Wind speed reductions by large-scale wind turbine deployments lower turbine efficiencies and set low generation limits

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Wind turbines generate electricity by removing kinetic energy from the atmosphere. Large numbers of wind turbines are likely to reduce wind speeds, which lowers estimates of electricity generation from what would be presumed from unaffected conditions. Here, we test how well wind power limits that account for this effect can be estimated without explicitly simulating atmospheric dynamics. We first use simulations with an atmospheric general circulation model (GCM) that explicitly simulates the effects of wind turbines to derive wind power limits (GCM estimate), and compare them to a simple approach derived from the climatological conditions without turbines [vertical kinetic energy (VKE) estimate]. On land, we find strong agreement between the VKE and GCM estimates with respect to electricity generation rates (0.32 and 0.37 W_e m^{-2}) and wind speed reductions by 42 and 44%. Over ocean, the GCM estimate is about twice the VKE estimate (0.59 and 0.29 W_e m^{-2}) and yet with comparable wind speed reductions (50 and 42%). We then show that this bias can be corrected by modifying the downward momentum flux to the surface. Thus, large-scale limits to wind power use can be derived from climatological conditions without explicitly simulating atmospheric dynamics. Consistent with the GCM simulations, the approach estimates that only comparatively few land areas are suitable to generate more than 1 W_e m^{-2} of electricity and that larger deployment scales are likely to reduce the expected electricity generation rate of each turbine. We conclude that these atmospheric effects are relevant for planning the future expansion of wind power.

momentum | natural limits | surface stress | wind energy | vertical transport

Wind power is a renewable energy source that could meet the primary human energy demand with extensive large-scale deployment. Over the last decade, wind power deployment has increased by 23% per year, contributing 2.2% of the global electricity demand in 2010 and 3.7% in 2014 (1). Many governments are pursuing ambitious plans to further increase the proportion of wind energy within their energy systems. By 2035, the International Energy Agency predicts that even with the projected increase in global electricity demand to 2.6–4.3 terawatts (TW_e = 10^{12} watts of electricity), wind power is projected to contribute 22–28% (0.95–1.2 TW_e) of this electricity demand (2).

Plans for future wind power deployment are commonly derived from observed wind speeds in combination with assumed turbine characteristics and spacing (e.g., refs. 3–5). However, this approach is only applicable for a few isolated wind turbines or when a row of wind turbines are aligned perpendicular to the wind direction (common offshore). Increasing wind turbine deployment uses an increasing share of the kinetic energy of the atmosphere, thus likely slowing down wind speeds. Climate models can explicitly simulate these effects (6–8) and yield a 10-fold reduction of the expected large-scale electricity generation rate from 3 to 5 W_e m^{-2} reported in studies using observed wind speeds (3–5, 9, 10) down to 0.3–0.5 W_e m^{-2} reported in climate model studies (6–8), with about 1.0 W_e m^{-2} possible in more windy regions like the US Midwest (6, 8, 11–13).

However, climate models are inherently complex and computationally intense and do not allow for the use of observed wind fields to derive limits for large-scale wind power use. Ideally, one would combine the effect of reduced wind speeds with the realism of observed wind fields and thereby obtain better estimates of wind power limits of different regions. Here, we present such an approach, test it against climate model simulations for different regions across land and ocean, and evaluate the implications of atmospheric effects on the electricity generation rate of individual wind turbines. Our approach uses the atmospheric momentum balance as the physical basis to predict how wind speeds decline in the presence of wind turbines. This approach therefore includes the effect that more wind turbines lower wind speeds, yielding the limit (or maximum rate) of kinetic energy that can theoretically be extracted from the atmosphere by the turbines. This approach [vertical kinetic energy (VKE) (6, 7, 13)] thus estimates the large-scale limit of wind power generation within a region.

