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1 **Assessment of wind and wave energy in China seas** 2 **under climate change based on CMIP6 climate model**

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10

11 **Abstract:** With the intensification of global warming, the distribution of marine renewable
12 energy resources are changing. In this study, the wind and wave energy resources in the coastal
13 waters of China under four combined climate change scenarios and the Shared Socioeconomic
14 Pathways (SSPs), namely SSP126, SSP245, SSP370, and SSP585 are investigated. The wind data
15 from the latest Coupled Model Intercomparison Project (CMIP6) climate model is analysed with
16 Multi-model ensemble (MME) approach, which is consequently used to generate the wave data by
17 the FVCOM-SWAVE wave model for historical conditions (2000-2014) and further climate
18 scenarios (2080-2100). The impact of the climate change scenarios on the wind and wave energy
19 generation performance is also assessed using the Total Harmonic Distortion (THD) index. The
20 results indicate that with the increase of the greenhouse gas emissions, the wind energy increases in
21 the northern South China Sea, the Bohai Sea and the Yellow Sea, and the wave energy increases in
22 the Bohai Sea, the Yellow Sea and the northern South China Sea, while a slight decrease is found in
23 the southern South China Sea. The performance of the wind and wave energy generation is affected
24 by the future climate change scenarios, where the wind energy generation is found to be more stable
25 than the wave energy at the study site. The results from this study provide useful guidance for the
26 future deployment of wind and wave energy in the China's coastal waters.

27 **Keywords:** climate change; CMIP6; China seas; wave energy; wind energy

1. Introduction

The greenhouse gas emission is evidenced as the main factor to cause the global warming and climate change. Use of clean energy is one of the important ways to reduce greenhouse gas emission and mitigate the impacts of climate warming [1]. Marine clean energy mainly includes offshore wind energy, ocean thermal energy, tidal range energy, tidal current energy and wave energy. Amongst, offshore wind and wave energy have attracted much attention in many countries because of their abundant resources, high energy density, and the advantage of not occupying land areas [2-3]. In terms of energy potential, wind energy has the best potential, with offshore wind farms already being widely developed around the world [4]. Wave energy is the sum of kinetic and potential energy on the ocean surface, the total reserves of which are much larger than solar and wind energy in some areas (e.g. Baltic Sea and the Danish part of the North Sea as reported in [5]), with the advantages of having less impact on the environment, wide availability and no need for immigration amongst others. With the continuous development of its economy, China increasingly demands more energy, especially clean energy [1]. China has a long coastline, with broad distributions and abundant ocean clean energy resources. However, the spatial and temporal distributions of wind and wave energy resources vary significantly. Therefore, to help the development of wind and wave energy in China, it is necessary to understand their distribution characteristics for fully evaluating the economic and technical feasibility [6-9].

Generally, the distribution of wind and wave energy resources could be evaluated using the local wind and wave data, which can be categorized to four types as described below:

- Type I (based on regional observation data): A large number of researchers have conducted statistical analysis of regional wind and wave energy based on observation data, for example, in the Llobregat Delta [10], the United States [11] and the west coast of Sweden [12], and China [13]-[14]. Because the construction of meteorological and oceanic observation stations is costly and tedious, the temporal and spatial resolution of observation data is relatively low, which hinder the relevant research.

- Type II (based on satellite data): With the development of satellite technology, researchers have started to use satellite datasets to investigate the distribution of wind energy and wave energy resources, for example, in India [15], Canadian waters [16], Vietnam [17], southeast Australia [18],

Indonesia [19] and Globally [20]. In addition, Hong et al. [21] used geographic information systems (GIS) to investigate the available offshore wind energy resources within China's exclusive economic Zone. Wang et al. [22] used the AVISO multi-satellite altimeter data to explore the wave feature of Chinese coastal waters, showing that the wave energy is larger in the north-central part of the South China Sea, the Luzon and Taiwan Straits, with a strong seasonality being more abundant in autumn and winter seasons.

- Type III (based on reanalysis data): Reanalysis data is a kind of combination of the observation data and satellite (or numerical modelling) data. For example, the reanalysis wind and wave data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) and National Oceanic and Atmospheric Administration (NOAA) are widely used. The reanalysis data have been used for the assessment of wind and wave energy in different regions worldwide, as those in Indian [23-24] and central Mediterranean Sea [25-26]. These data have also been used extensively in studies in the Chinese coastal waters. Wen et al. [27] analysed the spatial and temporal characteristics of wind resources in the South China Sea based on the Japanese 55-year reanalysis (JRA-55) dataset. Ding et al. [28] analyzed the distribution of significant wave height, wave period, and the other wave characteristics in the South China Sea by analyzing 37 years of ERA-interim high-resolution ($0.125^{\circ} \times 0.125^{\circ}$) wave data and evaluated the wave energy resources based on the wave parameters. Sun et al. [29] verified the ERA5 wave data in Chinese waters with buoy data, and analyzed the long-term trends of wave energy distributions along the Chinese coastline using the ERA5 wave data, indicating that the East China Sea and the South China Sea are the most suitable sea areas for wave energy development.

- Type IV (based on numerical simulations): With the development of computational technology, more researchers have studied the global wind and wave energy through numerical modeling [30]. Christie et al. [31] evaluated the wave energy in the Canary Islands using SWAN model. Langodan et al. [32] assessed the potential of wind and wave energy in the Red Sea based on the Weather Research and Forecasting (WRF) model and the WAVEWATCH III (WWIII) model respectively. Kilcher et al. [33] used the WWIII model driven by NOAA's wind field to obtain wave energy distribution along the US west coast. In China, Li et al. [13] used the regional climate model COSMO-CLM (CCLM) to construct a wind hindcast at 100 m height over the Bohai and the Yellow Sea for 35 years (1979-2013) and then assessed the distribution of wind energy resource. Wang et

al. [34] used the WRF and WWIII model to simulate 30-year wind and wave fields in the South China Sea and then assessed the wind and wave energy resources in the study region. Zheng et al. [35] assessed the wind energy and wave energy resources in the China Sea by WWIII model. Wang et al. [36] used the atmospheric model WRF to conduct a continuous simulation of wind field in the Bohai Sea to determine the wind energy resources from 1995 to 2014, and then used the wave model SWAN to simulate the waves in the same time for wave energy assessment.

Most of the existing studies on the distribution of ocean clean energy, especially the wave energy, are based on historical data and model simulations. However, whilst the use of clean energy can mitigate climate warming, the changing climate can influence the distribution of clean energy distributions [37]-[38], therefore considering the impacts of climate change in assessing marine clean energy becomes important.

As the future distribution of wind and wave resources depends on the changes in local wind speeds and waves, the Coupled Model Intercomparison Project (CMIP) is a commonly-used tool for the analysis of the meteorological and oceanic factors under the changing climate. CMIP is an international collaborative project initiated by the World Climate Research Programme (WCRP), which has gone through a number of phases with the most recent Phase 6 (CMIP6). In the previous phase of the CMIP, CMIP5 contains more than 50 models from more than 20 model groups worldwide for the climate change projection based on the Representative Concentration Pathway (RCP), typically using four pathways: RCP2.6, RCP4.5, RCP6.0, and RCP8.5, to represent the radiative forcing values ranging from low to high [39]. With the data provided by CMIP5, many studies have been carried out for the wind and wave climate and energy resources exploitation around the world. To understand the wind and wave climate, Erikson et al. [40] used CMIP5 wind field data from two radiative forcing scenarios RCP4.5 and RCP8.5 to project future wave parameter changes in the Northeast Pacific Ocean. Shope et al. [41] analysed changes in the extreme wave climate of tropical Pacific islands in the 21st century under the RCP4.5 and RCP5.8 scenarios. Hemer et al. [42] assessed the global wave climate using CMIP5 data. Based on the future wind and wave data, Zheng et al. [43] compared the global wind energy characteristics for the years 2080-2099 (future) and 1980-1999 (past). Rusu et al. [44] assessed the wave energy in the Black Sea at the end of the 21st century.

Following the latest updates of CMIP, as one of the sub-programs of CMIP6, ScenarioMIP

combines and integrates the future global average radiative forcing level and the level of economic development corresponding to the radiative forcing with the Shared Socioeconomic Paths (SSPs) [45]. For example, SSP126, SSP245, and SSP585 are the new versions of the scenarios combining RCP2.6, RCP4.5, and RCP8.5 with SSP1, SSP2, and SSP5 respectively, whilst SSP370 represents a sustainable development scenario for land-use changes and emissions (especially SO_2) [46]. ScenarioMIP provides many global large-scale oceanic and atmospheric variables relevant to the construction of climate change, taking into account the impacts of climate change on renewable energy. CMIP6 aims to understand past, present and future climate change by collecting and comparing simulation results from various Global Climate Models (GCMs). The results of CMIP6's simulations of the current climate and future climate projections at each stage provide the corresponding information basis for the reports of the United Nations Intergovernmental Panel on Climate Change (IPCC) [47]. Thus, the CMIP6 dataset is widely used to predict atmospheric and oceanic variables under climate change. Globally, Lemos et al. [48] used the SSP585 data from EC-Earth GCM to study the effect of different model parameterizations on the current global wave climate description. Jiang et al. [49] established a global 3-hourly wind-wave and swell data for wave climate and wave energy resource research from 1950 to 2100 based on CMIP6 data and several wave models. Ibarra-Berastegui et al. [50] analysed future global offshore wind and wave energy trends under the SSP126 and SSP585 scenarios using two CMIP6 models (EC-Earth3 and ACCESS-CM2) dataset, and the study showed that only 10-15% of coastal wind and wave generated theoretical electricity will change significantly. Meanwhile, many scholars have conducted studies using CMIP6 data to analyse the impact of climate change on regional wind and wave power potential, such as in Europe [51], North America [52], the Black Sea [53] and Gulf of Oman[38], etc.

China has abundant offshore wind energy along its coasts, especially in southern Zhejiang, Fujian and eastern Guangdong Provinces [54], and has high potential of wave energy in the South China Sea and the East China Sea, particularly in autumn and winter seasons [29]. Considering the influence of changing climate, Zheng et al. [55] analyzed the wave energy distribution in China's coastal waters using the WWIII wave model driven by CMIP5 wind data. Using the CMIP6 data, Zhang et al. [56] applied a downscaling method to study China's offshore wind energy resources in the 21st century. In general, studies on the future wind and wave energy under the climate change

in China seas are scarce, especially under the scenarios provided by CMIP6. Although some of the global scale studies could reflect the offshore clean energy distribution in China seas, their spatial resolutions were rather low to meet the needs for regional energy plan, especially in the nearshore regions. To guide the future plan of offshore energy development in China, the future wind and wave energy distribution in the China seas is worth investigating under the latest scenarios with the combined climate and shared socioeconomic pathways.

In this study, the wind field under four scenarios: SSP126, SSP245, SSP370, and SSP585, provided by the CMIP6, are used to drive the FVCOM-SWAVE wave model in an attempt to gain further understanding of the long term impacts of climate change on wind and wave energy distributions in China's coastal waters. The paper is organized as follows. Section 2 describes the data, numerical models and analysis methods. Section 3 is the assessment of future distribution and changing trends of wind speed, wave parameters, and wind and wave energy resources based on the data obtained. Section 4 is the future wind and wave energy distribution and their changing trends in the coastal regions of China. Section 5 is an evaluation of the performance of wind and wave energy generation in China's coastal waters, focusing on the impacts of climate change. Followed in Section 6 is the conclusion.

2. Materials and methods

2.1 Wind Data

2.1.1 ERA5 reanalysis wind data

ERA5 is the fifth generation of reanalysis products developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 contains 28 atmospheric assimilation systems and provides hourly, daily, and monthly atmospheric, land, and oceanic variables on a global scale with a spatial resolution of 0.25° from 1950 to the present day, and is highly reliable reanalysis information for studies related to mean and extreme wind speed, therefore, it is widely used around the world [57]. In this study, the hourly 10 m wind speed in ERA5 reanalysis data are used to validate the CMIP6 historical wind speed data from 2000 to 2014.

2.1.2 CMIP6 Climate model

CMIP6 has the largest number of participating models, the best-designed scientific experiments, and the most comprehensive modeling data provided since the implementation of the CMIP program [58]. As the sub-program of CMIP6, ScenarioMIP conducted a new series of future long-term (century timescale) integrations, incorporating input from climate science and integrated assessment modeling communities. These data were generated by an updated version of the Global Climate Models (GCMs) and driven by a set of emission and land use scenarios based on the new SSPs methodology, which reflects climate evolution trends based on different climate change scenarios and climate policies [58]. These new scenarios are based on a matrix utilizing the SSPs and forcing levels of the RCPs as axes [59]. ScenarioMIP is divided into core experiment Tier-1 and Tier-2 experiments based on their relative priorities and contains eight groups of future scenario experiments.

