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Potential Climatic Impacts and Reliability of Very Large Scale Wind Farms

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This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Chien Wang* and Ronald G. Prinn

Abstract

Meeting future world energy needs while addressing climate change requires large-scale deployment of low or zero greenhouse gas (GHG) emission technologies such as wind energy. The widespread availability of wind power has fueled legitimate interest in this renewable energy source as one of the needed technologies. For very large-scale utilization of this resource, there are however potential environmental impacts, and also problems arising from its inherent intermittency, in addition to the present need to lower unit costs. To explore some of these issues, we use a three-dimensional climate model to simulate the potential climate effects associated with installation of wind-powered generators over vast areas of land or coastal ocean. Using windmills to meet 10% or more of global energy demand in 2100, could cause surface warming exceeding 1°C over land installations. In contrast, surface cooling exceeding 1°C is computed over ocean installations, but the validity of simulating the impacts of windmills by simply increasing the ocean surface drag needs further study. Significant warming or cooling remote from both the land and ocean installations, and alterations of the global distributions of rainfall and clouds also occur. These results are influenced by the competing effects of increases in roughness and decreases in wind speed on near-surface turbulent heat fluxes, the differing nature of land and ocean surface friction, and the dimensions of the installations parallel and perpendicular to the prevailing winds. These results are also dependent on the accuracy of the model used, and the realism of the methods applied to simulate windmills. Additional theory and new field observations will be required for their ultimate validation. Intermittency of wind power on daily, monthly and longer time scales as computed in these simulations and inferred from meteorological observations, poses a demand for one or more options to ensure reliability, including backup generation capacity, very long distance power transmission lines, and onsite energy storage, each with specific economic and/or technological challenges.

Contents

1. INTRODUCTION

World energy demand is predicted to increase from ~430 EJ/year (14 TW) in 2002 to ~1400 EJ/year (44 TW) in 2100 [Reilly and Paltsev, 2007]. Any effective energy contributor needs to be implemented on a very large scale (*e.g.*, provide 10% of the year 2100 demand). Among the current energy technologies with low or zero greenhouse gas (GHG) emissions, electrical generation using windmills is percentage-wise the fastest growing energy resource worldwide. In the US, it has grown from 1.8 GW of capacity in 1996 to more than 11.6 GW (~ 0.37 EJ/year) in 2006, but this is still negligible compared to future energy demand.

The solar energy absorbed by the Earth is converted into latent heat (by evaporation), gravitational potential energy (by atmospheric expansion), internal energy (by atmospheric and

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oceanic warming, condensation), or kinetic energy (*e.g.*, by convective and baroclinic instabilities) [Lorenz, 1967]. Averaged globally, internal energy, gravitational potential energy, latent heat, and kinetic energy comprise about 70.4, 27.05, 2.5, and 0.05% respectively of the total atmospheric energy [Peixoto and Oort, 1992]. However, only a small fraction of the already scarce kinetic energy is contained in the near surface winds that then produce small-scale turbulent motions due to surface friction. Eventually the turbulent motions downscale to molecular motions, thus converting bulk air kinetic energy to internal energy.

However, it is not the size of these energy reservoirs, but the rate of conversion from one to another, that is more relevant here. The global average rate of conversion of large-scale wind kinetic energy to internal energy near the surface is about 1.68 W/m^2 (860 TW globally) in our model calculations. This is only about 0.7% of the average net incoming solar energy of 238 W/m^2 (122 PW globally) [Lorenz, 1967; Peixoto and Oort, 1992]. The magnitude of this rate when windmills are present is expected to differ from this, but not by large factors. The widespread availability of wind power has fueled legitimate interest in harnessing it for energy production [*e.g.,* Carter, 1926; Hewson, 1975; Archer and Jacobson, 2003]. Windmills convert wind power into electrical power. However, the turbulence near the surface, which also feeds on wind power, is critical for driving the heat and moisture exchanges between the surface and the atmosphere that play an important role in determining surface temperature, atmospheric circulation and the hydrological cycle.

Because of the low output (~MW) of individual wind turbines, one needs to install a large number of the devices to generate a substantial amount of energy. For example, presuming these turbines are effectively generating at full capacity only 1/3 of the time, about 13 million of them are needed to meet an energy output of 140 EJ/year (4.4 TW), and they would occupy a continental-scale area. While the amount of energy gained from global deployment of surface wind power may be small relative to the 860 TW available globally, the accompanying climate effects may not be negligible. A previous study using atmospheric general circulation models with fixed sea surface temperatures suggests that the climatic perturbation caused by a large-scale land installation of windmills can spread well beyond the installation regions [Keith *et al.*, 2004].

2. METHODS

To explore the potential climate impacts of very large-scale windfarms, we use, for the first time, a fully coupled atmosphere-ocean-land system model, specifically the Community Climate Model Version 3 of the U.S. National Center for Atmospheric Research with a mixed layer ocean [Kiehl *et al.*, 1998]. In order to isolate the climate effects of windmills from those due to greenhouse gas increases, all runs were carried out with current greenhouse gas levels. The chosen T42 spatial spectral resolution provides an approximately 2.8 by 2.8 degree grid point spacing in the horizontal, and there are 18 vertical layers.

Seven model runs with 60-year durations were carried out and are reported here. Each run takes about 40 years to reach climatic steady states that approximately repeat annually after that.

