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A seasonal grade division of the global offshore wind energy resource

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Abstract

Under the background of energy crisis, the development of renewable energy will significantly alleviate the energy and environmental crisis. On the basis of the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-interim) wind data, the annual and seasonal grade divisions of the global offshore wind energy are investigated. The results show that the annual mean offshore wind energy has great potential. The wind energy over the westerly oceans of the Northern and Southern Hemispheres is graded as Class 7 (the highest), whereas that over most of the mid-low latitude oceans are higher than Class 4. The wind energy over the Arctic Ocean (Class 4) is more optimistic than the traditional evaluations. Seasonally, the westerly oceans of the Northern Hemisphere with a Class 7 wind energy are found to be largest in January, followed by April and October, and smallest in July. The area of the Class 7 wind energy over the westerly oceans of the Southern Hemisphere are found to be largest in July and slightly smaller in the other months. In July, the wind energy over the Arabian Sea and the Bay of Bengal is graded as Class 7, which is obviously richer than that in other months. It is shown that in this data set in April and October, the majority of the northern Indian Ocean are regions of indigent wind energy resource.

Key words: global ocean, wind energy, annual grade division, seasonal grade division

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1 Introduction

Many economically developed regions of the world are distributed in coastal areas, where there is often the lack of resources, particularly electricity. Power shortages can have serious socioeconomic effects, and the consideration of local conditions in fully exploiting clean energy resources such as wind, wave, and solar energy will have a positive effect on alleviating the energy crisis (Zhang et al., 2013; Hou et al., 2015), promoting environmental protection and coping with the global climate variation (Zheng et al., 2014a, b; Carvalho et al., 2014a; Wan et al., 2015; Zheng and Li, 2015; Zheng et al., 2016a). The offshore wind energy is considered a safe and non-polluting renewable resource that has large, widely distributed reserves and therefore, it has become the focus of much attention.

There is clear need for a resource evaluation and planning in advance for a wind energy development. Toward the end of the last century, researchers began evaluations of offshore wind energy resources; however, such investigations were restricted by limited observational data. Previous researchers have made great contribution to the evaluation of the local offshore wind energy resources. But there are a few researches about the whole global offshore wind energy. The rapid development of observational and computational technologies, including satellite, buoy, simulation, and reanalysis data, has made it possible to perform large-scale high-resolution research on the ocean wind energy resource (Jung et al., 2013; Chadee and Clarke, 2014). On the basis of the observation data, Youm et al. (2005) analyzed the distribution characteristics of the wind energy resources in northern coastal sea area of Senegal. They pointed out that the annual average wind speed and the annual average wind power density (WPD) in this area is, respectively, 3.8 m/s and 158 W/m^2. Dvorak et al. (2010) have analyzed the wind energy resource assessment of the offshore California. Their result show that using only currently available turbine tower support technologies (0–50 m depth), between 17% and 31% respectively of CA electricity need could be provided. In 2005, Archer and Jacobson (2005) have firstly performed the excellent evaluation of the global onshore and coastal wind power at 10 and 80 m height. The results show that globally, about 13% of all reporting stations experience the annual mean wind speeds being greater than or equal to 6.9 m/s at 80 m (i.e., wind power class 3 or greater). They also pointed out that even if only 20% of this power could be captured, it could

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satisfy 100% of the world's energy demand for all purposes. Using combines multiyear mesoscale modeling results, in 2008, Liu et al. (2008) used QuikSCAT (Quik scatterometer) wind data to produce contour maps of the global WPD in June, July, August (JJA) and December, January, February (DJF). They found that the WPD in the winter hemisphere was significantly higher than that in the summer hemisphere. In JJA, large areas of the WPD are mainly distributed in the Southern Hemisphere westerlies (1.0–1.4 kW/m^2) and the waters surrounding Somalia (about 1.2 kW/m^2). In DJF, the large center is located in the Northern Hemisphere westerlies (1.0–1.4 kW/m^2). Carvalho et al. (2014b) forced a weather research and forecasting (WRF) model with different initial and boundary conditions and conducted ocean surface wind simulations to determine which data set provided the most accurate ocean surface wind simulation and offshore wind energy estimates. The simulation results of the models driven by the NCEP-FNL and NCEP-GFS analyses were found better than those produced using the NCEP-CFSR and NASA-MERRA reanalyses. Capps and Zender (2010) evaluated the global ocean wind power potential and the global ocean 80 m wind energy, accounting for surface layer stability. They demonstrated that during 2000–2006, available 80 m high WPDs, between 100 and 500 W/m^2, existed over approximately 50% of the ice-free ocean surface area. Adams and Keith (2013) have pointed out that the estimates of the global wind resource that ignore the impact of wind turbines on slowing the winds may substantially overestimate the total resource.