This study mainly adopts the research data related to the core experiment Tier-1, which includes primarily four SSPs, namely SSP126, SSP245, SSP370 and SSP585, as shown in Table 1. Among them, SSP126 is the optimistic scenario, which represents a scenario of sustainable socio-economic development with low radiative forcing of about 2.6 W/m^2 by 2100. SSP245 and SSP585 represent medium and negative climate scenarios, with intensified emission. SSP245 assumes a world following contemporary social, economic, and technological trends, with uneven development among countries and slow progress in achieving sustainability goals. The CO_2 emission is projected a growth until 2040, then a steadily declination until the end of the century, with radiative forcing peaking at 4.5 W/m^2 by 2100, corresponding to a global mean air temperature increase of about 2.5°C from the pre-industrial era and 1.5°C from the current era. SSP585, based on fossil-fueled development with strong investments in health and education, results in high global energy demand from energy-intensive lifestyles. This leads to rapid economic growth and environmental degradation. It projects strongly growing CO_2 emission until 2080, then slightly declining until the end of the century, with radiative forcing peaking at 8.5 W/m^2 by 2100, resulting in a global mean air temperature increase of about 5°C from the pre-industrial era and 4°C from the current era. SSP370 is a new radiative forcing scenario, which represents a sustainable land-use change and high emissions (especially SO_2), with a stabilized radiative forcing of about 7.0 W/m^2

in 2100. CMIP6 provides wind speed data with daily intervals. In total the wind data of 16 GCMs are selected and compared in this study, as shown in Table 2 .

Table 1 Key information of scenarios

Scenarios	Shared Socioeconomic Pathway	Emission Level	Radiative Forcing Level
SSP126	Sustainability	Low emissions	2.6
SSP245	Middle of the Road	Middle emissions	4.5
SSP370	Regional Rivalry	Medium to high emissions	7.0
SSP585	Fossil-fueled Development	High emissions	8.5

Table 2 Key information of CMIP6 models

No	Model Name	Region	Grid	Model Provider
1	ACCESS-CM2	Australia	144×192	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology
2	ACCESS-ESM1-5	Australia	145×192	
3	BCC-CSM2-MR	China	160×320	Beijing Climate Center
4	CMCC-CM2-SR5	Italy	192×288	Euro-Mediterranean Center on Climate Change
5	CMCC-ESM2-0	Italy	192×288	
6	EC-Earth3-Veg-LR	European Countries	160×320	EC-Earth-Consortium (12 European countries)
7	GFDL-ESM4	America	288×180	Geophysical Fluid Dynamics Laboratory
8	IITM-ESM	India	94×192	Indian Institute of Tropical Meteorology Pune
9	INM-CM4-8	Russia	180×120	Russian Institute for Numerical Mathematics Climate Model
10	INM-CM5-0	Russia	180×120	
11	IPSL-CM6A-LR	France	144×143	Institute of Pierre Simon Laplace
12	MIROC6	Japan	256×128	Atmosphere and Ocean Research Institute, National Institute for Environmental Studies, Japan Agency for Marine-Earth Science and Technology
				University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan
14	MPI-ESM1-2-HR	Germany	192×96	Max Planck Institute for Meteorology
15	MPI-ESM1-2-LR	Germany	192×96	
16	MRI-ESM2-0	Japan	160×320	Meteorological Research Institute

2.2. Numerical model

2.2.1 Wave model description

The FVCOM-SWAVE wave model developed at the University of Massachusetts [60] is applied in this study. It is the wave module of the ocean model FVCOM [61] which could be conveniently coupled with the other modules in the FVCOM modeling framework, to modelling the wave-current interaction, sea temperature and salinity, water quality, etc. The uncoupled wave-only mode is used in this study, but it can be easily coupled with other module in the future work. FVCOM-SWAVE is an unstructured-grid finite-volume version converted from the widely used wave model SWAN [62]. The main governing equation is the spectral action balance equation.

$$\frac{\partial N}{\partial t} + \nabla \cdot [(\overline{C_g} + \overline{V})N] + \frac{\partial C_\sigma N}{\partial \sigma} + \frac{\partial C_\theta N}{\partial \theta} = \frac{S_{tot}}{\sigma} \quad (1)$$

where N is the wave action density spectrum, t is the time, σ is the relative frequency, θ is the wave direction, C_σ and C_θ are the wave propagation velocities in spectral space (σ, θ) , $\overline{C_g}$ is the group velocity, and $\overline{V}$ is the source-sink term defined as:

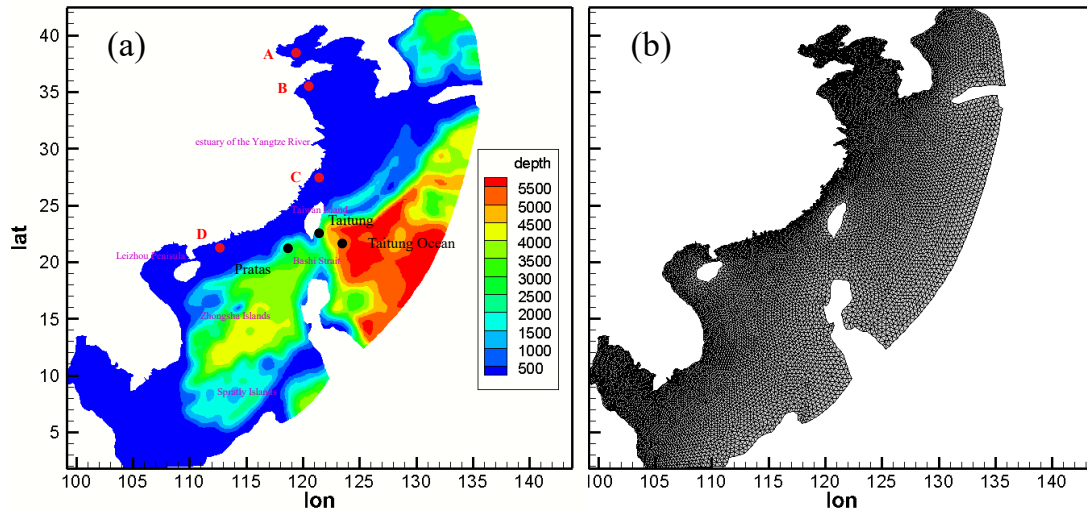
$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds,w} + S_{ds,b} + S_{ds,br} \quad (2)$$

where S_{in} is the function for wind-induced wave growth, S_{nl3} is the nonlinear transfer of wave energy from three-wave interactions, S_{nl4} is the nonlinear transfer of wave energy from four-wave interactions, $S_{ds,w}$ is the wave decay from white capping, $S_{ds,b}$ is the wave decay from bottom friction, and $S_{ds,br}$ is the wave decay from depth-induced wave breaking.

2.2.2 Model setup

A China seas model is established based on the FVCOM-SWAVE model which covers the Bohai Sea, the Yellow Sea, the East China Sea, the South China Sea and some of the adjacent sea areas as shown in Fig. 1. The model uses an unstructured mesh with 12,480 nodes and 23,832 elements. The resolution of the open boundary is 0.45° and the resolution of the coastline is 0.15° . Bathymetric data is obtained from the General Bathymetric Chart of the Oceans (GEBCO) 30 arc-second global bathymetric dataset, with corrections at the nearshore areas using available ocean maps and then interpolated onto the model grid. The daily wind data which interpolated to 0.25° grid is used as the surface boundary to obtain the wave elements (wave height and wave period) by

234 performing wave-only simulations.



235
236 *Fig. 1 Schematic diagram of the wave model: (a) water depth (m); (b) computational grid*

237 In wave simulations, wind-induced wave growth encompasses both linear growth as described
238 by Cavaleri and Rizzoli [63] and exponential growth as outlined by Komen et al. [64]. The
239 interactions between triple and quadruple waves are modeled using the Lumped Triad
240 Approximation (LTA) introduced by Eldeberky [65] and the Discrete Interaction Approximation
241 (DIA) proposed by Hasselmann et al. [66], respectively. White-capping dissipation is applied using
242 the formula provided by Komen et al. [64]. Bottom friction dissipation is modeled according to the
243 Madsen form developed by Madsen et al. [67]. Additionally, wave breaking induced by depth is
244 addressed through the bore-based model proposed by Battjes and Janssen [68].

245 2.2.3 Model Validation

246 As for model validation, the computed significant wave heights (H_s) driven by the ERA5
247 reanalysis wind data are compared with the measured data at three deep water observation stations,
248 i.e. Pratas Station (2600 m depth), Taitung Station (2600 m depth) and Taitung Ocean Station (5600
249 m depth), as shown in Fig. 2. It can be seen that the H_s generated by the ERA5 wind field are
250 generally consistent with the observed data. However, it is obvious that the wave heights simulated
251 during the tropical cyclone period are underestimated. This is due to that the ERA5 reanalysis wind
252 data lacks the large wind speed during tropical cyclones [69]. As the CMIP data is also calculated
253 by the climate model without the correction of observations, the CMIP6 wind could also
254 underestimate the wind speed during tropical cyclones. Since wind and wave energy converters do

not normally operate during the tropical cyclone period for a safe reason, the wind and wave data obtained in this study could be effectively used to analyze future wind and wave energy distribution.

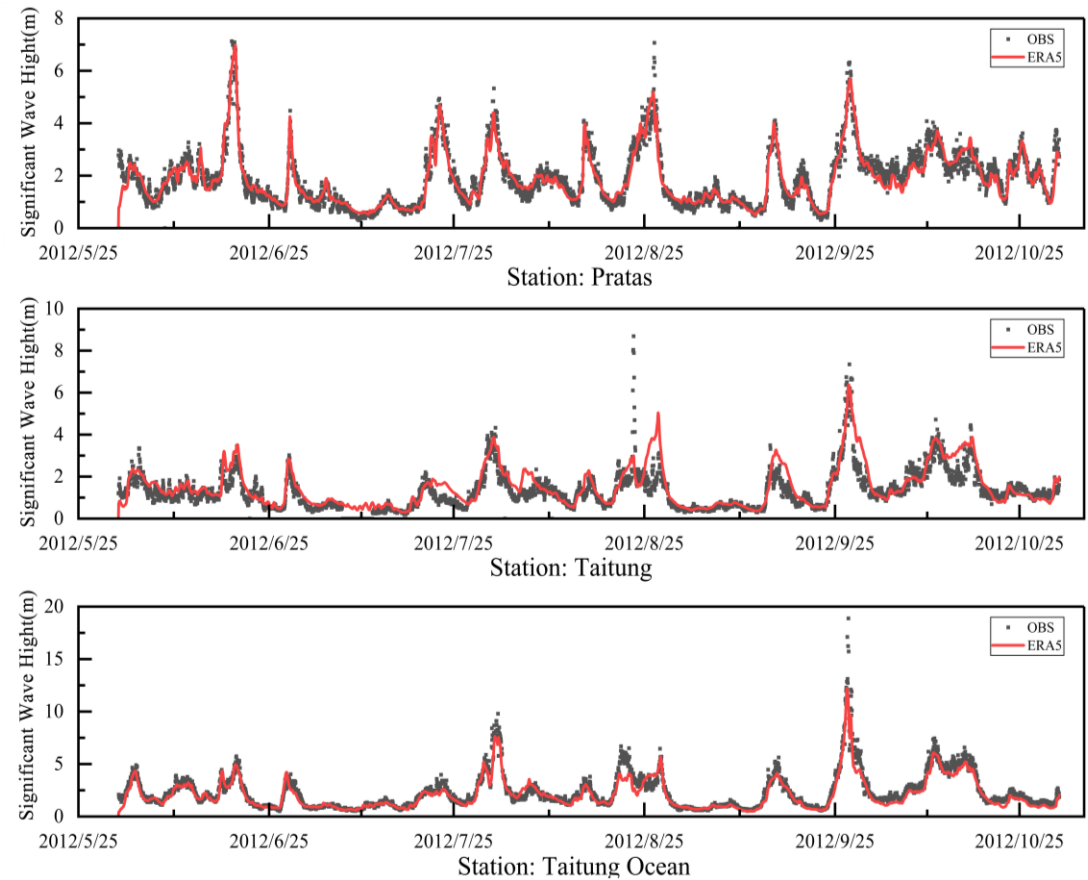


Fig. 2 Comparison of measured (OBS) and simulated wave heights (driven by ERA5 wind) at Pratas, Taitung Ocean, and Taitung Stations.

2.3 Data simulation capability

Due to the differences in the simulation ability of different GCMs in CMIP6 for different regions, it is necessary to validate those models before applying them in the study region. Using the ERA5 wind data as the reference, the simulation ability of 16 single models from the CMIP6 during the year 2000 to 2014 are evaluated. For consistency, the hourly ERA5 data is averaged to generate the daily average.

