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On the potential change in wind power over the US due to increases of atmospheric greenhouse gases

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Abstract

Wind power (WP) is a likely source of renewable energy to reduce fossil CO_2 atmospheric emissions. However, WP availability might be affected by climate changes induced by such emissions. In this study a refined regional climate model, appropriate for resolving near-surface flows, was used to generate WP climatologies for the US consistent with present and mid-21st century enhanced atmospheric CO_2 level. In both cases the regional climate simulation was forced by lateral boundary conditions based on simulations of the Hadley Centre general circulation model. Simulated present WP showed reasonable general agreement with patterns observed in most locations. In most of the US the enhanced CO_2 simulation showed a trend of decreased daily average WP availability in the range of 0–30%. However, in limited areas in the southern and northwestern US, an increase in WP, peaking at 30%, was simulated. Under the enhanced CO_2 climate scenario, the present relatively high WP availability in northern Texas and western Oklahoma, as well as in the northwest US, are almost unaffected. A decline in WP is simulated in the north–central US and the western mountainous region. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

In recent years there has been a world-wide accelerated increase in the generation of electricity from wind power (WP) which is supplied to the national/state power

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grid [1]. This trend has been motivated by technological advancement in wind turbines that reduce energy production cost, as well as by environmental concerns about the use of non-renewable energy sources. Presently WP production is the most advanced and commercially available solar energy technology. Concerns about increased emissions of CO_2 and other greenhouse gases motivated the well-known Kyoto Protocol calling for a reduction in the emission of these gases. Continuing political pressure and mounting public concern will likely increase further the incentive for renewable energy and, in particular, wind energy.

Electric energy production in the US has been linked to local utility monopolies and thus constraints are imposed on shifting electricity (including WP-generated electricity) from state to state, where it may replace capacity required to be generated by fossil fuel. In the US a national electric grid is likely to be established in the coming years following implementation of electric utility industry deregulation [2]. Under this scenario of electric power distribution, the economics of WP feeding into the national electric grid will become more attractive, as the usage of WP will not be limited to the locale of its production. A continuing trend of increased WP production will contribute to reducing the growth of CO_2 emissions. The WP contribution may be beneficial in this context for two objectives: (1) energy displacement (i.e., reducing the amount of electrical energy required by conventional generation because of WP usage), and (2) capacity displacement (i.e., reducing the amount of conventional generating capacity required because of contributed WP capacity).

Various geographical locations in the US have been identified to be rich in WP based on observational analyses [3,4]. Among these are the coastal northwest and northeast of the US, northern Texas and northwestern Oklahoma, the north–central High Plains and various locations in the Rocky Mountains and western coast region. Assuming following the above arguments that economic incentives will encourage the development of WP parks in locations rich in wind energy, we might ask, how might potential climatic changes due to increased atmospheric greenhouse gases (GHG), and in particular CO_2, affect the capacity of such wind energy parks? Prediction of climate response to increasing CO_2 using general circulation numerical models (GCMs) has indicated, for example, a weakening of the south–north atmospheric temperature gradients and consequently a northward shift of mid-latitude weather systems affecting the US [5]. It is likely, therefore, that some modifications in the present surface wind field climatology would be associated with the enhanced CO_2 climate scenario. Quantification of the potential changes in WP in the enhanced CO_2 climate would be beneficial in consideration of any plans to develop substantially the WP sources in the US.

We have used GCM and atmospheric regional model results to explore the potential variation in WP availability in the US. For this purpose we have compared the present and mid-21st century WP fields (by the year 2050, the atmospheric CO_2 concentration is projected to rise by ~70% from present levels under a scenario of an annual increase of 1% in CO_2 emission). It is acknowledged that there are some questions in the scientific community regarding the validity of GCM-predicted enhanced CO_2 climate scenarios. However, in recent years there appears to be a growing scientific consensus supporting their use as a first approximation for potential enhanced CO_2 climate [6]. Bearing in mind the scientific uncertainty about enhanced CO_2 impact on climate, the results presented in this paper should be considered as exploratory.