Four of the five runs (denoted VL, L, H, and VH) used different schemes to simulate the windmill effects over land, while another run (REF) excludes any windmill effects and thus serves as the control or reference. Besides the land installation simulations, we have also conducted two additional runs (denoted OL and OH) in which we simulate installing windmills over all coastal regions between 60^{o}S and 74^{o}N in latitude where the ocean depth is shallower than 200 meters. As before, comparisons of the oceanic windmill runs with the REF run serve to isolate the climate effects of the windmills. Unless otherwise indicated, the means of the last 20 years (years 41-60) of each of the model integrations are used in the analyses.

Previous model studies of wind farms of various scales have used methods to increase the surface roughness to simulate the aerodynamic effect of windmills [Baidya Roy *et al.*, 2004; Keith *et al.*, 2004; also see the review by Crespo *et al.*, 1999]. We adopt the same general approach, but use model-provided parameters for objects similar to windmills. We selected the global land regions covered by grass (including cold C3 and warm C4) and shrub (including evergreen and deciduous) to be the sites for installation of the windmills over the land. This choice is influenced by the generally lower economic value and high wind speeds over such lands, but future studies might investigate alternative strategies. The windmill farm effect is simulated specifically by modifying the model surface roughness and/or displacement height coefficients over the global grass and shrub regions in the land model of the CCM3 system. The selected roughness and displacement height in the four windmill runs are: Run VL, 0.12m (double the original value) and 0.34m (unchanged); Run L, 0.16m (arbitrary) and 0.34m; Run H, 0.75m (arbitrary, close to the value of 0.77m of the needle leaf deciduous tree in the model) and 0.34m; and Run VH, 2.62m and 23.45m (based on the evergreen forest in the model). In the ocean-based experiments, an additional surface drag of 0.007 and 0.001 over the installed regions has been applied in the Runs OH and OL, respectively, to simulate the windmill effect on wind power extraction. The former value is about the same as a reported measurement over mesoscale windfarms (see Keith *et al.*, 2004) while the latter is about double the average sea surface roughness (Peixoto and Oort, 1992). Note that the equations describing the atmosphere-ocean interfacial interactions in the model are highly parameterized and defining a formulation to mimic windmills with equivalent realism to the one used for the land-based experiments is difficult. Therefore, the two ocean experiments are for exploratory purposes only.

Except for the changes made to the surface roughness or displacement height described above, we keep all other surface properties in these regions identical to their standard CCM3 settings. The model calculates the actual surface properties based on weighted values over all surface types in a given grid. Our method for land installations avoids changing uniformly the above two surface properties of a given model grid to those of a modeled windmill farm unless one or both of the two selected surface types (grass, shrub) dominate the grid.

The rate of conversion of large-scale kinetic energy to turbulent kinetic energy can be described by a term in the equation for the change in the mean flow kinetic energy per unit volume of air (KE) with time t [Stull, 1988]:

$$\frac{dKE}{dt} = -\rho \overline{u_i' u_j'} \frac{\partial U_i}{\partial x_j} = \tau_{i,j} \frac{\partial U_i}{\partial x_j}. \tag{1}$$

Here, i, j = 1, 2, 3 are the three directions of the spatial coordinates, x, U is the mean wind speed, u' is the deviation of the actual wind from the mean (so that it reflects the turbulent motions), ρ is the air density, and τ is the surface stress. The same term exists in the equation of change of turbulent kinetic energy but with an opposite sign. The surface stress is derived in the land surface model (LSM) or the mixed-layer ocean model of CCM3 as a function of surface properties including roughness and displacement height. The change in the rate of downward transport of cascaded kinetic energy due to the simulated windmill effects are calculated continuously at each model time step (20 minutes) by comparing the surface stress values derived with and without the perturbed surface roughness and/or displacement, respectively. These calculated changes are then used to calculate the uptake of wind power by the simulated windmills which is then partially converted to the actual electrical power output.

The various changes in surface properties lead to an increase of surface momentum drag and a decrease of local near-surface wind speed. The changes in surface momentum drag in Run L were up to 0.0025, depending on the dominance of the grass and shrub types in the given model grid (**Figure 1**). This effect is enhanced in Runs H and VH, and reduced in VL. We install the windmills over 58 million km^2 of shrub and grass lands in the major continents, or over 10 million km^2 of the global coastal oceans where the depths are less than 200 meters (Figure 1). The relevant model parameters were changed to remove the amount of near-surface atmospheric kinetic energy needed to match various energy production targets. We make no specific assumptions about the type and spacing of these windmills; our interest is only in determining the impacts of removing the kinetic energy from the near-surface atmosphere needed to drive them.

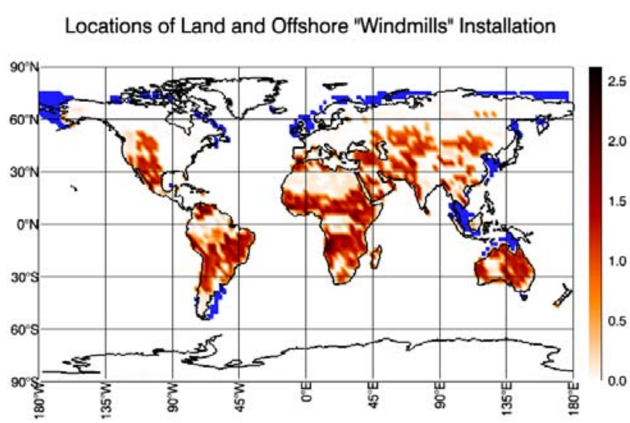


Figure 1. Locations of land installations are indicated by the modeled change of surface drag coefficient (non-dimensional) averaged over the final 20 years of the 60-year Run L (see color code on right hand side). The drag values have been scaled by a factor of 1000. Also shown are the locations of offshore installation regions where the ocean depth is shallower than 200 meters (blue shading).

