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RESEARCH ARTICLE

Onshore-offshore wind energy resource evaluation based on synergetic use of multiple satellite data and meteorological stations in Jiangsu Province, China

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Abstract The demand for efficient and cost-effective renewable energy is increasing as traditional sources of energy such as oil, coal, and natural gas, can no longer satisfy growing global energy demands. Among renewable energies, wind energy is the most prominent due to its low, manageable impacts on the local environment. Based on meteorological data from 2006 to 2014 and multi-source satellite data (i.e., Advanced Scatterometer, Quick Scatterometer, and Windsat) from 1999 to 2015, an assessment of the onshore and offshore wind energy potential in Jiangsu Province was performed by calculating the average wind speed, average wind direction, wind power density, and annual energy production (AEP). Results show that Jiangsu has abundant wind energy resources, which increase from inland to coastal areas. In onshore areas, wind power density is predominantly less than 200 W/m^2, while in offshore areas, wind power density is concentrates in the range of 328–500 W/m^2. Onshore areas comprise more than 13,573.24 km^2, mainly located in eastern coastal regions with good wind farm potential. The total wind power capacity in onshore areas could be as much as 2.06 $\times$ 10^5 GWh. Meanwhile, offshore wind power generation in Jiangsu Province is calculated to reach 2 $\times$ 10^6 GWh, which is approximately four times the electricity demand of the entire Jiangsu Province. This study validates the effective application of Advanced Scatterometer, Quick Scatterometer, and Windsat data to coastal wind energy monitoring in Jiangsu. Moreover, the methodology used in this study can be effectively applied to other similar coastal zones.

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Keywords wind energy resource, wind power density, ASCAT, QuikSCAT, Windsat

1 Introduction

The trend toward clean energy is irreversible (Obama, 2017), and replaceable sources of energy, especially green and renewable energy, are gaining increasing attention due to a heightened awareness of national energy security, regional sustainable development, and global climate change (Purohit and Purohit, 2009; Barrington-Leigh and Ouliaris, 2017). Compared to other energy sources (e.g., oil, coal, natural gas), wind energy has zero carbon emissions, is low-cost, inexhaustible, and capable of meeting ever-growing electricity demands; therefore, its market share has increased in recent years (Ohunakin and Akinnawonu, 2012; Thornton et al., 2017). In China, the total installed wind power capacity rose from 2.6 GW in 2006 to 168 GW in 2016, which is the fastest growth rate of all renewable energy sources (Jiang et al., 2013; Shen et al., 2017). Under the ongoing "13th Five-Year Plan" of "Wind Power Development", China aims to reach an installed capacity of 210 million kW of wind power by the end of 2020. To achieve this goal, accurate assessment of wind energy resources is required for energy risk mitigation and development of a low carbon economy in China.

Common methods for wind energy assessment can be divided into three overall groups. The first is based on analysis of historical time series of wind data, the second uses forecasted values from a numerical weather prediction (NWP) model as an input, and the third involves simulations based on satellite remote sensing data. Initial assessments of onshore wind energy resources are based on data from meteorological observation stations by means of statistical analysis and spatial interpolation techniques (Troen and Petersen, 1989; Heng et al., 2001; Truewind Solutions, 2001; Anon, 2004; Archer and Jacobson, 2005; Ramachandra and Shruthi, 2005). Despite the advanced evaluation techniques of the first group of methods, meteorological observation stations are usually sparsely distributed and data is often missing. The use of models in the second group makes up for the lack of meteorological observation data and is an essential tool for forecasting wind power (Manwell et al., 2002; Coppin, et al, 2003; Kariniotakis et al., 2005; Yu et al., 2006; Dvorak et al., 2010; Jimenez et al., 2010; Shimada and Ohsawa, 2011; Foley et al., 2012). NWP models such as WRF can obtain higher spatial resolution results and can be used for both offshore and offshore wind energy resource assessment. However, this method depends heavily on NWP model selection, which is affected by the geographical area, the resolution (both spatial and temporal) and the forecast horizon, as well as the accuracy, computational time, and number of runs. Different models lead to notably different assessment results. In addition, evaluation results are susceptible to external factors (e.g., thermal effects, wake affects). As for offshore wind energy resource assessment, due to a lack of meteorological observation stations, satellite data is increasingly used in Europe, the United States, and other developed countries (Ahsbahs et al., 2017; Nagababu et al., 2017). Typically, wind energy resource assessment is performed using SAR (Hasager et al., 2005, 2006; Christiansen et al., 2006), QuikSCAT (Pickett et al., 2003b; Tang et al., 2004; Pimenta et al., 2008; Risien and Chelton, 2008; Carvalho et al., 2013; Hasager et al., 2015), and Windsat (Quilfen et al., 2007).

There are many regions in the world where wind power development is hindered by a lack of accurate wind information (Lima et al., 2015). Particularly in offshore areas, meteorological observation data are scarce and a complete data set is difficult to obtain for a study area. Hence, combining satellite and meteorological data is an important breakthrough in the evaluation of wind energy resource potential. In addition, wind resource estimation may be biased if using wind observations from only one satellite (Hasager et al., 2015) because of low temporal resolution, the selected model, obstacles along coastal zones, etc. Therefore, the synergetic use of multiple satellite data is a necessary and superior alternative method for wind energy resource evaluation. It can not only improve the temporal resolution of satellite data, but increase the total number of samples and decrease the statistical uncertainty.

The aim of this study is to estimate both the onshore and offshore wind energy resources in Jiangsu Province based on meteorological data from 2006 to 2014 combined with satellite data (Advanced Scatterometer(ASCAT), Quick Scatterometer (QuikSCAT), and Windsat) from 1999 to 2015. This paper presents the study area and datasets in Section 2, the methodology in Section 3, the result in Section 4, and the discussion and conclusions in Section 5 and Section 6, respectively.

2 Materials

2.1 Study area

Jiangsu Province, located on the east coast of China, is a typical wind power development zone and one of the most prosperous provinces in China (Fig. 1). In recent years, wind power there has developed rapidly. Jiangsu's wind power installed capacity reached 2444 MW in 2013 and 65610 MW in 2016. According to "Jiangsu Province wind power development plan (2006–2020)", four wind power bases and 36 land-based wind farms are planned, with a total installed capacity of 3780 WM (Table A2 in supplementary material A). As for offshore wind power, according to the National Energy Administration, Jiangsu Province has 18 offshore wind power projects, two of which projects are in operation, eight are under construction, two have been approved, and six are beginning preliminary work (Table A3 in supplementary material A). As part of the 13th Five-Year Plan, China proposed onshore and offshore wind power capacity goals for Jiangsu of 6500 MW and 4500 MW, respectively, by 2020.

Jiangsu belongs to the Middle-Lower Yangtze River Plain, which has long been influenced by the impact of the Yangtze and Huaihe Rivers. Therefore, Jiangsu has a plain-dominated terrain, with the plain constituting approximately 70% of the province, and with elevations below 50 m in most regions (Fig. A1 in supplementary material A). Jiangsu has abundant precipitation and the annual average temperature is 13°C–16°C, as it is controlled by the East Asian monsoon, and has characteristics of both continental and oceanic climates. In Jiangsu Province, winter brings the winter monsoon with a prevailing northerly wind direction, and summer brings the summer monsoon with a prevailing east to southeasterly wind direction. Spring and autumn are transitional periods between the winter and summer monsoons.

Jiangsu Province is close to the Yellow Sea, and the total length of the coastline of Jiangsu Province is 954 km. The main landform along the Jiangsu coast is tidal flats, accounting for more than 90% of the entire coastline (Zhao et al., 2015). The offshore area includes the South Yellow Sea radial sand ridges, which are the largest tidal sand ridges on the Chinese continental shelf. Long-term deposition has provided the bulk of the tidal flat resources for Jiangsu Province, which creates excellent conditions for the development and utilization of wind energy resources.