The goal here is to evaluate the broader geographic applicability of the VKE approach over a range of climatic conditions by comparing VKE estimates to those simulated by a general circulation model (GCM) with various intensities of wind power deployment. We then modify VKE to improve the agreement with the GCM estimate, referring to it as the mVKE approach. Not only do the wind power limits predicted by mVKE and the GCM approach match within a factor of 2, but they also agree well with previously published estimates using other GCMs (6, 8, 11, 14). These mVKE estimates are substantially lower than estimates based only on observed wind speed and technical characteristics of

Significance

Understanding the limits of electricity generation from winds is a requirement for planning a renewable energy future. A difficulty in estimating such limits is that wind turbines remove kinetic energy from the atmosphere, so that many turbines should reduce wind speeds, ultimately setting a limit to how much kinetic energy can be taken out of the atmosphere. We show that this slowdown effect can be accounted for by detailed climate model simulations and a relatively simple method that does not directly simulate atmospheric dynamics. This slowdown effect is critical to consider, as it makes each turbine less productive and shows that few land areas can yield more than 1.0 W_e m^{-2} of electricity at large scales.

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the turbines (3–5, 15). The reduction in wind speeds plays a central role in shaping these lower estimates: it directly impacts the electricity generation rate of each turbine, regardless of its technical design. We then discuss that including these atmospheric effects is critical to planning for the expansion of large-scale wind power.

Methods

We evaluate wind power limits at large scales in the climatological mean using two approaches: the GCM and VKE approaches. In the GCM approach, the Planet Simulator GCM of the atmosphere (16, 17) is used for sensitivity simulations of a wide range of installed capacities (0.02–1360 $MW_i\ km^{-2}$) at the global scale, similar to previous studies (6–8, 11–14). The effect of wind turbines is described by an additional drag component in the surface momentum flux in the model. This added drag in combination with the simulated wind speeds is then used to estimate the rate of electricity generation by the wind turbines. From our simulated range of installed capacities, we then identify the maximum electric energy generation rate over land and ocean, and refer to it as the "GCM" estimate.

In the VKE approach, the wind speeds (v_0) and surface momentum fluxes (τ_0) from the control simulation of the GCM without turbines (indicated by the subscript 0) are used to estimate the large-scale wind power limit. The VKE estimate uses the maximum electricity generation rate at large-scale, described by $G_{e,VKE} = (4\sqrt{3})/27 \cdot \tau_0 \cdot v_0$. Note that this expression only uses the natural conditions of the control climate and no technical specifications. This limit is associated with a reduction in wind speeds by $1 - (\sqrt{3})/3 \cdot v_0 = 42\%$ or to $58\% \cdot v_0$, which is a direct consequence of the kinetic energy extraction by the wind turbines in combination with the momentum balance of the lower atmosphere. To improve the agreement with the GCM estimate, we then derive a correction $\tau_m = f(\tau_0)$, whereas the velocity reduction is given by the same expression as above. This correction yields a modified estimate of $G_{e,mVKE} = (4\sqrt{3})/27 \cdot \tau_m \cdot v_0$, where τ_m is the modified surface momentum flux. We refer to this modified estimate as the mVKE estimate. More details on the methodology are provided in *SI Appendix*.

Results and Discussion

We first identify the wind power limits within the GCM sensitivity simulations and the associated changes in wind speeds (Fig. 1). Fig. 1*A* shows the mean electricity generation rates simulated at progressively higher installed capacities. As would be expected, electricity generation first increases with greater installed capacity but then reaches a maximum rate of about 0.37 $W_e\ m^{-2}$ on land (0.59 $W_e\ m^{-2}$ over ocean) at an installed capacity of 24.3 $MW_i\ km^{-2}$ on land (9.1 $MW_i\ km^{-2}$ over ocean). Note that the generation rate does not "saturate," as suggested by ref. 8, but rather generation reaches a maximum limit, beyond which electricity generation is reduced due to the further slowdown in wind speeds (6, 7, 13).

This reduction in wind speeds with greater installed capacities is shown in Fig. 1*B*. Compared with the control climate without turbines, the wind speed is reduced from a mean of 4.6 $m\ s^{-1}$ on land (7.8 $m\ s^{-1}$ over ocean) to 2.6 $m\ s^{-1}$ at the maximum (3.9 $m\ s^{-1}$ over ocean), which represents a decrease by 44% (50%). Note that these generation rates and wind speed reductions show a large extent of spatial variation (Fig. 2 *C* and *D*) and temporal variation that is not discernible in the means shown in Fig. 1.

