established which can be used to carry out regional division and determine key development areas.

(2) Based on recent 6 years' AVISO data and assessing method established in this paper, wave energy was assessed in Northwest Pacific which is a demonstration application for the method in this study. The results show that in Northwest Pacific, P_w are gradually increasing from nearshore waters to offshore waters, from low latitude areas to middle latitude areas and present stripped distribution with P_w equal 2–60 kW/m. Areas with large P_w values (approximately 35–60 kW/m) are primarily located in westerlies in north of Northwest Pacific where wave energy are abundant and present cricoid distribution. P_w present obvious seasonal variation. P_w are largest in winter and are smallest in summer. In autumn and spring, P_w are centered. It can be seen except summer, wave energy are abundant in winter, spring and autumn which are key periods for wave energy utilization. Most areas have *ULF* values of 90% above where the value of wave energy is greater. Rich level frequency are relatively higher. Except for nearshore waters, *RLF* are 30% above in most areas. Abundant and stable areas of wave energy is located in middle latitude westerlies areas. In winter, spring and autumn, wave energy are stable and abundant. In abundant areas, wave energy are stable

with *COV*<1.2. But maximum P_w are higher in westerlies areas where maximum P_w are above 400 kW/m. Although wave energy are abundant in westerlies areas, but the development of wave energy is relatively difficult and the maintenance cost is higher for WECs. So westerlies areas are not suitable for siting wave power plants. In other sea areas including China's seas, Japan Sea, Okhotsk Sea and south waters of 30°N, maximum P_w are generally 300 kW/m below. The defensive demand of wave power plants and WECs is relatively lower which is advantage to energy development in these areas. Along latitude direction, the richest areas of wave energy are located around 21°N and in westerlies areas. Along longitude direction, total wave energy are increasing from west to east. Wave energy in the range of $1\ \mathrm{m} \leqslant H_s \leqslant 4\ \mathrm{m}$ and $4\ \mathrm{s} \leqslant T_e \leqslant 10\ \mathrm{s}$ is 80% above of total wave energy in China Sea, Japan Sea and waters from equator to 20°N where we can design WECs according to this wave state range to obtain higher utilization ratio of energy. The exploitable wave energy is more close to theoretical wave energy in nearshore waters and equator sea areas which is a good characteristic for wave energy development. The more abundant the wave energy are, the lower the *WEER* are. In this case, the difference of the estimations between theoretical and exploitable wave energy will increase. The evaluation of exploitable wave energy is very meaningful for siting wave power plants. In Northwest Pacific, rich areas are large and approximately account for 70% of all sea area. For world-wide, Northwest Pacific is a rich region of wave energy where wave energy has a great potential for development and utilization.

Acknowledgements

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