Taylor diagram is used for the standard deviation (σ), centred root mean square errors (RMSE) and correlation coefficients (R) of multiple variables in the same polar coordinates to visually compare the simulation capabilities of the different models [70], which can be calculated using the following formulas:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (f_i - \bar{f})^2} \quad (3)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N [(f_i - \bar{f}) - (r_i - \bar{r})]^2} \quad (4)$$

$$R = \frac{\frac{1}{N} \sum_{i=1}^N (f_i - \bar{f})(r_i - \bar{r})}{\sigma_f \sigma_r} \quad (5)$$

where N is the number of total samples; $\bar{f}$ and $\bar{r}$ denote the mean values of f and r ; σ_f and σ_r are their standard deviations.

The Taylor diagrams of the wind speed of 16 selected GCMs in comparison with ERA5 wind field are shown in Fig. 3. The simulation capability of these models in two different region scales are evaluated. One is the extended model domain containing land and ocean between longitude 100 °E to 140 °E and latitude 0 °N to 45 °, which corresponds the original area of downloaded wind data (not shown here), and the other is the model domain of China seas as shown in Fig. 1. It is clear in Fig. 3 that different GCMs have similar performance in the extended domain, but show variate in the China seas domain. This indicates that the simulation capacity of wind data in different GCMs may have larger differences above the sea than the land. Finally, five GCMs (BCC-CSM2-MR, EC-Earth3-Veg-LR, GFDL-ESM4, MPI-ESM1-2-HR, and MRI-ESM2-0, abbreviated to BCC, EC, GF, MPI, MRI respectively and marked in red in Fig. 3 with better simulation ability in this study domain are selected to drive the FVCOM-SWAVE wave model to generate the wave fields in this study.

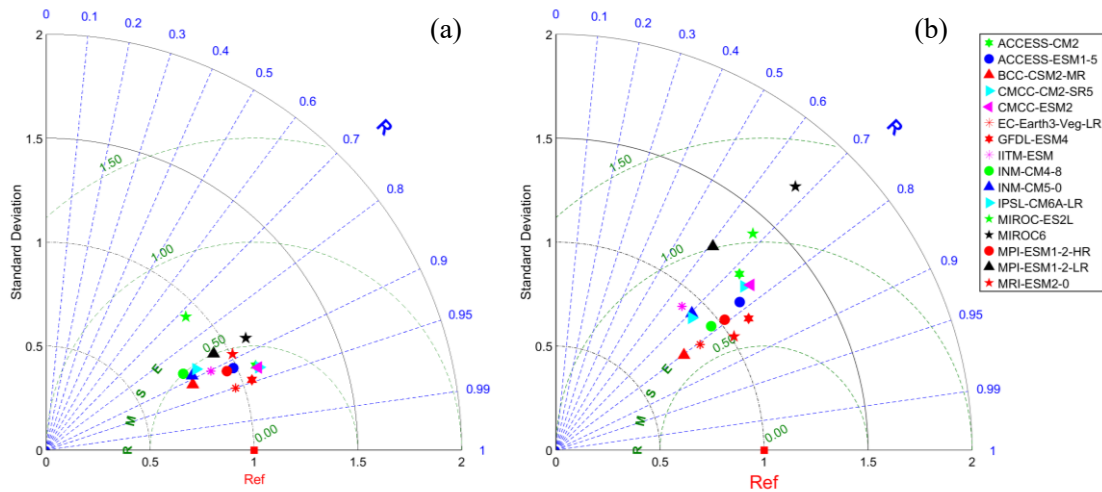


Fig. 3 Taylor diagram of wind speed for CMIP6 comparing with ERA5 values for the historical period of 2000-2014: (a) extended domain between 100 ° E ~ 140 ° E and 0 ° N ~ 45 ° N, (b) the

study area as shown in Fig. 2 (“Ref” denoting the reference fields of the ERA-5 reanalysis wind speed)

The wave model is driven by the wind speed data of the selected 5 CMIP6 GCMs as introduced in Section 2.1, with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$ and a time resolution of 1 day. The time period of 2000-2014 is used to represent the historical condition. As different SSPs are defined according to the radiative forcing peaking by 2100, the time period of 2080-2100, which could guide a long-term plan of energy development under the climate change, is used to represent the future condition, for an effective use of computing resources. Also, the wave model is driven by the ERA5 wind for the historical time period (2000-2014) for validation. The model output parameters include the H_s and peak period, with an output time interval of 1 h. The detailed set-up of different numerical experiments could be seen in Table 3.

Table 3 Numerical experiments

experiments	Model name	Time	Scenarios	Input variable	Frequency
validation	ERA5	2000-2014	Historical	vas, uas	daily
Historical	BCC-CSM2-MR(BCC)	2000-2014	Historical	vas, uas	daily
	EC-Earth3-Veg-LR(EC)	2000-2014			
	GFDL-ESM4(GF)	2000-2014			
	MPI-ESM1-2-HR(MPI)	2000-2014			
	MRI-ESM2-0(MRI)	2000-2014			
	MME	2000-2014			
Future	BCC-CSM2-MR	2080-2100	SSP126	vas, uas	daily
	EC-Earth3-Veg-LR	2080-2100			
	GFDL-ESM4	2080-2100			
	MPI-ESM1-2-HR	2080-2100			
	MRI-ESM2-0	2080-2100			
	MME	2080-2100			

Multi-model ensemble (MME) of data not only reduces the amount of computation, but also

effectively reduces the excessive influence of a single mode on the results. The wind data in 5 selected GCMs with relatively good simulation capability are used to drive the wave model from 2000 to 2014 for wave prediction, and then the MME of these five wave datasets are calculated and used for analyzing future changes in wave characteristics. Fig. 4 shows the Taylor diagrams of historical wind speed and Hs of five selected GCMs and their MMEs. It is obvious that the wind speed and Hs of the five GCMs are well simulated in the modelling area, and the MME of wind speed and Hs are more consistent with the historical data than the single model. It is worth noting that when dealing with the wind speed data for the input of wave model, two trials are conducted, i.e., driving the wave model using the MME of wind speed or driving the wave model using the wind speed of single GCMs and then create the MME of waves. It is found that the waves driven by the wind speed MME is obviously underestimated, for both Hs and wave period, thus the wave data used in this study is driven by the wind speed of single GCMs. Finally the MME of waves is calculated and used for the following analysis.

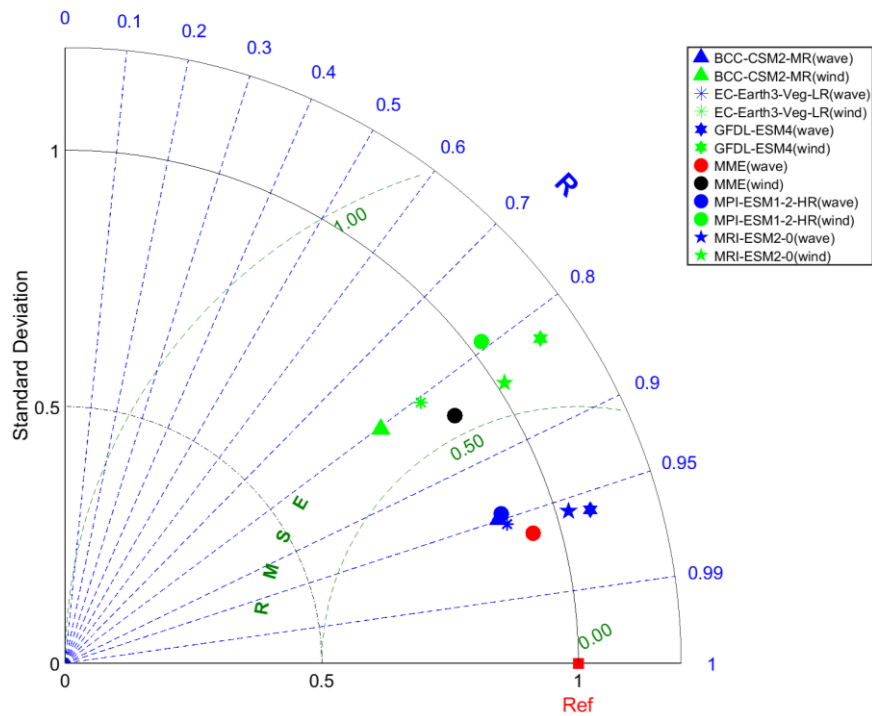


Fig. 4 Taylor diagram for simulations and reference values of Hs (Blue) and offshore wind speed (green) in China seas for the historical period of 2000-2014 based on 5 selected GCMs. MME (Red for wave and black for wind) denotes the multi-model ensemble, and “Ref” denotes the reference fields of ERA5

326

327 2.4 Factors to assess the energy reserves

328 Since the installation height of offshore wind turbines (WT) are usually 100 m, the 10 m wind
329 speed data from the CMIP6 model is converted to that at the 100 m height for computing the wind
330 power density (WPD), with the following equation:

$$331 \quad v_{100} = v_{10} \left(\frac{z_2}{z_1} \right)^a \quad (6)$$

332 where v_{100} is the wind speed (m/s) at a height 100 m; v_{10} is the wind speed at 10 m; z_1 and z_2
333 equal to the 10m and 100m respectively which are the height of the wind speed; a is an empirically
334 derived coefficient, which is equivalent to 0.1 for a stable ocean atmosphere [71].

335 WPD is most widely used in wind energy resource assessment, and it is calculated from wind
336 speed following the equation [72]:

$$337 \quad WPD = \frac{1}{2} \rho v_i^3 \quad (7)$$

338 where ρ is the air density (1.225 kg/m³ at 288.15 K and 1000 hPa) and v_i is the wind speed at 100
339 m.

340 Wave energy density (WED) is an important metric for assessing regional wave energy
341 resource, and the following empirical formula is commonly used for WED calculations in deepwater
342 regions:

$$343 \quad WED = 0.49 H_s^2 T_e \quad (8)$$

344 where H_s is the significant wave height and T_e is the wave energy period, which is obtained from
345 the FVCOM-SWAVE model output of the peak wave period T_p , with the following relation:

$$346 \quad T_e = \alpha T_p \quad (9)$$

347 where $\alpha = 0.9$ is adopted according to the previous study [69].

348 Representative wave converter device (WEC) and WT are selected for future energy analysis
349 of the selected locations along the coasts. The AquaBuoy WEC is selected according to the water
350 depth of selected locations. Fig. 5(a) shows the selected power matrix of AquaBuoy WEC system,
351 with the matrix numbers representing the expected output power of the unit at the corresponding H_s
352 and wave energy period (T_e). For the available wind energy, the SWT-3.6-120 WT is selected
353 because its hub height is site specific. Fig. 5(b) presents the power curves of the offshore WT [62].

The detailed parameters of these two converters are listed in Table 4. The selection of different converters must influence the calculated energy reserves, thus the comparisons between wind and wave energy in this study are based on the energy density, while the total energy reserves calculated using the representative converters are used for a trend analysis for single wind/wave energy resource under the climate change.

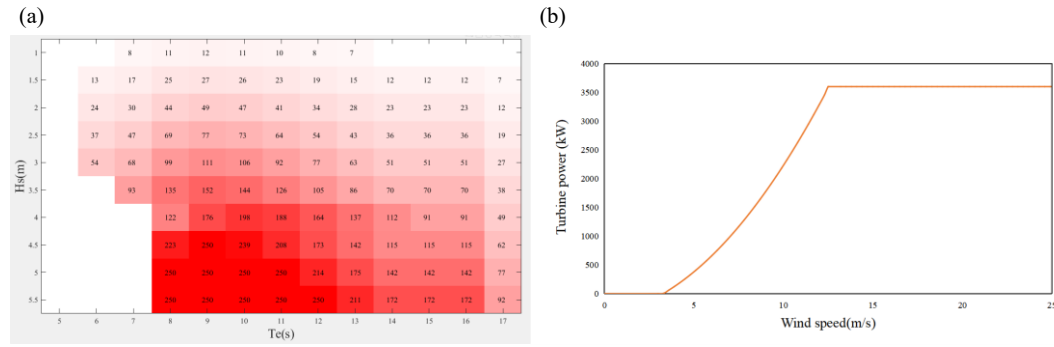


Fig. 5. Power output for selected (a) wave energy converter and (b) wind turbines (adopted from [73]).

Table 4 Parameters of WT and WEC (adopted from [73])

Offshore Wind Turbines		Wave Energy Converters	
Systems	SWT-3.6-120	Systems	Aqua Buoy
Rated capacity(kW)	3600	Rated capacity(kW)	250
Hub height(m)	90 or site specific	Water depth(m)	20-50
Cut-in value(m/s)	3	Category	Point absorber
Rated Wind speed(m/s)	12.5		
Cut-out value(m/s)	25		

To evaluate the performance of the wind and wave energy generation, the Total Harmonic Distortion (THD) index is applied in this study [74] as,

$$THD = \frac{\sigma}{\bar{x}} \quad (10)$$

where σ and $\bar{x}$ represent the standard deviation and average value of x , respectively. Eq. 10 can be used for the wind and wave energy. THD is an index of the quality of power delivered to the energy grid, and is used to assess the smoothness of power at a particular site. Therefore, smaller THD values indicate more stable power quality [62].