Many excellent researches on the global offshore wind energy resource have been presented by the previous researchers (Doubrawa et al., 2015). But there are a few studies on the grade division of the global offshore wind energy until now, especially on the seasonal grade division. In 2005, the National Renewable Energy Laboratory (NREL, 2005a) of the United States Department of Energy (DOE) presented a wind power class map of the global oceans based on the magnitude of the WPD derived from QuikSCAT wind data. The results show that large areas of the global oceans are rich sources of the wind energy (greater than Class 4). In 2014, with reference to the standards established by the DOE and National Development and Reform Commission (NDRC) of China (Elliott et al., 1986; NREL, 2005b; General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China, 2004), and with consideration of the wind speed, WPD, and occurrence of effective wind speed in conjunction with the last 24 a cross-calibrated multi-platform (CCMP) wind field data, Zheng and Pan (2014) conducted a grade division of the wind resource over the global oceans, which was generally consistent with the results of the DOE. They found that the range of the areas of the indigent wind energy resource was smaller than that determined previously, i.e., the potential of the global ocean wind energy resource is greater than expected.

Establishing a grade division of the wind energy resource provides an important reference for macroscopic site selection, which is currently based on the grade division of the annual wind energy resource of previous researches. In the actual site selection process, the resource grade division in different months is usually of concern; thus, a fine-scale scientific reference would be beneficial. In this study, based on the ERA-interim wind data, the grade divisions of the global annual and seasonal mean offshore wind energy resources are investigated.

2 Data and methods

2.1 *ERA-interim wind data*

The ERA-interim wind data (ECMWF, 2016) mostly uses the observation sets acquired for ERA-40, supplemented with data for later years from the ECMWF operational archive. Initial indications are that the interannual variability in the ERA-interim wind data is better than that in ERA-40, which was already superior to other reanalysis wind products (Kent et al., 2013; Zheng et al., 2013). These data are available with several spatial resolutions, and for this study, the highest spatial resolution of 0.125° × 0.125° was selected. The data were processed in the following format: domain, (90°S–90°N, 0.125°–359.875°E); spatial resolution, 0.125° × 0.125°; time series, 00:00 January 1, 1979 to 18:00 December 31, 2014; time resolution, 6 h intervals.

2.2 *Wind power classification standard*

According to the calculation method of the WPD of Zheng et al. (2012), Zheng et al. (2016b) and Kozai et al. (2012), we obtained the 6 h global offshore WPD 10 m above the sea surface for the period January 1979 to December 2014 using the ERA-interim wind data. According to the standard of the wind power classification (Table 1) and using the 36 a (1979–2014) 6 h WPD data, the grade divisions of the annual and seasonal mean offshore wind energy resources of the global oceans are presented. Table 1 presents the seven classes of the wind power classification: Class 1 corresponds to indigent, Class 2 corresponds to available, Class 3 corresponds to subrich, and Classes 4–7 correspond to rich potential.

The factors considered in the standard of the wind power classification include the wind speed, the WPD, and the significant interval. This paper specifically examines the significant interval. In the development of the wind energy resources, wind speeds of 5–25 m/s are usually considered favorable for the collection and conversion of the wind energy. This wind speed interval is called the effective wind speed of the wind energy resource development. Generally, the significant interval represents the number of hours of effective wind speed (it sometimes also rep-

Table 1. Standard of wind power classification (NREL, 2005a)

Wind power class	Wind speed/m·s^{-1}	Wind power density/W·m^{-2}		Significant interval/h	Resource potential
		Method 1	Method 2		
1	0	0	0	0	indigent available subrich
2	4.4	100	50	2 000	
3	5.1	150	150	3 000	
4	5.6	200	200	5 000	
5	6.0	250	250	>5 000	rich
6	6.4	300	300		
7	7.0	400	400		
	9.4	1 000	1 000		

resents the occurrence of the effective wind speed).