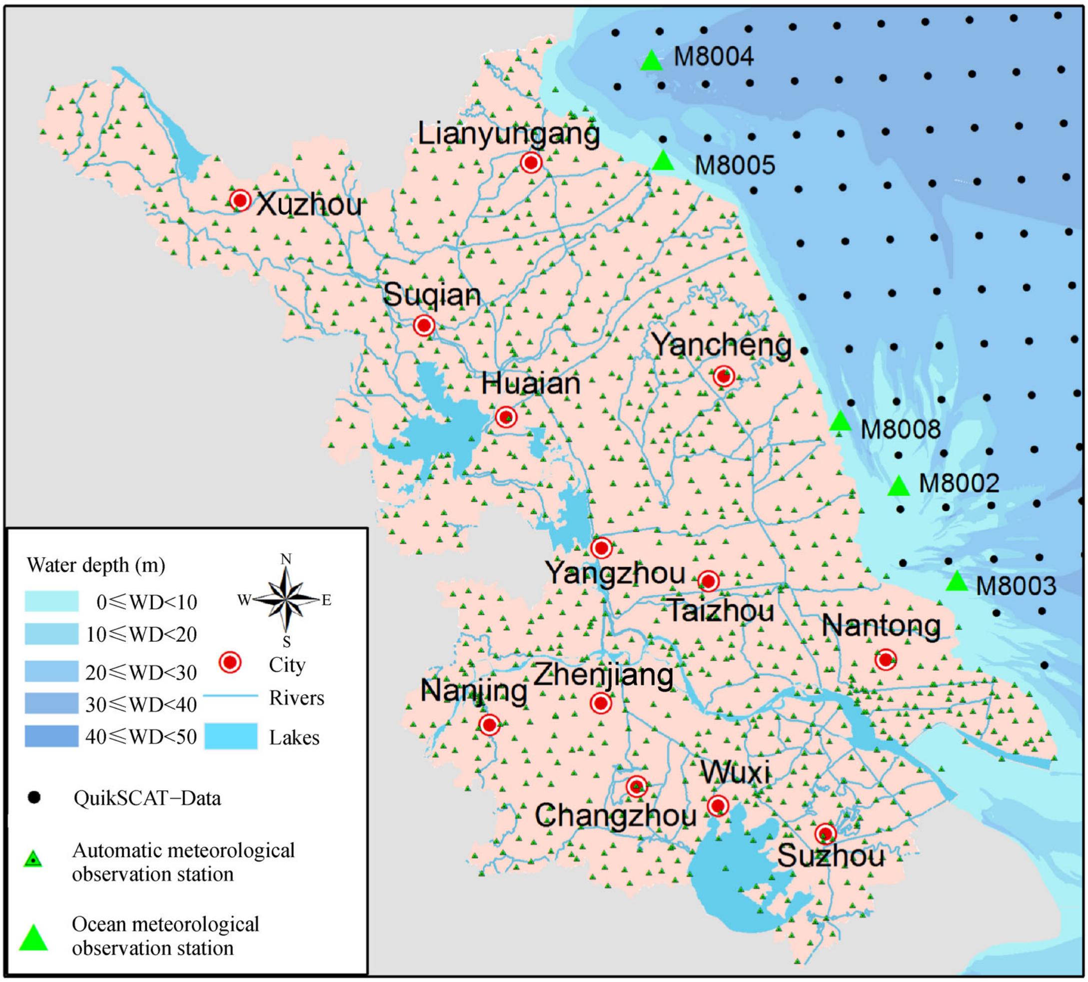

Fig. 1 Geographical location of the study area and the distribution of meteorological observation stations and QuikSCAT–data.

2.2 Datasets

The datasets used in this study include meteorological observation data, satellite data, and other auxiliary data. For meteorological observation data, this study used daily wind data from 1082 automatic meteorological observation stations in Jiangsu Province from 2006 to 2014, including data from 70 urban manual meteorological observation stations, 19 marine automatic meteorological stations, 875 encrypted automatic meteorological stations, and 117 automatic precipitation stations. The temporal resolution of these observations is one hour. Due to the different environments and equipment of the meteorological stations, the observation data inevitably contain some invalid information. To obtain more accurate data, we excluded invalid values (e.g., 9999) of wind speed/direction from the observed meteorological data, and converted all meteorological data to shapefile format after re-projection.

For satellite data, we used vector wind data extracted from ASCAT, QuikSCAT, and Windsat satellites to evaluate the wind energy resources in Jiangsu Province. ASCAT data are from Remote Sensing Systems (RSS) (Version-2.1) daily wind vectors (January 2008 to December 2015). Compared to previous versions of wind vectors, we used a new geophysical model that calibrates the data by reducing the impact of rain. QuikSCAT data are from RSS (Version-4) daily wind vectors (July 1999 to November 2009). In this version, Windsat data (no rain conditions) were used for data correction, which improves the accuracy of QuikSCAT wind field data. Windsat data are from RSS (Version 7.0.1) Medium Frequency (18.7 VH, 23.8 VH, 37.0 VH) daily wind speed data (February 2003 to December 2015). The spatial resolution of these three datasets is 0.25° × 0.25°, and the data are spatially correlated. All the satellite data is formatted in binary files, which include latitude, longitude, and wind vector information.

Regarding other auxiliary data, regional boundary vector data used in this study are 1:4 million Chinese administrative division data. Bathymetric data is GEBCO_2014 Grid data released in 2014. The British

Ocean Data Center (BODC) provides free data for all sea-wide ranges worldwide, with a spatial resolution of 30" × 30". SRTM 30 m DEM data was used, and land use data was Jiangsu Province 2010 land use type data.

3 Methods

Data from ASCAT, QuikSCAT, Windsat, and 1082 meteorological observation stations were synthesized and used to evaluate the wind energy potential in Jiangsu Province. The method includes the following main parts (Fig. 2): 1) correction of satellite retrieved wind data; 2) assessment of wind energy resources; and 3) evaluation of wind power potential in Jiangsu Province.

3.1 Verification of satellite data applicability and wind vector data correction

3.1.1 Applicability analysis of satellite data in Jiangsu Province

As satellite observations are generally obtained by inverting the roughness of sea surface data, wind field data may be affected by the roughness of the coastline, complex weather conditions, and heterogeneous sea surface conditions. Therefore, satellite observation data are only regionally applicable, which requires that data is validated and corrected to improve accuracy before assessing the wind energy resource (Figs. 3 and 4 and supplementary material C). As the ocean meteorological observations and satellite data can not completely coincide in space and time, we set several matching rules. First, we select satellite data and ocean meteorological observations that are closest in space, and the distance between them should be less than 25 km to ensure that ocean meteorological observations fall within the satellite data grid. Second, we select ocean meteorological observations and satellite data that are closest in time, with a time difference of less than half an hour. Moreover, each observation site must have only one matching satellite observation. Using these matching rules, we obtained 2644 QuikSCAT data points, 1087 ASCAT data points, and 492 Windsat data points to validate ocean meteorological observations (Table 1). The average deviation, mean absolute deviation, root mean square error (RMSE), correlation coefficient, and other parameters were employed to verify the deviation between satellite-derived wind data and ocean meteorological observations, and to test the applicability of each type of satellite-derived wind data for Jiangsu.

3.1.2 Correction of satellite retrieved wind data

To reduce deviation of satellite retrieved wind data and obtain more accurate results for wind energy resource assessment, the satellite retrieved wind data were corrected using the linear relationships between meteorological data and satellite data. Wind speeds from ASCAT data and QuikSCAT data were generally higher than the actual observations, whereas wind speeds from Windsat data were much lower than actual meteorological data, confirming the importance of satellite data correction (Fig. 5). In addition, the deviation was significantly reduced after calibration of the data. Specifically, the absolute mean error of the corrected data was greatly reduced, and the RMSE between the primary data and adjusted data also decreased.

3.2 Wind energy resource assessment in Jiangsu Province

3.2.1 Wind speed extrapolation at a certain height

This study used average wind speed, wind power density, and hours of effective wind speed to estimate the wind energy resource potential. Because wind power density is independent of wind generator type and reflects the influence of wind speed, wind speed frequency distribution, and air density, it is the most convenient, valuable, and comprehensive index to measure the potential wind power resources in a region. Generally, the wind vector data correspond to ground wind speed. Therefore, to obtain wind speed at the height of wind turbines, wind speed extrapolation is required. The exponential law or logarithmic law equations are typically used to describe the wind speed profile. However, when the height is over 60 m, the logarithmic law equation (Manwell et al., 2002; Pimenta et al., 2008; Sliz-Szkliniarz and Vogt, 2011) is preferred. The logarithmic law equation is defined as follows:

Table 1 Comparison of satellite data used to validate ocean meteorological observations

Meteorological station	QuikSCAT (2007)	QuikSCAT (2008)	ASCAT (2008)	Windsat (2008)
M8002	194	224	186	166
M8003	342	311	193	158
M8004	216	254	177	168
M8005	276	293	212	–
M8008	78	456	319	–
Total	1106	1538	1087	492

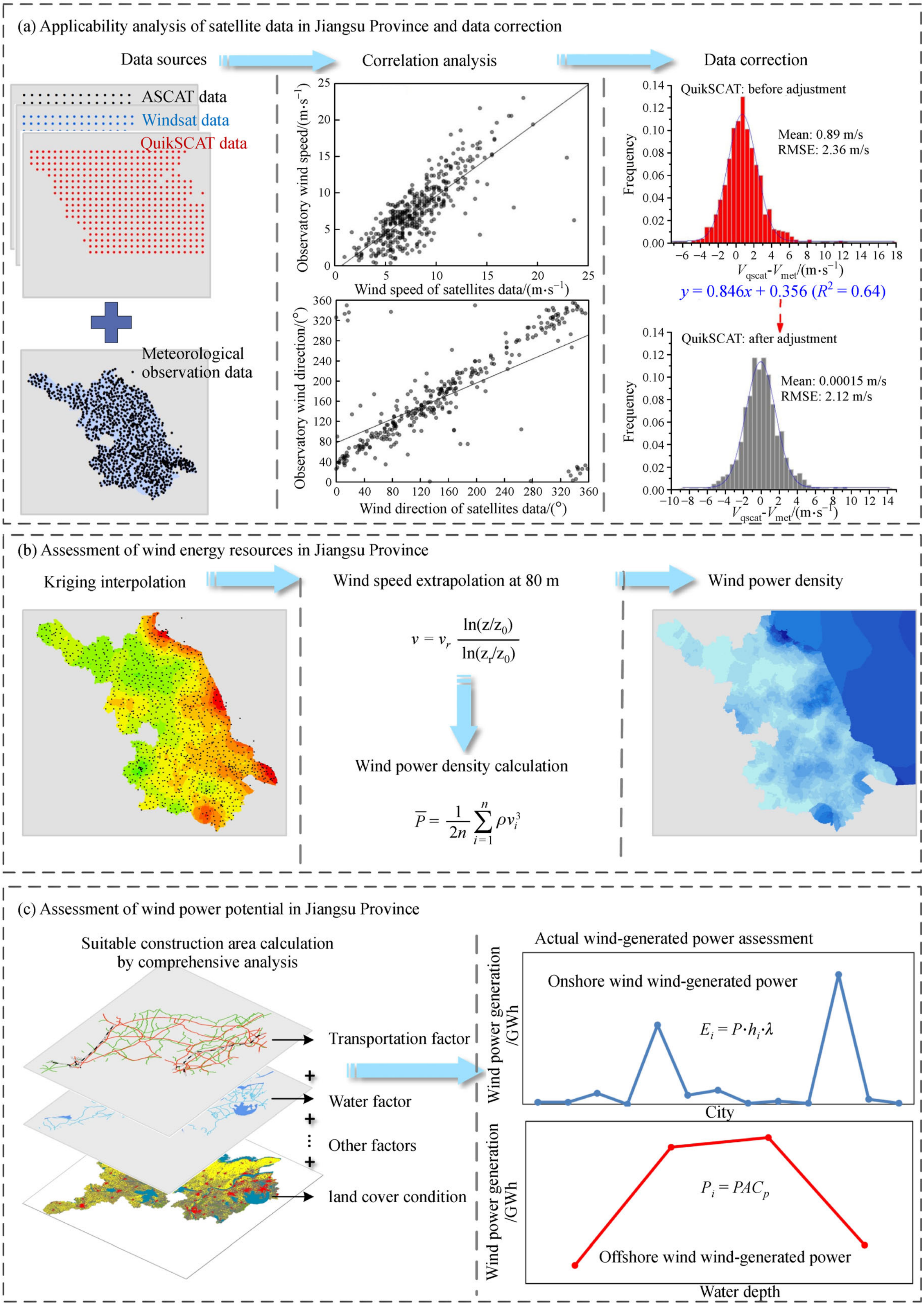

Fig. 2 Conceptual diagram of the basic steps of the method used in this study. (a) Applicability analysis of satellite data in Jiangsu Province and data correction; (b) onshore-offshore wind energy resource assessment for Jiangsu Province; and (c) onshore-offshore wind power potential assessment for Jiangsu Province.

