Effects of global warming on wind energy availability

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The use of wind energy reduces our greenhouse gas emissions into the atmosphere. In this study, we proposed a generic power-law relationship between global warming and the usable wind energy (Betz's law). The power law index (~4, region dependent) is then determined using simulated atmospheric parameters from eight global coupled ocean-atmosphere climate models (CGCMs). It is found that the power-law relationship holds across all eight climate models and also is time scale independent. Reduction of wind power scales with the degree of warming according to a generic power-law relationship. Thus, the earlier we switch to clean energy, and thereby decrease the global climate warming trend, the more cost-effective will be the harnessing of wind energy. This relationship is an area-averaged consequence of the reduced poleward temperature gradient as the climate warms during the 21st Century; it does not imply spatial uniformity over a region of interest. [doi:10.1063/1.3486072]

The use of clean alternative energy reduces our greenhouse gas emissions into the atmosphere.[1] Although wind energy exists ubiquitously on Earth, it has not spared the effects of global warming. Here we would like to point out that harnessing wind energy quickly is imperative, simply because this energy resource will shrink as our climate warms. Delayed investment means more investment, technologically and financially, or both.

The global poleward temperature gradient drives the overall circulation pattern of the earth's atmosphere. As the Earth rotates, our atmosphere operates such that the most effective means to transport energy and angular momentum poleward is through a relay system from the tropics to the subtropics via the Hadley circulation and from that point via midlatitude, synoptic eddies of a baroclinic nature (high and low pressures on lower level weather maps). The present atmosphere is water vapor constrained[2,3] such that only a limited section ahead of a trough contains clouds and precipitation, with the released latent heat transported to higher latitudes. Any factor that alters the equator-pole temperature contrast will affect the strength and pattern of the large-scale, time-averaged circulation. Because turbines rely on winds within the boundary layer, surface topography adds yet another formidable degree of complexity. All known physics considered, the current global coupled ocean-atmosphere climate models (CGCMs) are well-posed to address whether increased temperatures will change the circulation strength and geographical patterns so as to affect the available amount of wind energy.

On the whole, free atmospheric winds at mid- and high-latitudes are predominantly quasigeostrophic, thus established and maintained by baroclinity, which when time-averaged tends to follow the diminishing poleward temperature gradient. As it warms generally, the poles will tend to warm faster, since the comparatively small polar regions must balance extra heat from the rest of the globe. This effect is amplified by net radiative losses at the poles, due to decreased polar albedo as the ice caps melt to open ocean. Thus, a strong inverse correlation is retained between regional warming and a diminishing poleward temperature gradient.

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Current modern turbines have a hub height around 80–100 m and thus utilize winds within the boundary layer, where friction may alter the wind vector aloft. If such "Ekman pumping,"[4] along with dynamic effects induced by local topography, is viewed as a quasiconstant loss factor to link wind speeds in the free atmosphere to those available to turbines, there may exist a power law relationship between total wind power decreases and changes in spatially differential warming. This may be depicted by the form $P=P_0(1-\delta T/T_{\mathrm{mean}})^{\eta}$, where P_0 is the presently available wind power, P is wind power at a future time, δT is the amount of temperature warming over the region of interest, T_{mean} is the mean temperature over the region, and η is a numerical exponent characteristic of the region. We find that such a power law relationship is valid for sufficiently large regional areas, especially in the mid- to high-latitudes.

The following discussion focuses on China, which has committed itself to use more clean energy in the future.[1] To render our results more useful in guiding further evaluation of wind energy potential in China, we also assumed the use of GE 1.5 MW xle turbines (with a cut-off wind speed of 5 m/s at an air density of 1.2 $\mathrm{kg/m^3}$) as the standard device for tapping wind resources.[1] This is a monsoonal region. Thus horizontal temperature gradient forcings include those caused by the land-sea contrast. This region is also affected by the Tibetan Plateau through topographically induced katabatic winds. The related physics are parametrized in modern CGCMs.

