Potential Climatic Impacts and Reliability of Large-Scale Offshore Wind Farms

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Potential climatic impacts and reliability of large-scale offshore wind farms

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Abstract

The vast availability of wind power has fueled substantial interest in this renewable energy source as a potential near-zero greenhouse gas emission technology for meeting future world energy needs while addressing the climate change issue. However, in order to provide even a fraction of the estimated future energy needs, a large-scale deployment of wind turbines (several million) is required. The consequent environmental impacts, and the inherent reliability of such a large-scale usage of intermittent wind power would have to be carefully assessed, in addition to the need to lower the high current unit wind power costs. Our previous study (Wang and Prinn 2010 *Atmos. Chem. Phys.* **10** 2053) using a three-dimensional climate model suggested that a large deployment of wind turbines over land to meet about 10% of predicted world energy needs in 2100 could lead to a significant temperature increase in the lower atmosphere over the installed regions. A global-scale perturbation to the general circulation patterns as well as to the cloud and precipitation distribution was also predicted. In the later study reported here, we conducted a set of six additional model simulations using an improved climate model to further address the potential environmental and intermittency issues of large-scale deployment of offshore wind turbines for differing installation areas and spatial densities. In contrast to the previous land installation results, the offshore wind turbine installations are found to cause a surface cooling over the installed offshore regions. This cooling is due principally to the enhanced latent heat flux from the sea surface to lower atmosphere, driven by an increase in turbulent mixing caused by the wind turbines which was not entirely offset by the concurrent reduction of mean wind kinetic energy. We found that the perturbation of the large-scale deployment of offshore wind turbines to the global climate is relatively small compared to the case of land-based installations. However, the intermittency caused by the significant seasonal wind variations over several major offshore sites is substantial, and demands further options to ensure the reliability of large-scale offshore wind power. The method that we used to simulate the offshore wind turbine effect on the lower atmosphere involved simply increasing the ocean surface drag coefficient. While this method is consistent with several detailed fine-scale simulations of wind turbines, it still needs further study to ensure its validity. New field observations of actual wind turbine arrays are definitely required to provide ultimate validation of the model predictions presented here.

Keywords: offshore wind farms, climate impact

1. Introduction

The climatic impacts associated with the greenhouse gas emissions from fossil fuel energy sources has stimulated a search for alternative energy technologies with low or zero greenhouse gas emissions. The widespread availability of wind power has fueled substantial interest in this renewable energy source as a potential alternative to fossil-fuel-based sources. However, to meet even a relatively small fraction of the predicted world energy demand of about 44 TW in 2100 (Reilly and Paltsev 2007), several million or more wind turbines would need to be deployed globally.

In a previous study (Wang and Prinn 2010), we used a three-dimensional global climate model that coupled the atmosphere with a land surface model and a slab ocean model to study the potential climatic impacts of large-scale deployment of wind turbines over semi-arid grasslands. We adopted a method that modified the land surface roughness and displacement height, to simulate the wind turbine effects. We conducted a series of long-term integrations of the climate model and found that using wind turbines to meet 10% or more of global energy demand in 2100 could cause surface warming exceeding 1 K over the designated land installations. Significant temperature changes remote from the land installation sites, and alterations to the global distributions of rainfall and clouds also occurred.

In this previous study we also investigated the impacts of wind turbines installed over coastal oceanic regions. We simulated the effects of these marine-based turbines by adding an increment to surface drag coefficient of the ocean, and we found an opposite local temperature effect, namely a local cooling rather than a local warming, compared with the land-base installations.

In the subsequent study reported here, we revisit the potential climatic impacts and reliability of large-scale deployment of offshore wind turbines. In order to examine the validity of our previous results for offshore installations, we have used a newer version of the three-dimensional global climate model with increased spatial resolution. A set of simulations was conducted covering a larger range of geographical areas for the installations and with different assumed strengths of the wind turbine effects. The methods used in our simulations are described in section 2 followed by sections devoted to the results and the conclusions.