3. RESULTS

In Run L with a moderate change in the surface roughness over the installed land regions, the reduction of wind power due to the windmills is about 20 TW, or 630 EJ/yr, which is about 2.3% of the total rate of conversion of mean flow to turbulent kinetic energy at the Earth's surface and 23% of the conversion rate over the actual areas of the windmill installation. No more than 59% of the kinetic energy contained in an air-stream tube having the same cross section as a disc-shaped obstacle can be converted to useful work by the disc (the Lanchester–Betz–Joukowsky limit) [Kulk, 2007]. The actual conversion efficiency of this kinetic energy to electric power is likely to be lower than 30% [Dodson *et al.*, 2005]. With a conversion efficiency of 25%, the windmills in Run L would provide about 158 EJ/yr (5 TW). In three other numerical experiments, the kinetic energy extracted by the windmills was either reduced or enhanced compared to Run L (*e.g.* reflecting the effects of lowering or raising the windmill spatial density). The computed electrical energy outputs are about 72, 344, and 603 EJ/yr (2.3, 11 and 19 TW) in Run VL, H, and VH, respectively. The offshore shallow ocean installations provide about 96 and 30 EJ/yr (3.0 and 0.95 TW) in Run OH and OL, respectively.

The computed air temperature over the installation regions in Run L is elevated by more than $1^{o}C$ in the lowest model layer (~30m thick at sea level) in many regions (**Figure 2**), but the increase, averaged over the entire global land surface, is only about 0.15 ^{o}C. Although the surface air temperature change is dominated by the increase over the windmill-installed areas (Figure 1), the changes go well beyond these areas (Figure 2). The frequency distributions for temperature changes for Run L and the other three land-based runs, are also shown in Figure 2. The global land-average temperature changes are 0.05, 0.16, and $0.73^{o}C$, respectively, for these three other land-based runs (VL, H and VH). In all these runs, except for Run VL, the global patterns of these changes are consistent with Run L (Figure 2). These patterns also have some similarities to the previous study by Keith *et al.* [2004] over land, but not over the oceans, since that study assumed fixed ocean temperatures.

