Monitoring, modeling and mitigating impacts of wind farms on local meteorology

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ABSTRACT: Utility-scale large wind farms are rapidly growing in scale and numbers all over the world. Data from a meteorological field campaign show that such wind farms can significantly affect near-surface air temperatures. These effects result from enhanced vertical mixing due to turbulence generated by wind turbine rotors. The impacts of wind farms on local weather can be minimized by changing rotor design or by siting wind farms in regions with high natural turbulence. Using a 25-year long climate dataset, we identified such regions in the world. Many of these regions, such as the Midwest and Great Plains in the U.S., are also rich in wind resources, making them ideal candidates for low-impact wind farms.

1 INTRODUCTION

Wind power is one of the fastest growing energy sources in the world. Most of this growth is in the industrial sector based on large utility-scale wind farms (Wiser et al., 2007). Recent studies have investigated the possible impacts of such wind farms on global and local weather and climate. While debates exist regarding the global-scale effects of wind farms (Keith et al., 2004; Kirk-Davidoff and Keith, 2008; Sta. Maria and Jacobsen, 2009), modeling studies agree that wind farms can significantly affect local-scale meteorology (Adams and Keith, 2007; Baidya Roy et al., 2004). However, these studies are based only on model simulations but are not validated against observational evidence. In this paper we used field data from and numerical experiments with a regional climate model to answer the following critical questions arising from the prior studies:

i. Does observational evidence from near-surface air temperature data in operational wind farms support the modeling studies?
ii. Can atmospheric models replicate the observed patterns of near-surface air temperatures within wind farms?
iii. How can these impacts be minimized to ensure long-term sustainability of wind power?

2 OBSERVED IMPACTS OF WIND FARMS

While observed data on wind speed in and around operational wind farms are readily available, information on other meteorological variables do not exist in the public domain. The only available information is temperature data from a wind farm at San Gorgonio, California, collected during 18 June - 09 August, 1989 (Fig. 1). To the best of our knowledge, this is the only meteorological field campaign conducted in an operational wind farm. The wind farm consisted of 23 m tall turbines with 8.5 m long rotor blades arranged in 41 rows that were spaced 120 m apart.

Data from the field campaign shows that near-surface air temperatures downwind of the wind farm are higher than upwind regions during evening, night and early morning hours while the reverse holds true for the rest of the day (Fig. 2a). Thus, this wind farm has a warming effect during night and a cooling effect during the day. The observed temperature signal is statistically significant for most of the day according to the results of a Mann-Whitney Rank Sum Test.

A possible explanation for this phenomenon can be drawn from the hypothesis proposed by Baidya Roy et al. that turbulence generated in the wake of the rotors enhance vertical mixing (Baidya Roy et al., 2004). In a stable atmosphere when the lapse rate is positive, i.e., a warm layer overlies a cool layer, enhanced mixing mixes warm air down and cold air up, leading to a warming near the surface. In an unstable atmosphere with negative lapse rate, i.e., cool air lying over warmer air, turbulent wakes mix cool air down and warm air up, producing a cooling near the surface. Vertical profiles of temperatures from the Edwards Air Force Base corroborate this hypothesis. This base is the World Meteorological Organization (WMO) recognized weather station nearest to the San Gorgonio wind farm. Data shows a positive lapse rate at 4 am and negative lapse rates at 10 am and 4 pm at the base during the field campaign (Fig. 2b). The corresponding temperature signal from the San Gorgonio wind farm (Fig. 2a) shows a warming effect at 4 am but a cooling effect at 10 am and 4 pm. This pattern is consistent with the proposed hypothesis.

3 SIMULATED IMPACTS OF WIND FARMS

We conducted a set of 306 simulations to test if regional climate models are capable of replicating the observed patterns of local warming/cooling under positive/negative lapse rates. Using the Regional Atmospheric Modeling System or RAMS (Cotton et al., 2003; Pielke, et al., 1992), we simulated a small wind farm consisting of a 7x3 array of wind turbines. Each turbine was 100 m tall with 50 m rotor blades (100 m rotor diameter), spaced 10 rotor diameters, i.e., 1 km apart. Wind turbine rotors were represented as elevated sinks of momentum and sources of turbulence (Baidya Roy et al., 2004).We initialized the model with atmospheric sounding data for February 1, May 1, August 1 and November 1 2009, from 21 WMO stations in western U.S. These soundings collectively represent the wide range of possible stability conditions over the entire annual cycle. With each of the 153 available soundings, we conducted a pair of 1-hour long simulations: a control case and a wind farm case with the wind turbine parameterization turned off and on, respectively. We then conducted a pairwise comparison of the wind farm and control cases to quantitatively estimate the effect of wind farms on near-surface air temperatures under different stability conditions.