These estimates compare well to previous studies (Table 1). When averaged over the whole globe, our GCM simulations yield a mean maximum rate of 0.53 $W_e\ m^{-2}$ (270 TW_e), which is comparable to previous model-based estimates of 0.44–0.55 $W_e\ m^{-2}$ (224–282 TW_e; rows n and o in Table 1) (8, 14). Over land, our GCM estimate of 0.37 $W_e\ m^{-2}$ (49 TW_e) compares well to the range of 0.26–0.54 $W_e\ m^{-2}$ (34–71 TW_e; rows q–s in Table 1) (6, 8, 19). The GCM-based estimates reproduce the higher generation rates of the US Midwest and Western Europe at about 1 $W_e\ m^{-2}$ (Fig. 2*C*) (6–8, 11–13). The ocean estimates also agree broadly in magnitude [rows v and w in Table 1 (8), as well as being visually comparable to the simulations by ref. 14]. All of these generation rates are lower than large-scale estimates of 3–6 $W_e\ m^{-2}$ derived in studies that used observed wind speeds ("climatology-based estimates"; rows c, f, h, j, and k in Table 1). Note that these climatology-based estimates are about 10 times higher than GCM-based estimates and the mVKE estimate because previous climatology-based estimates neglected the slowdown effect.

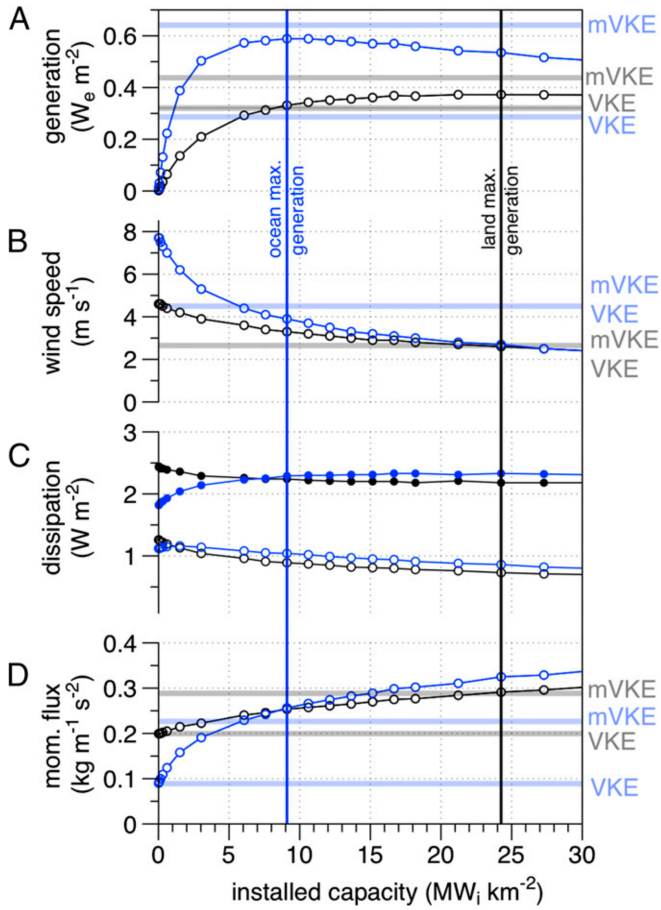

Fig. 1. Simulated global-scale sensitivity of annual means of the rate of electricity generation (*A*), wind speed (*B*), dissipation of the total atmosphere (solid points) and near the surface (open points) (*C*), and (*D*) downward flux of horizontal momentum to the installed capacity of wind turbines for ocean (blue) and land (black). The vertical lines mark the installed capacities that yield maximum generation rates over ocean (9 $MW_i\ km^{-2}$) or land (24 $MW_i\ km^{-2}$). The horizontal lines show the values estimated or used by the VKE and mVKE approaches (blue for ocean; black for land).

Also consistent with previous estimates is the total dissipation rate, shown in Fig. 1*C*. As dissipation balances the kinetic energy generation in the climatological mean, it provides an estimate of kinetic energy generation of about 2.5 $W\ m^{-2}$, which sustains atmospheric motion. This rate is consistent with long-standing estimates of 2–3 $W\ m^{-2}$ derived from atmospheric energetics (22, 23). About half of the generated kinetic energy is dissipated near the surface, with a mean value of about 1.2 $W\ m^{-2}$ (Fig. 1*C*, open circles). Dissipation near the surface decreases because wind speeds are reduced with greater installed capacity, but total atmospheric dissipation remains almost constant. This finding indicates that dissipation is being shifted aloft to higher altitudes in the lower atmosphere. The limit to wind power generation in our simulations is thus below the ~1.2 $W\ m^{-2}$ dissipation rate of the lower atmosphere, consistent with what has been proposed previously (18).