3 Grade division of annual mean

First, we calculated the annual mean wind speed (figure omitted) and the annual mean WPD (Fig. 1a). Usually, wind speeds of 3–25 m/s are considered suitable for development and this range is defined as the significant interval. Here, the annual mean occurrence of the significant interval is presented in Fig. 1b. Then, according to the standard of the wind power classification, we determined the grade division of the annual mean offshore wind energy resource over the global oceans, as shown in Fig. 2.

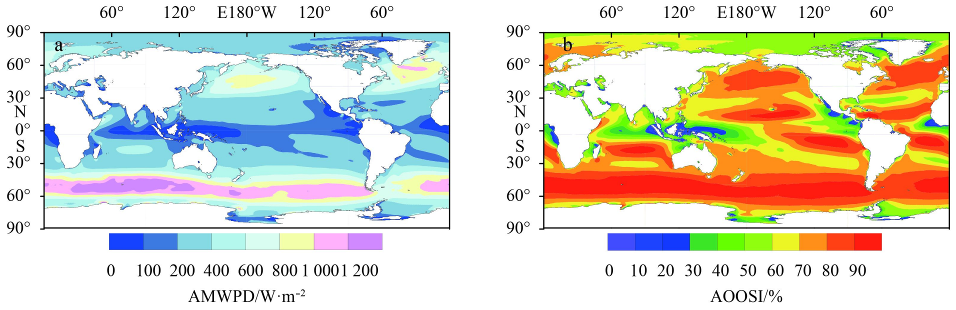

Fig. 1. Annual mean wind power density (AMWPD) (a) and annual occurrence of significant interval (AOOSI) (b) over the global oceans.

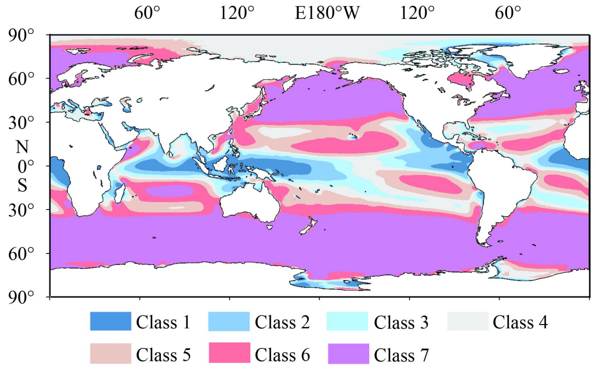

Fig. 2. Grade division of annual mean offshore wind energy resources over the global oceans according to ERA-interim wind data.

It is clear found from the annual mean WPD (Fig. 1a) that only some small-scale areas of equatorial waters have WPD of less than 100 W/m^2. On the large-scale, the WPD of the global oceans is greater than 200 W/m^2. The areas of the greatest WPD are mainly located in the Southern Hemisphere westerlies (greater than 800 W/m^2; even greater than 1.2 kW/m^2 in the center of the area) and the Northern Hemisphere westerlies (0.6–1.2 kW/m^2 in the Pacific westerlies; 0.6–1.2 kW/m^2 in the Atlantic westerlies). The WPD over most of the mid-latitude oceans is approximately 200–600 W/m^2. There is a good agreement between our result and those of NASA (2008) and Liu et al. (2008). The WPD at the high-latitudes of the Northern Hemisphere is 200–400 W/m^2. It is worth noting that the WPD in the surrounding waters of the China's seas is optimistic, of about 200–400 W/m^2 in most waters, even above 600 W/m^2 in the large value center.

