Abstract: With the purpose of achieving carbon emission reduction targets, the wind power industry has developed rapidly in recent years. Wind power is greatly affected by climate change, and the increase or decrease of wind speed directly affects wind energy production. Based on the numerical simulation results from a high-resolution (~25 km) regional climate model PRECIS, we analyze the changes of future wind speed and wind power potential in the “Three North” (TN) region in China. Firstly, we verify whether the PRECIS can capture the current spatiotemporal patterns in simulating the wind speed compared with observation (CN05.1). The results show PRECIS has a good ability in reproducing the spatiotemporal patterns of wind speed in the eastern part of the TN region, but still has great uncertainty in the northwest. In the future, the projected wind power density in the TN region will increase by about 0.7% in the middle of the 21st century, but will drop significantly in the end of the century (~−3.32%). Furthermore, wind power density will increase significantly in winter. However, the wind speed in spring and summer will generally decrease. It is predicted that most of the Northwest (NW) and North (N) will have strong inter-annual variability in the middle of this century, and will be more stable at the end of this century. It should be noted that the potential of wind energy in Northeast (NE) will grow steadily in this century, which will have certain guiding significance for future wind power planning in this region.

Keywords: wind energy potential; “Three North” region; PRECIS; climate change

1. Introduction

The fifth IPCC assessment report (AR5) indicates that the climate system is undoubtedly getting warmer. The atmosphere and oceans have warmed, snow and ice have melted, and sea levels have risen. Meanwhile, many extreme weather and climate events (such as extreme precipitation and heat waves) have been observed since around 1950, in which both human and natural systems have demonstrated vulnerability to climate variability. Net carbon dioxide emissions are the decisive factor for future global warming, so we need to make greater efforts than before to reduce carbon emissions and kick carbon habits. To limit global warming within 1.5 °C above pre-industrial levels, the world must limit its carbon emissions to at least 49% of 2017’s level by 2030 and then become carbon neutral by 2050 to meet this target, according to a summary of the IPCC report [1]. Luderer et al [2] thought that achieving this goal would require a reduction of 64 ~ 95 billion tonnes of carbon dioxide emissions.

For this purpose, countries around the world are working on how to slow down global warming. European governments have agreed in 2016—in response to the Paris climate agreement—to cut greenhouse-gas emissions by at least 40% by 2030 relative to the level in 1990 [3]. China is now the
world’s largest energy consumer and carbon dioxide emitter and has a major responsibility for reducing carbon emissions [4]. China signed the Paris agreement and set its targets for action on climate change by 2030 as follows: reduce CO$_2$ emissions per unit of GDP (carbon intensity) by 60%–65% from 2005, and peak CO$_2$ emissions by 2030. In 2017, China’s CO$_2$ emissions per unit of GDP were about 46% lower than in 2005, and some targets for 2020 have been met ahead of schedule. Nevertheless, in order to achieve the goal of controlling climate change to 1.5 °C, the unprecedented pressure of emission reduction still poses great challenges to China. Increasing the proportion of non-fossil energy in primary energy is an important means to deal with global warming, and it is also an inevitable trend.

With the rapid development of renewable energy in recent years, the installed capacity of wind power and solar energy has been increasing. Due to the more mature technology and lower cost, wind power should be placed on the priority position in the development of renewable energy. Globally, there are five major hotspots of abundant wind resources, including the central-northern region of North America, southern South America, northern/north-western Europe, northern Asia and the central-south-eastern region of the Asian continent [5]. This energy source, which has little carbon emissions, will potentially contribute to climate change mitigation [6].

China has abundant wind energy resources, with an estimated 1400 GW of onshore wind energy reserves (50 meters) and 600 GW of offshore wind energy reserves. The last decade was the golden age of wind power development. As the most promising renewable energy source in China, a comprehensive assessment of wind energy production has determined that by 2030, and the potential of integrated wind power generation in power grids will reach 11.9% to 14% of China’s estimated energy demand [7].

On the other hand, though wind energy has made great contributions to mitigating global warming, the development of wind energy is also being challenged by a changing global climate. By analyzing the observed wind speed data, China has experienced a significant decline in wind speed over the past half-century, especially in North China [8,9]. Yu et al. [10] analyzed the variation trends of 80-meter wind speed in and around China from 1979 to 2011, and indicated that the seasonal and interannual variability is very strong, particularly in summer and autumn. China and its surrounding sea areas showed a decreasing trend dominated by the sharp decline since 2005. Owing to the negative trend of wind energy in China, people began to doubt whether this clean energy source had sustainable development potential.