Wind power intensity is defined as $P=0.5\rho A|\vec{V}|(|\vec{V}|^2-|\vec{V}_0|^2)$ (Betz's law[5]), where ρ is air density and is estimated using air temperature and pressure using the state equation, $\vec{V}$ is the intake wind speed, $\vec{V}_0$ is the exiting wind speed, and wind ingestion area A and $\vec{V}_0$ are turbine parameters. A warming climate affects air density and wind speed, two controlling factors for available wind energy. The multiple climate model simulations of the 20th and 21st centuries from the World Climate Research Program's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) archive allow us to assess monthly changes in wind power intensity within China for 30-year periods at the end of the 20th and 21st centuries (Fig. 1). We used climate model estimated air temperatures, air pressure, and wind speeds as near to hub height (80–100 m for GE 1.5 MW xle's) as was available to evaluate the above-proposed power law relationship. We used as wide a range of climate models as possible from the CMIP3, given constraints on data availability. Figure 1 illustrates wind power changes in simulations with eight different climate models in the WCRP's CMIP3 archive: CNRM-CM3, GFDL-CM2.1, INM-CM3, MIR-hires, CCSM3, ECHAM5, HadCM3, and CSIRO.

For this suite of models, we find that the following relationship applies to China as $P=P_0(1-\delta T/T_{\mathrm{mean}})^{3.718}$. P_0 and P are present and anticipated power intensities, respectively, as estimated by CGCM provided meteorological parameters, under current climate (1971–2000) and at a future time (2071–2100). The nearly fourth degree exponent may derive from the fact that wind power output is linear with density but increases with the cube of the wind speed (Betz's law). This relationship is time scale independent. For models with subdaily data (e.g., MIROC-hires, ECHAM5, CNRM, and CSIRO have daily and three-hourly data), we examined this relationship on a daily time scale and the relationship was shown to hold. Based on the three-hourly data, the wind distribution shifts toward categories below 5 m/s, and thus becomes unavailable to the GE 1.5 MW turbines (with a cut-in wind speed of 3.5 m/s). For the upcoming 30 years, an additional empirical factor of about 0.9 must be applied to the above relationship in order to model the capacity factors. All eight models indicate that accessible wind energy will degrade over the course of this century (e.g., the CCSM and HadCM3 indicate an $\sim$14% reduction in wind power, Fig. 1). That all eight models lie alongside the diagonal straight line (Fig. 1) is a clear indication that the above-proposed power-law relationship holds across climate models, or, more directly that the reduction of wind power scales with the degree of warming according to a generic power-law relationship. This relationship is an area-averaged manifestation of the reduced poleward temperature gradient as climate warms during this century; it does not imply spatial uniformity over the region of interest. In fact, geographical heterogeneity remains significant for the mountainous parts of China (to be detailed soon).

These climate model estimates apply to a mild future greenhouse gas emissions scenario, the Special Report on Emission Scenarios A1B [SRES A1B (Ref. 6)], one of three nonmitigated IPCC