2. Methodology

GCMs use relatively coarse horizontal grid resolution (typically 200–400 km). Although these models produce the general climatic features on a global scale, their grid resolution is not sufficient to resolve flow patterns in detail needed for WP evaluations, especially over mountainous areas (where the terrain is strongly smoothed due to the coarse grid resolution). However, in order to evaluate future surface flow in an enhanced atmospheric CO_2 climate scenario, GCMs are the only option available to be used. In order to overcome to some extent the limitation posed by coarse grid resolution, a local downscaling of the GCM output may be adopted [7]. Our modeling approach employs a relatively refined grid regional model over the US which is one-way nested to the GCM.

The GCM adopted in this study is the HadCM2 [8], which is a coupled atmosphere–ocean model that uses a finite difference grid of 2.5° latitude by 3.75° longitude (about 300 km in mid-latitudes). The HadCM2 driving output for our scenario simulation is from a transient simulation that assumed a 1% per year increase in the emission rate of effective greenhouse gases after 1990. (It should be noted that aerosol effects are not included in this HadCM2 scenario run.) A detailed description of HadCM2 simulations appears in Ref. [8].

The regional climate model adopted in this study is the RegCM2 [9,10], which in our implementation uses a horizontal grid resolution of 52 km and physical formulations similar to those used in GCMs. In particular the RegCM2 enables improved resolution of terrain, which is important in providing more realistic patterns to the WP fields. However, even with this relatively refined horizontal grid resolution, local terrain effects on flow are resolved only crudely for WP siting considerations. Overall the regional model provides the background pattern of flow and WP fields, but may misrepresent local small-scale effects (when the horizontal scale of meteorological forcing is less than about 100 km). For example, effects of local topography, land cover or sea breezes would only be crudely reflected in the simulated WP fields. Refined grid simulations capable of capturing the impact of these processes on WP [11] are presently prohibited by computer capacity in climatic studies. Thus the information obtained from the regional model is indicative of approximate patterns of WP, which is appropriate given the approximate character of enhanced CO_2 atmospheric predictions. Regional climatological studies with the RegCM2 have indicated reasonable agreement with observed climatological patterns [12].

In this study we nested the high-grid-resolution regional climate model (RegCM2) into the low-grid-resolution GCM (HadCM2) over the continental US. Two 10-year climate simulations for the continental US were performed using RegCM2, one forced by lateral boundary conditions from the GCM present climate and the other forced by the GCM enhanced CO_2 climate scenario. The 10-year window selected for present climate corresponds roughly to later years in the 20th century. The enhanced CO_2 climate scenario corresponds to the 2040s. The regional model's lateral boundary conditions were updated every 6 h within the buffer zone (generally located outside the US) where the model-predicted variables were gradually nudged to GCM output. Both model runs were for 3 months plus 10 years, with the first 3 months discarded from analysis to reduce spinup effects. The simulation forced by the current GCM climate provides a basis for evaluating RegCM2's capability to produce mesoscale climate details over the US, while differences between the GCM control and the scenario forced simulations are used to infer climate changes.

We processed the simulated wind speed in terms of WP at the first model level (~40 m), which is assumed also to be the characteristic height of wind energy turbines. The WP was computed based on the standard formula for wind power

$$\mathrm{WP}=\frac{1}{2}\rho_{\mathrm{a}}V^3, \tag{1}$$

where ρ_{a} is the air density and V the wind speed.

3. Results

All of the results presented in this study are based on average 10-year values. The 00UTC, 06UTC, 12UTC and 18UTC WP fields were included in the presentation of the results. Annual and seasonal daily average WP patterns are computed from simulations of the present climate and are presented along with the change in WP under the GCM climate scenario. The seasons are defined as follows: winter — December, January and February; spring — March, April and May; summer — June, July and August; and fall — September, October and November.