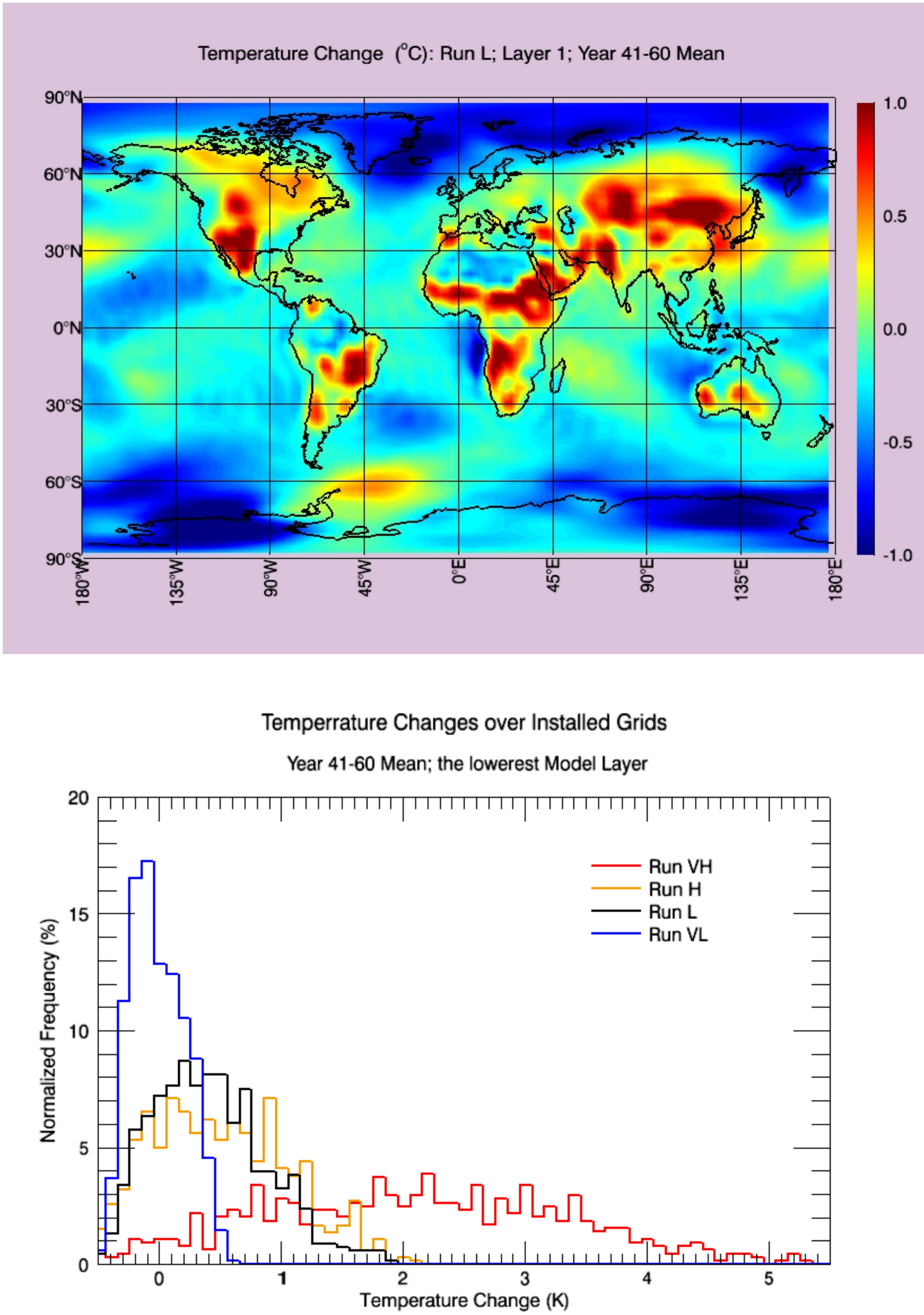


Figure 2. Temperature changes (Run L minus reference, REF) in the lowest model layer resulting from large-scale deployment of windmills over land sufficient to generate 158EJ/year of electric power (upper panel); and normalized frequency of temperature changes over the installation regions in Runs VH, H, L, and VL (lower panel). Both refer to averages over years 41-60.

The warming caused by the windmills is limited to the lowermost atmospheric layers (**Figure 3**). Above the planetary boundary layer, a compensating cooling effect is expected and observed in many regions, because the turbulent transfer of heat from the surface to these higher layers is reduced. This should be contrasted to the relatively uniformly distributed warming throughout the troposphere induced by rising greenhouse gases [IPCC, 2007].

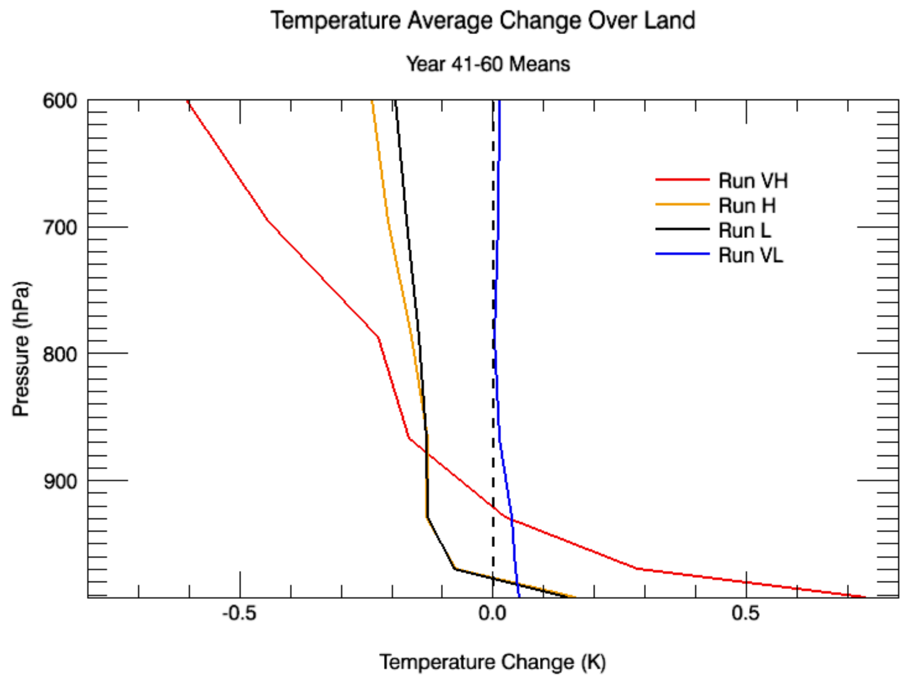


Figure 3. Horizontally averaged temperature changes (relative to the reference, REF) over land in the 4 windmill installation runs. All data are 20-year means from year 41 to 60.

Increasing surface roughness (to simulate the windmills) without significantly lowering the near-surface wind speed should increase near-surface turbulent latent and sensible heat transport and thus cool the surface. However, changes in surface roughness over a region with a very large width in the prevailing wind direction indeed cause a significant reduction in the wind speed based on our results that weakens the near-surface turbulent transport, and thus warms the surface (**Figure 4**). Our results suggest that the latter effect prevails over the majority of the installation regions. Note that, like the effects on temperature, the effects of these windmill installations on surface heat fluxes, spread well beyond the installation regions and often have opposite signs to those in the installation regions (**Figure 5**). These long-range effects are likely to be very model-dependent. Dynamical mechanisms involving Rossby waves for long-range effects of large-scale changes in land surface friction have been proposed [Kirk-Davidoff and Keith, 2008]. Long-range effects are also computed in climate model simulations where regional energy budgets are altered by aerosols [Wang, 2007].