Figure 3a shows a scatter plot of the change in the near-surface air temperature (wind farm – control) under different environmental lapse rates. The lapse rate was calculated as the average vertical gradient of potential temperature between the surface and 300 m altitude at the beginning of the simulations. It is clear from the figure that our simulations can capture the basic pattern of temperature change observed in the San Gorgonio wind farm. All the model realizations almost exclusively lie in the first and third quadrant, indicating that wind turbine rotors create a warming under positive lapse rates and a cooling under negative lapse rates. The temperature change under wind farms were also a function of ambient hub-height (second atmospheric layer) wind speed (Fig. 3b). The temperature signal can be approximated as a Gaussian function of hub-height wind speed, becoming zero at speeds less than 2m/s or greater than 20 m/s and peaking at approximately 12 m/s.

Another interesting feature is the relationship between the temperature signal and the simulated ambient turbulent kinetic energy (TKE). Ambient TKE was calculated by averaging the TKE in the lowest 4 atmospheric layers in the control runs. Figure 3c shows that the temperature effects are larger when ambient TKE is low and vice versa. This implies that if the ambient environment is turbulent, the additional turbulence generated by the rotors does not have a strong impact. Since atmospheric turbulence is a key predictor of surface kinetic energy dissipation rate, the impacts of the rotors are stronger when background surface KE dissipation rate is high (Fig. 3d). A sigmoid curve fitted to the scatter plot indicates that the impact of the rotors starts to decrease as the dissipation rate becomes larger than 2.7 W/m^2 and become almost zero at dissipation rates higher than 6 W/m^2.

4 LOW IMPACT WIND FARMS

Based on our understanding of how wind farm rotors interact with atmospheric boundary layer (ABL) flow, we can envisage 2 distinct strategies to minimize the impacts of wind farms on surface temperature. One option would be to reduce the turbulence generated by rotors. It is evident from the simulations that turbulence in the rotor wakes plays a key role in determining how wind farms affect the ABL. To further explore the role of rotor-generated turbulence, we conducted a series of sensitivity experiments with the TKE added by rotors set to 0, 0.5, 1, 2, 5, 10 and 15 m^2s^{-2}. We ran an ensemble of 153 simulations for each case with initial conditions from WMO soundings. Figure 4a shows that rotors that generate more turbulence in their wakes are likely to have a stronger impact on near-surface air temperatures.

Rotor-generated turbulence also affects the KE absorbed by the wind turbines (Fig. 4b). The energy expended in generating this turbulence comes from the KE of the mean flow. Consequently, rotors that generate more turbulence in their wakes further reduce the KE available to downstream turbines. Thus, designing new rotors that generate less turbulence in their wakes also increase the productivity of wind farms.

One interesting feature in Figure 4b is that power absorbed increases for TKE values between 0 and 0.5 m^2s^{-2} but decreases thereafter. This indicates that a small amount of turbulence in the wake is actually beneficial for wind farm operations. This turbulence triggers entrainment of KE from above to replenish the KE deficit in the wakes. However, there is a limit to this benefit. Rotors that generate more than 0.5 m^2s^{-2} of TKE consume more KE than that replenished by entrainment. Hence, wind farms built with such rotors are less productive.

An alternative option to designing low-turbulence rotors would be to look for an optimal siting solution. The results of the numerical experiments indicate that the impacts of wind farms are likely to be small in regions where background ABL turbulence is high due to natural reasons. It is impossible to identify such regions with global long-term climatological data because data on ABL turbulence does not exist. Instead we identified these regions by considering the surface KE dissipation rates. KE in atmospheric flow exists at a wide range of spatial scales. However, this KE is dissipated only at extremely small scales, mostly near the surface. ABL turbulence accelerates surface KE dissipation by breaking down large-scale flow into successively smaller and smaller eddies (Stull, 1993). Hence, surface KE dissipation can act as an indicator of ABL turbulence. Indeed, the simulated ABL TKE and surface KE dissipation rates are strongly correlated with r=0.9475 (P<0.00001). Also, the temperature signal exhibits similar relationships with ABL TKE and surface KE dissipation rate (Fig. 3c-d).