374

375 3. Future variability of wind and wave energy

376 3.1 Long-term variation of wind speed

377 To determine the potential wind and wave energy, wind speed is the key parameter, therefore
 378 the long-term variation of the wind speed over both the extended domain and the study site as it is
 379 provided is first conducted here on four SSP scenarios, namely, SSP126, SSP245, SSP370 and
 380 SSP585, using linear regression analyses. Fig. 6 shows the changes of the mean wind speeds over
 381 the period of 2015-2100. In Fig. 6(a), the long-term change of mean wind speed for SSP126 shows
 382 a slightly increasing trend, and SSP245 remains almost unchanged. For SSP370 and SSP585, the
 383 long-term changes of mean wind speed show a significant decreasing trend. However, as shown in
 384 Fig. 6(b), the trend in China seas domain (this study site) shows a similar trend for the SSP126 and
 385 SSP370 scenario, but the long-term change of the mean wind speed in the area for SSP245 shows
 386 an increasing trend while SSP585 remains unchanged. The linear regressions are statistically
 387 significant at a level of 5%.



388

Fig. 6 Regional mean wind speed (WS) during 2015-2100 in: (a) extended domain (100°E ~ 140°E and 0°N ~ 45°N); (b) this study area (as shown in Fig. 2)

In addition, the spatial linear regression trends for wind speed over the extended domain for the period of 2015-2100 are shown in Fig. 7. The overall trend is relatively insignificant, with the change of wind speed at most area over the domain falling within the range of -0.005 to 0.005 m/s per year and passing the 0.05 significance test. However, the wind speed in the coastal waters exhibits an increasing trend in the East China Sea with emissions intensified, but decreasing further afield in the ocean, except for that decreases in SSP370 scenario, indicating its implication on the potential wind and wave energy in the area in long term.

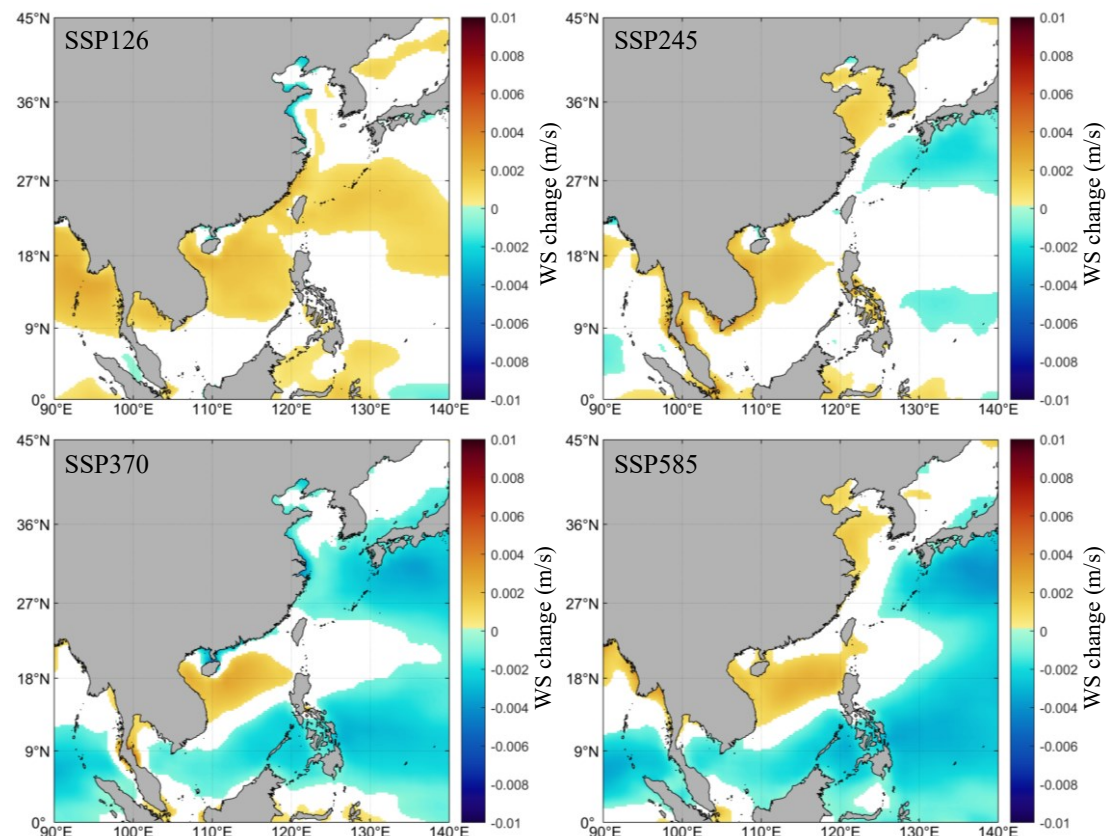


Fig. 7 Linear regression of annual wind speed (WS) change in China seas during 2015-2100. The blank areas represent the grid points not passing the 0.05 significance test.

3.2 Distribution of wind speed and wave height

Focusing on China's coastal waters (as shown in Fig. 1), the future variability of wind speed and Hs are also analyzed on the MMEs of wind and wave, where the wind data is interpolated to the

same grid as the wave data. The multi-year (2080-2100) mean wind speed for different SSPs in the study areas are shown in Fig. 8. The multi-year mean wind speed in all climate scenarios are greater than 6 m/s in most of the study area and roughly 5 m/s nearshore. Highest sea surface wind speed is found in the South China Sea, with the mean wind speed being over 8 m/s. The bottom panels of Fig. 8 display the difference of wind speed between future scenarios (2080-2100) and historical condition (2000-2014), with the positive values indicate an increase trend in the future and negative values indicate a decrease trend. It is worth noting that all scenarios show an increase trend with the change of wind speeds in the north part of the South China Sea in the future, with emissions intensified. The opposite trend is observed in the East China Sea and the southern South China Sea, especially in the SSP585, where wind speeds in the East China Sea decrease by more than 0.2 m/s. Comparing the projections of other SSPs, SSP370 shows a significantly decrease trend in the waters around the estuary of the Yangtze River and Leizhou Peninsula, which is opposite to the change of other SSPs. The nearshore areas (under 50 m water depth) show relatively small variations (within ± 0.1 m/s in general).

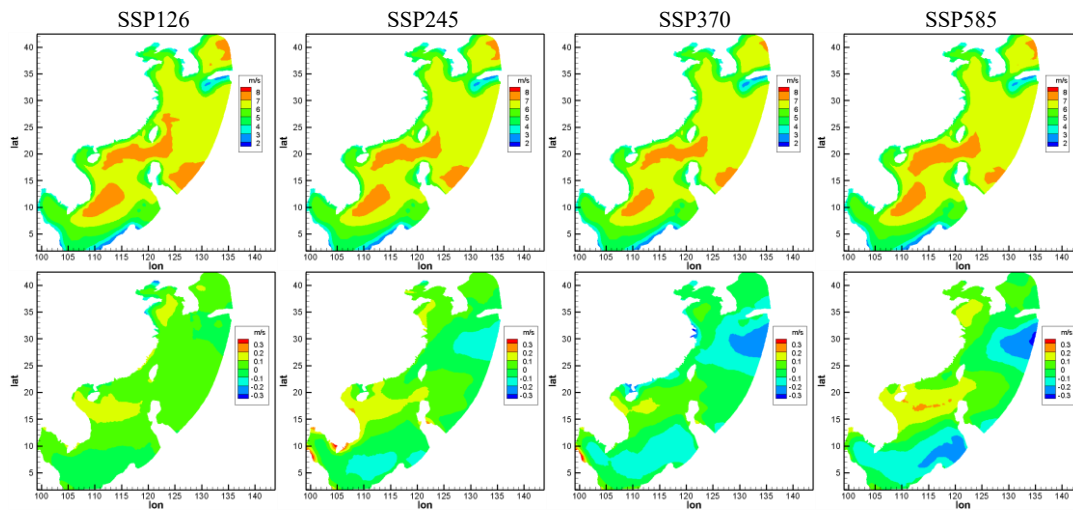


Fig. 8 The multi-year (2080-2100) mean wind speed for different future scenarios (top panels) and their differences (bottom panels) with historical data

Fig. 9 shows the distribution of multi-year mean H_s under four SSPs from 2080-2100 with 5 selected GCMs respectively. It can be seen that the maximum H_s is greater than 1.6 m in the southern part of Taiwan Island in all 5 GCMs, among which the GF and MRI show that the maximum H_s can be over 1.8 m. Most of the GCMs show that the H_s in the South China Sea exceeds 1.4 m, while only the MPI have lower value (in the range of 1.2-1.4 m). Since different GCMs could have

relatively large diversity, also shown in Fig. 4, the MME data of Hs for the five GCMs is established to reduce the excessive influence of a single model on the simulation results.

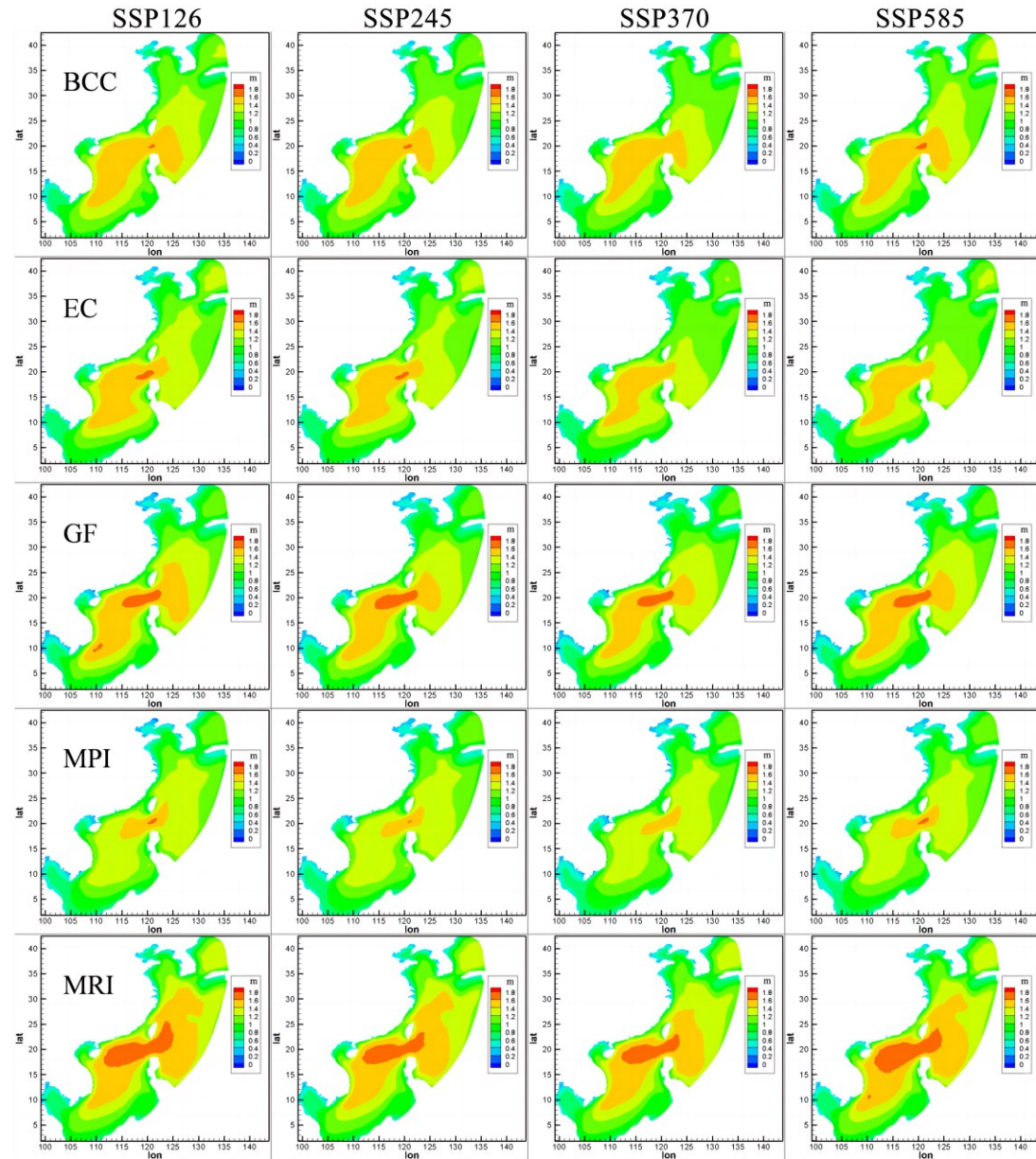


Fig. 9 Multi-year (2080-2100) mean Hs for different future scenarios with 5 selected GCMs

Based on the MMEs, Fig. 10 shows the spatial distribution of the multi-year (2080-2100) mean Hs under different scenarios and their difference between historical data (2000-2014). The mean Hs in the South China Sea and the southern part of Taiwan Island under the four SSPs are up to 1.4 m, while Hs in the majority of the Bohai Sea are in the range of 0.4-1 m. The Hs in majority of the Yellow Sea is over 1 m. As shown in the bottom panels of Fig. 10, there is no significant decrease in Hs in the SSP126. The SSP245 shows no apparent change in Hs compared to the historical

scenario. The results of SSP370 indicate that majority areas in the southern South China Sea and the East China Sea are on a decreasing trend. SSP585 on the other hand are characterized by a clear trend in the study area, especially in the South China Sea, with an increasing trend in the near continent and a decreasing trend in the southern South China Sea.