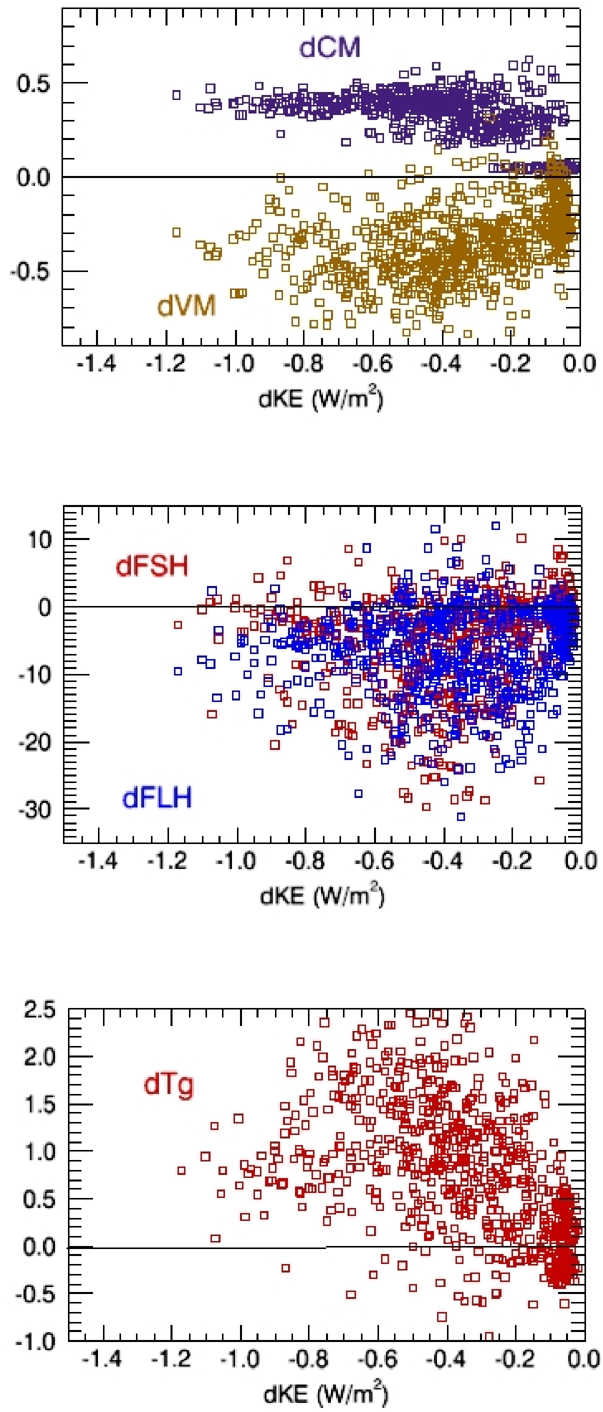


Figure 4. Changes in surface momentum drag coefficient (dCM; unit-less), wind magnitude (dVM; m/s), sensible (dFSH; W/m^2) and latent (dFLH; W/m^2) heat fluxes, and surface air temperature (dTg; K) over the model grids where the kinetic energy losses (dKE; W/m^2) due to windmills occur. Results shown are year 41-60 means of Run L minus Run REF.

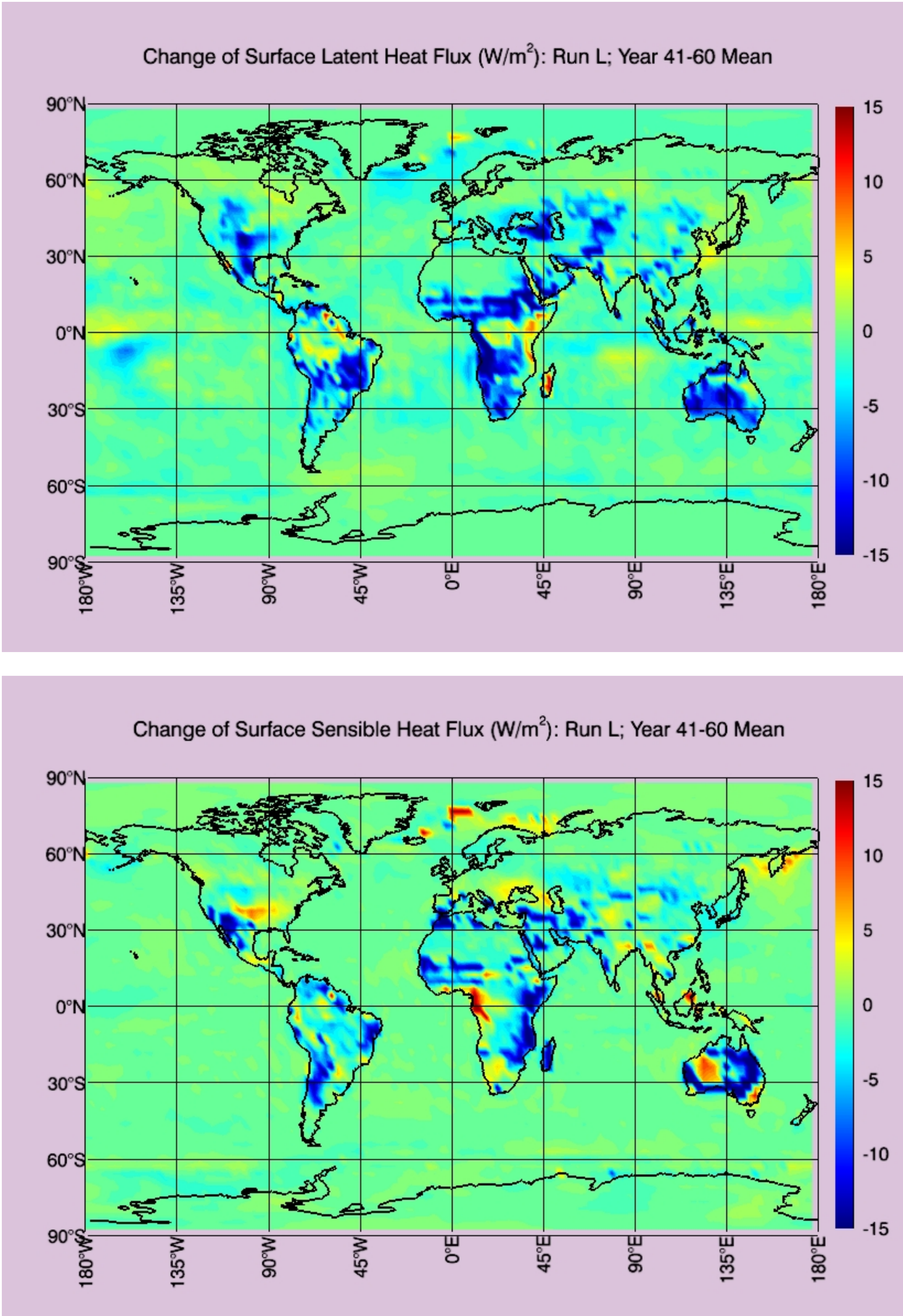


Figure 5. Surface heat flux changes for Run L (Run L minus Run REF) for latent heat (upper panel) and sensible heat (lower panel) fluxes. Both panels are in W/m^2 and averaged over years 41-60.