On the basis of the 6-hourly WPD for the period 1979–2014, statistics of the annual mean occurrence of the significant interval are derived (Fig. 1b). In Table 1, the significant interval represents the number of hours of the effective wind speed, which in this paper is converted into the occurrence of the effective wind speed. It is clear that the occurrence of the significant interval over most of the global oceans offers reason for optimism because it is greater than 50% over large areas and even greater than 80% in the regions of the Northern and Southern Hemisphere westerlies; only in some small-scale areas of equatorial waters it is less than 30%. The occurrence is 40%–60% in the Bohai Sea and the Yellow Sea. In most of the East China Sea and the South China Sea, the occurrence is 60%–80%.

The annual grade division of the offshore wind energy resource over the global oceans (Fig. 2) reveals the potential of the wind energy development. The wind energy over most of the westerly oceans of the Northern and Southern Hemispheres belongs to Class 7. Over the mid–low latitude regions of the Pacific and Atlantic oceans, it mainly belongs to Classes 4–6. Similarly, over the Arabian Sea, it mainly belongs to Classes 4–7. Over the Gulf of Mexico, wind energy belongs to Classes 4–5, whereas over the Caribbean Sea, it belongs to Class 6. Over the central and southern East China seas (Yellow Sea and East China Sea), and over the central and northern South China Sea, it belongs to Classes 5–6. Zheng et al. (2012) conducted a wind energy grade division for the China's seas and found that over the central and southern East China Sea, and over the central and northern South China Sea, it belongs to class 3 or above. Clearly, the results of the current paper are more optimistic than the findings reported by Zheng et al. (2012). Wind energy over the Bay of Bengal belongs to Classes 3–5, whereas that over the Arabian Sea belongs to Classes 4–7. According to Table 1, Classes of wind energy greater than 4 describe a “rich” resource potential.

The regions of the indigent wind energy are distributed mainly over the near-equatorial regions of the Indian Ocean, the western Pacific Ocean, and the eastern Atlantic Ocean and the low-latitude regions of the eastern Pacific Ocean. It is worth noting that the wind energy over the Arctic Ocean (high-latitude regions greater than 60°N) belongs to Class 4, which could be interesting regarding potential future development in that region. In 2014, Zheng and Pan (2014) produced a global ocean wind energy grade division diagram (Fig. 3), which is largely in agreement with the grade divisions of most regions in this paper. The main difference is that wind energy over the Arctic Ocean region is classified as Class 3 by Zheng et al. (2012), whereas this paper classifies it as Class 4. By comparing the magnitude of the wind speed and the WPD, the results of this paper are found to be consistent with Zheng et al. (2012). The variance of the wind energy

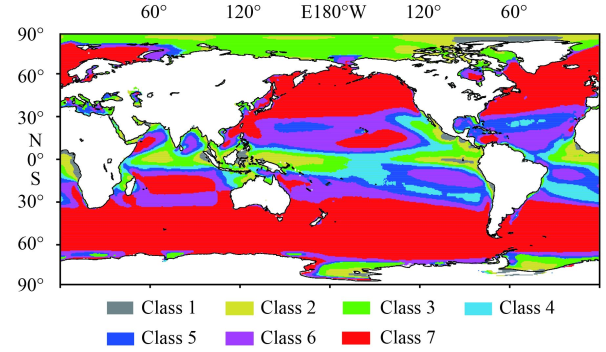

Fig. 3. Grade division of annual mean offshore wind energy resources over the global oceans according to CCMP wind data presented by Zheng et al. (2012).

grade division at the high latitudes of the Northern Hemisphere could result from differences in the occurrence of the effective wind speed.

4 Grade division in different seasons

With reference to the method of grade division of the annual mean offshore wind energy resources, the grade division of the global offshore wind energy resources in January, April, July, and October is shown in Fig. 4.

First, we calculated the average wind speed (figure omitted) in January, the average WPD (figure omitted) in January, and the occurrence of the significant interval in January for the past 36 a (figure omitted). Then, according to the standard of the wind energy classification, the grade division of the offshore wind energy resources in January over the global oceans is obtained, as is shown in Fig. 4a. The grade divisions of the global offshore wind energy resources in April, July, and October were similarly determined and are presented in Figs 4b–d, respectively.