Climate change will have a major impact on the planning and operation of the power system [11]. For wind power, the direct impact of climate change is to change the wind speed acting on the blades. Since the wind energy density is proportional to the cube of the wind speed, it significantly affects the power generation [12]. It is noted that the current wind power construction is largely based on the assumption that wind speed will not change in the future. However, whether it is the analysis of historical data or future wind energy forecasts, global wind resources are changing dramatically, and in many places, this trend is even negative. Considering the vigorous development of wind energy, the forecast of wind resources is particularly important to the planning of wind power systems.

Time series analysis methods and intelligent algorithms are often used to predict wind power within a few days, and mature wind prediction systems have been developed and installed in wind farms. However, the way to predict wind power changes over the next few decades is to use climate models that quantitatively study climate change by simulating atmospheric physical processes. The global climate model does not contain detailed terrestrial processes and is used to simulate wind speed changes at first. Chen et al. [13] assessed the ability of nine CMIP5-coupled atmosphere–ocean general circulation models (AOGCMs) in simulating the near-surface wind over China. They concluded that GCMs showed lower interannual variability and could not reproduce the recent decline in near-surface wind speeds, which have been shown in observations. Moreover, they indicated that the uncertainty among different GCMs in RCPs is smaller than that in previous climate scenarios. Carvalho et al. [14] used a multi-model ensemble of 21 CMIP5 models to forecast the wind power in north-central Europe,
indicating an increase in wind power near the Baltic sea and a decrease in wind power near the Mediterranean Sea in the future, but little interannual variation across Europe.

On the other hand, the regional climate model, which can capture the characteristics of regional scale temperature, precipitation distribution and soil water change that are difficult to be distinguished by many atmospheric circulation models, has become an important tool for climate prediction. Hueging et al. [15] used the ECHAM-driven regional climate model CCLM and REMO to capture future European wind energy density and its interannual variation, and predicted that wind energy potential in northern and central Europe would increase, while southern Europe showed a declining trend in all seasons except over the Aegean Sea. Tobin et al. [12] used 15 RCM under A1B scenario to assess the impact of climate change on European wind energy in this century and came to a similar conclusion: in the middle and late of this century, the change in wind energy potential is within 15% and 20%, respectively. According to a study by Pryor et al. [16], wind energy in the United States will not change beyond the historical range for at least the next 50 years, and wind resource-rich regions will continue to contribute to the wind power industry. However, there are different opinions about the declining trend in wind speed. For example, Johnson et al. [17] used the output of the four RCM combinations provided by NARCCAP to predict the average wind speed of 50 meters over the continental United States, which is expected to increase the available wind energy in Kansas, Oklahoma, and Texas, and cleverly calculated the considerable additional power generated by climate change in the wind power increase area. Jiang et al. [18] used three regional climate models to simulate the 10-meter wind speed in China and concluded that RCMs had better ability to simulate distribution and variation characteristics of mean wind speed than their driving GCMs, and predicted that the annual and winter mean wind speed in future is lower than that in history. In addition, researchers have been studying more and more extreme wind speeds in recent years. Mo et al. [19] used the reanalysis data NCEP/NCAR to explore the spatial-temporal variation trend of extreme wind speed. According to three GCMs predictions, Jiang et al. [20] predicted that the annual and seasonal maximum wind speeds will decrease in future periods.

In general, current studies mostly use CMIP5 global climate models to forecast China’s future wind energy. However, these large-scale models may ignore some local details, especially in areas with complex terrain. The “Three North” region (TN) is the main area of wind energy distribution in China, but the research of wind energy forecasting is very rare. In addition, compared to mean wind speed, extreme wind speed is also of great significance because it poses a threat to the efficiency and safety of the wind turbines. Therefore, in this paper, we use a high resolution (25 km) regional climate model to simulate the spatiotemporal variability of mean and extreme wind speeds in the TN region, and further analyze the variation trend of wind energy potential under the RCP4.5 scenario.