2. Methods

In this study, we used the Community Atmospheric Model version 3 (CAM3) of the Community Climate System Model (CCSM), developed by the US National Center for Atmospheric Research (NCAR) (Collins *et al* 2006). This model is a newer version than the Community Climate Model version 3 (CCM3) used in our previous study (Wang and Prinn 2010). A slab ocean model and the Community Land Model (CLM) are also dynamically coupled with CAM3 in our study to simulate the long-term climate responses to the parameterized offshore wind turbine effects. The model has a spatial resolution of 2° by 2.5° along the latitudinal and longitudinal directions, respectively, and 26 vertical layers. This configuration is also a step upward from the configuration in our previous CCM3-based simulations (i.e., 2.8° by 2.8° and 18 vertical layers). The reader can find the details of CAM3 and CCSM3 models, documentations, and related publications on NCAR websites including: http://www.cesm.ucar.edu/models/atm-cam/ and http://www.cesm.ucar.edu/models/ccsm3.0/.

To simulate the climate effect of offshore wind farms, we used a similar parameterization method to that used in our previous study in which we modified the surface drag coefficient to represent a turbine-induced change to the surface roughness (Wang and Prinn 2010, Keith *et al* 2004, Frandsen *et al* 2006, Kirk-Davidoff and Keith 2008, Calaf *et al* 2010). We have specifically conducted six simulations containing various assumptions about the offshore wind turbine effects. The wind turbines in these six simulations were installed over offshore regions between 60°S and 74°N in latitude, where the ocean depth is shallower than 200, 400, or 600 m (occupying 11.2, 15.0, or 18.5 million km^2) respectively, and with an assumed turbine-induced increment in surface drag coefficient over the installed regions of either 0.007 or 0.001, respectively. The higher (designated H) of the two adopted increments in drag coefficient is based on a reported measurement over mesoscale wind farms (see Keith *et al* 2004) while the lower one (designated L) is about double the average sea surface drag coefficient of about 0.001 (Peixoto and Oort 1992). In subsequent discussion, a notation specifying the ocean depth (200, 400, or 600 m) and the increment in drag coefficient (H or L) will be used; for example, Run 200H has an increment of 0.007 in drag coefficient and the wind turbines are installed where the ocean depth is shallower than 200 m. Each run lasts 60 years and takes about 40 years to reach climatic steady states that approximately repeat annually after that. By comparing the results of each of these six simulations with a reference run that excludes the offshore wind turbine effects, we derive the climatic impacts of the turbines in each run. Unless otherwise indicated, the means of the last 20 years (years 41–60) of each of the model integrations are used in the analyses. Similar to our previous studies, all runs were carried out with current-day greenhouse gas levels in order to isolate the climate effects of wind turbines from those due to greenhouse gas increases.

Note that the equations describing the atmosphere–ocean interfacial interactions in the model are highly parameterized (Large and Pond 1981, 1982), and defining a formulation to mimic ocean-based wind turbines, even with an equivalent realism to the one used for the land-based experiments in our previous study, is difficult. Therefore, our numerical experiments are designed to be explorative rather than definitive.

The power gain (P) from mean flow kinetic energy due to wind turbines is calculated at the surface by calling the module of ocean surface flux calculation twice, without and with wind turbine effect (Wang and Prinn 2010, Boville and Bretherton 2003) and subtracting:

$$P = -\{[\tau_U U + \tau_V V]^{\mathrm{wind}} - [\tau_U U + \tau_V V]^{\mathrm{nowind}}\}. \quad (1)$$

Here, U and V represent the latitudinal and longitudinal mean wind speeds, respectively; and τ is the surface stress in the corresponding direction. All variables are defined at the surface. The superscript wind and nowind represent the values from the calls with or without the wind turbine effect, respectively. The P values are calculated continuously at each model grid and time step (30 min) and outputted as monthly means.