January is in winter in the Northern Hemisphere (Fig. 4a). Thus, there is considerable influence from cold air and the area over which the wind energy is assigned to Class 7 in this season is clearly greater than that in other seasons; the wind energy across almost the entire region of 30°–60°N in the Northern Hemisphere belongs to Class 7. In addition, the wind energy over the oceans near 10°N and the South China and East China seas belongs to Class 7, whereas it is assigned to Classes 4–5 over the oceans greater than 60°N. The wind energy over most of the northern Indian Ocean is clearly less than that over the other oceans of the Northern Hemisphere. Generally, it is assigned to Classes 1–3; only the coastal oceans of Somalia have relatively abundant wind energy. The wind energy over the Gulf of Mexico and the Caribbean Sea belongs to Classes 4–7. January is in summer in the Southern Hemisphere and the extent of the areas of the westerly oceans with wind energy of Class 7 is obviously smaller than that in the other seasons.

In April (Fig. 4b), the strength and frequency of the cold air in the Northern Hemisphere is gradually weakened, and the ranges of the areas of the greatest wind energy are obviously narrowed. The entire northern Indian Ocean is classed as a region of indigent wind energy (Class 1). The wind energy resource over the coastal regions of China decreases from Class 7 in January to Class 4, and it even decreases to Classes 1–3 over the central and southern South China Sea. The wind energy over the high-latitude oceans greater than 60°N decreases from Classes 4–5 to 3–4. The areas of the regions of the indigent wind energy expand noticeably over the oceans near the equator. The wind energy over the Gulf of Mexico belongs to Classes 4–5, whereas it is assigned to Class 6 over the Caribbean Sea. It is worth noting that a large area in which wind energy belongs to Classes 6–7 exists over the low-latitude central ocean of the North Pacific. The ranges of the areas in which wind energy is assigned to Class 7 over the westerly oceans of the Southern Hemisphere are obviously larger than those in January.

In July (Fig. 4c), the Northern Hemisphere is in summer and the ranges of the areas with wind energy of Class 7 over the westerly oceans are clearly smaller than those in January and April. Wind energy over most of the oceans greater than 60°N belongs to Class 3. Under the influence of a strong southwest monsoon, the wind energy over the entire Arabian Sea and Bay of Bengal is assigned to Class 7. The wind energy over the South China Sea in July is spatially more abundant than that in April, but the southwest monsoon has less impact on the wind energy resource of the

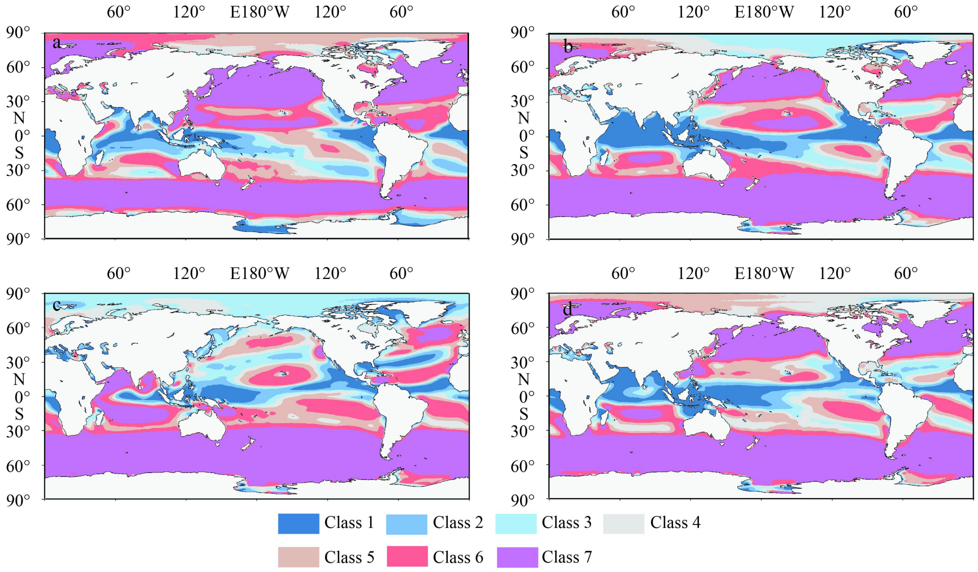

Fig. 4. Grade division of global offshore wind energy resources in January (a), April (b), July (c) and October (d).