2. Study Domain

The topographic map of the TN region is presented in Figure 1, and we divided it into three sub-regions, namely, Northeast (NE), North (N), and Northwest (NW) [21,22], where China’s wind power capacity is concentrated. Specifically, the TN region has most of China’s large wind power bases and contributes 74% to China’s installed wind power capacity and 71% to wind power generation [23]. At the provincial level, western and eastern Inner Mongolia, Gansu and Xinjiang currently lead in installed wind power capacity, accounting for 26%, 14%, 14% and 14% of the country’s installed wind power capacity, respectively [9]. In the past half-century, wind energy in these areas has shown a sharp decline trend and increased interannual variability, which has increased the uncertainty of the sustained and stable operation of wind power. Therefore, we hope that the forecast of future wind energy in northern China can be of reference value to the wind power stations under construction and planning in these areas.
3. Data and Methods

3.1. Data

China’s meteorological stations are unevenly distributed, with more stations in the east and fewer in the west. In the TN region, the density of stations in Xinjiang, Qinghai and western Inner Mongolia is small, and the use of station data will generate great uncertainty in these places. RCM simulations have small grid spacing and average distribution, so it is better to test the simulation results with gridded observation data with high spatial resolution [24]. In this paper, we select a lattice observation data set with a resolution of 0.25° × 0.25° as the comparison data (called CN05.1 afterwards). The dataset is based on observations from 2416 China’s ground meteorological stations and is obtained by spatial interpolation [25]. Here, we selected the daily wind speed data from 1975 to 2004 for comparative verification on behalf of China’s historical wind speed climate.

Compared with GCMs, regional climate models have higher resolution and can better represent fine physical processes, and have unique advantages in simulating mesoscale weather features such as cyclones and monsoons. Among numerous RCMs, the PRECIS regional climate model system developed by the UK Met Office Hadley Centre is one of the most popular uses around the world. PRECIS is a high-resolution atmospheric and land surface model of a limited area which is locatable over any part of the globe to provide regional climate information for impacts studies [26]. PRECIS has 50 and 25 km resolutions at the equator of the rotated regular latitude–longitude grid and contains 19 levels in the vertical. It uses regular longitude and latitude grids and mixed vertical coordinate systems to describe dynamic flow, atmospheric sulfur cycle, clouds and precipitation, radiation process, surface, and deep soil, etc. Boundary conditions are required at the limits of the model’s domain to provide the meteorological forcing for the RCM. Information about all the climate elements as they evolve through being modified by the processes represented in the model is produced. Recently, PRECIS has been validated for its skill in simulating temperature and precipitation over China due to its high resolution and universal applicability [27–29].
In this study, we use the global climate model HadGEM2-ES as lateral boundary conditions to drive PRECIS. HadGEM2-ES is an AOGCM developed by the Hadley center of the UK meteorological office. The atmospheric resolution is N96 (1.875° × 1.25°), the vertical resolution is 38 levels, and the temporal resolution of the atmosphere and land is 30 minutes [30]. Moreover, the RCP4.5 climate emission scenario is chosen as a future scenario of the PRECIS with a spatial resolution of 0.22° × 0.22° (~ 25 km) to simulate changes in wind speed and wind energy potential during the middle century (2021–2050, 2030s) and late century (2070–2099, 2080s).

In our study, the regional climate model PRECIS is used to predict the wind power density of the “Three North” (TN) region in the future, rather than a certain wind farm. We used the output of PRECIS, i.e., 10-m wind speed, to simulate and project the future wind power potential, as shown in Figure 2.

![Study Flow Chart](image)

**Figure 2.** Study Flow Chart.

3.2. Methods

3.2.1. Wind Speed at Hub-Height

The wind speed generated by PRECIS is 10 m high, while the hub-height is about 70 m. Thus, wind speed is first extrapolated from 10 m up to the turbine hub-height (here 70 m) by using a vertical wind profile described by the empirical power law shown in Equation (1):

\[ v_2 = v_1 \left( \frac{h}{h_0} \right)^m \]  

(1)

where \( v_2 \) is the wind speed at the turbine hub-height, and \( v_1 \) is the wind speed at \( h_0 \) (10 m). \( m \) is the wind shear exponent, and the typical value is 0.143. However, this way for extrapolating vertically the wind speed does not account for spatiotemporal variations in the boundary layer stability. Assuming that the spatiotemporal variation of the stability of the boundary layer is minimal, \( m \) can be expressed as:

\[ m = 0.37 - 0.0881 \times \ln v_1 \]  