We next evaluate how well these estimates are predicted from the climatic conditions of the control simulation by the VKE approach. The inputs of VKE are wind speed and surface momentum flux, and the resulting estimates are shown in Fig. 1 (also see rows a, e, i, and l in Table 1). The VKE estimates are within a factor of 2 of the GCM estimates over 87% of the land surface (*SI Appendix*, Fig. S3), with VKE yielding a mean of

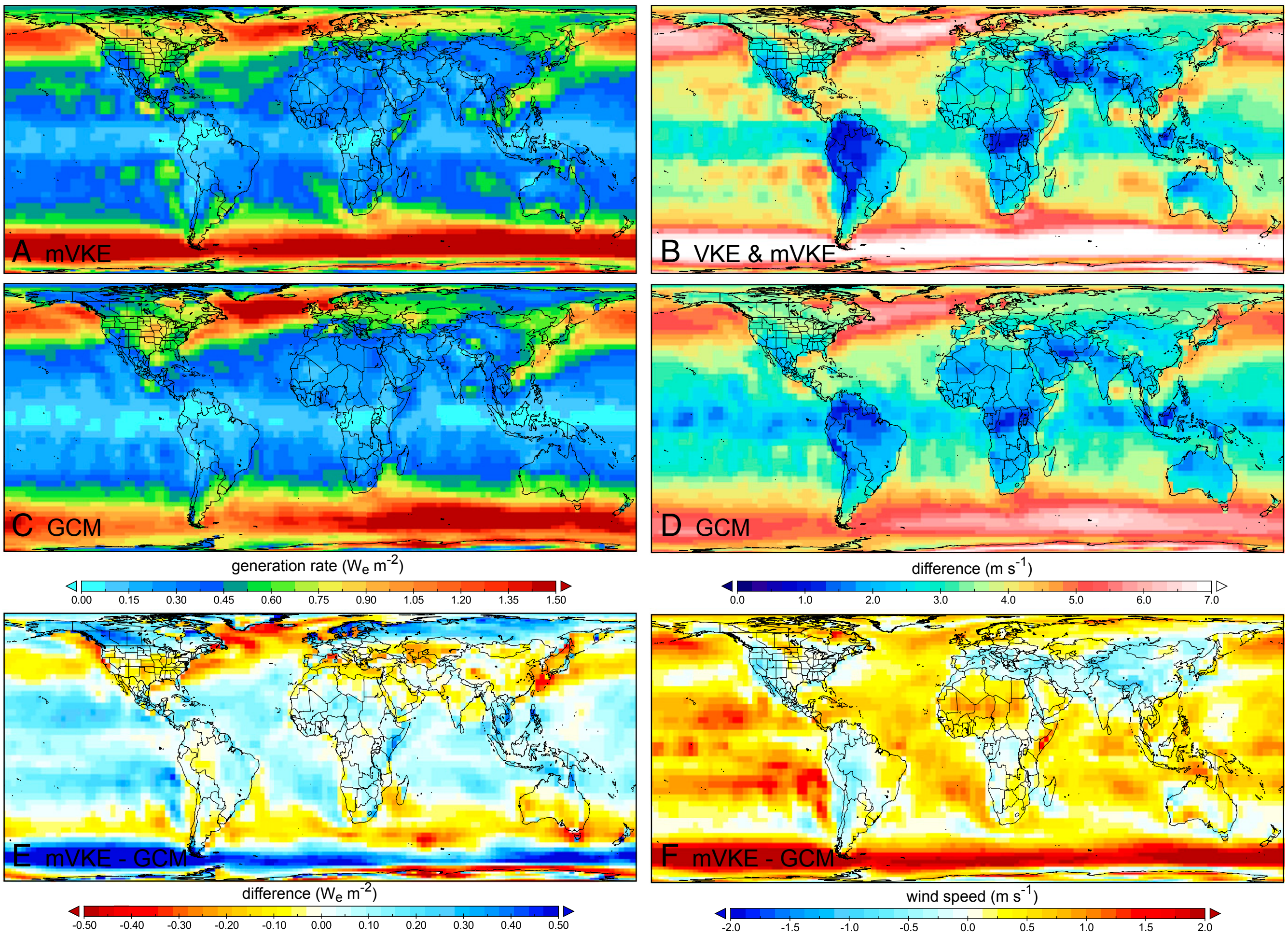

Fig. 2. Annual means of the maximum electricity generation rate estimated by the mVKE (*A*) and GCM (*C*) approaches, as well as the associated wind speeds from mVKE (*B*) and GCM (*D*). *E* and *F* show the differences between the mVKE and GCM approaches.