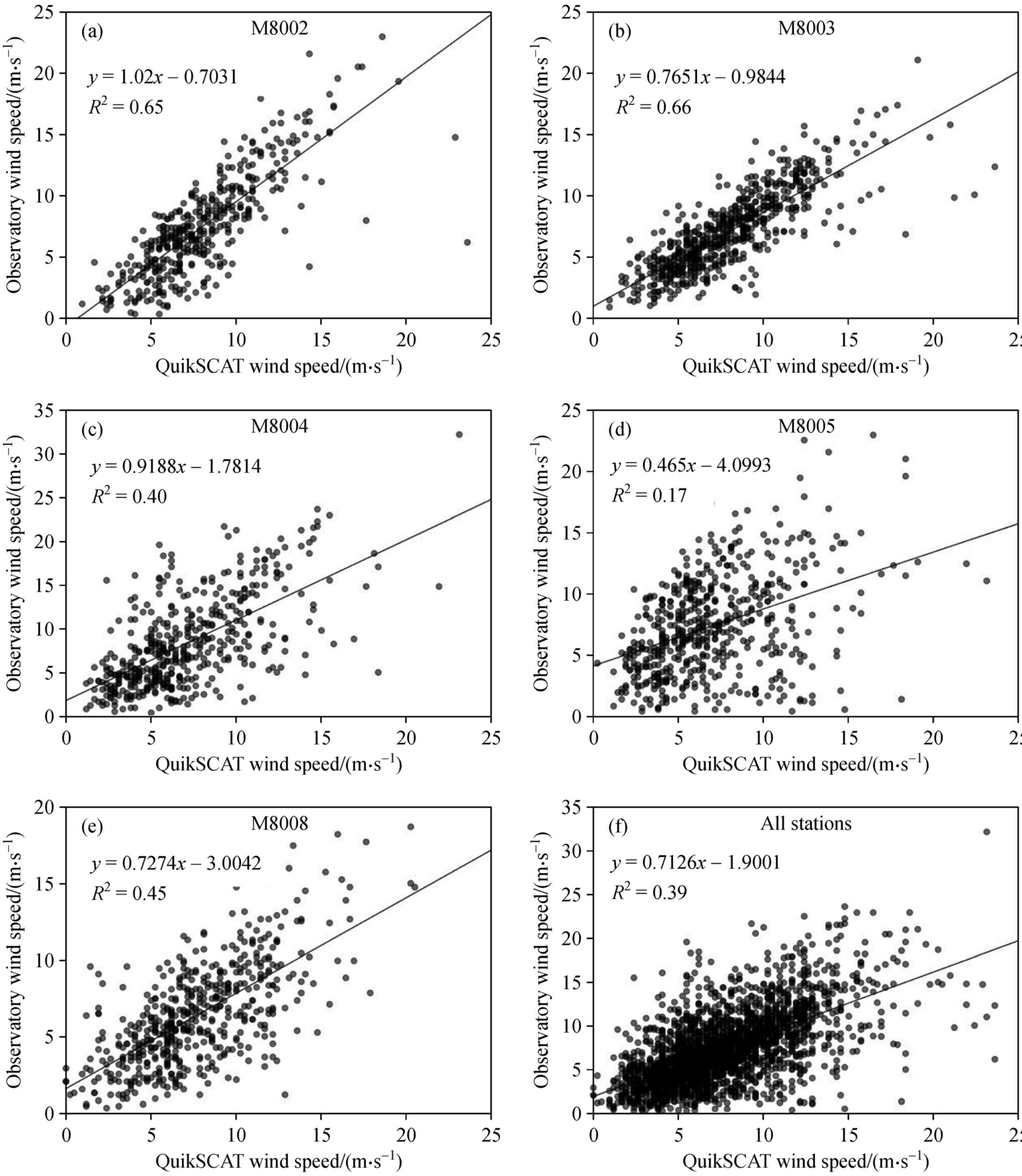

Fig. 3 Correlation analysis of wind speed between QuikSCAT data and ocean meteorological observation data for (a)–(e) the different observation stations and (f) all stations used in this study.

$$v = v_r \frac{\ln(z/z_0)}{\ln(z_r/z_0)}, \quad (1)$$

where v is the wind speed at a specified height; v_r is the observed wind speed; z is the height of the wind turbine hub, which is 80 m in this research; z_r is the height of the observed wind speed; and z_0 is the roughness length (Manwell et al., 2002; Pimenta et al., 2008; Frank et al., 2015), which is determined by the land-use data for Jiangsu province from 2010 (supplementary material A).

3.2.2 Hours of effective wind speed

According to the "National Wind Energy Resource Evaluation Technical Standard", a wind speed of 3–20 m/s is the effective wind speed, which is an important indicator for evaluating wind speed stability.

$$t = \sum_{v_n = v_t}^{v_0} T(v_n), \quad (2)$$

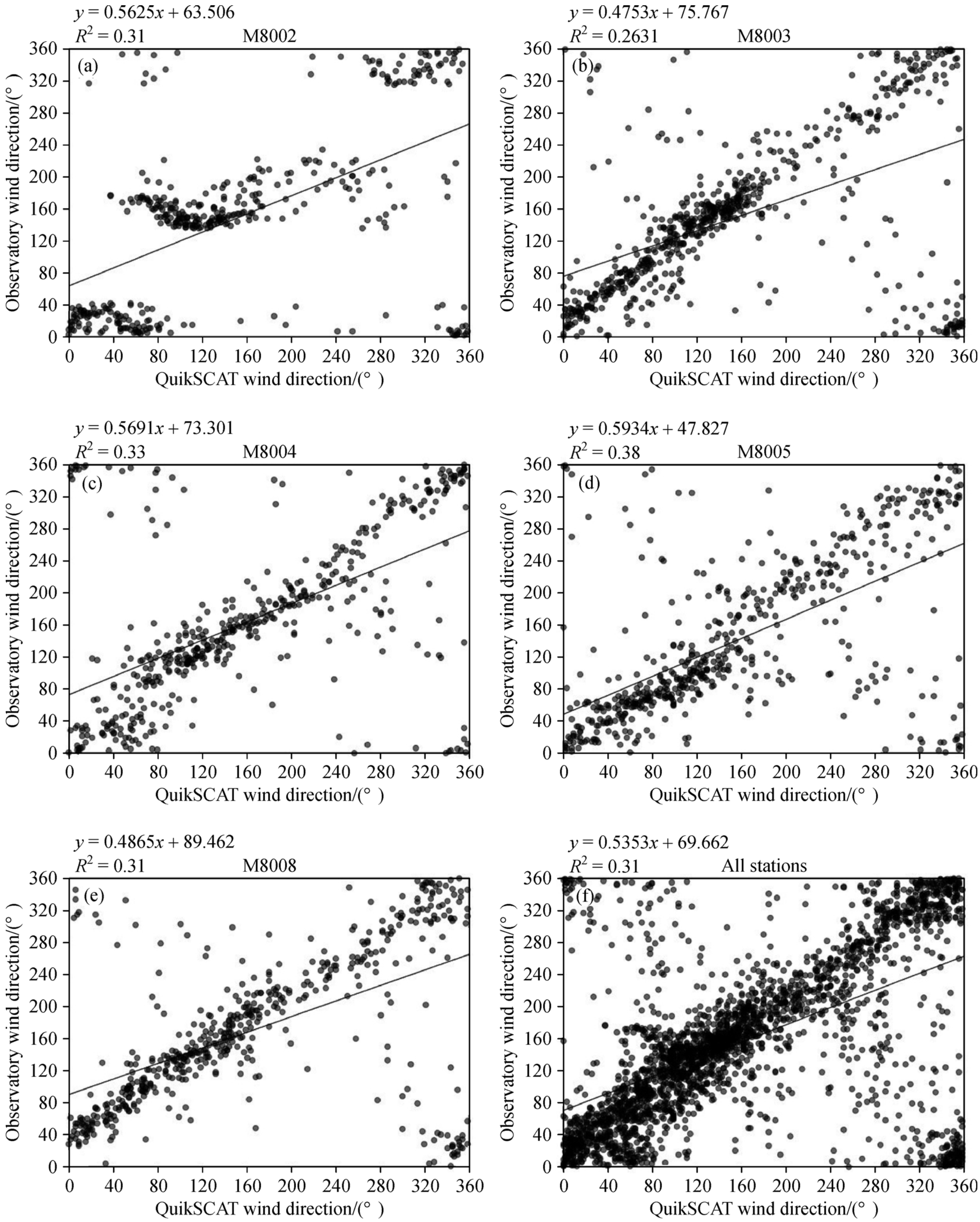

Fig. 4 Correlation analysis of wind direction between QuikSCAT data and ocean meteorological observation data for (a)–(e) the different observation stations and (f) all stations used in this study.

where v_0 is the cut-out wind speed, v_t is the cut-in wind speed, and $T(v_n)$ is the number of hours when wind speed is v_n.