(2)
Therefore, an alternative formula was examined here [22,30,31].

$$v_2 = v_1 \left( \frac{h}{10} \right)^{0.37 - 0.0881 \ln v_1}$$  \hspace{1cm} (3)

### 3.2.2. Wind Power Density (WPD)

WPD is an important measure for assessing the potential of wind energy. It is defined as [31]:

$$P = \frac{1}{2} \rho v^3$$  \hspace{1cm} (4)

where $P$ is wind power density, $v$ is the wind speed at an adjusted to hub-height (70 m), and $\rho$ is the air density, which is related to temperature and elevation [32]:

$$\rho = \left( \frac{353.05}{T} \right) \exp^{-0.034 (z/T)}$$  \hspace{1cm} (5)

### 3.2.3. Statistical Analysis Methods

To estimate the performance of PRECIS quantitatively, we use some statistical parameters, such as bias, Pearson correlation coefficient ($R$) and root mean squared error (RMSE) [33]. Their definitions are as follows:

$$\text{Bias} = \frac{\sum_{i=1}^{n} (S_i - A_i)}{n}$$  \hspace{1cm} (6)

$$R = \frac{\sum_{i=1}^{n} (A_i - \bar{A})(S_i - \bar{S})}{\sqrt{\sum_{i=1}^{n} (A_i - \bar{A})^2 \sum_{i=1}^{n} (S_i - \bar{S})^2}}$$  \hspace{1cm} (7)

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (S_i - A_i)^2}{n}}$$  \hspace{1cm} (8)

Where $A_i$ represents the observation in the grid, $S_i$ the simulated values, $\bar{A}$ is the mean of the measured values, $\bar{S}$ is the mean of the simulated values, and $n$ is the number of observations.

### 4. Result

#### 4.1. Historical Period

The monthly average wind speed characteristics over sub-regions in China between observation and PRECIS in the historical period (1975–2004) are shown in Figure 3. Overall, the PRECIS model can simulate the monthly change trend in the annual cycle, and capture the peak of wind speed in April (Figure 3a–d). In the winter months (December–February), PRECIS overestimates the wind speed in the NE and N regions (Figure 3e,f), while underestimates the NW and the whole TN regions (Figure 3g,h). From March to June, the bias from PRECIS for all sub-regions is negative relative to the observation, with the most bias in April, about -1 m/s. PRECIS shows an agreement with CN05.1 in the NE from July to November. However, PRECIS does not simulate the monthly wind speed well in the NW region in most months (Figure 3c,g).
Figure 3. Spatially averaged monthly wind speeds (a–d) over the TN region from PRECIS (blue line) and observation (red line). The biases are shown in the second row (e–h).

The annual mean wind speed, wind power density and 90th wind speed distribution of PRECIS and observation in the TN region from 1975 to 2004 are calculated (Figure 4). In terms of the annual mean wind speed (Figure 4a–c), PRECIS has a good performance to reproduce the spatial distribution characteristics of mean wind speed in hub-height height. Specifically, compared with the CN05.1 (Figure 4c), PRECIS simulates better in the eastern region, with a bias of about 0.5 m/s. However, PRECIS significantly underestimates the wind speed of 70 m in the north of Inner Mongolia and the west of Qinghai province, while an obvious positive deviation occurs in the Tarim Basin of Xinjiang. These results are also similar to other studies [5,32]. The distribution characteristics of wind power density simulated by PRECIS are similar to the wind speed (Figure 4d–f). Compared with the CN05.1, the wind energy results are simulated well in the northeast and east of the N region, although there is a negative deviation in the north of Inner Mongolia and the Qinghai-Tibet where wind energy is abundant. According to the 90th wind speed (Figure 4g–i), the deviation of PRECIS for the NE and most parts of the N region is within 1.5 m/s, but the deviation in Xinjiang is positive and in western Qinghai is negative.