Note that that the fractional changes of surface drag in our two ocean-based runs are very high compared to the land cases, owing to the much higher intrinsic surface roughness over land than over ocean (**Figure 6**). Therefore, in contrast to the land-based experiments, this substantial increase in surface drag in the ocean-based experiments creates much stronger turbulence that substantially opposes the wind reduction effect due to the roughness change. This leads to an enhancement in ocean-atmosphere heat fluxes, particularly latent heat fluxes, and thus to local cooling over almost all of the installation regions (**Figure 7**). As in the land-based runs, the temperature changes in the coastal ocean-based runs also occur well beyond the installation regions with similar vertical profiles (not shown) to Figure 3, but with opposite signs. Note that these results in these two ocean runs are likely not reliable, since they are dependent on the single CCM3 model option available to us for making the changes to ocean surface properties necessary to simulate the drag effects of windmills over water.

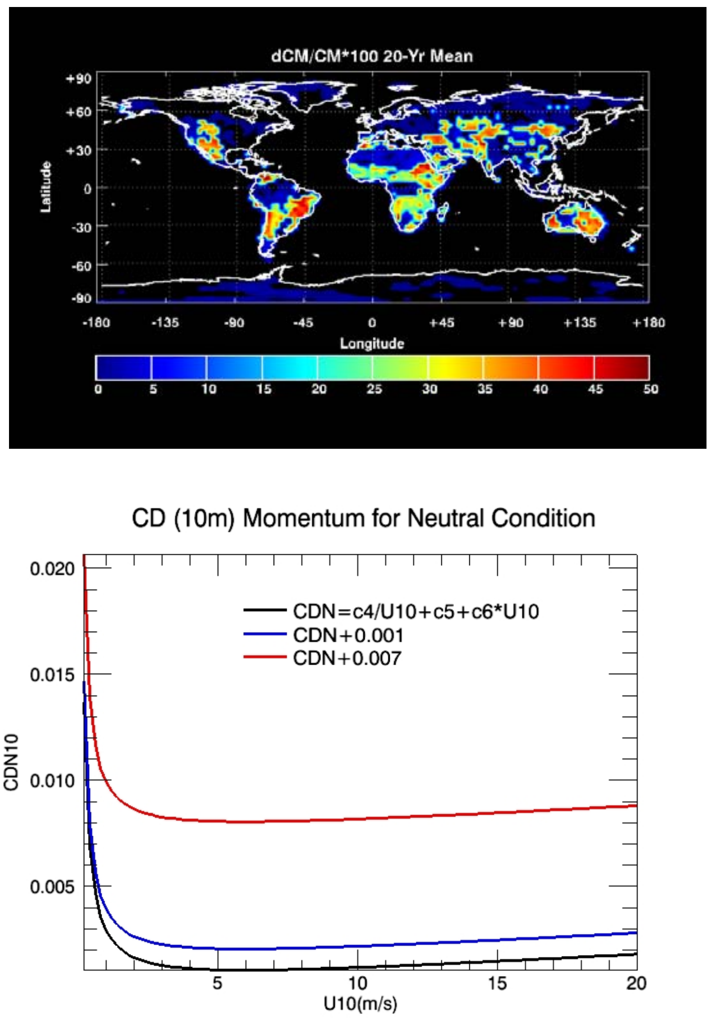


Figure 6. Percentage changes of surface momentum drag coefficient (dCM/CM*100) due to the simulated windmills over the land (upper panel); and surface momentum coefficients (CDN10) without (black line) and with (Run OL, blue line; Run OH, red line) the simulated windmills over the ocean (lower panel).

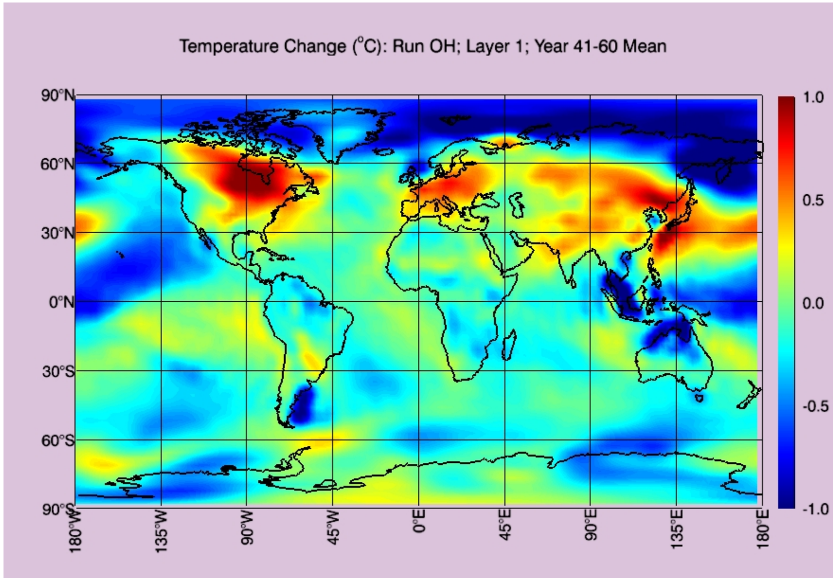


Figure 7. Same as Figure 2 (upper panel) but for Run OH.