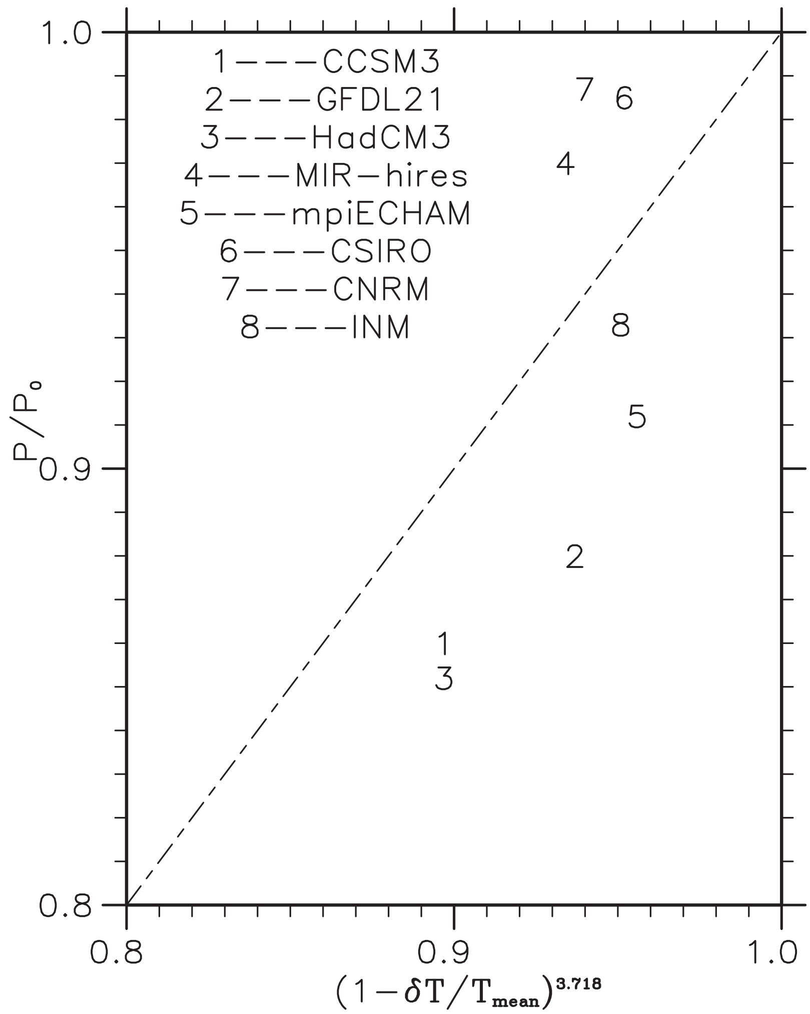

FIG. 1. The eight CGCMs simulated changes in wind power (longitudinal axis) between periods (2071–2100, P) and (1971–2000, P_0) vs a climate warming index (transverse axis). We averaged wind power values over all model grid boxes within China and over the entire period of 30 years. We took spatial and temporal averages only over those grid points with wind speeds confined by the cut-in and cut-out wind speeds. The same operation was performed for temperature. The boundary mask for China is provided by Lu. Each number represents a climate model simulation (CMIP identifiers as in the legend). Climate projections of the 21st century atmospheric variables are under a moderate scenario for greenhouse gas emissions [SRES A1B (Ref. 6)]. In the CMIP3 project, model simulations of 20th century climate derive from a modeling experiment called the 20th Century Climate in Coupled Models (20C3M) simulating present-day atmospheric conditions.

SRESs: B1 (low, 550 ppmv CO_2 concentration by 2100), A1B (medium, 720 ppmv), and A2 (high rate of emission, 850 ppmv) emission scenarios. The A1B scenario foresees a world characterized by low population growth, very high GDP growth, very high energy use, low land-use changes, medium resource availability, and rapid introduction of new and efficient technologies. A1B thus reflects the most recent trends in the driving forces for emissions. Strong emission scenarios such as A2 indicate more severe reductions in available wind resources, as is apparent from our formula as δT increases. Also, the climate models' simulated reduction of poleward temperature gradient may underestimate reality because, although all eight climate models considered the positive feedback associated with variations in snow and ice coverage as a key factor amplifying climate change at high northern latitudes (e.g., Ref. 7), none have explicitly implemented recent findings of methane emission from permafrost frozen soils and seeping methane clathrates along the arctic continental shelves[8] as possible mechanisms for amplified polar warming. Moreover, driven by a