3.2.3 Wind speed interpolation method

The 1082 meteorological stations do not cover the entire study area. To obtain data for the entire study area, an appropriate interpolation method needed to be selected. This study trialed four interpolation methods (Spline, Natural Neighbor, Inverse Distance Weighted (IDW), and Kriging), and compared them by a cross-validation method. Finally, the Kriging interpolation method was chosen for this study (discussed in Section 5.2).

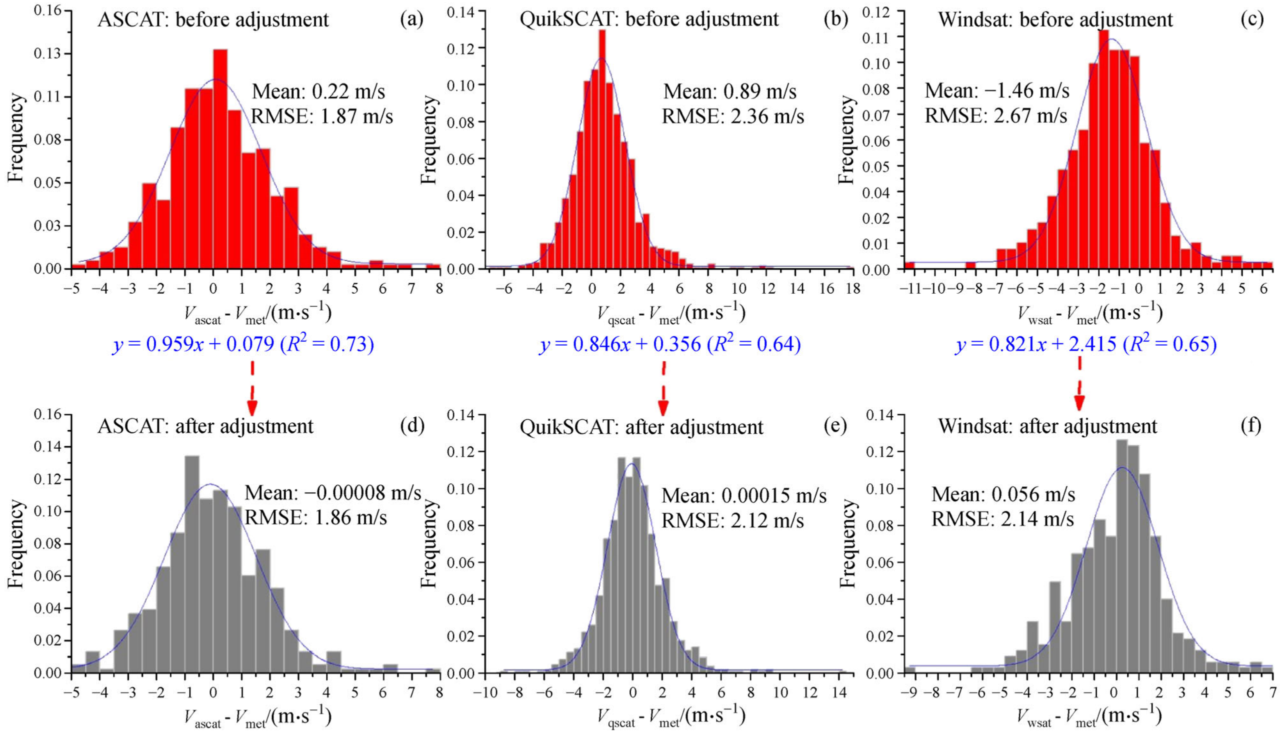

Fig. 5 Residual error distribution ($V_{\text{satellite data}}$ $-V_{\text{meteorological data}}$) before and after adjustment. (a), (d) Comparison before and after ASCAT data correction; (b), (e) comparison before and after QuikSCAT data correction; and (c), (f) comparison before and after Windsat data correction.

3.3 Assessment of wind-generated power potential in Jiangsu Province

In addition to considering the natural attributes, such as wind speed, we should also consider socio-economic, technological, and other social attributes of the study area. During the process of wind farm construction, the following aspects are considered.

1) Exclusion of areas that are not suitable for wind power development. We need to eliminate the areas that are not suitable for wind farm construction by considering socio-economic factors, land cover conditions, and transport factors (Table 2).

Table 2 Wind energy limiting factors and exclusion areas

Exclusion areas	Limiting factors	Buffer/m
Railway, highway	Security, visual pollution	400
Cities, factories, mines, residential areas, villages	Security, noise pollution	3000
Water	Security	400
Forest	Visual pollution, land use restrictions	500

2) Selection of a reference wind turbine. Of the current mainstream wind turbine products, the Vestas V80 was chosen as the reference wind turbine for onshore areas, and the CCWE3000D and SL5000 were selected for offshore areas. Table 3 gives the basic parameters of the selected wind turbines.

Table 3 Characteristics for the reference wind turbines

Parameters	Vestas V80	CCWE3000D	SL5000
Power rating/kW	2000	3000	5000
Cut-in wind speed/(m·s^{-1})	4	3	3.5
Cut-out wind speed/(m·s^{-1})	25	25	25
Rated wind speed/(m·s^{-1})	14	12	12.5
Vane number	-	3	3
Impeller diameter/m	80	103	128
Hub height/m	80	-	-
Swept area/m^2	5027	8328	12,795

3) Estimation of actual power generation. The actual wind power generation in onshore and offshore areas was calculated by Eq. (3) and Eq. (4), respectively.

$$E_i = P \cdot h_i \cdot \lambda, \tag{3}$$

$$P_t = PAC_p, \tag{4}$$

where E_i is the annual power generation; P is the actual output of wind power generation; h_i is the equivalent full load hours; λ is the wind field correction factor; P_t is the actual output power; P is the wind power density; A is the swept area of the wind turbine; and C_p is the conversion efficiency (the average conversion efficiency of CCWE30000D and SL5000 is 42.37% and 36.20%, respectively). For more accurate assessment results, we referenced the technology of Shanghai Donghai Bridge wind farm construction and considered existing offshore wind farm construction technology.

4 Results

4.1 Wind farm characteristics in Jiangsu

Wind speed and wind direction are important parameters for describing wind characteristics. In the wind farm planning process, accurate knowledge of the distribution of wind direction is crucial. Using this, the layout of wind turbines can be designed to reduce the influence of wind power wake and yaw. Our analysis of the annual average wind speed distribution in Jiangsu Province (Fig. 6)

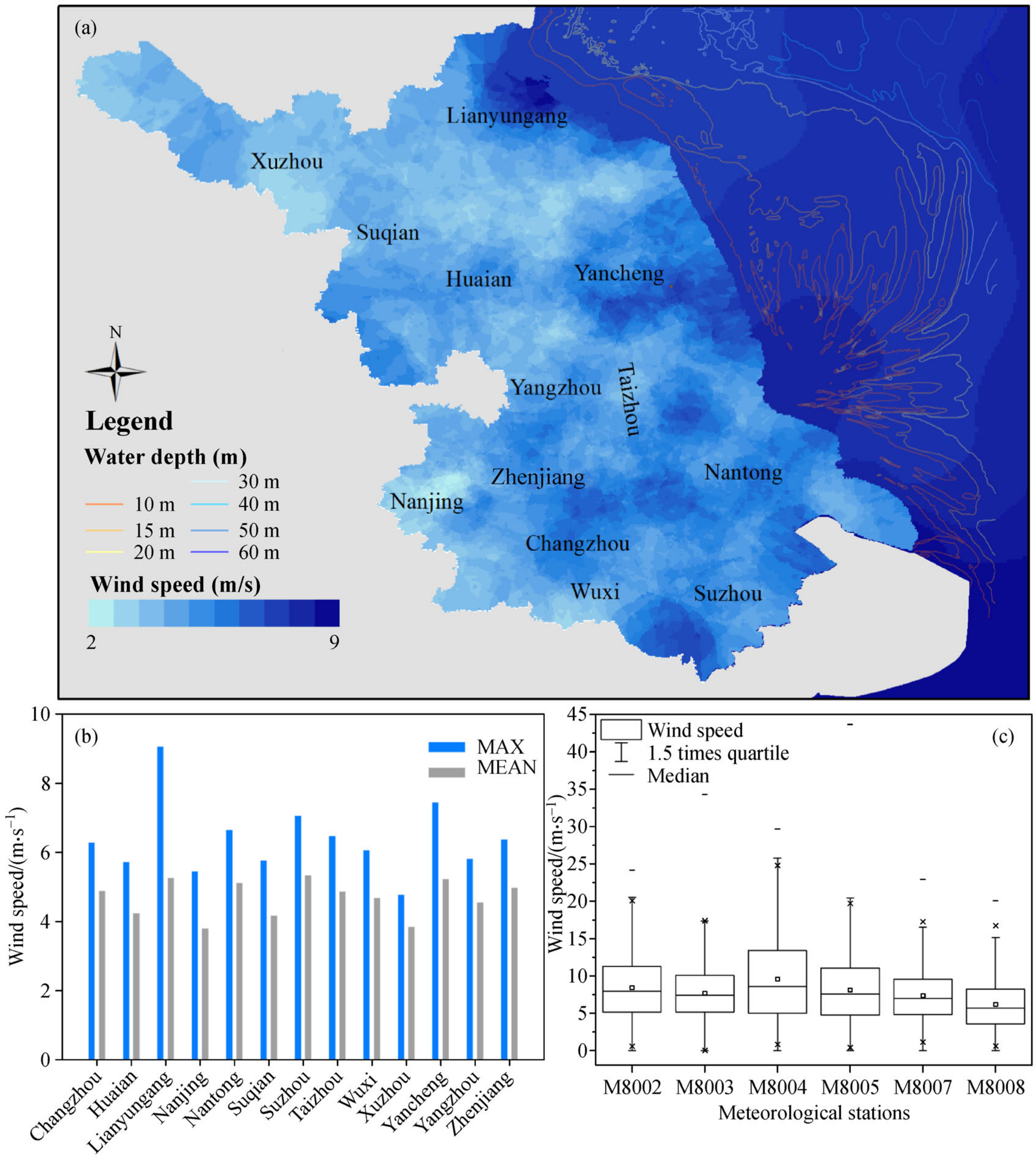

Fig. 6 Onshore-offshore annual average wind speed of Jiangsu Province. (a) Distribution of onshore-offshore wind speed; (b) wind speed statistics for cities; and (c) wind speed statistics of ocean meteorological observation stations.