The spatially extensive changes in temperatures and surface heat fluxes for the land installations are sufficient to affect the global distributions of cloud cover, especially the lower clouds (not shown), and precipitation (**Figure 8**). The rates of convective precipitation (Figure 8) are generally reduced in the Northern Hemisphere and enhanced in the Southern Hemisphere, symptomatic of a shift in the atmospheric Hadley Circulation [Wang, 2007]. In the mid-latitudes, especially in the Northern Hemisphere, changes in large-scale precipitation also appear (Figure 8), indicating an impact on mid-latitude weather systems. Although the changes in local convective and large-scale precipitation exceed 10% in some areas, the global average changes are not very large.

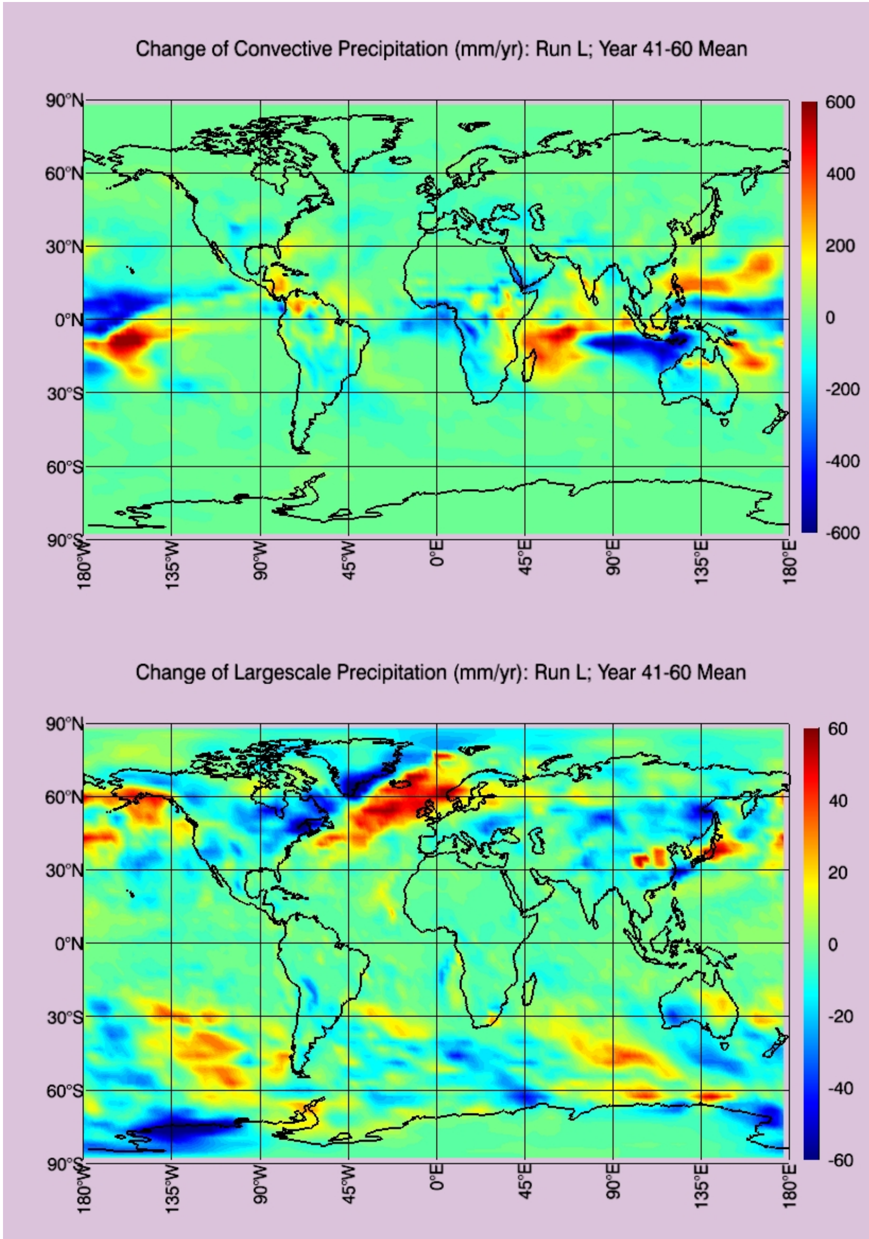
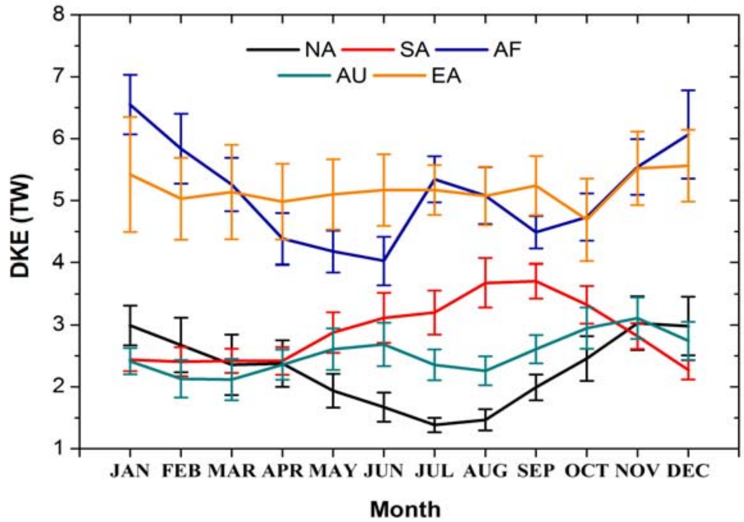


Figure 8. Precipitation changes (Run L minus Run REF) for: convective precipitation (upper panel), and large-scale precipitation (lower panel). Both are in mm/yr and averaged over years 41-60.