We calculated surface KE dissipation rate for global land surface Using Monin-Obukov Similarity Theory (Louis, 1979; Stull, 1993)from the JRA25 dataset (Onogi et al., 2007). This is a 25-year long (1979-2004) 6-hourly dataset aggregated on to a 2.5^o x 2.5^o grid using data from a wide range of sources including surface stations, meteorological towers, radiosondes and satellites. With 41 levels in the vertical, this dataset has a higher vertical spatial resolution than other reanalysis datasets, making it the most appropriate for our analysis. According to our estimate, the global average KE dissipation is 2.1 W/m^2. This value corresponds well with another study using a different method from other reanalyses data (Boer and Lambert, 2008).

Figure 5 shows the surface KE dissipation rates averaged over the 1979-2004 period. We know from Figure 2d that the impact of wind farms starts decreasing sharply as ambient surface KE dissipation rate becomes larger than 2.7 W/m^2 and becomes almost zero at dissipation rates higher than 6 W/m^2. Expectedly, the surface KE dissipation is high in regions with high topography like the Rockies, Andes, Himalayas and the Tibetan Plateau. Due to their relative inaccessibility, these regions are not suitable for wind farms. Same consideration eliminates Greenland and Antarctica as candidates. Large parts of North and Central America, southern tip of South America, northern Europe, Russia, northern China, the Rift Valley and southern parts of Africa, southern Australia and New Zealand seem to be ideal for low-impact wind farms.

This analysis identifies regions where wind farms are likely to generate lower impacts on near-surface air temperatures. The map in Figure 5 has considerable overlaps with the wind resources map shown in Figure 1 of Lu et al. (2009). For example, in the U.S., the Great Plains and the Midwest regions seem to be ideal for harvesting wind energy because wind farms in these wind-rich regions are likely to produce relatively less impacts on surface temperatures.

Both the engineering and siting solutions have pros and cons. The engineering solution is expensive because it involves designing new rotors. However, it is particularly attractive because apart from minimizing impacts, it will improve the productivity of the wind farm. Additionally, it will also reduce structural damage to turbines from turbulence in the wakes of upstream rotors (Ekington et al., 2005; Lackner and van Kuik, 2009). On the other hand the siting solution is convenient because it can be implemented with currently available technology. But it requires wind farms to be sited in regions with high background ABL turbulence. Background turbulence is generally weaker than wake turbulence but prolonged exposure may be damaging to the rotors (Lackner and van Kuik, 2009).

5 DISCUSSIONS

This study has significant implications for future energy and land use policy. Wind power can be a part of the solution to the atmospheric carbon problem (Pacala and Socolow, 2004). Acknowledging the potential of wind energy, all large industrial economies are prominently featuring wind power in their plans for the future (Global Wind Energy

Council, 2009). Even though wind currently contributes a small fraction of the total energy consumed by humans, all trends indicate that wind power is on the verge of an explosive growth, most of it being in the industrial sector consisting of large wind farms (Wiser et al., 2007). Many of these wind farms are coming up over agricultural land, helping farmers substitute their income with rent from utility companies. Impacts from wind farms on surface meteorological conditions are likely to affect agricultural practices in these farms. If the wind farms are sufficiently large they may also affect downstream surface meteorology (Kirk-Davidoff and Keith, 2008). As wind farms become larger and more ubiquitous, it is essential that their possible environmental impacts are assessed and properly addressed to ensure the long-term sustainability of wind power.

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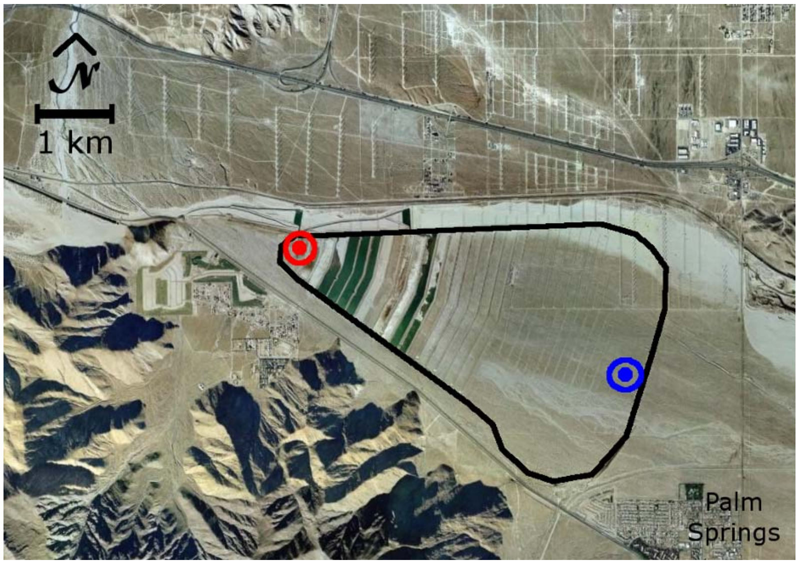