indicates that offshore wind speed is much higher than onshore wind speed, reaching 9 m/s, while the lowest is 2 m/s inland (Fig. 6(a)). Moreover, the average wind speed tends to increase from inland to coastal areas. Figures 6(b) and 6(c) show the statistical profiles of onshore and offshore average wind speed, respectively, for Jiangsu Province. Of onshore areas (Fig. 6(b)), Lianyungang has the highest wind speed of up to 9 m/s, followed by Yancheng and Nantong. For offshore areas (Fig. 6(c)), wind speeds in Jiangsu did not change substantially from 2006 to 2014. The average wind speed is approximately 7 m/s, and the average wind speed of site M8004 is the highest, while site M8008 is the lowest. However, wind speed at the 80 m height along the coast line changes abruptly due to highly variable conditions; offshore areas are vast, flat, and smooth (with lower roughness), and thus weather fronts are felt more acutely than on land. Therefore, thermal effects, wake affects, and coastal land mass effects are amplified (Foley et al., 2012).

To evaluate wind speed stability, we conducted a statistical analysis of the hours of effective wind speed for all 1082 automatic meteorological observation stations in Jiangsu Province. Table 4 lists the hours of effective wind energy for several representative stations. We then drew a map of annual effective hours at the 80 m height by spatial interpolation (Fig. 7). We found that the annual effective hours in most of the province are more than 2000 h, exceeding 4000 h for coastal areas. In general, wind energy is available if the annual effective hours exceed 2000 h, and more than 4000 h indicates plentiful wind energy (Zhu and Xue, 1983; Zhou et al., 2011). Thus, we suggest that the wind speed in Jiangsu Province is relatively stable and suitable for wind power generation.

Because the temporal resolution of the observed data is higher than that of the satellite inversion data, we used coastal oceanic observational data to calculate the offshore wind field variation characteristics of Jiangsu Province. Figure 8 presents an eight-direction wind rose chart based on observation data from six ocean observation stations in Jiangsu coastal areas from 2006 to 2014. During the year, the wind speed is concentrated in the range 5–15 m/s, and the frequency is over 50%. The offshore wind speed and wind direction are generally relatively stable. The prevailing wind direction is relatively clear, and predominantly southeast.

4.2 Spatial distribution of wind energy resource in Jiangsu

The distribution of annual average wind power density in Jiangsu Province decreases from the coast inland (Fig. 9). Among the cities of Jiangsu, Lianyungang has the most abundant wind energy; the wind power density of the Lianyungang coastal areas is more than 600 W/m^2, which represents a local high-value region due to its special geographic location. In contrast, Xuzhou, Nanjing, Suqian, and other inland areas have poor wind resources, and the wind power density in these areas is less than 200 W/m^2. As for the Jiangsu offshore area, the wind power density at the 80 m height is concentrated in the range 328–500 W/m^2, and is essentially parallel to the distribution of longitude. The offshore wind power density is lower in the northwest, and higher in the southeast. According to the

Table 4 Hours of effective wind speed for 17 representative stations

Station number	Station name	Longitude/°E	Latitude/°N	Hours of effective wind energy/h
58343	Changzhou	119.95	31.79	6199
58358	Dongshan	120.43	31.07	5503
58251	Dongtai	120.28	32.85	5787
58040	Ganyu	119.11	34.83	4292
58241	Gaoyou	119.45	32.80	6478
58141	Huaian	119.15	33.28	5751
58265	Lvsi	121.61	32.07	6459
58046	Taizhou	119.89	32.52	3970
58259	Nantong	120.88	31.98	5585
58150	Sheyang	120.25	33.76	7187
58138	Xuyi	118.52	32.58	5379
58130	Xuzhou	117.92	33.89	3714
58345	Liyang	119.48	31.43	4632
58247	Yangzhong	119.83	32.24	5978
58354	Wuxi	120.35	31.61	6180
58250	Jiangyan	120.16	32.51	5257
58132	Siyang	118.70	33.73	4170

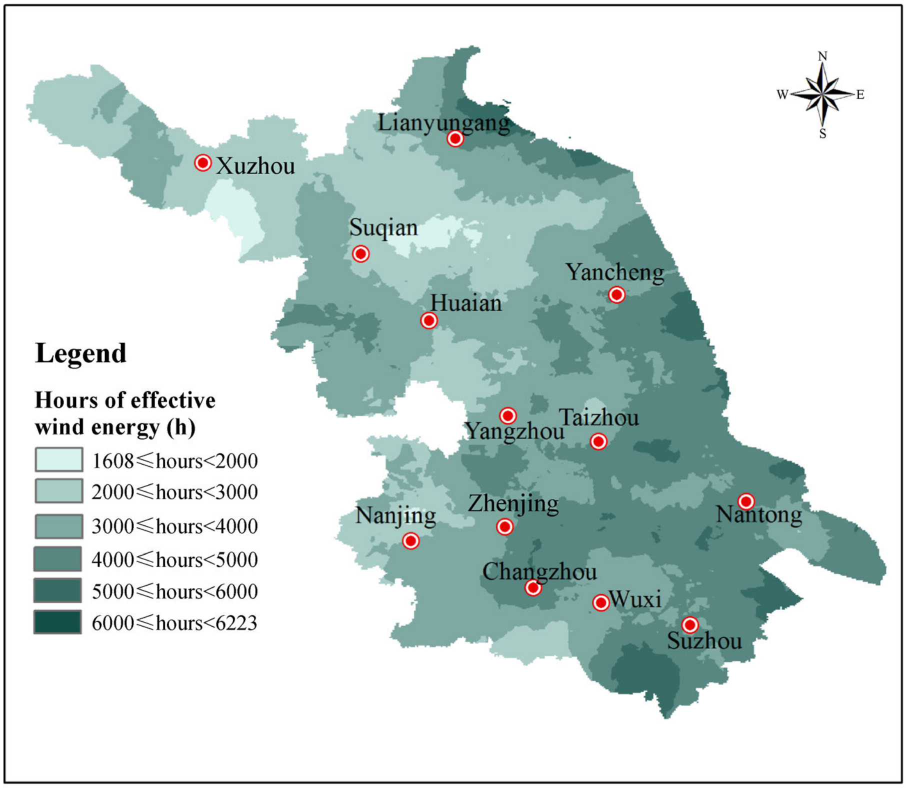

Fig. 7 Annual hours of effective wind speed at 80 m in Jiangsu Province.

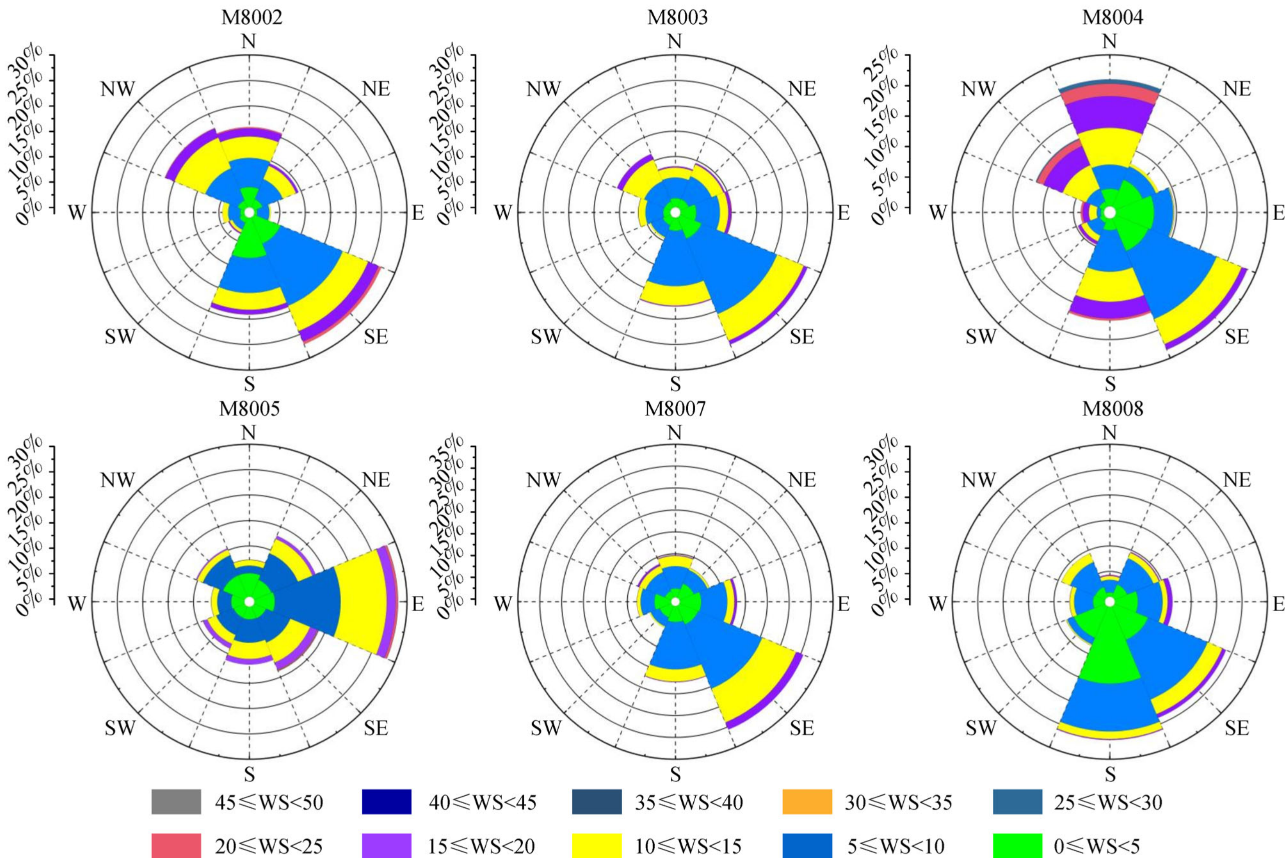

Fig. 8 Wind rose diagrams for different ocean meteorological observation stations in the Jiangsu offshore area, 2006–2014.