It is worth noting that, by the usual standards of atmospheric modeling, simulated wind speed accuracy within an error of $\pm 1\ \mathrm{m\ s^{-1}}$ is regarded as quite accurate. However, since WP is proportional to V^3, a relatively small bias in wind speed yields a relatively large bias in WP for moderate or high values of V ($\Delta\mathrm{WP}/\Delta V \cong 1.5V^2$). When the wind speed is, for example, $7\ \mathrm{m\ s^{-1}}$, an error of $\pm 1\ \mathrm{m\ s^{-1}}$ in the predicted wind speed would translate to an error of ~75 $\mathrm{W\ m^{-2}}$ in WP. Errors in predicted wind speed caused by model horizontal grid resolution limitations in resolving local flows, particularly when associated with variable topography, are likely to be larger than $1\ \mathrm{m\ s^{-1}}$. This uncertainty has to be considered when interpreting the simulated WP magnitudes.

3.1. Seasonal daily mean WP

Fig. 1 presents the seasonal daily mean WP in the continental US. Evaluation of seasonal WP patterns is important since the economical significance of WP fed into electric utility grids is seasonally dependent. In summer and winter the US national demand for electricity peaks due to demand for space cooling/heating (the summer

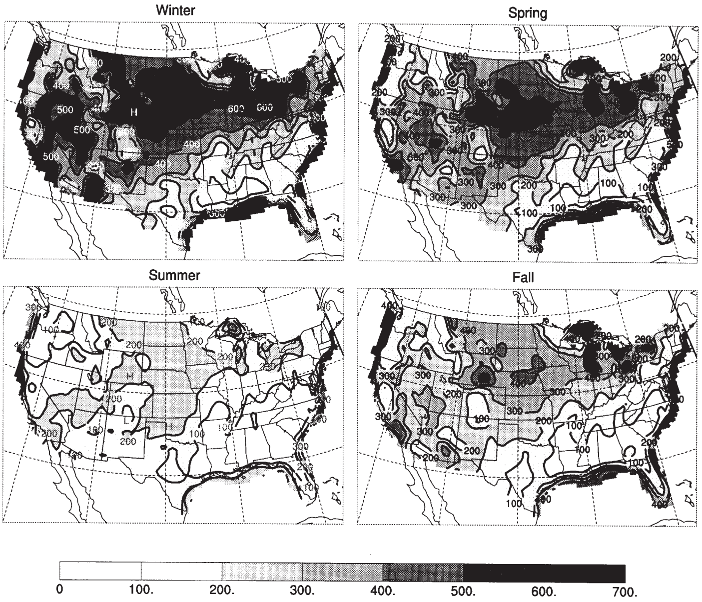

Fig. 1. Simulated seasonal daily mean wind power (W m^{-2}) over the US for the present climate.

peak is higher than the winter one). Therefore, WP is typically of higher economic value in summer and winter than in spring and fall. The simulated seasonal WP patterns are in general agreement with the observed patterns reported in Ref. [4]. However, simulated WP along the Appalachian Mountains, Ozark Mountains and a portion of the Cascade Mountains appears to be underpredicted.

Simulated WP over the US peaks during winter due to strong pressure gradients in wintertime meteorological systems and stronger zonal flow, while generally it is lowest in summer when sub-synoptic meteorological processes dominate. In winter the simulated WP is high over the northwestern coastal US, the western mountain area, the coastal areas of the eastern US, and also over the Great Lakes. Over mountainous regions topographically induced dynamic effects on the flow generate high WP fields. Over water surfaces reduction in low-level atmosphere turbulence enhances flow and the corresponding WP. In summer the simulated enhanced WP is related more to mesoscale processes, including low-level jets in the central US and thermally induced daytime upslope flows over extensive mountainous slopes. Spring and fall WP patterns and magnitude reflect an intermediate situation between winter and summer over the western US mountains area. In the central US, however, spring WP attains only slightly lower values of WP compared with winter. This feature is partially attributed to a more developed daytime atmospheric boundary layer in spring compared with winter, producing more efficient downward flux of horizontal momentum and intensification of near-surface wind [13]. Offshore intensification of WP is simulated along large segments of US coasts for all four seasons.