Figures 5 and 6 are the distributions of seasonal mean wind speed, the wind power density at a 70-m height in the TN region from 1975 to 2004. “ANN”, “DJF”, “SON”, “JJA” and “MAM” indicating annual, winter, fall, summer and spring, respectively. Although PRECIS shows a good performance in simulating in seasonal mean wind speed and WPD, some local regions, such as the NE, the northern part of Inner Mongolia and the Qinghai Tibet plateau, show the largest negative deviation in the spring, and the wind speed is also underestimated by 1.5–2.5 m/s and the wind power by 50–100 W/m². In summer (Figure 6b,f,j), most areas in the NE and N regions present better results, but the wind speed in the Xinjiang region is significantly overestimated, indicating that simulated wind resources in Xinjiang in summer is highly uncertain. In winter (Figure 6d,h,l), the 70 m wind speed and wind power density distribution simulated by PRECIS is closer to CN05.1 than those in other seasons. The wind speed deviation is less than 1.5 m/s and the wind power deviation is less than 25 W/m² in most regions except the Qinghai Tibet plateau.
Figure 4. The spatial distribution in mean wind speed in 70 m (m/s) for (a) CN05.1, (b) PRECIS, (c) biases during 1975–2004. Plots (d–f) are same as plots (a–c) but for wind power density and plots (g–i) are the spatial distribution for 90th wind speed.

Figure 5. The spatial distribution in seasonal mean wind speed from PRECIS (first row), CN05.1 (second row) and their bias (third row) over the TN region during the historical period. From the first to the fourth column are spring (MAM), summer (JJA), autumn (SON) and winter (DJF), respectively.
In terms of regionally averaged wind speed (Table 1), the bias of PRECIS in the N and NE regions is between −12.5% and 10.72%, the R is between 0.4 and 0.7, and the RMSE is between 0.7 and 0.9. However, PRECIS shows a worse result in the NW, with the root mean squared error of above 2.0 and the smaller correlation coefficient, resulting in a poor performance in the TN region directly. Similar results in seasonal, the model shows a better ability in the N region but worse in the NW region.

### Table 1. Bias, Pearson correlation coefficient (R), root mean squared error (RMSE) for PRECIS with respect to CN05.1 in mean annual and seasonal wind speed during 1975–2004.

| Region | Season | R     | Bias (%) | RMSE |
|--------|--------|-------|----------|------|
| NE     | MAM    | 0.57  | −12.50   | 1.15 |
|        | JJA    | 0.56  | −2.29    | 0.64 |
|        | SON    | 0.37  | −2.77    | 0.88 |
|        | DJF    | 0.43  | 10.33    | 0.91 |
|        | ANN    | 0.47  | −2.57    | 0.82 |
| N      | MAM    | 0.73  | −5.81    | 0.95 |
|        | JJA    | 0.51  | 4.21     | 0.78 |
|        | SON    | 0.72  | 7.10     | 0.73 |
|        | DJF    | 0.62  | 10.72    | 0.85 |
|        | ANN    | 0.69  | 3.46     | 0.72 |
| NW     | MAM    | 0.02  | −23.42   | 2.80 |
|        | JJA    | −0.13 | −13.93   | 2.70 |
|        | SON    | 0.24  | −21.96   | 2.30 |
|        | DJF    | 0.68  | −21.02   | 2.05 |
|        | ANN    | 0.19  | −20.07   | 2.35 |
| TN     | MAM    | 0.30  | −14.33   | 2.04 |
|        | JJA    | 0.18  | −7.69    | 1.90 |
|        | SON    | 0.36  | −4.59    | 1.64 |
|        | DJF    | 0.63  | −1.51    | 1.59 |
|        | ANN    | 0.38  | −7.46    | 1.69 |
4.2. Future Changes of Wind Power Potential

4.2.1. Changes in Annual Cycle

As shown in Figure 7, PRECIS simulation results show that the changes of mean wind speed in the annual cycle mid-21st century (2030s) are within 6%. It is projected that the wind speed will increase significantly in all northern regions and the wind power density will increase by 10% in the winter (December to February). However, the wind speed of spring (March to May) tends to decrease, especially in May, the wind speed decreased by 1.4%–3.1%, about 0.1–0.18m/s. In summer months, the wind speed will decrease in the middle of the century and slightly increase in autumn. In the late 21st century (2080s), the decline of wind speed in spring will be more obvious, especially in May when the wind power density will fall by 10%–25%, and in other months there will be a certain decline. However, it is worth noting that wind power density in the NE will increase by 10% during the summer (Figure 7e). On the whole, the wind speed will decrease the most in May of this century, and increase from November to February. By the end of the century, the wind speed of almost all months had more decline than that of the mid-21st century (2030s).