South China Sea than the northern Indian Ocean. The wind energy over the Gulf of Mexico belongs to Classes 1–2, but it is assigned to Classes 6–7 over the Caribbean Sea. In July, the Southern Hemisphere is in winter. At this time, the ranges of the areas of the westerly oceans over which the wind energy resource is assigned to Class 7 are the greatest of the represented months, and they even extend north to 30°S.

In October (Fig. 4d), with the gradually increasing prevalence of cold air in the northern Hemisphere, the ranges of the areas over the westerly oceans in which wind energy is assigned to Class 7 are obviously larger than those in July. The wind energy over the central and southern East China Sea and the northern South China Sea belongs to Class 7. The northern Indian Ocean has lower wind energy because its position in the lower latitudes means it is unaffected by the cold air. The entire Arabian Sea and northeastern Bay of Bengal are classified as regions of the indigent wind energy resource, but there is a large region with abundant wind energy over the oceans south of Sri Lanka. The wind energy over the Gulf of Mexico and the Caribbean Sea belongs to Classes 4–5, as is the case over most of the ocean greater than 60°N. The ranges of the areas over the westerly oceans of the Southern Hemisphere in which the wind energy belongs to Class 7 are slightly smaller than those in July.

5 Conclusions

This study investigated the annual and seasonal grade division of the global offshore wind energy resources and the following conclusions have been drawn.

(1) With regard to the annual grade division of the global offshore wind energy resource, the wind energy over the westerly oceans of the Northern and Southern Hemispheres belongs to Class 7. The wind energy over the mid–low latitude regions of the Pacific and Atlantic Oceans belong to Classes 4–6. Over the Arabian Sea, the Gulf of Mexico, and the Caribbean Sea, the wind energy belongs to Classes 4–7, 4–5, and 6, respectively. The wind energy over the central and southern East China Sea and the northern South China Sea belong to Classes 5–6, whereas that over the Bay of Bengal and the Arctic Ocean belongs to Classes 3–5 and 4, respectively. In the near-equatorial regions of the Indian Ocean, the western Pacific Ocean, and the eastern Atlantic Ocean and in the low-latitude regions of the eastern Pacific Ocean, the wind energy belongs to Class 1, i.e., these areas lack a substantial wind energy resource.

(2) With regard to the seasonal grade division of the global offshore wind energy resources, the ranges of the areas over the westerly oceans of the Northern Hemisphere in which the wind energy resource assigned to Class 7 are the largest in January, followed by April and October, and smallest in July. In July, there is no area of Class 7 wind energy resource over the western north Pacific Ocean, and the areas of Class 7 wind energy in other regions are very small. The ranges of the areas over the westerly oceans of the Southern Hemisphere in which the wind energy resource is graded as Class 7 are the largest in July (extending north to 30° S) and slightly smaller in the other months. In July, the wind energy resource over the Arabian Sea and the Bay of Bengal mainly belongs to Class 7, which is obviously richer than that in the other months. In April and October, the majority of the northern Indian Ocean is a region of the indigent wind energy resource (Class 1). This area of poor wind energy over the Indian Ocean near the equator is largest in April, followed by January and October, and smallest in July. The ranges of the areas of the indigent wind energy resource over the near-equatorial regions of the western Pacific Ocean are the largest in April and October and are relatively small in January and July. The extent of the areas of the indigent wind energy resource over the low-latitude regions of the eastern Pacific Ocean are the largest in April, followed by January and July, and the smallest in October. The ranges of the areas of indigent wind energy resource over the near-equatorial regions of the central and eastern Atlantic Ocean are the largest in January and relatively small in July and October.

In this study, the graded division of the global offshore wind energy resource in four representative months has been analyzed, which has revealed the benefit a fine-scale scientific reference would provide regarding macroscopic site selection for the exploitation of the wind resource potential.

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