Figure 1. Google Earth map of San Gorgonio area showing the wind farm boundary in 1989 and locations of upwind (red) and downwind (blue) meteorological towers. The wind farm layout has changed significantly since then. Many of the small turbines from the original site have been removed and a large number of taller, more modern turbines have been added. The new turbines to the north of the old wind farm are clearly visible in the image.

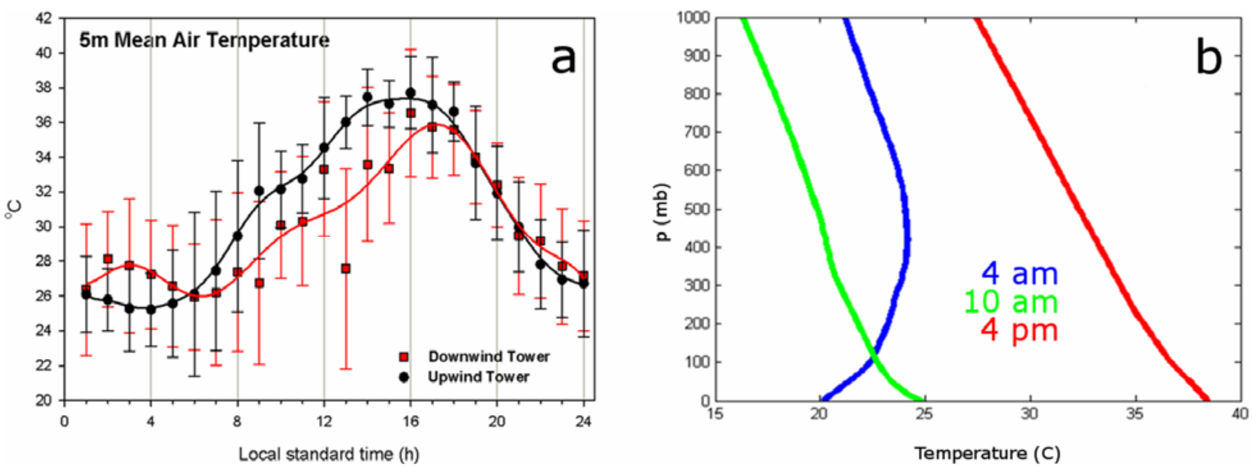

Figure 2. (a) Observed mean near-surface air-temperature patterns at the San Gorgonio wind farm during the field campaign. (b) Observed mean vertical profiles of temperature at Edwards Air Force Base during June-August 1989.