![Figure 7. Percentage changes in monthly mean wind speed change (a-d) and wind power density (e-h) in mid-21st century (2021–2050, 2030s) (red line) and late-21st century (2070–2099, 2080s) (blue line) compared with the baseline period (1975–2004).](image)

4.2.2. Changes in Spatial Distribution

Figure 8 shows the changes in annual mean wind speed, 90th wind speed and wind power density in two future periods (2030s and 2080s) under the scenario of RCP4.5. The PRECIS model shows the wind speed in the three sub regions will increase slightly in the early part of this century (Figure 8a), with an increase range of 0.33% to 0.47% (Table 2). The areas where wind speed dropped are mainly in western Inner Mongolia and Xinjiang. The 90th wind speed showed a larger geographical decline compared with the annual mean wind speed. For example, the annual mean wind speed in NE will increase slightly in the future period, while the 90th wind speed shows a decreasing trend. The variation of wind power density is similar to that of wind speed, but the variation amplitude is larger (Figure 8c,f). It is projected that the wind power density will increase in the NE and N regions (by 0.07% and 0.46%, respectively) in the middle of the century, but decrease slightly in the NW region (by −0.06%). At the end of this century, the trend of wind speed change is even more significant than the previous period. The annual mean wind speed in the N and NW regions will decrease by −1.04% and −1.23%, and increase by 0.30% in the NE region (Figure 8d). The wind power density in the TN region will decrease by −3.32%, and the wind power density in the NW will decrease the most (about −5.18%).
As the motivation of wind power generation, wind speed has obvious seasonal characteristics, so it is of practical significance to study the future changes of seasonal mean wind speed and wind power density. Figure 9 shows the change of the seasonal mean wind speed and wind power density under RCP4.5 in the middle of the century (2030s) and the end of the century (2080s). Overall, the PRECIS model predicts that wind speed in the TN region will decrease in spring, with the greatest decrease in the NE region (−2.08%) and the least decrease in the NW region (−0.52%). In summer, the wind speed in the TN region still decreases, while the wind speed will increase in the eastern and northwestern parts of Inner Mongolia (Figure 9b). The average wind speed in autumn will increase in most parts of N and NE, while the wind speed decreases in most parts of NW, but the overall trend was still a weak increase. It is worth noting that, due to climate change, the winter wind speed in the whole TN region will increase significantly in the middle of the century, among which the NW region will have the most significant change in wind speed, increasing by 4.13% (Figure 9d). In general, the wind speed decreased in spring and summer in the middle of the century, but increased in autumn and winter, and the wind speed changed the most in winter, increasing by 2.91% in the TN region as a whole.
4.2.3. Interannual Variability in Future

The interannual variability is calculated as the standard deviation of the average annual wind speed and wind power density in each period. As can be seen from Figure 10, the region with the largest interannual variation of wind speed in the middle of the century is in the hinterland of Xinjiang, followed by the North China Plain (Figure 10a), while the interannual variation is relatively small in the eastern part of NW. The spatial distribution of interannual variation of wind power density in the middle of the century is similar to that of wind speed, but the interannual variation is larger. For example, the interannual variability of Xinjiang hinterland is over 20 W/m². In the late 21st century, the interannual variability of wind speed in most parts of NE and N will be lower than that in the 2030s (Figure 10b). The interannual variability is the smallest in the NE and the largest in the NW region.
The wind speed in the N region is the highest in all seasons except summer. The wind speed in the NW is lower than that in the NE and N regions in autumn and winter, but it is higher than that in summer. Figure 11 shows the interannual changes of the average seasonal wind speed in the TN region from 2021 to 2099. The wind speed in almost all seasons shows a trend of decline in this century, especially in winter. In spring, the wind speed in the N region and the whole TN region will decrease slightly, with the fastest decline in the NW, with a trend of $-0.017 \text{ m s}^{-1} \text{ decade}^{-1}$, but a slight increase in the NE. The mean wind speed in summer is similar among the three regions. The summer wind speed in the NW region shows a decreasing trend of $-0.02 \text{ m s}^{-1} \text{ decade}^{-1}$, but the NE region maintains a rising trend in spring, with a changing trend of $0.017 \text{ m s}^{-1} \text{ decade}^{-1}$. In autumn, the average wind speed in all areas will decrease at a speed of about $-0.01 \text{ m s}^{-1} \text{ decade}^{-1}$, but increase somewhat after 2085. In winter, the trend of the whole TN area is $-0.022 \text{ m s}^{-1} \text{ decade}^{-1}$, and the wind speed in NE and N regions will decrease at $-0.01$ and $-0.026 \text{ m s}^{-1} \text{ decade}^{-1}$, respectively. It can be seen that the mean wind speed in the N region is the highest in all seasons except summer. The wind speed in the NW is lower than that in the NE and N regions in autumn and winter, but it is higher than that in summer.