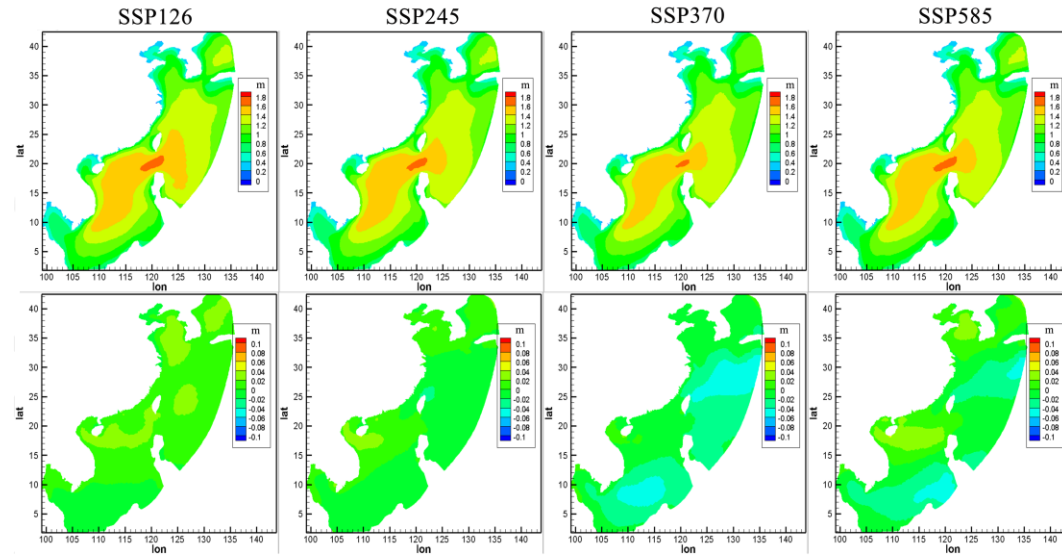


Fig. 10 Spatial distribution of the multi-year (2080-2100) mean Hs under different scenarios (top panel) and their difference between historical data (bottom panel); The positive value of the difference indicates an increase in Hs

3.3 Wind power density (WPD)

The WPD are estimated using the local wind speed using Eq. 7. Fig. 11 shows the multi-year mean WPD for four SSP scenarios from 2080 to 2100 and their difference to the historical value in the study area. The top panels of Fig. 11 shows that the maximum WPD is located in the South China Sea, near the Bashi Strait, reaching approximately 650 W/m². Similar to the multi-year mean wind speed, the multi-year mean WPD in the study area also shows a gradual increasing trend from nearshore to deep water area. The bottom panels of Fig. 11 shows the differences of mean WPD between future scenarios and historical values. To the end of the 21st Century, SSP126 projects small changes in most areas of the study site, with only significant increase of about 5% in the Yellow Sea. However, for the scenarios, the results show that climate change scenarios can significantly impact on the distribution of wind energy in the study site. In the long-term future, the WPD decrease is clearly enhanced in other climate scenarios compared to the SSP126. This is

particularly noticeable in the eastern East China Sea and the southern South China Sea, where WPD is projected to decrease over 15 W/m^2 . In contrast, the WPD in the northern part of the South China Sea shows an increase trend, by approximately 20 W/m^2 . The wind energy reduction is found in the southern South China Sea and the eastern East China Sea as emissions increase. For SSP585, the spatial patterns of the projected WPD changes are very similar to the SSP245 distribution but with higher magnitudes. SSP585 projects an increase of WPD in the northern part of the South China Sea, with the opposite trend in the eastern East China Sea and the southern South China Sea. Except for the northern South China Sea, SSP370 projects remarkable wind energy diminishes in the study areas, with an average decrease of more than 10 W/m^2 . Comparing the four SSPs indicates the changing trends of SSP245 and SSP585 a similar pattern, while SSP126 and SSP370 show a diversity, which may be caused by the different land use and radiative forcing when produce the original data. Thus, when analyzing the effects of climate change on the change of meteorological and oceanic factors using CMIP data, the SSP245 and SSP585 could be selected as the representative scenarios as initial estimation, which have already been utilized in many previous studies [75-76].

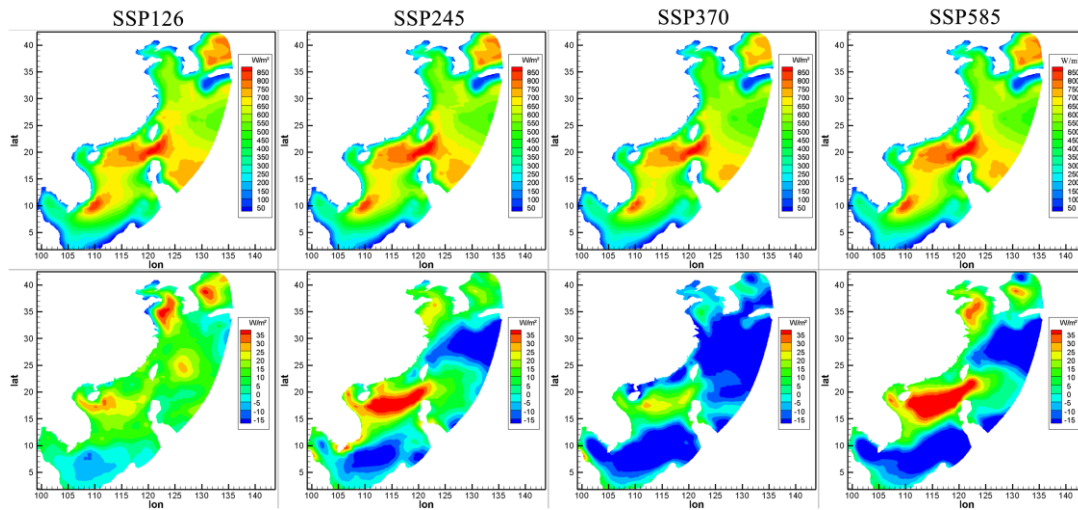


Fig. 11 Spatial distribution of the multi-year (2080-2100) mean WPD under different scenarios (upper panel) and their difference between historical data (bottom panel); The positive value of the difference indicates an increase in WPD

To quantitatively understand the change of WPD in different emission scenarios, based on the results shown in Fig. 11, the regional mean WPD in the Bohai Sea, the Yellow Sea, the East China Sea and the South China Sea are calculated, and the percentage differences of the regional mean

WPD of different scenarios to the historical situation are also calculated. As shown in Fig. 12, it can be seen that SSP245 and SSP585 have a similar trend which indicates an increase in WPD with the increase of emission except for the South China Sea. The northern and southern part of the South China Sea have obviously an opposite trend, thus this area should be considered separately, the same for the western and the eastern East China Sea. Among them, WPD in the eastern East China Sea and the southern South China Sea decreases with the emission intensified; on the contrary, in the western East Sea and the northern South China Sea, WPD increases. Considering the negative climate scenarios (SSP585) with the highest emission, the Bohai Sea has an increase of 4.3%, which is the highest. The Yellow Sea and the East China Sea both have an increase of 3.4%, while the South China Sea has a decrease of 1.5%. Focusing on the representative SSPs, i.e., SSP245 and SSP585, the results indicate that, if global warming continues to intensify, the wind energy in the Bohai Sea, the Yellow Sea and the western East China Sea may increase.

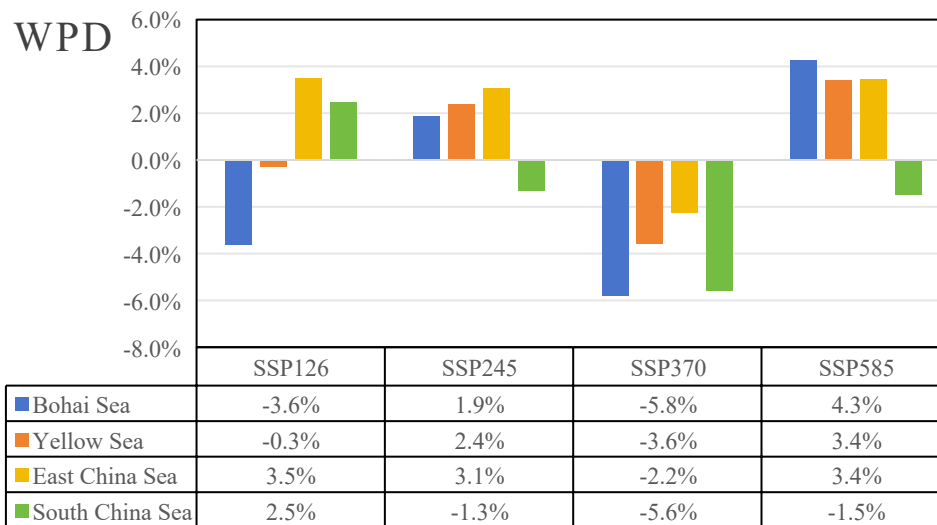


Fig. 12 The difference of the regional mean WPD (in the Bohai Sea, the Yellow Sea, the East China Sea and the South China Sea) under different scenarios from the historical data (in percentage)

3.4 Wave energy density (WED)

Based on the 21-year wave data generated by the FVCOM-SWAVE model (the MME of five selected GCMs), the potential WED are calculated using Eq. 8. Fig. 13 shows the multi-year mean

WED for the four SSPs in the study area. It can be seen that the maximum WED for all climate scenarios occurs in the southern waters of Taiwan Island, with the highest value of about 14 kW/m. The WED decreases from the areas of deep water to the land. Comparing the results for the future climate scenarios to the historical values, the SSP126 shows an increase of WED in the east of China seas, while very different results are obtained for SSP245 from the SSP126. For SSP245, the WED in the Yellow Sea and the Bohai Sea remains unchanged and in the far east of East China Sea, it shows a significant decrease, but an increase in the north of South China Sea. Same as the wind energy, WED of SSP370 show an overall decrease in the study area, significantly different from the those for other climate scenarios.

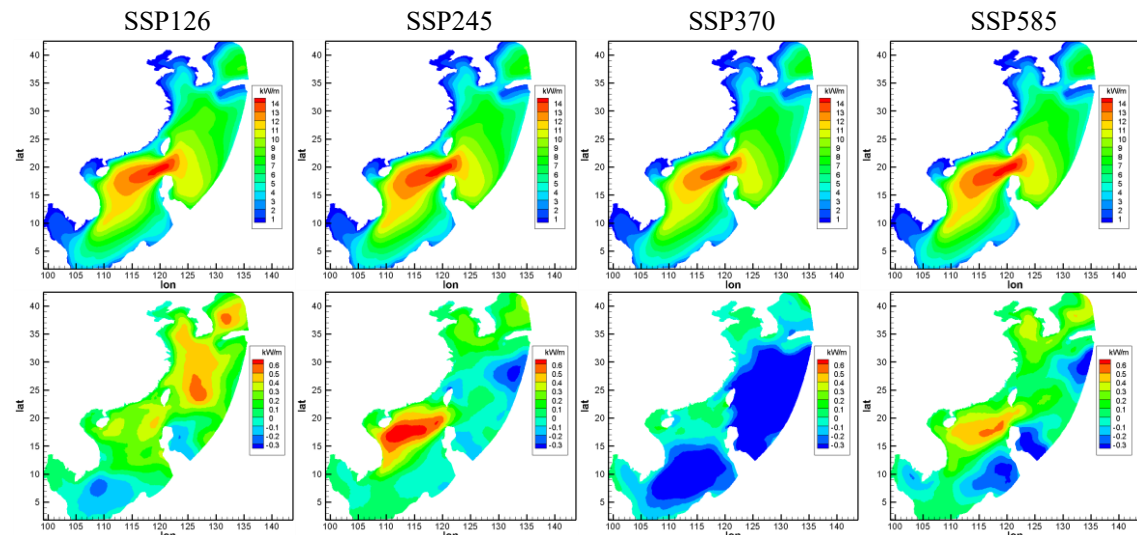


Fig. 13 Spatial distribution of the multi-year (2080-2100) mean WED under different scenarios (upper panel) and their difference from the historical data (bottom panel); The positive value of the difference indicates an increase in WED

Following the same analysis for the WPD, the percentage differences of regional mean WPD of different future scenarios to the historical values are estimated, as shown in Fig. 14. Focusing on the SSP245 and SSP585, the WED increases by 3.8% and 6.0% in the Bohai Sea, and by 5.7% and 8.6% in the Yellow Sea, but increases by 0.4% and 1.9% in the East China Sea. The proportion of wave growth is higher than the wind growth in these areas. The WED in the South China Sea shows a different pattern. In the SSP245 and SSP585, the WED increases by 4.2% and 3.2% in the South China Sea, while the WPD in the same scenarios decreases. Same as the wind energy, the southern and northern part of the South China Sea have opposite trends. The results shown in Fig. 13 and Fig.