0.32 W_e m^{-2}, whereas the GCM yields 0.37 W_e m^{-2}. The agreement over the ocean is not as good (*SI Appendix*, Fig. S3), with 33% of the ocean estimates within a factor of 2 (*SI Appendix*, Fig. S3), and VKE underestimating the mean (0.29 W_e m^{-2}) in comparison with the GCM (0.59 W_e m^{-2}).

We next look at two factors that shape the VKE estimate to understand the reason for this bias: wind speed and downward flux of horizontal momentum to the surface. VKE adequately captures the decrease in wind speed by 42% over land and ocean, which compares well with the GCM-based estimate of 44 and 50%, respectively (Fig. 1*B*). The spatial distribution of the reduction in wind speeds by VKE and the GCM also agree reasonably well (Fig. 2*C*, Fig. 3*B*, and statistical relationships in *SI Appendix, Supplement C*). This agreement is found over both land and ocean, although the magnitude is somewhat better reproduced over land. The underestimation by VKE is therefore not due to a general bias in estimating the wind speed reduction. Therefore, we attribute this deviation to the wind turbines enhancing the downward momentum flux.

The underestimation of VKE over oceans results from a substantial increase in the downward momentum flux (Fig. 1*D*), whereas VKE assumes this flux to remain unaffected. Comparing the control climate to the simulation at maximum wind power, over land, the downward momentum flux increases by 45% (0.20 to 0.29 kg m^{-1} s^{-2}), but over ocean, the flux nearly triples (+188%, 0.09 to 0.26 kg m^{-1} s^{-2}; *SI Appendix*, Fig. S2). These findings suggest that the assumption in the VKE approach of a fixed momentum flux is better justified over land than over ocean. Aspects of atmospheric stability seem to play only a marginal role in explaining the bias (*SI Appendix*), and we attribute this difference mostly to the difference in the empirical parameterizations of surface drag over oceans and land that are used in the climate model [and which are commonly used in GCMs (e.g., ref. 24)]. This may relate to a difference in the mechanism by which momentum is transported down to the surface over land and ocean, for instance by differences in boundary layer dynamics or gravity waves (25, 26) This, nevertheless, is likely to have relevant implications, as it suggests that wind power limits may generally be higher over ocean than over land. This aspect would need to be evaluated further.

We thus attribute the bias in VKE to changes in the downward momentum flux, which we correct for by using the GCM simulations (*SI Appendix, Supplement B* and Fig. S1). This bias uses separate corrections for ocean and land by empirically relating the surface momentum fluxes of the control climate and the modified surface momentum fluxes of the GCM estimate. The resulting mVKE estimate agrees more closely with the GCM simulations (Figs. 1–3), except for conditions of very high wind speeds like the Southern Ocean, where the decrease in wind speed is underestimated, thus resulting in an overestimation of the wind power limit. For conditions of low to medium wind speeds, the mVKE estimate agrees much better to the GCM estimate (Fig. 2*E*). Overall, the mVKE estimates (global: 0.59 W_e m^{-2}; land: 0.44 W_e m^{-2}; ocean: 0.64 W_e m^{-2})

Table 1. Comparison of wind power limits based on climatology (rows a–l) and GCMs (rows m–z)