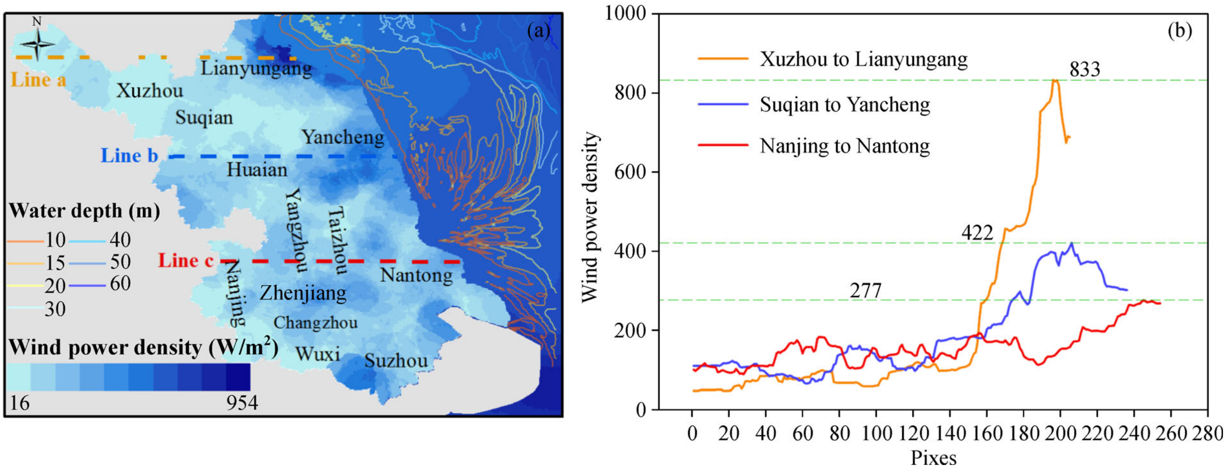

Fig. 9 Spatial distribution of annual average wind power density at 80 m height in Jiangsu Province. (a) Spatial distribution of onshore-offshore annual average wind power density; and (b) three profiles of wind power density from inland to coastal areas (profile locations shown in (a)).

national wind energy resource evaluation method, the level of offshore wind power density in Jiangsu is 3 to 4, which represents good development potential for wind power generation.

4.3 Monthly wind power density variations

The seasonal average wind power density distribution characteristics at the 80 m height in Jiangsu Province are consistent with the distribution of annual average wind power density. However, from our analysis of seasonal variability, we find that the distribution of average wind power density in Jiangsu Province differs significantly between the four seasons (Fig. 10). Specifically, the inland wind energy resource is most abundant in spring. Except for some poor wind resource areas, such as Nanjing, Xuzhou, Huaian, etc., wind power density in the province is typically higher than 200 W/m^2. In coastal areas, such as Lianyungang and Yancheng, the wind power density is over 600 W/m^2 in spring. In summer, wind energy resources are also abundant, and only exceeded during the spring. In contrast, wind energy resources in autumn and winter are much poorer, with an average wind power density below 200 W/m^2 in most areas.

As for offshore wind energy resources, there are clear monthly variations in offshore wind power density (Fig. 11), with high wind power density in January, February, November, and December, in which the maximum can reach 1000 W/m^2, and lower wind power density in all other months. High wind power density values are mostly in the range of 500−1000 W/m^2, and the distribution is basically parallel to the coastline, which shows an increasing trend from the radial sandbars to the distant sea. In contrast, the wind power density is substantially lower than 500 w/m^2 in April, May, June, and July, and the distribution of wind power density is more complex. Additionally, the highest wind power density in April, May, June, and July is located in the central radial sandbars, which contrasts to the situation during higher wind power density months.

4.4 Wind power generation in Jiangsu

This study uses the latest techniques, considers restrictions in wind farm planning, and performs overlay analysis to calculate areas suitable for wind farm construction in the study area. Approximately 15,623.41 km^2 of land in Jiangsu Province is suitable for wind farm construction. Excluding the intertidal zone (2050.17 km^2), the area suitable for construction is approximately 13,573.24 km^2, which accounts for 13% of the total land. An analysis of the spatial distribution of areas suitable for construction (Fig. 12) indicates that Yancheng and Nantong have the largest suitable areas. These two cities have high annual mean wind speeds and wind power density, and are therefore the best places for wind power construction. In addition, Yancheng and Nantong have large amounts of tidal flats, which has enormous potential for wind energy exploitation.

Regarding onshore areas, Yancheng and Nantong have the largest potential for wind energy development as these two cities are close to the sea, have minor fluctuations in terrain, expansive tidal flats, high wind speeds, and regular wind direction changes. The annual mean energy output of Yancheng and Nantong is 102,609.58 GWh and 62,893.33 GWh, respectively. Wind power energy is relatively abundant in Lianyungang, but there is a smaller suitable area for development than Yancheng and Nantong (Table 5) because Lianyungang is located in the marine erosion region with fewer tidal flats, and the seaside area is planned construction land. Nanjing is the least suitable area for wind power generation, with a suitable development

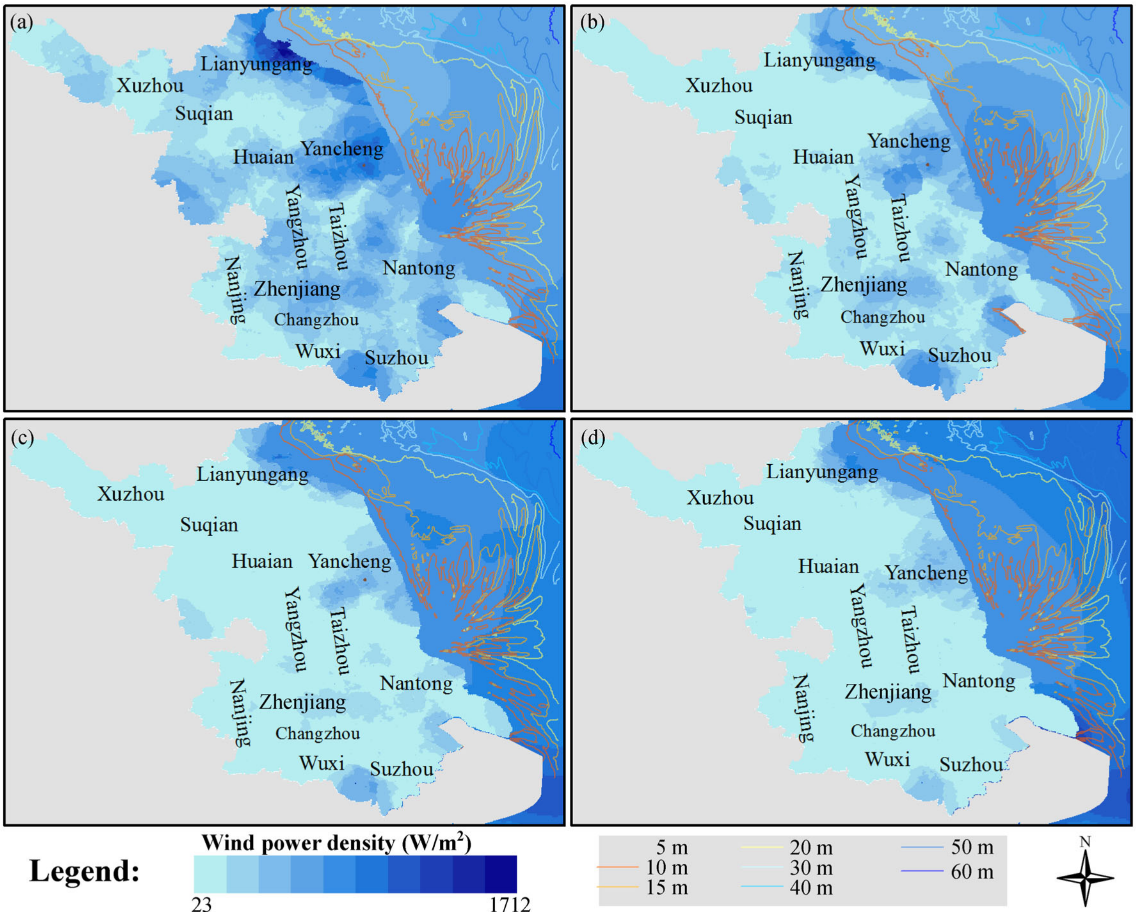

Fig. 10 Seasonal variation of average wind power density at the 80 m height in Jiangsu Province: (a) spring; (b) summer; (c) autumn; and (d) winter.