14 also indicate that the SSP245 and SSP585 are more representative than other SSP scenarios when studying the change of meteorological and oceanic factors under climate change.

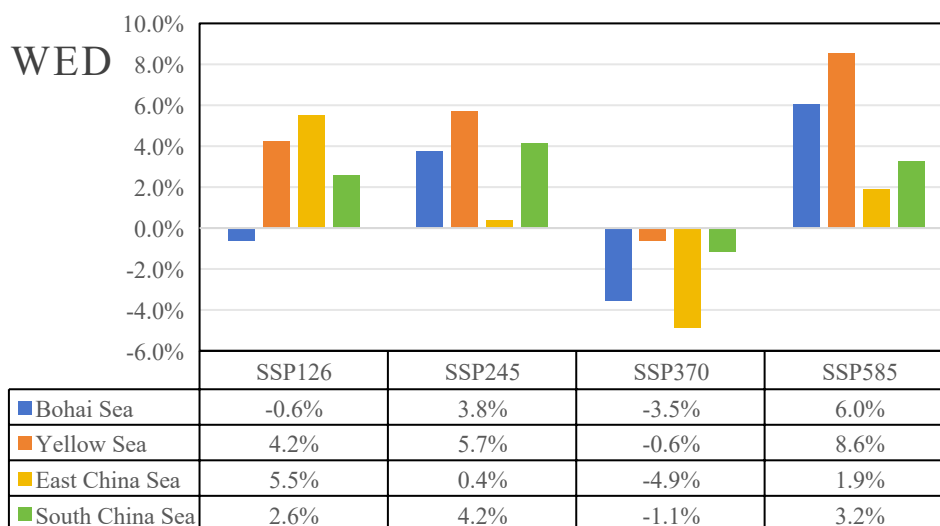


Fig. 14 The difference between the regional mean WED (in the Bohai Sea, the Yellow Sea, the East China Sea and the South China Sea) under different SSPs from the historical condition (in percentage)

The seasonal distribution characteristics of WED are further analyzed using the MME of waves. As shown in Fig. 15, wave energy is richer in autumn and winter than in spring and summer. The wave energy maxima in autumn are mainly located in the Bashi Strait and the waters around the Zhongsha Islands, with a maximum value of about 20 kW/m. Possibly due to the influence of the northeast monsoon, the wave energy maxima in winter move from the southern part of Taiwan Island to the southwestern part of the South China Sea in autumn, and the mean WED are all over 14 kW/m, with the maximal area located in the southern South China Sea, reaching 24 kW/m. The WED in the South China Sea in winter increases by about 40% compared to autumn. Generally speaking, the difference of WED in the Bohai Sea is negligible in all seasons, while that in the East China Sea and the South China Sea is significant. Comparing the seasonal WED for the four climate scenarios, with the intensification of climate change, there is a slight downward trend in the East China Sea and the Yellow Sea, while a slight increase in the South China Sea and the Bashi Strait.

It is worth noting that the WED in the Bashi Strait decreases with the intensification of emissions in autumn, while the opposite in the Zhongsha Islands.

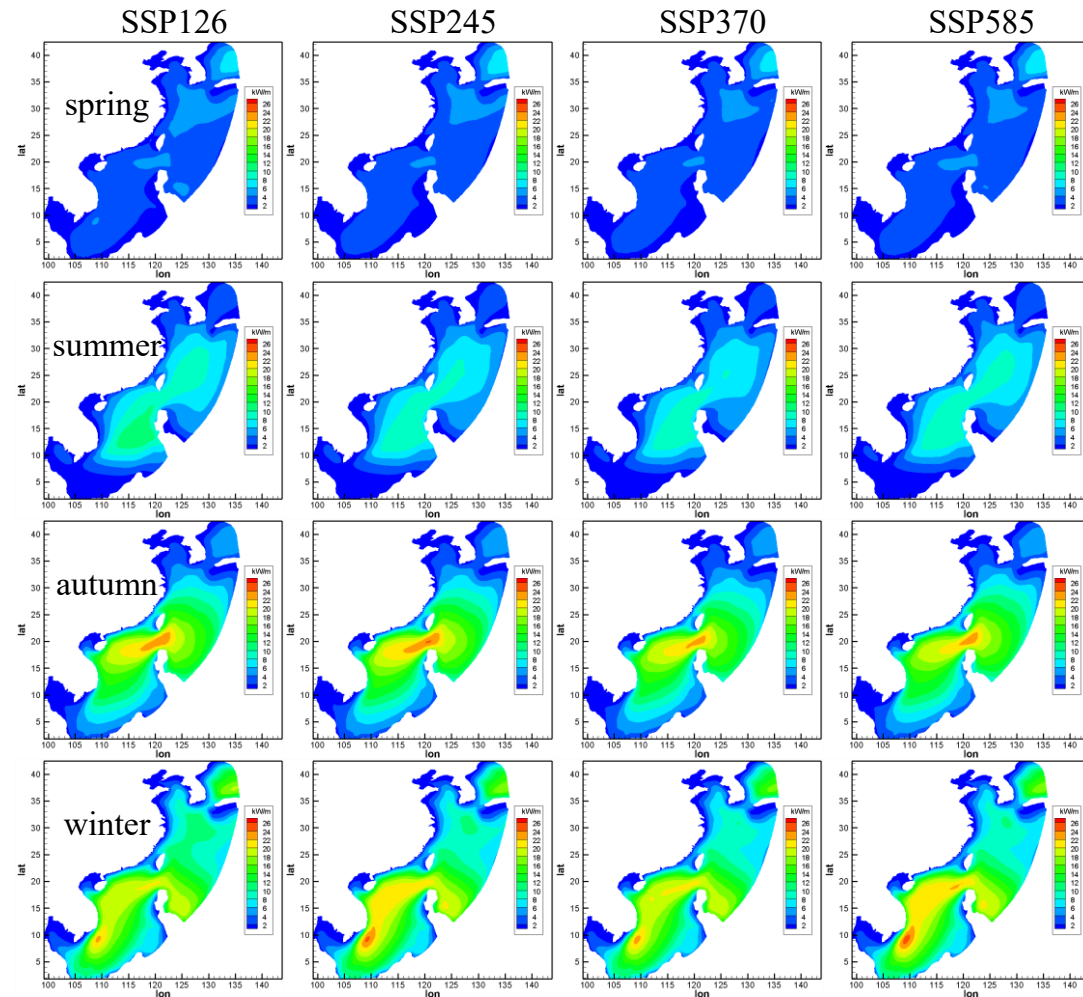


Fig. 15 The seasonal distributions of multi-year mean WED (kW/m) in the study site under different SSPs (MME).

4. Wind and wave energy in coastal regions

4.1 Long-term variation of wave height

Considering economic factors, the construction difficulty and water depth requirements of offshore wind farms, to gain a better understanding of the wind and wave energy characteristics in different coastal locations under different climate scenarios, 4 locations in the different coastal areas are selected to analyse offshore potential clean (wind and wave) energy based on existing offshore energy farm parameters and economic suitability and other principles [77]. Those selected locations,

as listed in Table 5 and illustrated in Fig. 1, represent the potential sites for clean energy development within their respective coastal regions, i.e. the Bohai Sea, the Yellow Sea, the East China Sea and the South China Sea.

Table 5 Details of 4 selected locations

Location	Location	Lon	Lat	Depth (m)
A	Bohai Sea	119.25°E	38.50°N	22.36
B	Yellow Sea	120.50°E	35.75°N	31.95
C	East China Sea	121.25°E	27.50°N	29.09
D	South China sea	112.75°E	21.25°N	42.05

First, the long-term variations of annual mean and maximum Hs for historical and future periods at the selected locations are analyzed. Fig. 16. shows the comparison of the long-term trends between SSP245 and SSP585. For SSP585, a decreasing trend of mean Hs is observed at all of the selected locations, which is in line with the results in many global scale studies [50]. For SSP245, there is no significant change of the trends in the mean Hs, although a slightly decrease at location A and increase at location C are observed. The changing trends of historical period and future period are obviously different, especially for the SSP245 scenario. For the maximum Hs, the results over historical period generally show an increasing trend at all selected locations. However, for the future period, except for location A under SSP245 and location B at SSP585 with an increasing trend observed, a decreasing trend is observed at all other locations. It should be noted that due to the limited computing resources, the wave data simulated is relatively short for the trend analysis, which could be improved by using the more advanced wave models or machine learning approach [78] in the future research.

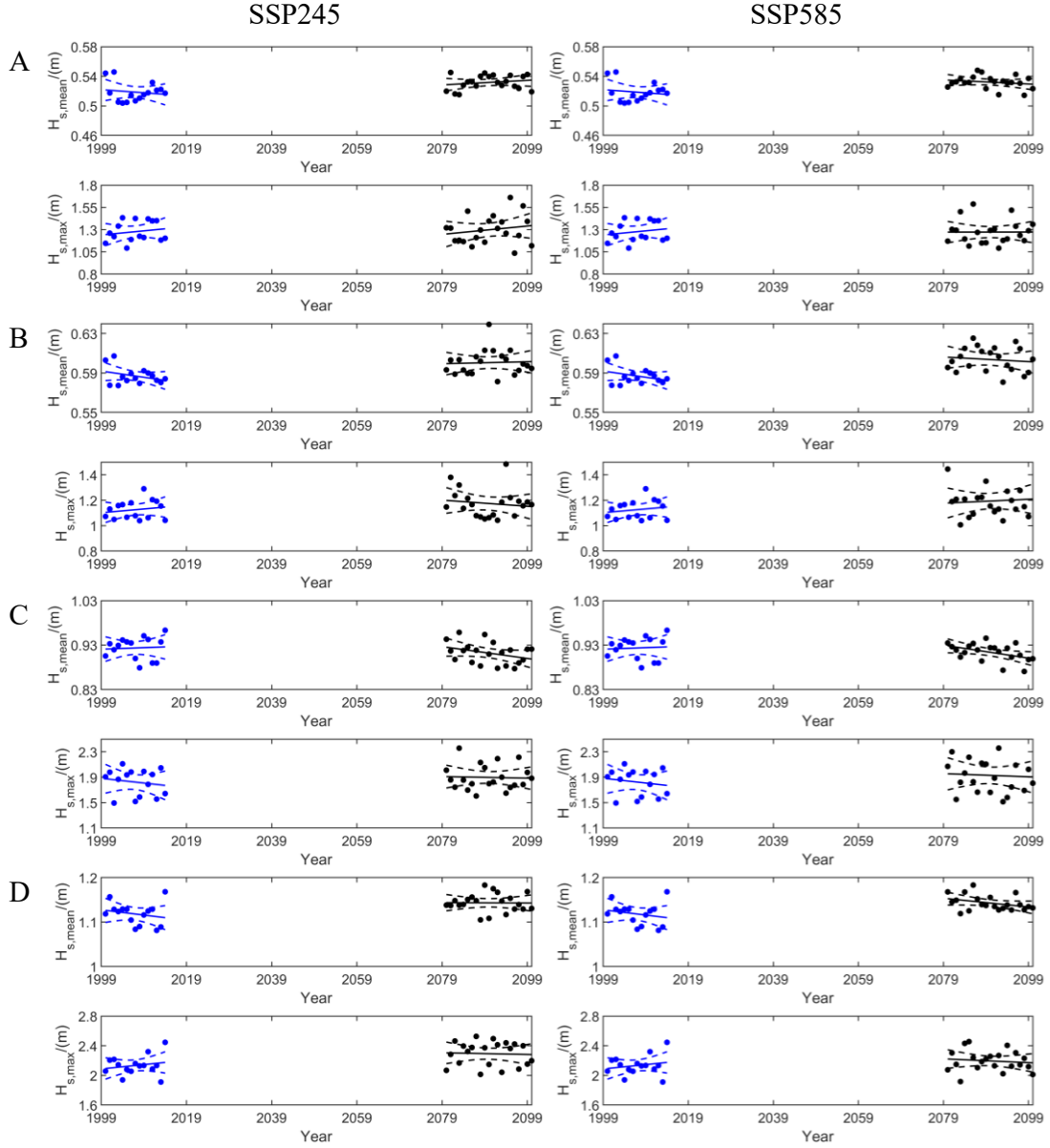


Fig. 16 Long-term variations of mean and maximum H_s for historical and future periods at selected locations for the historical and future periods under the SSP245 and SSP585. Dotted lines represent the 95% confidence bound.