To investigate the issue of wind variability leading to intermittency in wind power generation, we show in Figure 9 the average and standard deviation of the monthly-mean wind power consumption (DKE=dKE/dt in TW, see eqn. 1) for each month of the year and for each continent over the last 20 years of Run L. Also shown is the time series of these monthly-means over the last 20 years. Dividing DKE by 4 for a 25% conversion efficiency, the 20-year average generated electrical power over each continent is 0.57 (North America), 0.72 TW (South America), 1.28 TW (Africa/Middle East), 0.63 TW (Australia), and 1.29 TW (Eurasia). However, quite apart from the well-known day-to-night and day-to-day intermittency of windmills, from **Figure 9** there are very large (up to a factor of 2) and geographically extensive seasonal variations especially over North and South America and Africa/Middle East. Unfortunately the months of minimum generation usually coincide with maximum demand for air conditioning. In an electrical generation system dominated by windmills, reliability of supply cannot therefore be achieved simply by long-distance power transmission over these continents.



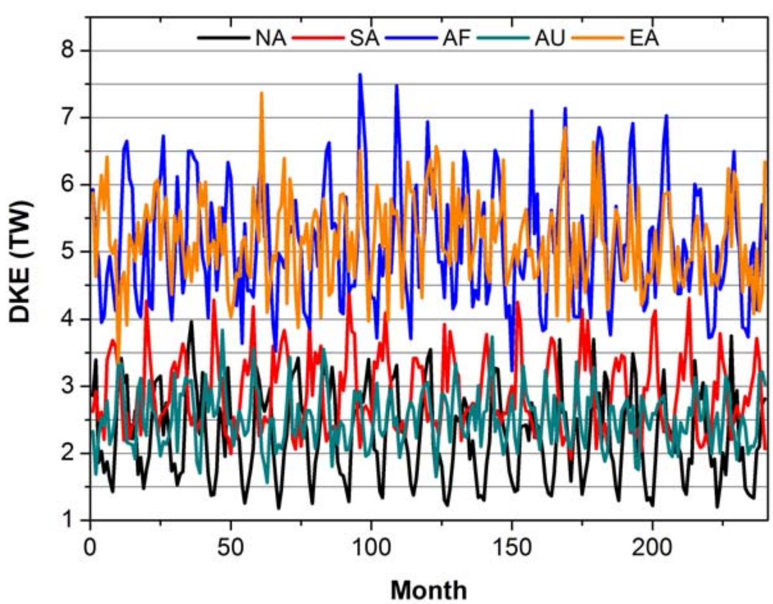


Figure 9. Twenty-year (years 41-60) averages and standard deviations (upper panel), and all values (lower panel), of the monthly mean wind power consumption (DKE=dKE/dt, equation 1) by simulated windmills installed in various continents: North America (NA), South America (SA), Africa and Middle East (AF), Australia (AU), and Eurasia (EA).

4. CONCLUSIONS

Meeting future world energy needs while addressing climate change requires large-scale deployment of low or zero GHG emission technologies such as wind energy. We used a three-dimensional climate model to simulate the potential climate effects associated with installation of wind-powered generators over vast areas of land and ocean. Using windmills to meet 10% or more of global energy demand in 2100 could cause surface warming exceeding 1^{o}C over land installations. Significant warming and cooling remote from the installations, and alterations of the global distributions of rainfall and clouds also occur.

Our ocean results indicating cooling over the installation regions and warming and cooling elsewhere are interesting, but suspect due to the unrealistic increases in surface drag needed to extract the target wind power. Specific new and realistic parameterizations for simulating the effects of windmills over the ocean will need to be developed and applied in general circulation models before reliable conclusions can be reached.

Installation of windmills over land areas that have alternative spatial extents, topographies and hydrological properties would produce different, but presumably still significant, climate effects. Due to the computed nonlinearity between the changes in surface roughness and the climate response, defining the optimal deployment of windmills is challenging. Environmental effects increase with power generated and decrease with conversion efficiency. Also, for the widely spaced windmills simulated in our runs, the environmental effects appear small when they are generating less than 1 TW globally even with current technologies.

Our results should be fairly robust to assumptions about the specific windmill technologies utilized. Increasing their efficiencies from 25% to 35% helps to lower, but does not remove the calculated climate effects. Our results are dependent upon the realism of the land surface and atmospheric boundary layer in our chosen climate model, and investigations with alternative models, including higher-resolution climate models with fully dynamical three-dimensional oceans are warranted. Appropriate field experiments to test our conclusions, and to explore better ways for simulating windmills in models, are also required.

Finally, intermittency of wind power on daily, monthly and longer time scales as computed in these simulations and inferred from meteorological observations, poses a demand for one or more options to ensure reliability, including backup generation capacity, very long distance power transmission lines, and on-site energy storage, each with specific economic and/or technological challenges.

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