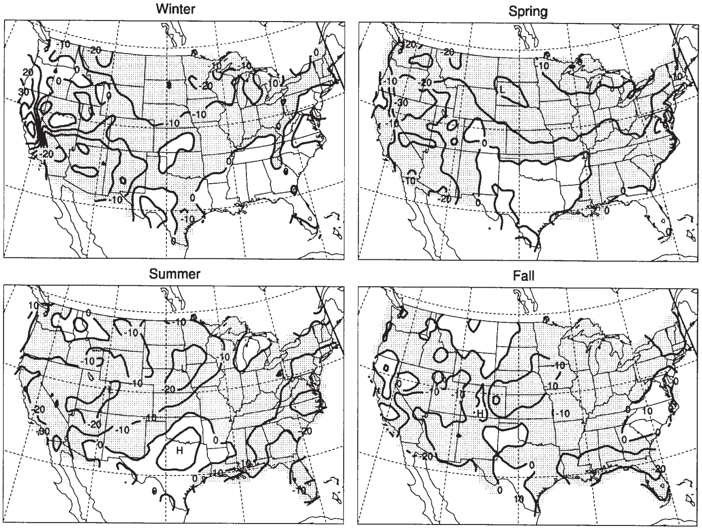

Fig. 2. Change (%) in seasonal daily mean wind power over the US between the enhanced CO_2 and present climate simulations (shading indicates decrease in WP).

Fig. 2 presents the difference in the seasonal daily mean WP between the enhanced CO_2 scenario and the present climate. Most of the US has reduced WP for all seasons with typical decreases of 10–20%. Worth noting is the summer WP decrease in the coastal areas of California, which reaches 30%. Relatively small areas of the US show increases in WP peaking at 30%, most notably in the south–central US. Also noteworthy is the increase in winter WP in the northwest coastal area of the US, and for all seasons in the Texas–Oklahoma area. Both locations are relatively rich in persistent WP resources.

3.2. Annual daily mean WP

Fig. 3(a) presents the simulated annual daily mean WP under the present CO_2 climate scenario (the average of the WP for the four seasons presented previously).

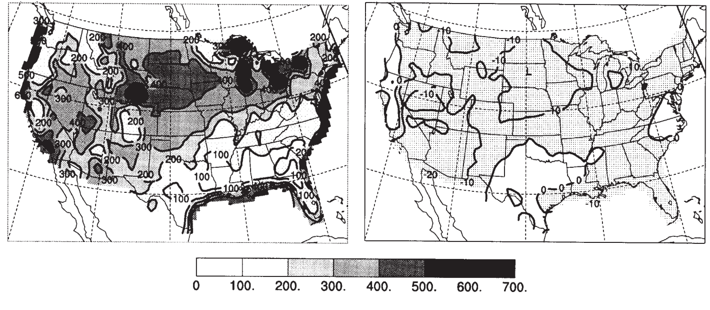

Fig. 3. (a) As Fig. 1, but for annual mean; (b) as Fig. 2, but for annual mean.

The simulation captured the observed annual pattern [3,4] of relatively high availability of WP over the Great Plains and the northern Rocky Mountains, and the northwest coastal US. Also, over the Great Lakes and north–central area of the US, large WP values are simulated in agreement with observations.

The difference in the annual daily mean WP between the enhanced CO_2 climate scenario and the present climate is presented in Fig. 3(b). The simulated range of change in WP is typically 10%. A decrease in WP in most of the US is simulated, except for the south–central US, the coastal northwest US and Virginia. The annual change in WP appears to be relatively secondary considering economical conditions of utilization of WP.