4.2 Distribution of future wind and wave energy in the coastal regions

Fig. 17 shows the multi-year mean WPD and WED at selected locations. It can be seen that the WPD and WED in most regions have smaller variations under different climate scenarios. All representative locations exhibit relatively constant wind energy distribution patterns. The multi-year mean WPD is highest at location D, with over 300 kW/m^2 , and lowest at B, with about 210 kW/m^2 , located in the South China Sea and the Bohai Sea, respectively. The WPD at location A and location C are seen less affected by climate change, with the maximum difference of 7%. However, the

distribution of WED is quite different. WED is found to be high in the East China Sea and the South China Sea, with the highest offshore wave energy generation found at location D. Affected by the terrain and depth of water, locations A and B have less nearshore wave energy potential, only 15% of those in location D. Fig. 17 depicts that WED in the China seas is high in the south and low in the north. The South China Sea has the most abundant wave energy resources. In terms of offshore wind energy development, the most suitable areas are in the Bohai Sea, the South China Sea, and the East China Sea. Regarding wave energy development, the more desirable areas are the South China Sea and the East China Sea.

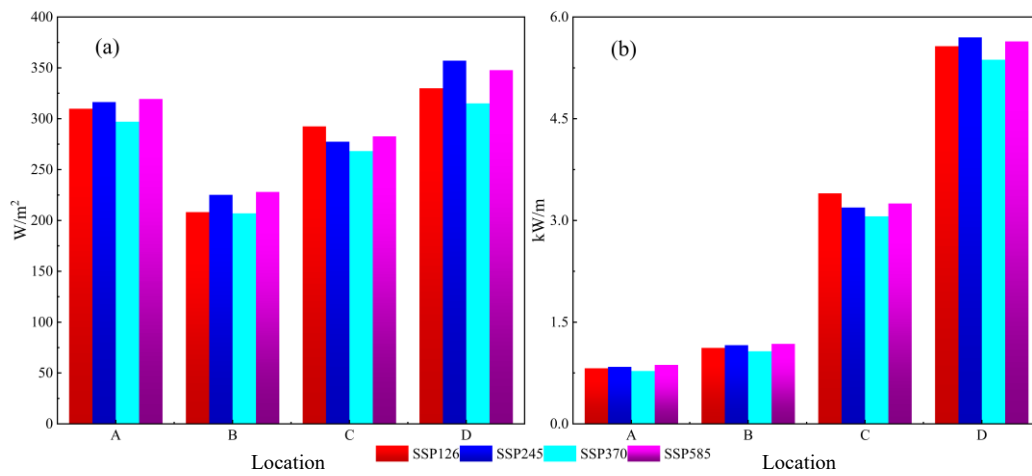


Fig. 17 Multi-year mean (a) WPD; and (b) WED at the selected locations.

Fig. 18 shows the distribution of sea state for climate scenarios SSP245 and SSP585 at 4 selected locations (A, B, C and D), taking into account the joint distribution of H_s and T_e . The numbers in Fig. 18 indicate the duration (in hours) with a given H_s and T_e annually (multi-year mean in 21 years). Meanwhile, the colours indicate their contribution (in percentage) to the total annual wave energy. As shown in Fig. 18, climate change has a relatively small impact on the nearshore sea state, with no significant change in the sea state at any of the 4 selected locations between SSP245 and SSP585, with a slightly increasing trend in H_s and T_e with increasing emission. For coastal areas of China, the sea states of selected locations A and B have H_s of less than 1 m and T_e between 2 and 4 s, contributing the most to the total wave energy. A wider distribution of sea state for wave energy generation can be seen at C and D, with the H_s between 1 and 2 m and T_e between 5 and 7 s contributing most to the wave energy. Even though locations C and D have greater H_s and T_e which generate more power, their complex sea state distribution necessitates optimization

of the design of the WECs. Despite the concentration of sea state at locations A and B, the H_s and T_e are lower and, therefore less power can be generated using the selected WEC.

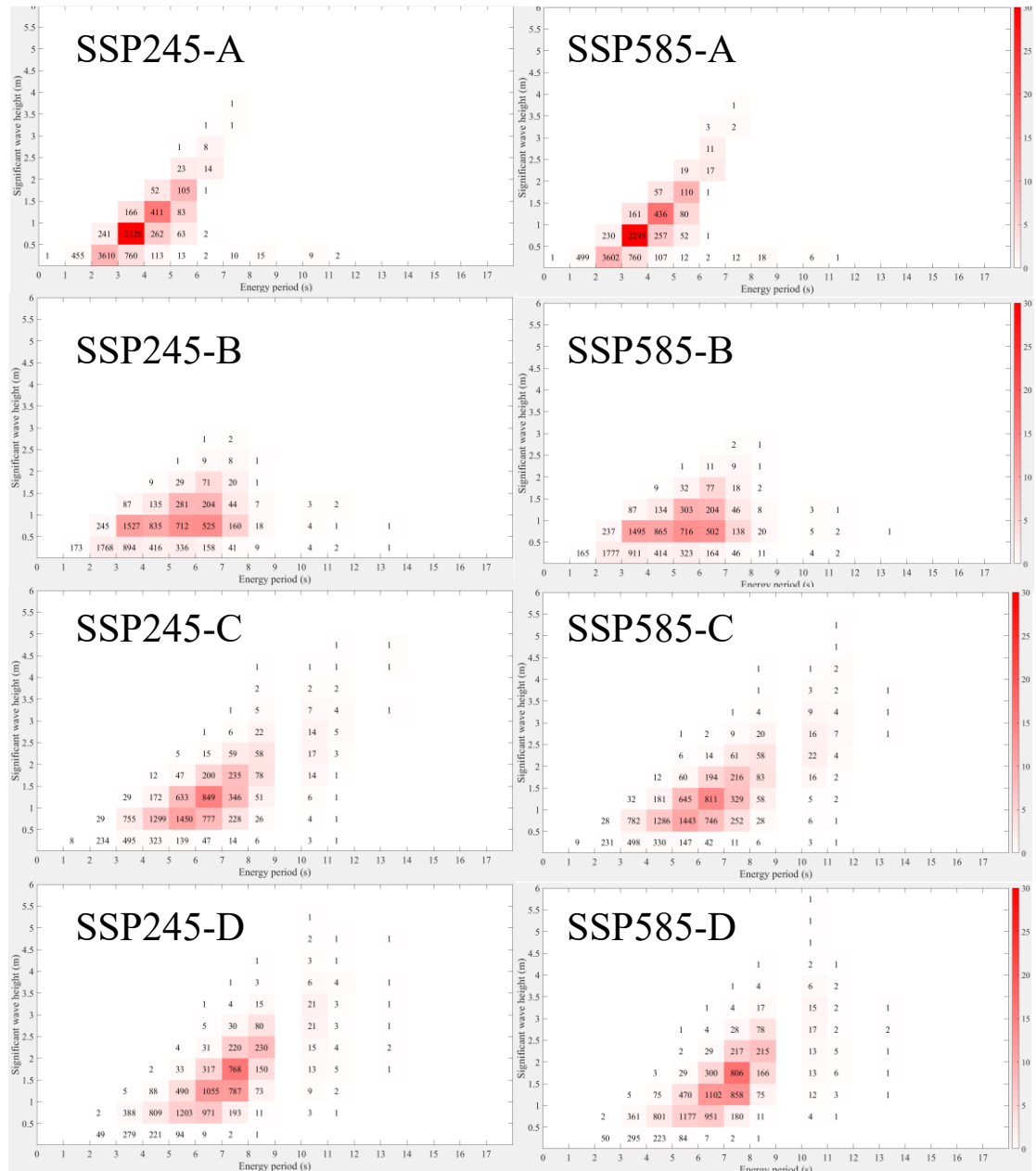


Fig. 18 Bivariate distribution of wave power density over significant wave height and energy period at 4 selected locations.

Suitable wind and wave energy generation locations are analyzed through selected WTs and WECs. Fig. 19 shows the multi-year mean total energy output of waves and winds at 4 selected locations for four future scenarios based on the selected WT and WEC introduced in section 2.4. The results show that the potential for offshore wind energy is much greater than that of wave energy which is mainly due to the higher energy exchange efficiency and rated power of selected WT than

WEC. Four selected locations have plenty wind energy resources, especially at locations A, C and D. For wave energy, locations C and D (along the East China Sea and the South China Sea) have higher energy reserves than A and B (Yellow and Bohai Seas). Thus, to select the potential site for wave energy generation, the coastline of the East China Sea and the South China Seas could be good options. Location C has the most significant wave energy potential under the SSP126 climate scenario, and all climate scenarios have a slightly rise compared to the historical scenario except for the SSP370, which has a much lower wave energy potential than the historical scenario. Conversely, at location D, only the SSP245 and SSP585 increased compared to the historical scenario, and the SSP126 declined by 8%. Different climate scenarios have different impacts on each sea area. The total wind energy in location A is less affected by climate change. It is worth noticing that the Yellow Sea has the least wind energy resource. The South China Sea has the wealthiest wave energy resource, while the Bohai Sea and the Yellow Sea are poorer.

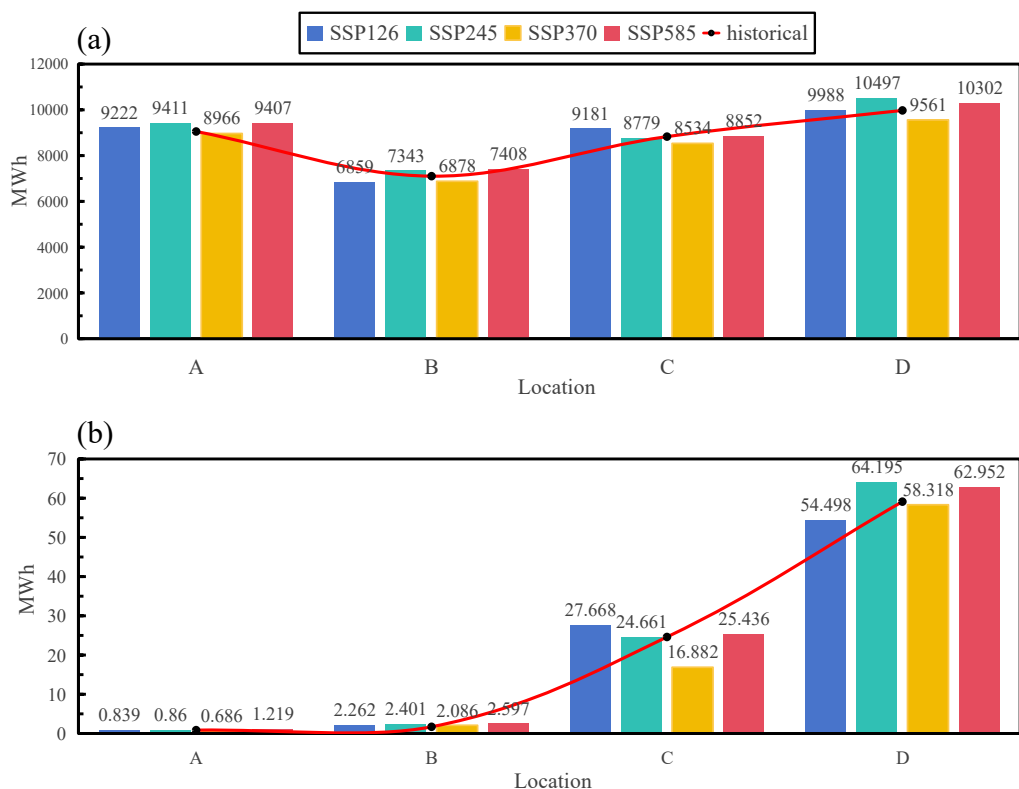


Fig. 19 Multi-year mean total energy output of: (a) wind; and (b) wave energy.

Furthermore, the difference of total wind and wave energy output between four SSPs and the

historical condition at the selected locations are estimated (in percentage), as shown in Fig. 20.

Focusing on the results of SSP245 and SSP585, for the wind energy, there is a slightly increasing trend in the Bohai Sea, the East China Sea and the South China Sea comparing to the historical data.

The difference between SSP245 and SSP585 is insignificant. The SSP370 scenario shows a significant decrease in all areas. The change in percentage of the total wave energy is significant, especially in the Yellow Sea, due to the small base value in the Bohai Sea and the Yellow Sea. For SSP245 and SSP585, the wave energy potential will be higher under the climate change, except for that in the Bohai Sea, where the total wave energy in SSP245 and SSP585 are similar. In general, the combined wind and wave energy potential will increase to some extent in coastal waters of China when the global emission increases.