Approach for estimation of wind power limit	Global coverage, %	Installed capacity, $MW_i\ km^{-2}$	Wind speed: Control, $m\ s^{-1}$	Wind speed: Max. gen., $m\ s^{-1}$	Wind speed: Reduced by, %	Electricity generation: $kWh\ m^{-2}\ y^{-1}$	Electricity generation: $\sum TW_e$	Electricity generation: $W_e\ m^{-2}$
Climatology-based								
Global								
a) VKE (this study)	100	n/a	7.0	4.0	42	2.7	158	0.31
mVKE (this study)	100	n/a	7.0	4.0	42	5.2	302	0.59
b) Gustavson (1979) (18)	100	6.0	—	—	—	2.2	130	0.25
c) Jacobson and Delucchi (2011) (5)	100	—	7.0	—	—	29.2	1,700	3.33
d) Jacobson and Archer (2012) (8)	100	11.3	8.1	—	—	30.0	1,750	3.43
Land								
e) VKE (this study)	26	n/a	4.6	2.7	42	2.8	43	0.32
mVKE (this study)	26	n/a	4.6	2.7	42	3.9	57	0.44
f) Archer and Jacobson (2005) (3)	3.2	9.0	8.4	—	—	37.9	72	4.33
g) Lu et al. (2009) (4)	26	8.9	—	—	—	8.3	126	0.95
h) IPCC (2012) (9), Rogner et al. (2000) (10)	6	n/a	—	—	—	54.7	190	6.24
Oceans								
i) VKE (this study)	71	n/a	7.8	4.5	42	2.5	104	0.29
mVKE (this study)	71	n/a	7.8	4.5	42	5.6	233	0.64
Oceans (nearshore)								
j) Lu et al. (2009) (4)	1.2	5.8	—	—	—	29.4	21	3.36
k) Capps and Zender (2010) (15)	1.2	13.2	9.4	—	—	55.8	40	6.37
Ice								
l) VKE (this study)	3	n/a	8.9	5.1	42	6.3	11	0.72
mVKE (this study)	3	n/a	8.9	5.1	42	6.4	12	0.73
GCM-based								
Global								
m) GCM (this study)	100	10.6	7.0	3.6	48	4.6	270	0.53
n) Jacobson and Archer (2012) (8)	100	11.3	8.1	4.0	51	3.9	224	0.44
o) Marvel et al. (2012) (14)	100	1.7–3.4	9.0	6.3	30	4.8	282	0.55
Land								
p) GCM (this study)	26	24.3	4.6	2.6	44	3.2	49	0.37
q) Miller et al. (2011) (6)	26	15.2	4.3	2.5	42	2.3	34	0.26
r) Jacobson and Archer (2012) (8)	26	11.3	7.5	4.5	40	4.7	71	0.54
s) Wang and Prinn (2010) (19)	11	—	—	—	—	2.9	19	0.33
t) Keith et al. (2004) (11)	2.6	—	—	—	—	10.4	16	1.19
u) Fitch (2015) (20)	0.4	10.0	3.2	2.3	29	5.5	1	0.63
Oceans								
v) GCM (this study)	71	9.1	7.8	3.9	50	5.2	213	0.59
w) Jacobson and Archer (2012) (8)	74	11.3	8.4	4.1	51	3.3	162	0.38
Oceans (nearshore)								
x) Wang and Prinn (2010) (19)	2	—	—	—	—	2.6	3	0.30
y) Wang and Prinn (2011) (21)	2.2	—	—	—	—	5.3	7	0.61
z) Wang and Prinn (2011) (21)	3.6	—	—	—	—	5.6	12	0.64

Estimates by VKE and mVKE are given by rows a, e, i, and l; estimates in rows b and g use long-term global mean near-surface atmospheric dissipation rates as a bound to electricity generation; estimates in rows c, d, f, g, h, j, and k use observed wind speeds and prescribed turbine characteristics without accounting for the reduction in wind speeds. A detailed description of the studies is provided in *SI Appendix, Supplement D*. IPCC, Intergovernmental Panel on Climate Change; Max. gen., maximum electricity generation; n/a, not derived for a specific installed capacity.

compare well with the GCM estimates (global: 0.53 $W_e\ m^{-2}$; land: 0.37 $W_e\ m^{-2}$; ocean: 0.59 $W_e\ m^{-2}$) and are within a factor of 2 over 92% of the nonglaciated land surface and over 93% of the ocean (*SI Appendix*, Fig. S3).

It is important to note that the current state of wind turbine deployment is well below the limits described here. In 2014, the global average generation rate of 0.12 TW_e resulted from a global installed capacity of 0.372 TW_i (1). Assuming only land-based turbines, this generation rate would translate into a wind speed reduction of about 0.05% on land, although this effect may be noticeably higher in some regions with many turbines installed.