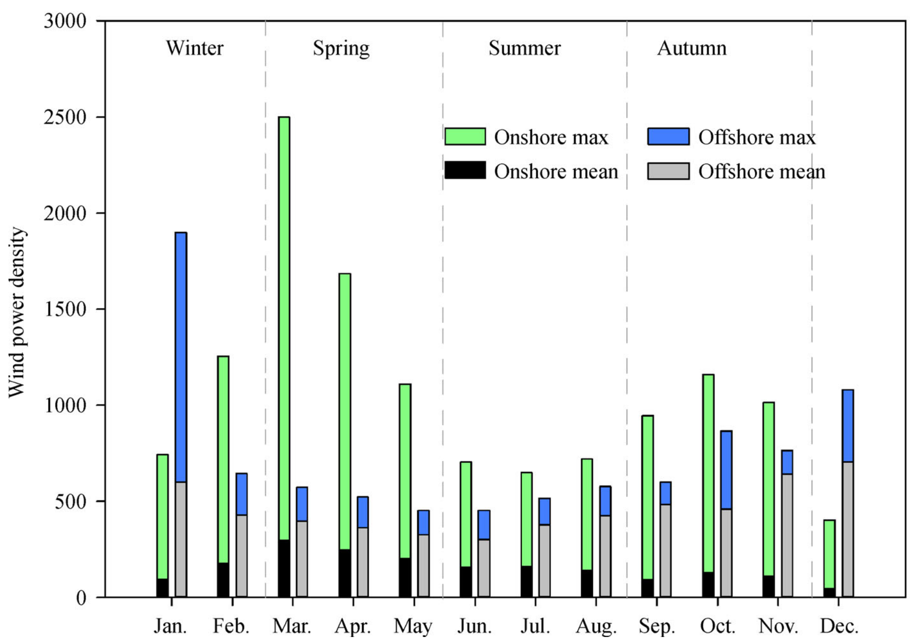

Fig. 11 Seasonal variation of average wind power density at 80 m height in Jiangsu Province.

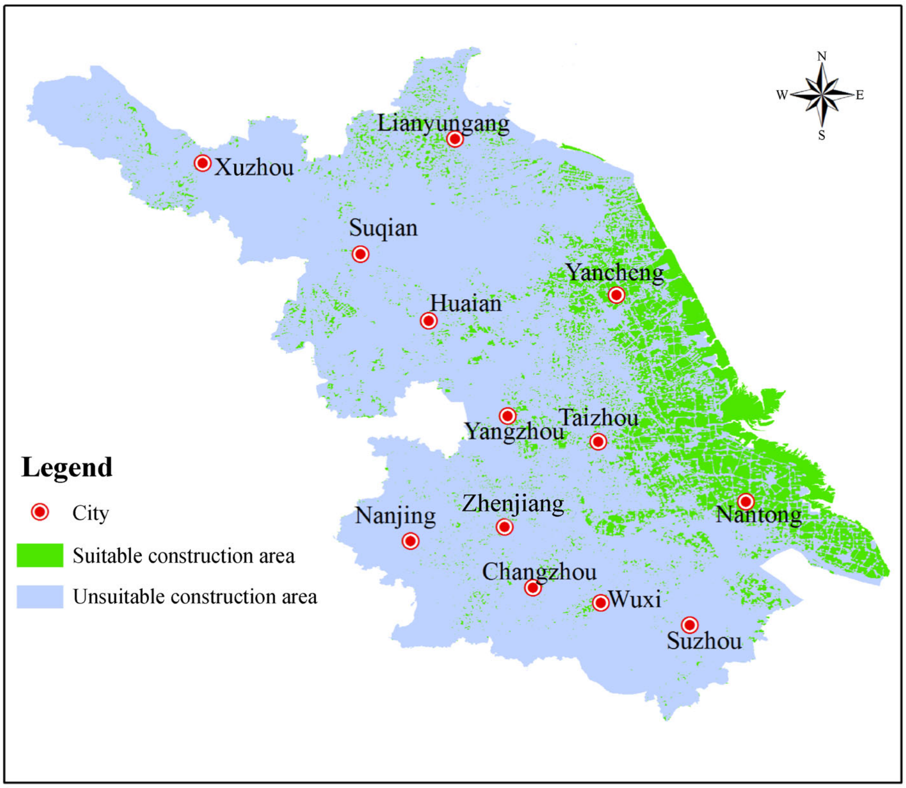

Fig. 12 Suitable areas for onshore wind farm development in Jiangsu Province.

Table 5 Potential wind power resources for different cities in Jiangsu Province

City	Suitable installation area/km^2	Annual generated energy/GWh	City	Suitable installation area/km^2	Annual generated energy/GWh
Changzhou	133.69	1805.10	Wuxi	94.63	887.84
Huaian	277.83	1613.07	Suqian	310.30	2182.81
Lianyungang	699.83	8795.96	Xuzhou	290.02	824.96
Nanjing	46.10	212.24	Yancheng	5503.81	102,609.58
Nantong	4459.41	62,893.33	Yangzhou	452.52	3909.51
Suzhou	404.79	7651.44	Zhenjiang	118.49	1198.92
Taizhou	781.83	11,490.63	sum	13573.24	206,075.39

area of only 0.6% of the total. Limiting factors include its inland location, complicated topography, and a large amount of developed land. In general, inland cities have less suitable areas for wind power, while cities in coastal areas have abundant potential for wind power development.

Under current conditions, onshore areas can produce 2.06×10^5 GWh of wind power energy. This approaches 42% of the total electricity use in Jiangsu in 2013 (the total was 4.96×10^5 GWh). Hence, Jiangsu has huge wind power potential. Efficient and reasonable development of wind power can relieve the pressure on power use throughout the whole province, alleviating both the dependence on thermal power generation and pollution of the environment.

Considering water depth data and existing offshore wind farm construction techniques, this study estimates the potential for offshore wind power generation in Jiangsu Province (Table 6). As Table 6 shows, the output power of the CCWE3000D generator is slightly higher than that of the SL5000. In terms of power generation potential, the annual average power generation in the whole offshore area is approximately 2×10^6 GWh, which is about four times the total electricity consumption in Jiangsu in 2013 (4.96×10^5 GWh in 2013). In this study, we evaluated the theoretical and technological potential for offshore wind power based on bathymetry data and current wind farm construction techniques. However, we did not analyze exclusion areas such as shipping lanes, marine conservation sites, and commercial fishing areas, nor the consis-

Table 6 Potential offshore wind power resources at different water depths in Jiangsu

Water depth[a)]/m	Area/km^2	CCWE3000D		SL5000	
		Output power/GW	Power generation/GWh	Output power/GW	Power generation/GWh
0–5 m	4236.45	14.85	111,870.15	14.07	106,023.89
5–25 m	48,807.61	111.35	838,850.43	105.53	795,012.71
25–50 m	39,067.54	118.75	894,618.12	112.54	847,866.01
50–100 m	13,771.76	31.90	240,320.18	30.23	227,761.21
Total	105,883.40	276.85	2,085,658.89	262.38	1,976,663.82

a) Depth ranges are selected based on current and near-term technology limitations.

tency of bottom geology with pile-driven foundations because relevant data is difficult to obtain.

5 Discussion

5.1 Data selection for wind energy resource assessment

The selection of wind field data is crucial in wind energy resource assessment, and directly determines the accuracy of assessment results. Traditionally, data regarding wind energy resources are derived from meteorological observatories, such as ocean observations from buoys, ships, etc., which are typically from a single point (Carvalho et al., 2013). However, such measurements are only sparsely available due to the high cost (Hasager et al., 2015), especially in coastal areas. Moreover, these observations often suffer from long periods of missing or invalid data. In recent decades, the development of remote sensing technology has provided a large amount of satellite-derived wind data, which seems to offer a suitable alternative. However, the availability of satellite wind data used for wind energy resource assessment must be validated. There are many related studies which verify the availability of satellite data by comparing wind data retrieved from satellites with ocean buoys, ships, and other data (Ebuchi et al., 2002; Pickett et al., 2003a; Xie et al., 2014; Xie, 2015). In present study, we selected three satellite datasets (i.e., QuikSCAT, ASCAT, and Windsat), and compared them with wind measured in-situ data from five ocean observatories located along the Jiangsu coastal zone. As shown in Tables 7 and 8 and supplementary material B, the wind speed correlation between all the satellite datasets and offshore observations is relatively high, which indicates a high accuracy of the wind speed inversion (Xie et al., 2014; Xie, 2015). However, satellite-derived wind data from QuikSCAT and ASCAT are higher than observed values, and their average deviation is 0.27 m/s and 0.17 m/s, respectively. Further, Windsat satellite-derived wind data is much lower than actual observations, with an average deviation of −1.55 m/s. Moreover, according to Table 6, the wind direction accuracy of the satellite-derived wind data is much lower than observations, which is reflected in the smaller correlation coefficient.

With the development of remote sensing technology, satellite-derived wind data are increasingly used for wind energy resource assessment, both for climatic studies and offshore wind energy projects. These include SAR, Lidar, Cross-Calibrated Multi-Platform (CCMP), etc. (Alvarez et al., 2014; Doubrawa et al., 2015; Hasager et al., 2015). The accuracy of satellite-derived wind data is affected by many factors, including a low spatio-temporal resolution (the temporal and spatial resolution in this study is one hour and $0.25° \times 0.25°$, respectively), or the influence of islands, boats, weather, etc., Rainy days have a particularly

Table 7 Comparison of wind speed between satellite data and offshore stations

Satellite data	Average deviation/(m·s^{-1})	Mean absolute deviation/(m·s^{-1})	RMSE/(m·s^{-1})	Correlation coefficient
QuikSCAT	0.27	2.39	3.29	0.62
ASCAT	0.17	2.13	2.96	0.7
Windsat	−1.55	2.42	3.19	0.78

Table 8 Comparison of wind direction between satellite data and offshore stations

Satellite data	Average deviation/(°)	Mean absolute deviation/(°)	RMSE/(°)	Correlation coefficient
QuikSCAT	2.9	52.76	95.64	0.56
ASCAT	0.31	49.18	93.78	0.58
Windsat	-	-	-	-

significant influence on scatter meter data. Combining wind observations from several satellites may limit the problem by increasing the total number of samples and decreasing the statistical uncertainty (Hasager et al., 2015). Thus, this study integrated satellite-derived wind data from QuikSCAT, ASCAT, and Windsat, which greatly improved the accuracy of satellite inversion data. In future research, higher spatio-temporal resolution satellite-derived wind data will greatly improve wind energy assessment accuracy.