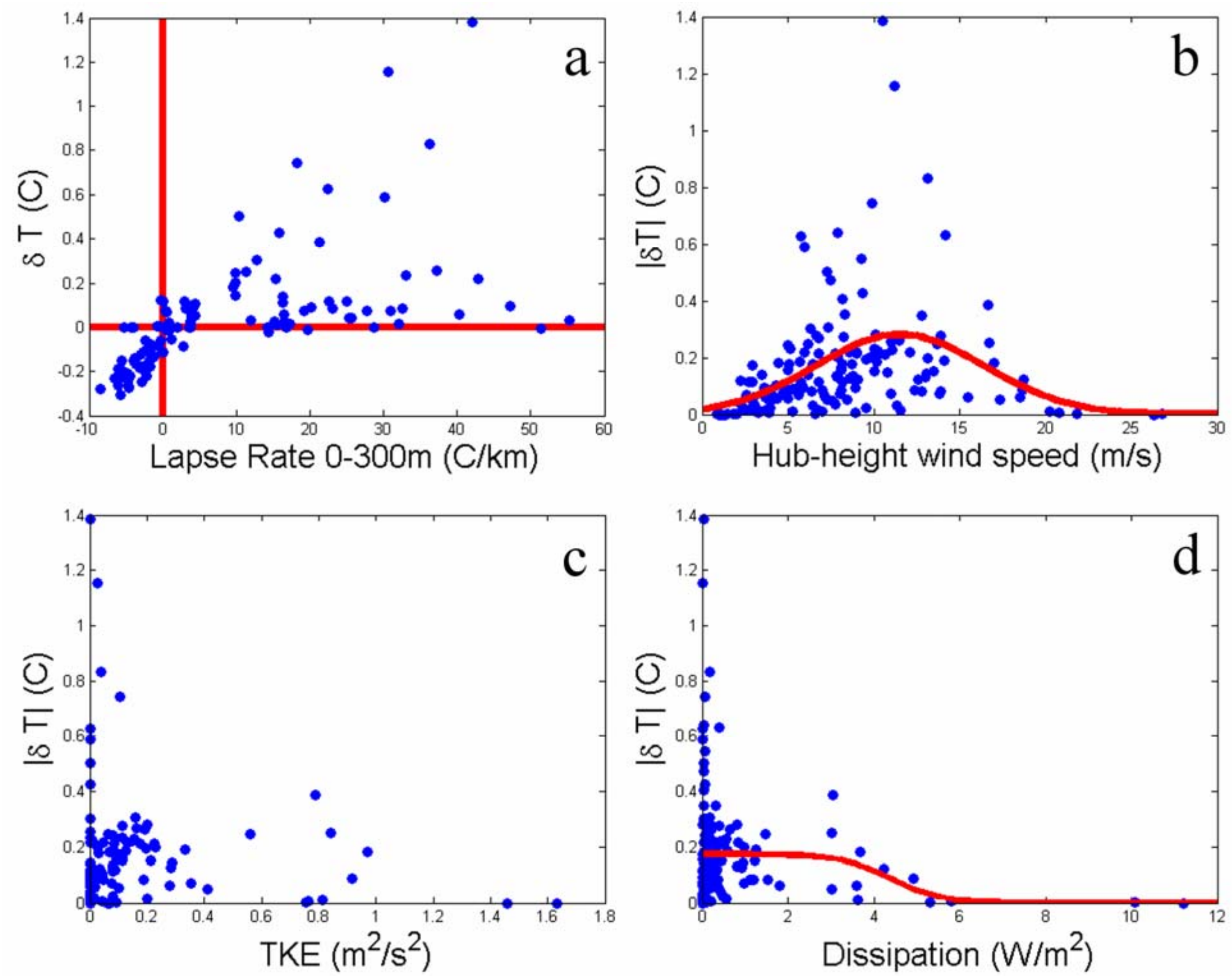

Figure 3. Simulated change in near-surface air temperatures within the wind farm plotted as a function of (a) 0-300 m potential temperature lapse rate at the beginning of the simulations; (b) background hub-height (100 m) wind speed; (c) background lower ABL (0-300 m) TKE; and (d) background surface KE dissipation rate. The variables plotted on the abscissa are from the control simulations while the variables on the ordinate are the difference between the control and wind farm simulations. The temperature change within the wind farm, wind speed, TKE and surface KE dissipation rates are averaged over the entire 1-hour long simulation period for the 21 grid cells containing the turbines.

