Wave energy analysis based on simulation wave data in the China Sea

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Abstract. In the current world, where human beings are severely plagued by environmental problems and energy crisis, the full and reasonable utilization of marine new energy resources will contribute to alleviating the energy crisis, contributing to global energy-saving, emission reduction and environmental protection, thus to promote sustainable development. In this study, we firstly simulated a 10-year (1991-2000) 6-hourly wave data of the China Sea, by using the Simulating WAves Nearshore (SWAN) wave model nested with WAVEWATCH-III (WW3) wave model forced with Cross-Calibrated, Multi-Platform (CCMP) wind data. Considering the value size and stability of the wave energy density, we analyzed the overall characteristics of the China Sea wave energy with using the simulation wave data. Results show that: (1) The wave energy density in January and October is distinctly higher than that in April and July. The large center of annual average Wave energy density is located in the north of the South China Sea (of about 12-16 kW/m). (2) Synthetically considering the value size and stability of the wave energy density and stability, the energy-rich area is found to be located in the north region of the South China Sea.

1. Introduction
With the fast development of human society, the environmental problems and resource crisis (especially energy crisis) have become more and more serious, which may cause serious threats for human survival and the sustainable development. Under this background, the clean and renewable energy resources have become the best choice to address the energy crisis [1-7]. Abundant and non-pollution wave energy has become a particular area of interest for the developed countries. Understanding the characteristics of wave energy resources is very important for the utilization of wave energy program [8], such as wave power generation.

Previous studies have made great contributions to the analysis of wave energy resources [9-10]. The use of observational data and numerical simulation to assess and divide the class of the wave energy resource has provided better references for site selection of wave energy development, for example, wave power plant location. In 2009, using the WW3 wave mode, Bedard [11] carried out offshore wave energy forecasting in the East Pacific. Early in year 2011, Zheng et al. [12] have analyzed the wave energy resources of the whole China Sea for the first time, by using simulation method which also were used in further research in the China Sea [13-14]. Zheng et al. [15] have presented the long-term trend of significant wave height and wave energy density for the period 1988-
The result can provide reference for the long term plan of wave energy development. Zheng and Li [16] and Zheng et al. [17] have revealed the propagation route and speed of swell and swell energy, which can provide reference for the forecasting of wave energy.

Previous researches have made great contribution to the simulation analysis of wave energy in the China Sea. However, most of them are a single usage of WW3 or SWAN wave model, which may affected by complex terrain. This study presented a numerical analysis of wave energy in the China Sea using the SWAN wave model nested with WAVEWATCH-III (WW3) wave model with the CCMP wind data as the driving field, to deal with the impact of terrain on the simulation analysis of wave energy properly. When comprehensively considering the value size and stability of the Wave energy density, this study analyzed the overall characteristics of the China Sea wave energy resource in an attempt to provide references for the site selection of resource development.

2. Data and Method

2.1. Method

Firstly, we drive SWAN wave model with CCMP wind data to simulate the long time series wave data of the China Sea. Then the precision of the simulation wave data is verified by using observed wave data, through calculating the correlation coefficient (CC), Bias and mean absolute error (MAE). The calculation method of CC and MAE are as follows,

**CC:**

\[
CC = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}}
\]  

(1)

**Bias:**

\[
Bias = \bar{y} - \bar{x}
\]  

(2)

**MAE:**

\[
MAE = \frac{1}{N} \sum_{i=1}^{n} |y_i - x_i|
\]  

(3)

![Figure 1. Precision of the simulation wave data.](image)

From the scatter Figure and CC, Bias and MAE, it is not hard to find a good agreement. An improvement of precision of simulation wave data is found, through comparing with Zheng et al. [18].
As a result, we can use this simulation wave data to analyze the wave energy of the China Sea. Comprehensively considering the value size and stability of the wave energy density, this study analyzed the overall characteristics of the China Sea wave energy resource in an attempt to provide references for the site selection of resource development.

2.2. SWAN wave model introduction
The third generation wave model SWAN nest with WW3 are used to simulate the 3-hourly China Sea wave field from 00:00 1 January, 1991 to 18:00 31 December, 2000.