3.3. Seasonal WP at 00UTC

Peak load of electric utilities typically occurs in the afternoon hours in summer or late afternoon/evening in the winter, so that WP at these hours is of high economic value. It is therefore worthwhile to examine the simulated WP pattern around these times. In the following we present the impact of the enhanced CO_2 climate scenario on WP availability at 00UTC for summer and winter.

The 00UTC seasonal WP patterns (Fig. 4) are similar to the daily average presented in Fig. 1, with the winter WP generally higher than in the summer. High availability of WP in both seasons is simulated in the coastal northwest, the western mountains, and the central to north–central US.

The pattern of change in WP in response to the enhanced CO_2 climate scenario (Fig. 5) shows qualitative resemblance to that presented for the winter and summer daily average WP. However, the magnitude of the increase/decrease in WP showed somewhat higher values and changes as high as 40% have been simulated.

4. Conclusion

Present climate and future enhanced CO_2 climate scenario simulated by a GCM were used to provide initial and lateral boundary conditions to a regional model for

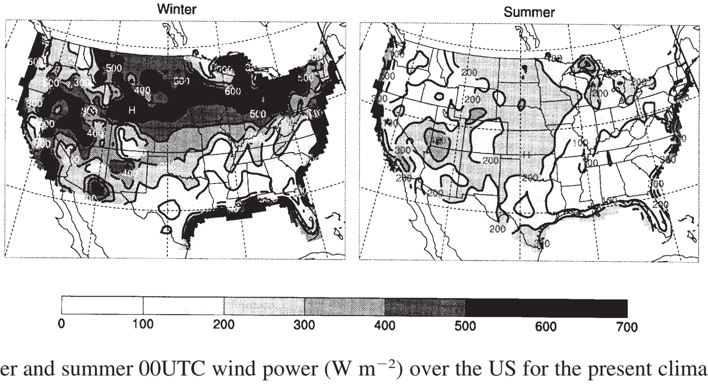

Fig. 4. Winter and summer 00UTC wind power (W m^{-2}) over the US for the present climate simulation.

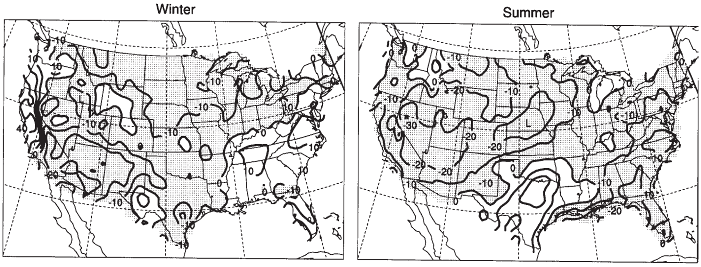

Fig. 5. Change (%) in the winter and summer wind power at 00UTC for the US between the enhanced CO_2 and present climate simulations (shading indicates decrease in WP).

climatological simulations of wind energy for the US. Both the GCM and the regional meteorological models are state-of-the-art. Possible limitations in the simulations of both models within the context of WP have been evaluated. Except for several geographical locations, the regional model was found to simulate reasonably the general patterns of present climate WP fields for the US as indicated from comparison with observations. Considering seasonal WP patterns it was found that, in most of the US, WP under the enhanced CO_2 climate scenario would decrease within the range of 0–30% on a seasonal basis. In small areas of the US, WP in the enhanced CO_2 climate scenario would increase in the range 0–30%. On an annual basis the WP changes were as high as ±10%. The central High Plains and the coastal northwest areas with relatively rich WP availability in the present climate were only slightly affected. However, a decline in WP was simulated in the rich WP fields in the north–central US, and the mountainous areas of northwestern US. Finally, it is worth emphasizing that the accuracy of the presented change in WP under enhanced atmospheric CO_2 climate scenario is linked to the capability of the GCM to capture realistically the patterns of this climate. Considering potential biases in GCMs predictions, it is suggested that the results presented in this paper should be viewed as exploratory.

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