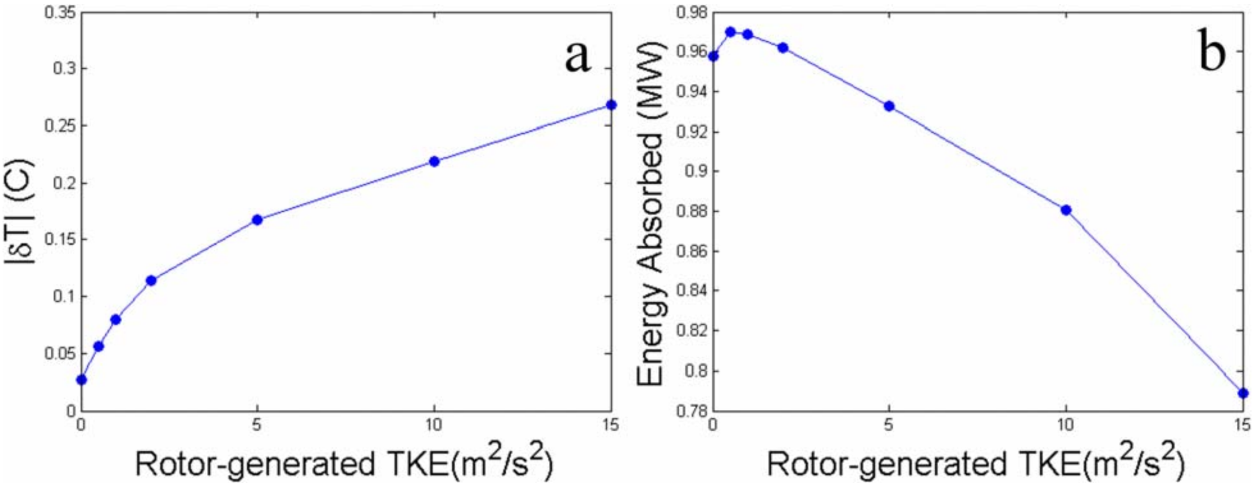

Figure 4. (a) Change in near-surface air temperature within the wind farm and (b) mean energy absorbed by each rotor as a function of rotor-generated turbulence.

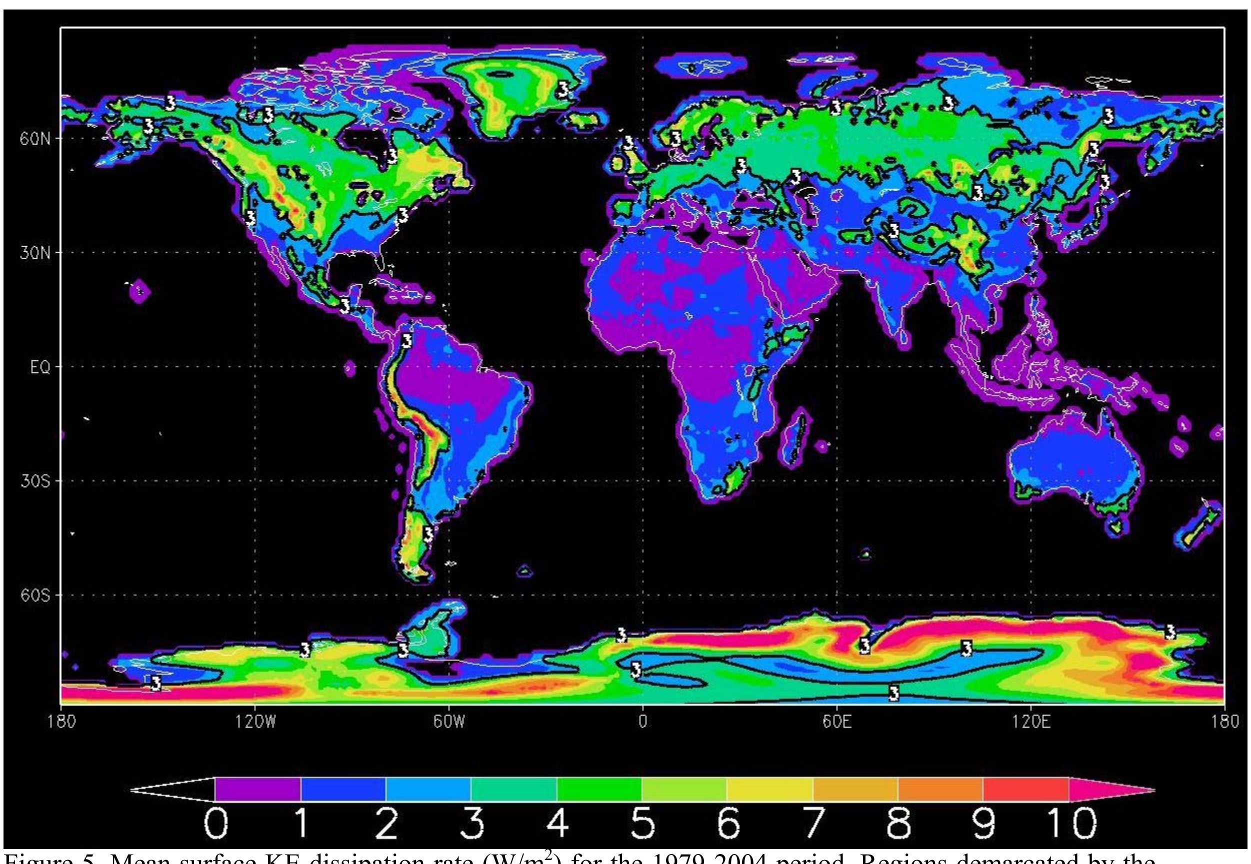

Figure 5. Mean surface KE dissipation rate (W/m^2) for the 1979-2004 period. Regions demarcated by the black line (3 W/m^2 contour) are ideal for low-impact wind farms.