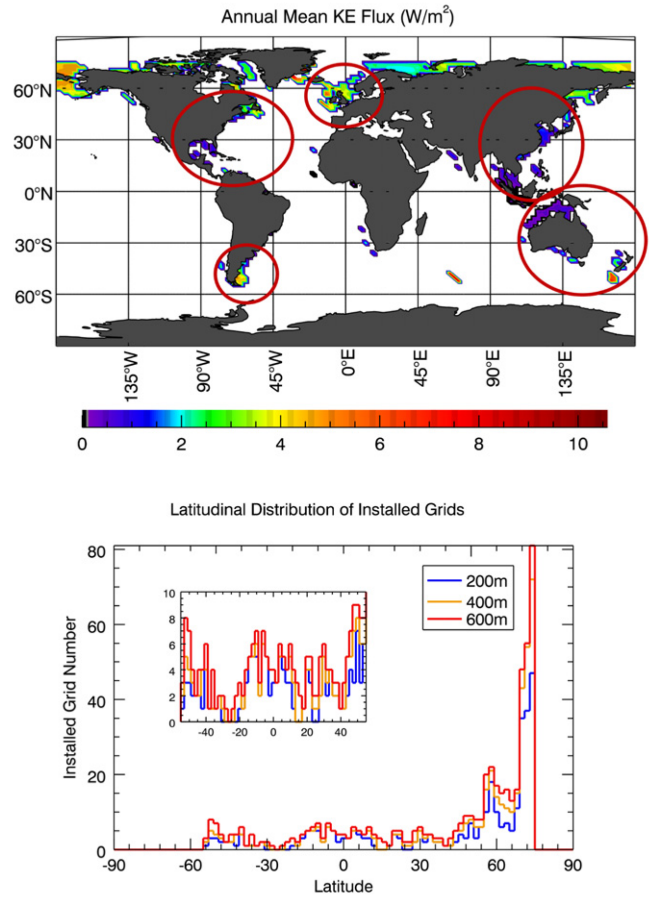

Figure 1. (Upper panel) Kinetic energy dissipation fluxes due to the modeled offshore wind turbine effects in W m^{-2}. Data shown are 20-year averages over model years 41–60 from Run 600H with offshore wind turbines being installed over coastal oceans with depths equal to or shallower than 600 m and using a drag coefficient incremented by 0.007. Red circles mark the regions selected for our intermittency and reliability analysis. (Lower panel) Installed grid numbers as function of latitude in various runs.

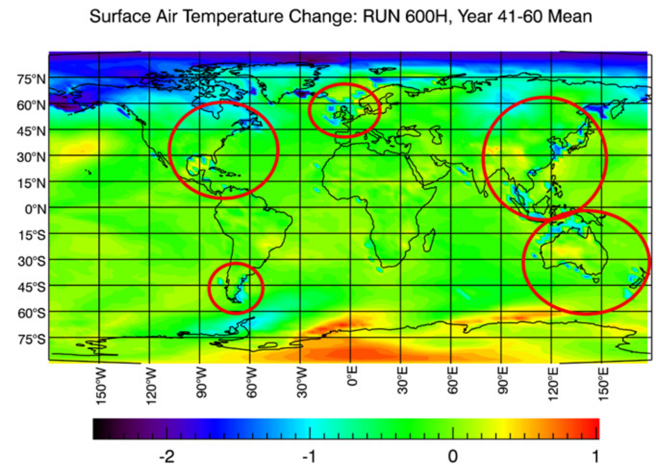

Figure 2. Surface air temperature changes (in K) caused by the installation of offshore wind turbines. Data shown are 20-year means from years 41–60, as derived from the model Run 600H with wind turbines installed over coastal oceans with depth shallower than 600 m and using a drag coefficient incremented by 0.007.

The distribution of the annual mean kinetic energy dissipation flux caused by including the offshore wind turbine effect is shown in figure 1. Five regions, free of sea ice, that are likely to become actual offshore turbine installation sites are marked with circles in the figure. These include the Southeast and East Asian coasts (AS), North American coast (NA), West European coast (EU), South American coast (SA), and Oceania (OC). We carry out several specific diagnostic analyses for each of these regions. Also shown in figure 1 is the number of model grids where offshore wind turbines were installed in each of the three depth configurations as function of latitude.