The control equation of WW3 wave model is as follows,

$$\frac{\partial N}{\partial t} + \frac{1}{\cos \phi} \frac{\partial}{\partial \phi} \phi N \cos \theta + \frac{\partial}{\partial \lambda} \lambda N + \frac{\partial}{\partial k} k N + \frac{\partial}{\partial \theta} \theta s N = \frac{S}{\sigma}$$

(4)

The control equation of SWAN wave model is as follows,

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x} (c_x N) + \frac{\partial}{\partial y} (c_y N) + \frac{\partial}{\partial \sigma} (c_\sigma N) + \frac{\partial}{\partial \theta} (c_\theta N) = \frac{S}{\sigma}$$

(5)

In order to eliminate the boundary effect, we set the calculation range of WW3 model as 5.125°S~45.125°N, 97.125°~140.125°E and then set the calculation range of SWAN model as 0.125°~40.125°N, 100.125°~135.125°E which contains main part of the China Sea and surrounding waters. The related calculation data are as follows: ocean wave spectrum girding: 24×25; wave direction: 24; resolution ratio: 15°; frequency divided into 25 bands from 0.0418Hz to 0.4056 Hz with each frequency band relation being. The spatial resolution of model output is 0.25°×0.25°. The time step is 1200 seconds and the output interval is every 6 hours. Compared to the inverting observation wave data from the T/P altimeter, we found that the simulation wave data had high reliability.

2.3. CCMP wind data
Set the long-term series, high spatial-temporal resolution CCMP wind data as the driving field of wave model, to simulate the 24-year China Sea wave field, based on which the wave energy characteristic is analyzed. The CCMP wind product is hosted at the PO. DAAC and has been evaluated and utilized extensively by the science community [19]. It is derived through cross-calibration and assimilation of ocean surface wind data from SSM/I, TMI, AMSR-E, SeaWinds on QuikSCAT, and SeaWinds on ADEOS-II. Cross calibration is performed by RSS under the DISCOVER project. These data sets are combined with conventional observations and a starting estimate of the wind field using a VAM. The VAM requires a background (or first guess) analysis of gridded u and v wind components as a prior estimate of the wind field. The ERA-40 is used as the background for the period July 1987 to December 1998. Beginning in 1999, with the benefits of 4DVAR and increased spatial resolution, the ECOP analysis outperforms the ERA-40 and is used here for the background. Its time resolution is 6 hours, space resolution is 0.25°×0.25°, with the time range from July 1987 to July 2011 and space range 78.375°S~78.375°N, 0.125°~379.875°E. The CCMP ocean surface wind product is widely used [2, 18].

3. Wave energy density in each representative month
We simulated the 6 hourly China Sea wave field from 1991 to 2000, by using the WW3 wave model with CCMP wind data as the driving field. Furthermore, we calculated and obtained the consecutive 3-hourly Wave energy density of the China Sea by using the simulation data, according to the calculation method of wave energy density [20, 21]. When comprehensively considering the value and stability of the wave energy density and stability, we made systematic assessments of the China Sea wave energy resource. Hopefully, the analysis will provide a scientific basis for the site selection of the projects such as marine wave power generation, sea water desalination, etc.

The China Sea wave energy density has obvious seasonal and regional differences, as shown in Figure 2. In January (representing winter, as shown in Fig.2a), under the obvious influence of the northeast trade wind caused by frequent and powerful cold airs, the wave energy density is clearly greater than that during the other seasons. The wave energy density in most sea areas of the South
China Sea is 10-30 kW/m. There were two centers with significant large values in the Wave energy density: the northern region of the South China Sea (25-30 kW/m) and the southeastern area of the Indo-China Peninsula (about 25 kW/m). The wave energy densities in April and July are on the low side as a whole. In April (representing the spring season, Figure omitted), which is the monsoon transitional season, wind speed is relatively slow, and the Wave energy density is also relatively small as a whole. Areas with relatively large values of the Wave energy density are mainly centered in the sea areas adjacent to the Ryukyu Islands (5-7 kW/m), and the northern region of the South China Sea (5-9 kW/m). In July (representing the summer season, as shown in Fig.2b), under the influence of the southwestern monsoon, a distinctive belt-like area with relatively large values was formed in the line of Ryukyu Islands-Luzon Strait- Pingxun Island (southeast area of the Indo-China Peninsula) with the wave energy density being 4-10 kW/m. In October (representing autumn, Figure omitted), the Wave energy density is smaller than that in January, and the large-value areas are mainly centered in the ocean areas to the east of Taiwan (15-18 kW/m), and the central and north area of the South China sea (9-24 kW/m). When considering the annual average distribution characteristics, except the Bohai Sea and Yellow Sea the annual average Wave energy density in most of the China Sea is above 2 kW/m. The area with large values is located in the north of the South China Sea (the sea area to the west of the Luzon Strait), with the annual average value being 12-16 kW/m.