Figure 11. Interannual mean wind speed change in (a) spring (MAM), (b) summer (JJA), (c) autumn (SON), (d) winter (DJF) during the period 2021–2099.
5. Summary and Discussion

In this study, we used the high-resolution PRECIS model driven by HadGEM2-ES to estimate future changes of wind speed and wind power density in the TN region. The potential changes were estimated for the near future decades (2030s) and the end of the 21st century (2080s) under the IPCC RCP4.5 emission scenario. The main results of this study are summarized in the following:

(1) Overall, PRECIS can simulate well the wind speed at a 70 m height in the baseline period, though underestimation in spring and overestimated wind speed in winter. The simulations show better results from July to November. With regards to spatial characteristics, the annual mean wind speed, wind power density and 90th wind speed simulated by PRECIS have a good consistency with the observed data, especially in the east of TN region.

(2) The PRECIS model predicts a slight increase in wind speed in the TN region in the middle of this century (about 0.39%), with strong seasonal and regional characteristics. However, by the end of the century, the wind speed in all regions except the NE region will decrease, varying from −1.04% to −1.23%. The variation of wind power density is similar to that of wind speed, but the variation amplitude is larger. The change is expected to be within 5.18% by the end of the century. The predicted spatial characteristics of wind energy are consistent with changes on a global scale. For example, Kamauskas et al. [34] found a decrease in wind power generation in the mid-latitudes of the northern hemisphere, and a decrease in wind power generation in Inner Mongolia. This may be related to the fact that the response of atmospheric circulation to the radiative change of surface temperature can be transmitted by downscaling. The study of Jiang et al. [35] predicted that the average wind speed would decrease in the N region and increase in the NE in this century. Gao et al. [36] forecasted the future changes of wind resources in China, and concluded that the regions with the most abundant wind energy have a slight decrease in wind resources (3% ~ 4%) under RCP4.5 and RCP8.5 scenarios. The decrease of horizontal pressure gradient force is the main reason for the decrease of wind speed. Warming at near-surface levels reduces the temperature and pressure gradient between the ocean and the land, and reduces the driving force of the wind [37].

(3) In terms of the mean seasonal wind energy, it is projected that in the next few decades (2030s), wind energy in most parts of the TN region will generally decrease in spring and summer, while wind energy in winter will increase. At the end of this century (2080s), the wind energy will show a significant trend of decrease, and only increased in winter. The significant increase of winter power density in the Three North (TN) region is consistent with the research conclusion of Guo et al. [38]. However, the results are different from some studies. For example, Jiang et al. [18] estimated the increase (decrease) of wind speed in summer (winter) in the TN region, but confirmed the increase in the NE region in winter. The reason that causes the difference may be the selection of GCM and the difference of spatial resolution. In addition, the uncertainty of the results in this paper also stems from the fact that only RCP4.5 emission scenario and a single regional climate model are used.

(4) The interannual variability of wind speed and wind power density are large, especially in the hinterland of Xinjiang and the North China Plain in future decades (2030s), leading to a higher irregularity of wind energy production. However, the interannual variability in most areas of NE and N regions shows a decreasing trend at the end of century.

In the future, the effective wind energy and available hours should be taken into account, and the changes of future wind power generation should be analyzed based on the distribution of wind farms. As the main source of onshore wind power in China, the reduction of wind energy in the TN region in this century will have a certain impact on the energy system in China. Therefore, the site selection of wind power should be based on future wind speed changes to make a more accurate assessment. In addition, the wind energy potential of NE will grow steadily in this century, which is of positive significance for wind power output and site selection of wind farms in this region.

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data resources; Z.P. helped perform the analysis with constructive discussions; B.H. provided suggestions on the revision of the manuscript. All authors have read and agreed to the published version of the manuscript.

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