5.2 Applicability of the interpolation method for Jiangsu Province

As the satellite inversion data and meteorological observation data used in this study are discrete point data, a spatial interpolation method was required to produce predicted wind data for the whole study area. Generally, interpolation methods neglect terrain effects; if the study area is mountainous, then the interpolation will introduce prediction errors. Therefore, it is necessary to discuss whether the terrain of the study area impacts interpolation before employing the interpolation method.

Jiangsu Province lies in the Middle-Lower Yangtze River Plain, and includes approximately 7×10^4 km^2 of plain-sand areas, which account for more than 90% of the total area of the Province. This results in flat land with an elevation below 50 m in most areas. Furthermore, the topographic relief in Jiangsu is predominantly below 20 m (Fig. A1 in supplementary material A). Considering that the terrain in Jiangsu has little effect on the wind interpolation results, and the 1082 meteorological stations provide sufficient samples, a spatial interpolation method was deemed appropriate for interpolating the data in our study area.

Spatial interpolation methods can be divided into deterministic interpolation methods (e.g., IDW interpolation, radial basis function interpolation, Tyson polygon interpolation) and geostatistical interpolation methods (e.g., Kriging interpolation method). Deterministic interpolation methods are mainly based on interpolation point similarity, whereas geostatistical interpolation methods mainly use the statistical properties of the data, and combine spatial autocorrelation between the observed values to carry out a comprehensive interpolation. To select the most suitable interpolation method and test the applicability of these methods for Jiangsu Province, we trialed four interpolation methods (Spline, Natural Neighbor, IDW, and Kriging) to acquire onshore wind speed data in Jiangsu Province. The interpolation results were tested by a cross-validation method, which is the most common and effective method for testing spatial interpolation, and can accurately reveal the integrity of the interpolation. In this study, 25% of the samples were randomly selected as verification points, and the remaining 75% of the samples were used as interpolation data. For an intuitive analysis of the accuracy of different interpolation methods, we used the mean error, mean relative error (MRE), mean absolute error (MAE), and RMSE to evaluate the accuracy of the different interpolation results (Table 9).

Based on the interpolation results, the four methods generally exhibit good applicability to Jiangsu Province. By comprehensively analyzing these four different interpolation methods, we found that the Kriging method and IDW method gave relatively good results. Figure 13 presents the results for Jiangsu Province according to the four interpolation methods. The distribution of the interpolation results, except for Kriging, is fragmentary and disjointed, and exhibits a concentric pattern around dispersed points, which is particularly prominent with the IDW method. However, this is not appropriate for rendering the spatial distribution of a measured parameter as a continuous surface of predicted values that represents the continuity and variability of the parameter, in this case wind speed, across geographic space. Therefore, we chose the Kriging method for this study because the interpolation results were superior for displaying both the global and local wind energy resource distribution characteristics of Jiangsu Province.

5.3 Impact of wind farms on the environment

As a clean energy source, wind energy is attracting increasing attention. However, the process of constructing wind farms will inevitably affect the regional ecological environment. In this study, we estimate the potential for wind farm construction in Jiangsu Province, but ignore its impact on the local environment, such as the harm caused to animals by the wind turbines, especially birds. (Desholm and Kahlert, 2005) noted that the establishment of wind farms will reduce the quality of bird habitats, which may force birds to give up their habitat. (Madders and

Table 9 Analysis of interpolation results

Item	Spline	Natural Neighbor	IDW	Kriging
Mean error/(m·s^{-1})	−0.64	−0.20	−0.19	−0.09
MAE/(m·s^{-1})	0.51	0.44	0.43	0.41
MRE/%	17.93	16.05	15.29	14.88
RMSE/(m·s^{-1})	0.74	0.60	0.59	0.58
Correlation coefficient	0.51	0.63	0.62	0.62

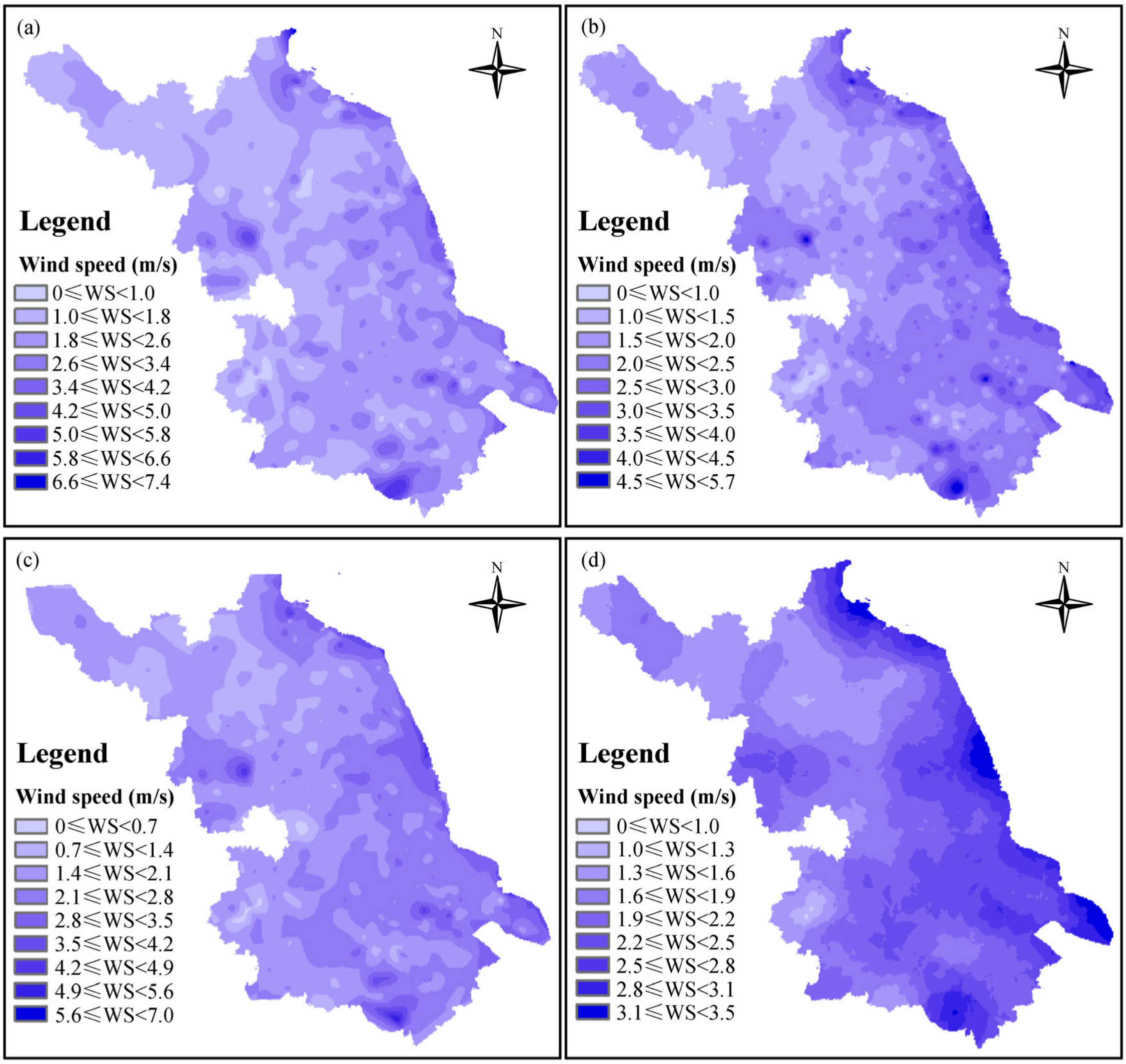

Fig. 13 Onshore wind speed results for Jiangsu Province determined by the four different interpolation methods: (a) Spline; (b) IDW; (c) Natural Neighbor; (d) Kriging.

Whitfield, 2006) also proposed that, when a wind farm is located along or near the migratory flight path of birds or where birds congregate, the probability of bird strikes are greatly increased. Furthermore, the construction of wind farms will lead to adverse visual impacts, including changes in landscape type, and the construction of varied power generation infrastructure (Madders and Whitfield, 2006).

In addition, when we calculate the impact of offshore wind energy, we tend to ignore the possibility that construction of wind farms will influence shipping routes, fish farms, and submarine geological conditions. Therefore, in future studies, we should fully consider these limiting factors, and improve the evaluation system so as to obtain more accurate and comprehensive evaluation results. Ecological protection and restoration measures constitute a long-term project that should operate throughout the life cycle of wind farms (i.e., construction, operation, and dismantling).

6 Conclusions

This study analyzed the distribution of wind energy resources and estimated the actual exploitation potential of wind energy in Jiangsu Province. This provides a technical basis for future decision-making related to the sustainable development and use of wind energy resources in Jiangsu. Moreover, this study verified the applicability of ASCAT, QuikSCAT, and Windsat satellite data in Jiangsu Province. In contrast to traditional research, we used multiple satellite datasets and large meteorological observation datasets to assess wind energy resources, and this synergetic approach greatly improved the accuracy of the evaluation. Further, the technology framework for onshore-offshore wind resource assessment provided in this study can be applicable to other regions with similar wind conditions to Jiangsu Province.

Although this research has progressed wind energy resource assessment in Jiangsu, the methodology has some limitations. The current analysis is a preliminary overview of wind resources in Jiangsu Province, and further steps should involve a numerical simulation or remote sensing validation for a deeper and more systematic understanding. In addition, further research should focus on wind speed discontinuity along the land-sea border, which should entail NWP or more high resolution remote sensing data.

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