3. Results

The raw wind power consumption by offshore wind turbines increases proportionally with installation area and the increment in drag coefficient assumed in the model (the value of this increment is intended to represent the spatial density of the installed wind turbines; e.g., Frandsen *et al* 2006, Calaf *et al* 2010). The value of this raw wind power consumption, calculated as the 20-year mean of years 41–60 is 27.2, 37.6, and 47.6 TW in Runs 200H, 400H, and 600H, respectively. The set with lower increment in drag coefficient provides lower values, namely 6.8, 9.6, and 12.3 TW, respectively, in Runs 200L, 400L, and 600L. The consumption values in Runs 200H and 200L are about double those derived using the CCM3 model in our previous study (Wang and Prinn 2010); this likely results from the increase of model spatial resolution in the newer version of the slab ocean model. The actual harvest ratio of the raw wind power consumption converted to electric power by wind turbines is not quantitatively well understood and values in the literature exhibit a large range (e.g., Wang and Prinn 2010, Baidya Roy and Traiteur 2010). To be consistent with our previous study, we assume a 25% conversion rate. This means that the estimated outputs of electric power from our various simulations are 6.8, 9.4, and 11.9 TW, respectively, for Runs 200H, 400H, and 600H, and 1.7, 2.4, and 3.1 TW, respectively, for Runs 200L, 400L, and 600L. These numbers would account for a fraction of 4–25% of the predicted 44 TW in future global energy needs in 2100, or 12–85% of current production of ~14 TW (Reilly and Paltsev 2007).

The calculated climatic impacts of the installed wind turbines are significant. The surface air temperature over many regions where offshore wind turbines were installed were reduced by nearly 1 K in the tropical and mid-latitude sites, with even greater reductions in the high-latitude sites (figure 2). A cooling in the Arctic region and a slight warming in Antarctica reflect an alteration to the large-scale circulation by the ocean surface roughness changes caused by offshore wind turbines that is more concentrated in the Northern Hemisphere. These remote large-scale responses, though rather weak in comparison, are consistent with previous findings (e.g., Kirk-Davidoff and Keith 2008, Wang and Prinn 2010). Averaged over all the installed regions, the annual surface air temperature reduction ranges from 0.4 to 0.6 K in the H cases and is about 0.2 K in the L cases. The surface cooling effect extends vertically into the lower and middle troposphere through mixing (figure 3(upper panel)).