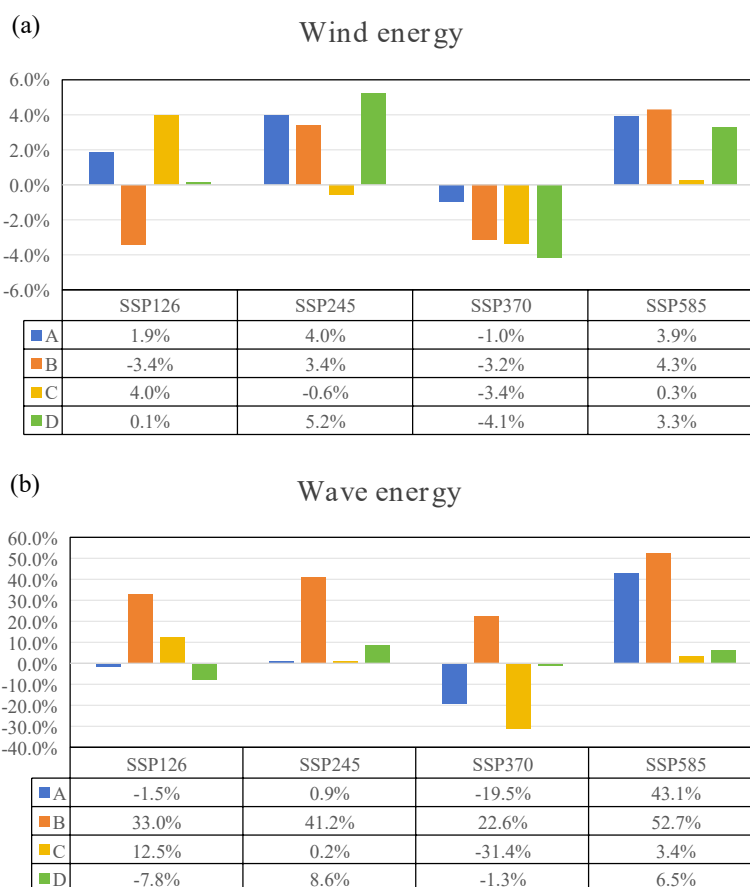


Fig. 20 The difference between the annual total power output during 2081-2100 under different SSPs from the historical conditions during 2000-2014 (in percentage)

5. Performance of wind and wave energy generation

Two criteria proposed by Rusu et al. [73] are adopted in this study to evaluate the performance of wind and wave energy generation in China. First, the wind and wave power density are classified in 7 classes, from C1 to C7, to indicate the energy potential from poor to superb as listed in Table 6. Fig. 21 shows the classification of multi-year mean WPD and WED. As the WT and WEC are currently constructed in the relatively shallow water area (the floating WT currently can be installed in a water depth of generally no more than 120 m), only the classification of multi-year mean WPD and WED in areas within 200m water depth are shown. The results show generally that the WED along the China's coasts is between C1 and C2, while the WPD varies from C1 to C7, with the high WED resources in the relatively deep water areas. This indicates that China's offshore wind energy resources are more abundant than wave energy resources. The distributions of the classifications are found to have similar patterns in the historical scenarios, SSP245 and SSP585. Therefore, the wind farm may remain as the main stream of offshore clean energy development for China in the future.

Table 6 Classification of WPD and WED (adopted from [73])

Wind/Wave power Classification	Energy potential	WPD (in W/m ²)	WED (in kW/m)
C1	Poor	<126	<5
C2	Marginal	126 - 201	5-25
C3	Fair	201-258	25-50
C4	Good	258-326	50-100
C5	Excellent	326-390	100-200
C6	Outstanding	390-509	200-500
C7	Superb	≥509	≥500

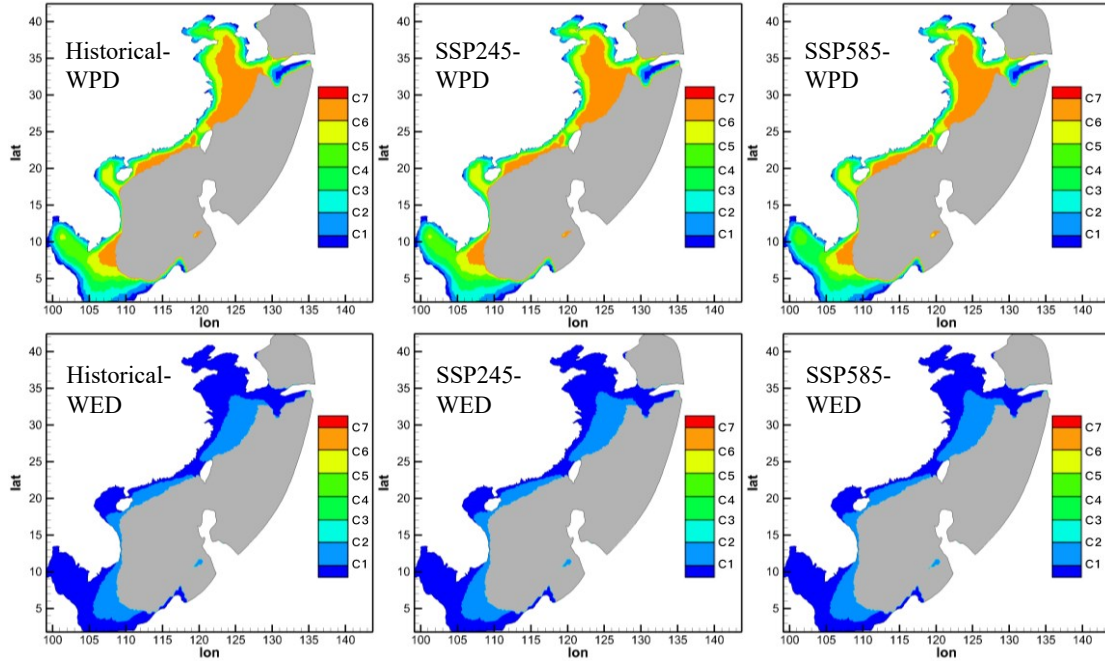


Fig. 21 The distribution of multi-year mean WPD and WED classes

The THD index is also used in this study to analyse the performance of wind and wave energy generation on the smoothness of power at the selected locations with Eq. 10. The locations with a small THD index are regarded as the sites to produce a stable power quality, i.e. a good performance of energy generation. Fig. 22 shows the calculated THD values under different SSPs and historical condition at 4 selected locations for wind and wave energy generation. In general, for both wind and wave energy generation, the highest THD values are found at location A, indicating that wind and wave energy generation is least reliable in the Bohai Bay, but more reliable at other locations with relatively lower THD values. However, the impact of climate change on the reliability of energy generation varies. At location A (the Bohai Bay), THD decreases when the climate change intensifies, indicating an improved reliability in energy generation, whilst at locations B (the Yellow Sea) and D (the South China Sea), THD increases with the increase of greenhouse gas emission, indicating a slight worsening of the reliability in energy generation. At location C (the East China Sea), the wave energy THD increase when the climate change intensifies, however, the wind energy THD decreases under SSP245 and SSP370, but increases under SSP585, indicating different or complex responses of the wind energy generation at this location to the climate change scenarios.

Comparing wind and wave energy generation, it is found that the THD index of wind energy is lower than that of wave energy in general for all cases. This indicates that the wind energy is more

stable than wave energy at all locations historically and in the future. The results provide useful guidance for the development of wind and wave energy generation in China's coastal waters in the medium and long term.

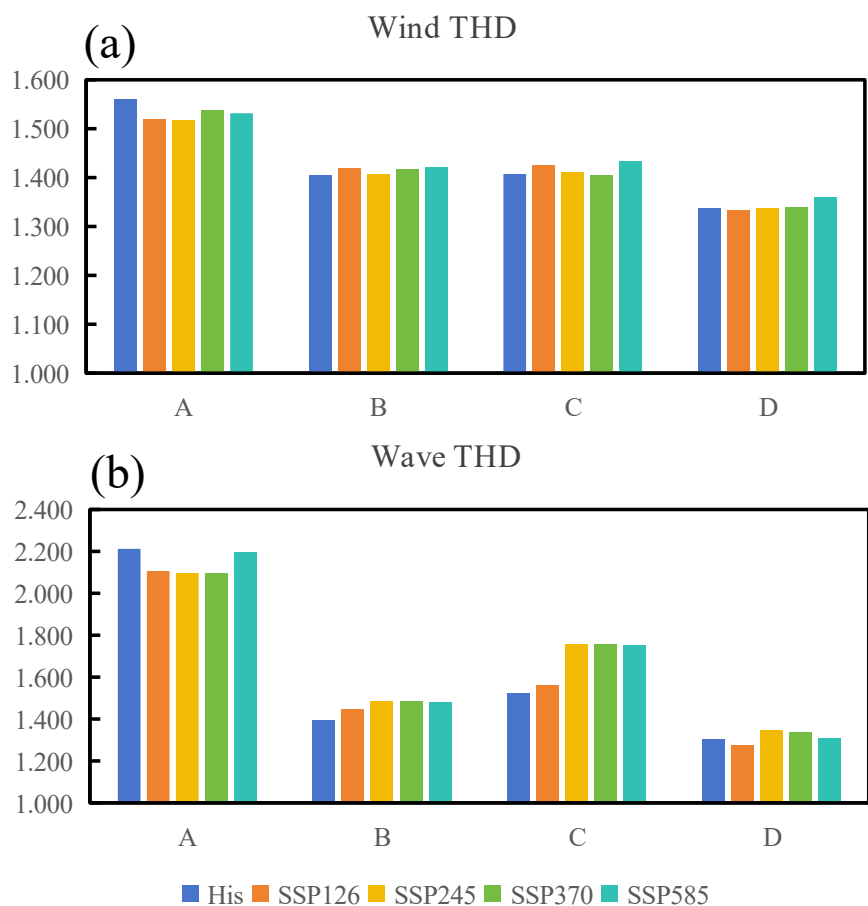


Fig. 22 THD values of (a) wind; and (b) wave energy at the selected locations under different scenarios and historical conditions

In recent years, it has seen an increasing trend in considering the joint development of wind and wave energy, with the studies on the co-generation systems of wind and wave energy for more effectively use the energy [79], as the co-generation systems can reduce the non-operation hours of the wind or wave converter devices. In addition, the wave energy device could absorb the offshore wave energy in the vicinity of the wind turbine platform, so to improve the stability of wind turbines [80]. Thus, for the development of co-generation systems of wind and wave energy, the results of THD analysis conducted in this study can provide insightful guidance on selecting the sites that are most suitable for the co-generation systems.

6. Conclusions

In this study, the change of the future wind and wave energy in China seas are assessed with four CMIP6 climate change scenarios: SSP126, SSP245, SSP370 and SSP585. The wind speed of 16 Global Climate Models (GCMs) in CMIP6 are first compared and it is found that BCC-CSM2-MR, EC-Earth3-Veg-LR, GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0 have the best performance in generating the wind field on China seas. The FVCOM-SWAVE wave model is then driven by the wind fields generated to simulate wave characteristics over the historical (2000 -2014) and future (2080-2100) periods under 4 climate change scenarios. The multi-model ensemble (MME) approach, which can better reflect the distribution of wind and wave in the Chinese coastal waters than using any single CMIP6 GCMs, is applied to the simulated wind speed, significant wave height and wave period to investigate the wind and wave energy resources in the China seas.

The results show that as the emission intensifies, the wind speed in the northern South China Sea increases noticeably, less so in the Bohai Sea and the Yellow Sea, and the opposite trend is observed in the southern South China Sea. The wave height is found to have a decrease trend in most of the deep water areas, which appears to align with the global trend. The wind power density (WPD) in general exhibits a similar distribution pattern of the wind speed. The wave power density (WED) is found to decrease in the East China Sea and the southern South China Sea, but slightly increase in the Bohai Sea, the Yellow Sea and the northern South China Sea, with a general trend of decrease northwards and landwards. The distribution of WED has prominent seasonal characteristics, with more energy being available in autumn and winter seasons and less in spring and summer seasons.

Comparing the results for four climate change scenarios indicates that the changes of wind and wave energy potentials under SSP245 and SSP585 follow a similar pattern, but some diversities are found for SSP126 and SSP370, which may be caused by the different land use and radiation forcing. Thus, the SSP245 and SSP585 scenarios appear to be more representative.

The performance analysis of wind and wave energy generation through the THD values indicates that the wind energy has a better stability in addition to the abundance in China's coastal waters, which may lead to a dominant position of wind energy in the marine clean energy development in the future. It can also help the selection of the suitable sites for the development of

co-generation systems of wind and wave energy in the region in the future for a more effective use of the energy and a safer operation of wind turbine.

The results of this study can provide valuable guidance for the future deployment of wind farms and wave energy generation systems in China. It is worth noting that effect of sea level rise, which could affect the tide and wave characteristics is not included in this study.

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