We find that the offshore wave energy density is greater than the nearshore. The area of the South China Sea has the largest values all year round. The densities in various seasons mostly exceeded 8 kW/m and reached more than 20 kW/m in winter and autumn. The wave energy density in most of the East China Sea and the South China Sea was greater than 3 kW/m in each season. The Bohai Sea, the north area of the Yellow Sea, the Beibu Gulf, and the Gulf of Thailand formed the low-value center all the year round. Previous researcher has pointed out that the annual average Wave energy density in the China Sea and adjacent waters is mainly within 8 kW/m. Although the China Sea does not locate in the global wave energy rich region, the results of our research show that the China Sea wave energy is much more abundant than that assessed with the traditional approach. As a whole, the China Sea wave energy was found to be more optimistic than the traditional assessment value, which has a good agreement with the result of Zheng et al. [13].

Figure 2. Wave energy density in January (a), July (b), and annual average (c) in the China Sea, units: kW/m.

4. Stability of the wave energy density
During development process of wave energy resource, the stability of wave energy density affects not only resource acquisition and conversion efficiency, but also equipment life expectancy. As a result, it also affects the cost significantly [22, 23]. In order to determine the stability of the China Sea wave
energy density, we calculated the coefficient of variation (Cv), Monthly Variability Index (Mv), and the Seasonal Variability Index (Sv). A smaller Cv correlates with greater stability of the energy flux density, greater Mv with greater monthly variation of energy density, and greater Sv with more seasonal variation of energy density (i.e. poorer seasonal stability) (Figures omitted) [14].

Overall, the wave energy density Cv in January and October is smaller than that in April and July. This means that the stability in January and October is better than that in April and July. The seasonal differences resulted from the influence of the monsoon. In January and October, the China Sea often suffered from the invasion of cold air, and the ocean waves caused by cold air are often relatively stable. In July, the sea areas are often subjected to the invasion of typhoons so that storm waves caused dramatic changes in wave height, resulting in poor stability. When considering the differences in regional stability, the Cv in the north area of the South China and East Sea was apparently smaller than other sea areas, implying that there was better stability.

The analyses show that the Mv and Sv in the Bohai Sea and Yellow Sea were obviously larger than those in other sea areas. This means that the monthly and seasonal stabilities of the Wave energy density were poorer. In the north area of the South China Sea, and the East Sea, both the Mv and Sv were located in the areas with low values, suggesting that the stabilities were better than those in other sea areas.

5. Conclusions
This study simulated the 3 hourly wave energy density for the period 1991-2000 in the China Sea, using the WW3 wave model forced by the CCMP wind data. We made a comprehensive consideration of the value and stability of the wave energy density. We analyzed the overall characteristics of the China Sea wave energy resource. The results show the following:
(1) The China Sea wave energy resource is much greater than the traditional assessment although it is not located in the global wave energy rich region. There are significant seasonal and regional differences in the China Sea Wave energy density. The density is obviously larger in January and October than that in April and July. In most waters, the annual average Wave energy density is above 2 kW/m, and the large-value area is located in the north of the South China Sea (the waters in the Luzon Strait and to its west) where the annual average value is 12-16 kW/m.
(2) When comprehensively considering the value size and stability of wave energy density, we find that the relatively rich area of the China Sea wave energy resource mainly distribute in the north waters of the South China Sea.

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