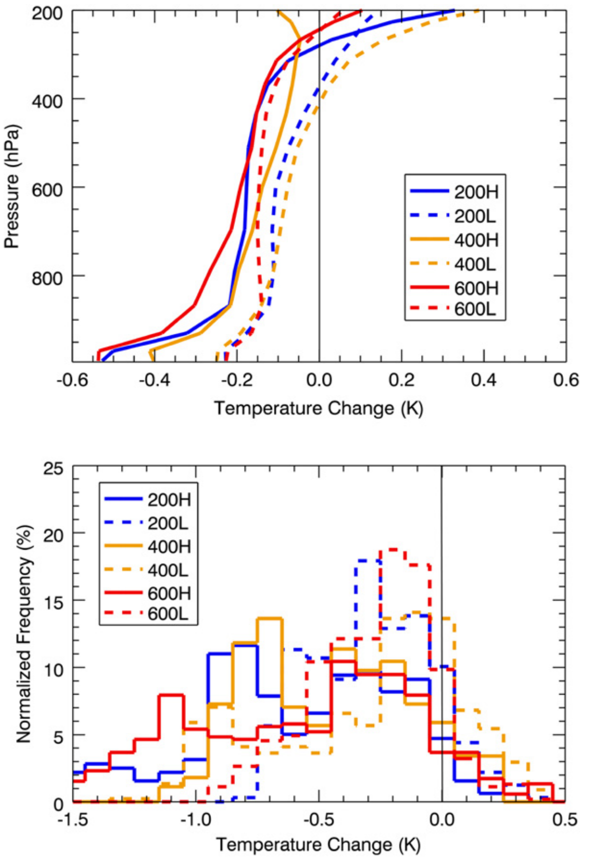

Figure 3. (Upper panel) Global horizontally averaged temperature changes over offshore installation regions from the six model runs including turbine effects relative to the reference run that excluded the wind turbine effect. (Lower panel) Normalized frequency of surface air temperature changes over offshore installation regions from the six different model runs. All data are 20-year means over model years 41–60. Total installed grid number is 318, 440, and 528 corresponding to three different depths, respectively.

The calculated temperature changes do not necessarily follow proportionally the changes in installed area and drag coefficient increment, as shown in Runs 400H and L compared to the others (figures 3(upper panel) and (lower panel)). This results mainly from the changes in the patterns in the geographical locations of the installation regions as we expand from the 200 m to the 400 and 600 m cases. From the greater cooling seen at the high latitudes (figure 2), when this expansion causes a greater (lesser) fraction of the installations to be in tropical latitudes as opposed to high latitudes, then the cooling will be less (more).

Further analysis of the model results suggests that the mechanism behind the cooling in surface air temperature over the offshore installation sites involves the enhancement of the vertical latent heat flux caused by the increasing turbulence due to the imposed increase in the surface drag coefficient. Over the ocean this change in the latent heat flux is generally not offset by the change in the sensible heat flux (Peixoto and Oort 1992). This is shown in figure 4, where over most installation sites the latent heat flux is higher than (and has an opposite sign to) the sensible heat flux (i.e., most points are above the diagonal that defines flux equality). Another difference between these offshore results and the earlier land results (in Wang and Prinn 2010), is that the reduction of the average wind speed due to the wind turbine effect (which would reduce the vertical shear and turbulent mixing in turn), is not large enough to offset the drag-induced enhancement to the turbulent mixing over the originally smooth ocean surface compared to the originally rough land surface.

Given the rather significant local temperature changes brought about by the offshore wind turbines (figure 2), we expect and observe impacts (not shown here for brevity) on the temperatures, clouds, precipitation and large-scale circulation beyond the installed regions. However, these non-local impacts or 'teleconnections' are much less significant than we saw in the land cases (Wang and Prinn 2010). This is likely due to the much lower response of the ocean to the imposed surface drag changes relative to the response of the land to the imposed changes in both surface roughness and displacement height.

Finally, as in Wang and Prinn (2010), we also examined the issues of intermittency, and hence reliability, of large-scale deployment of wind-driven electrical power generation by averaging seasonally the available wind power in various regions of the world (figure 5). The intermittency in power generation from offshore wind turbine installations is clearly seen in all selected analysis regions except for the South