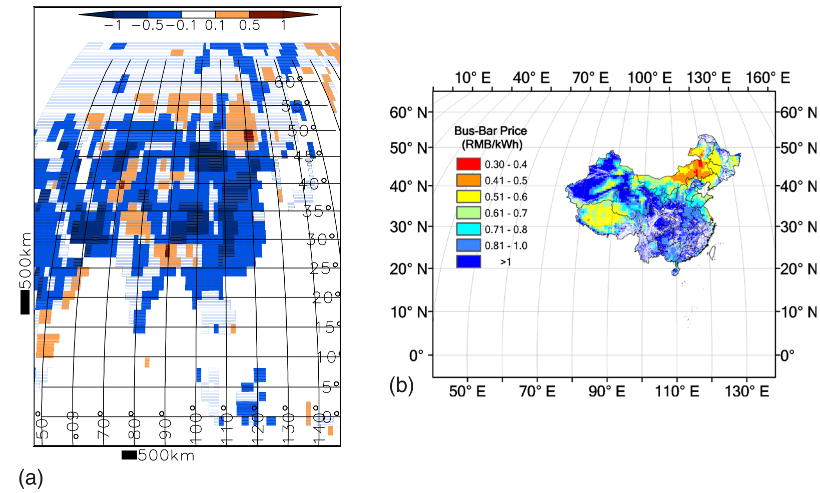

FIG. 2. Observed changes in wind speed [(1989–2008) minus (1951–1970), m/s] for land areas within 0–70 North and 50–150 East (a). The NCEP/NCAR reanalyses (www.esrl.noaa.gov/psd/data/gridded/tables/monthly.html) 10 m monthly wind speed is used in the analysis. Panel (b) is reproduced from Fig. 3 of Ref. 1 by its second author. The color shading indicates the geographical distribution of prices at which wind-generated electricity could be delivered profitably to the grid ("bus-bar" prices). The lower values are the most profitable. The pseudo-cylindrical-equiareal Mollweide projection is used to preserve relative Earth surface area. Areas with decreasing wind speeds far outnumber those with increasing wind speeds. As the climate warms, regions with decreasing wind speeds are a persistent and expanding feature of the China region.

tendency to maximize growth and reproduction, there may be further polar amplification from live ecosystems as the climate warms up.[9] Finally, an extremely relevant mechanism for the Tibet region of China is land-ice sensitivity to global warming. Currently, none of the eight climate models has interactive, physically complete land-ice dynamics[10] and hence are unable to describe the slackening in the cold katabatic winds flowing down from the Himalayas, due to increased melting of glaciers and snow cover in the lower regions. Given these unaccounted factors, there may be as much as 15% increase in investment costs to utilize the wind resources in China by the year 2030 and onward than was estimated in Ref. 1.

Climate prediction is about quantifying risks and probabilities. Although CGCMs are not able to project a specific day's wind pattern and strength, the climatological trend indicated for our region of interest seems reliable, considering the broad intermodel consensus. Actually, the extraordinary warming during the past 40 years may be a bellwether of changes to come at a more drastic pace. Figure 2(a) shows the observed wind speed changes in China between periods (1989–2008) and (1951–1970). For most areas, there is a decreasing trend for some regions at an alarming rate (e.g., over Tibet and Northeast China). Figure 2(b) is reproduced from Fig. 3 of Ref. 1 by one of its co-authors. The most severe reduction in wind speed, unfortunately, coincides with the most economically viable wind investment regions such as the Northeast (with bus-bar prices cheaper than 0.4 RMB/kWh).

In summary, it is generic to CGCMs that higher temperatures may lead to a weaker atmospheric circulation over, not just China, but also many higher latitude regions. This study provides an empirical relationship between warming and decreased wind power. This will provide an important guide in planning for the future installation of wind farms, i.e., by taking the effects of global warming into consideration. We show that the efficiency of tapping wind energy is adversely affected by future global warming. So, wind energy should be accessed as soon as possible. In this study, geographic features (i.e., slope angle and aspects) of the land surface are assumed to change at much longer time scales than transient climate changes of anthropogenic origin. Thermal and/or radiative differential heating exerted by local, finer (than climate model horizontal resolution) terrain features is not considered, neither is its sensitivity to climate change.

Repeating these analyses with increased climate model resolution will likely improve the power index estimate but is unlikely to nullify the power law relationship proposed here.

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