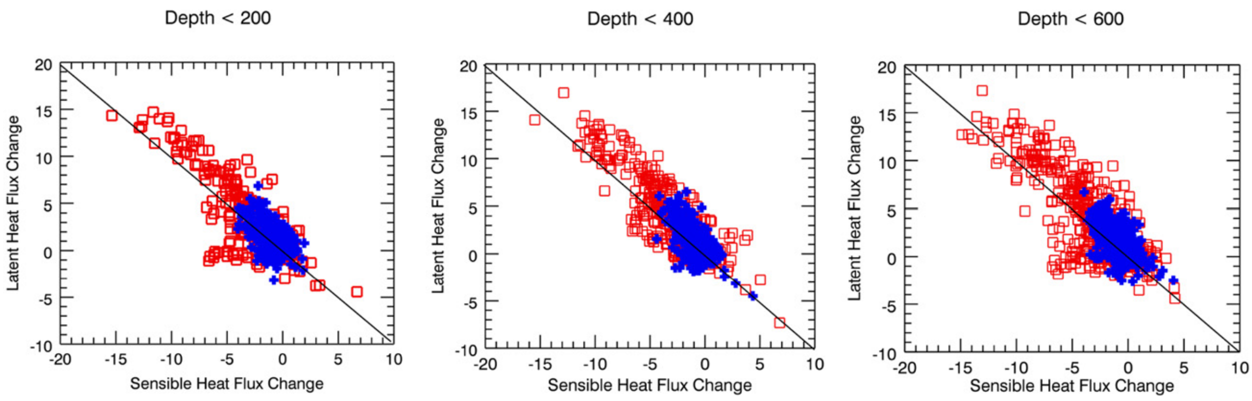

Figure 4. Latent heat flux change (vertical axis) is shown versus sensible heating flux change (horizontal axis) over offshore installation regions for wind turbines (both fluxes in W m^{-2}). Red and blue diamonds show the results from high (H) and low (L) incremented drag coefficient cases, respectively. All data are 20-year means over the model years 41–60.

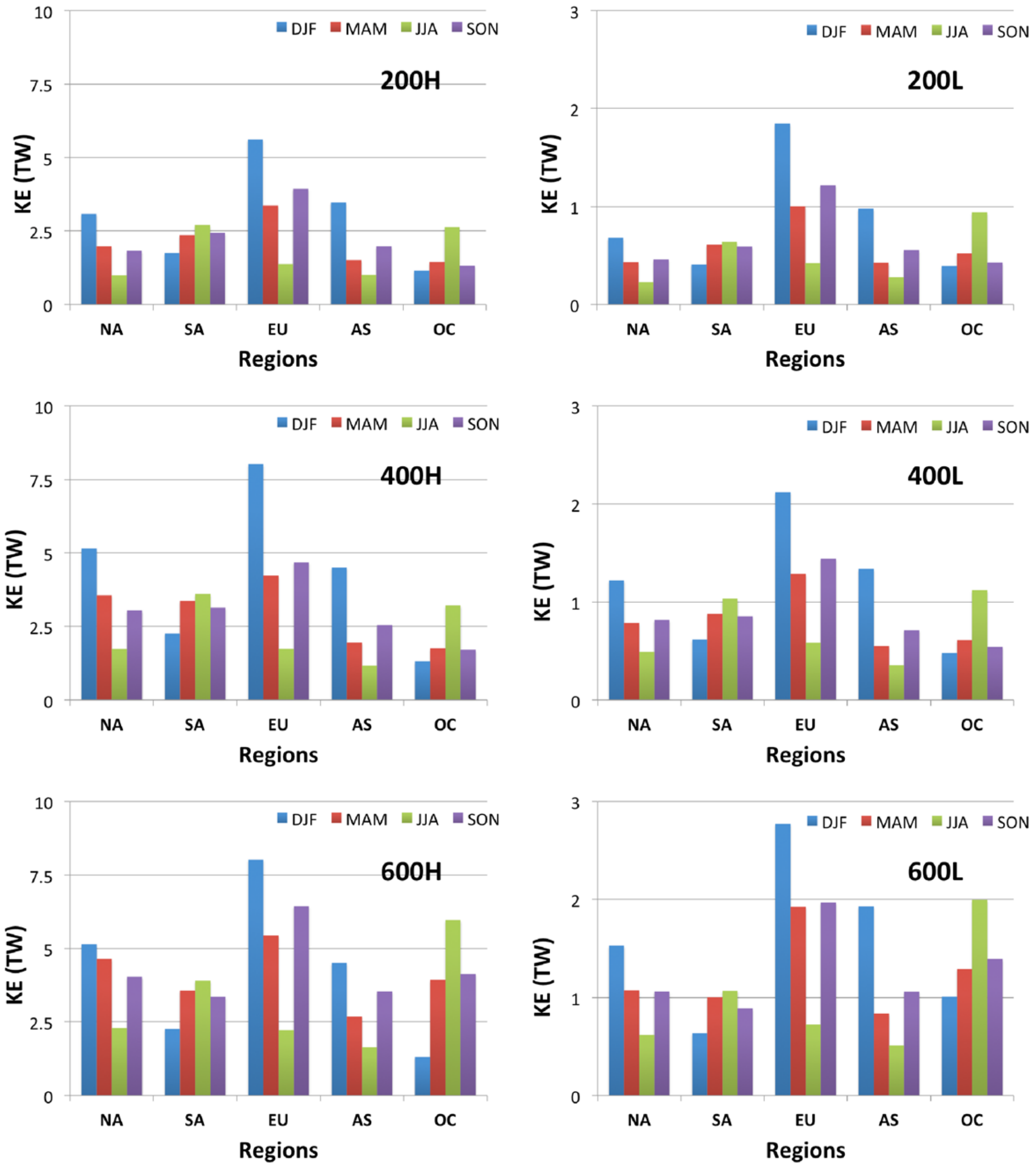

Figure 5. Seasonal averaged raw wind power consumption (TW) due to the installation of offshore wind turbines for the 6 installation runs for: (a) North American coast (NA), South American coast (SA), West European coast (EU), Southeast and East Asian coast (AS), and Oceania (OC). Data shown are twenty-year (years 41–60) averages. Here in the legend of color bars that DJF, MAM, JJA, and SON represents December–January–February, March–April–May, June–July–August, and September–October–November mean, respectively.

American coast (figure 5). Such intermittency is most serious over European coastal sites, where the potentially harvested wind power would vary by more than a factor of 3 from winter to summer. Wind power availability over coastal sites in North America, Southeast and East Asia, and Oceania also display variations of more than a factor of two between the peak wind season (winter in the Northern Hemisphere and summer in the Southern Hemisphere) and the lowest wind season. This would raise a significant issue for power management, requiring solutions such as on-site energy storage, backup generation, and very long-distance power transmission for any electrical system dominated by offshore wind power.

4. Conclusions

We used a three-dimensional climate model to simulate the potential climatic effects and intermittency of large-scale deployment of offshore wind turbines. Based on our calculations, installing sufficient numbers of wind turbines on coastal waters with depths less than 600 m over the globe could potentially supply up to 25% of predicted future world energy needs. However the issues of climatic impacts and, more importantly, reliability (given the significant intermittency of this energy source) remain to be addressed.

A local cooling effect exceeding 1 K in the highest density case is found to accompany the offshore installations.

However, in contrast to our previous simulations of land-based wind turbine installations, except for this local cooling effect, the offshore deployments cause only a small perturbation to the global large-scale circulation as recorded in the computed non-local responses in temperature, cloudiness, and precipitation. A number of reasons for this difference include the relatively smaller total areas of the offshore installations and the relatively smaller response of the climate to the installations compared to the land-based installations.

Our study highlights an intermittency issue for a potential power generating and distributing system that relies on the harvest of wind power from large-scale offshore wind turbine deployments. The inter-seasonal variation in potential power generation between the highest and lowest wind seasons is generally more than a factor of 2, and as high as a factor of 3 off the western European coast. The question of how to manage the transmission, storage, and backup power facilities needed under these circumstances needs to be carefully addressed before deployment of such a system.

Our study is intended to be exploratory, and the dependence of our results on the methods chosen to simulate wind turbine effects needs careful scrutiny. Questions include: how accurate is the specific surface drag-related parameterization chosen in the model, and how limiting is the coarse resolution of our (and all other) global climate models for such studies? Increased efforts in theoretical analysis and in very high resolution modeling (e.g., Frandsen 1992, Frandsen *et al* 2006, Vermeer *et al* 2003, Lange and Focken 2006, Calaf *et al* 2010, Baidya Roy and Traiteur 2010) could lead to the further improvement of the parameterization of the wind turbine effects in global models. Simultaneously, appropriate field experiments will need to be conducted to test and improve the accuracy of the parameterizations used in these models and to validate the conclusions drawn from modeling and theoretical studies such as those presented here.

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