The relevance of the reduced wind speeds in the presence of large-scale wind turbine deployments is that this combination results in progressively lower electricity generation by each individual turbine. Each turbine sees a horizontal flux of kinetic energy, $\rho/2\ v^3$ (commonly referred to as wind power density), that, to some extent, is used to generate electricity. With reduced wind speeds, this flux is reduced as well as the per-turbine generation rate and the average capacity factor (which compares the generation rate with what would be generated under optimal conditions). The average capacity factor derived from the GCM simulations is shown in Fig. 4*A*. The decrease in the capacity factor with greater installed capacity directly follows the slowdown of wind speeds and yields a reduction in wind power density according to $(v/v_0)^3$. At maximum wind power use, wind speeds are reduced to 58% of their original value, and lowers the capacity factor to 20% of what would be generated by an isolated turbine. With such a drop of electricity generation per turbine,

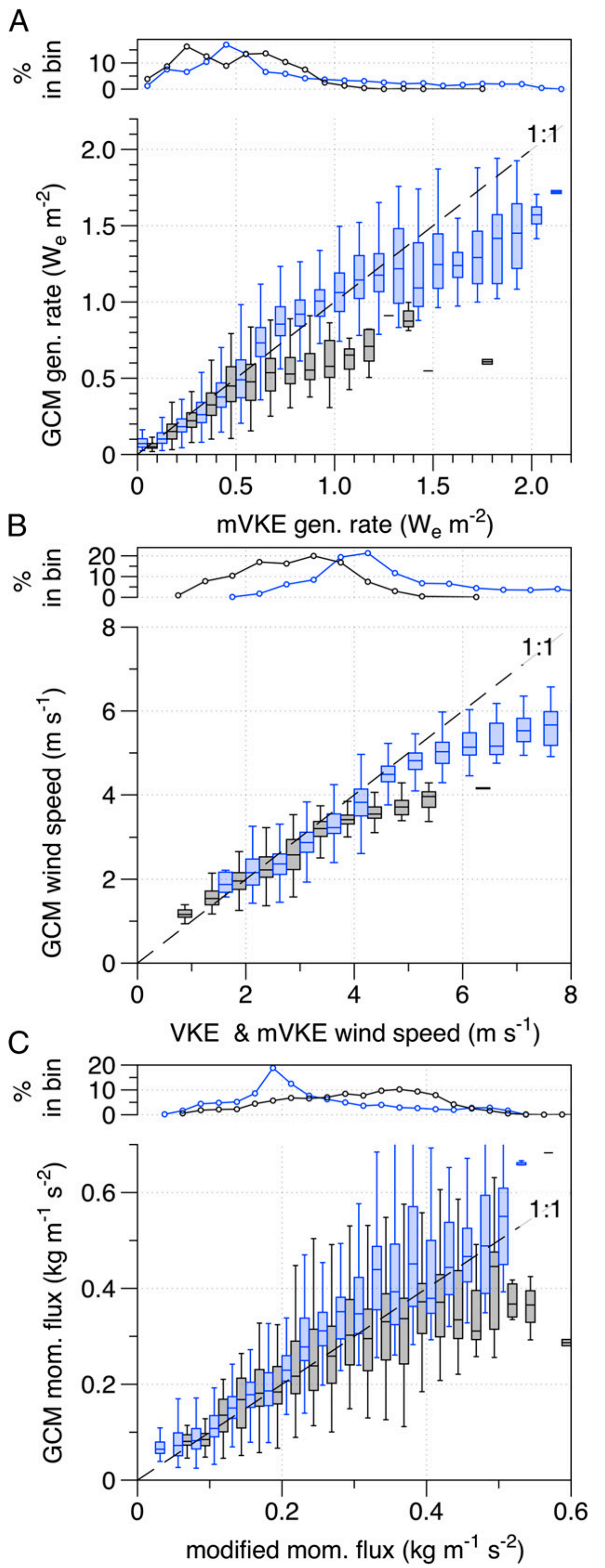

Fig. 3. Grid point comparison of the mVKE estimates to GCM-based estimates at maximum generation for land (black) and ocean (blue) for maximum electricity generation rate (*A*), wind speeds (*B*), and downward momentum flux to the surface (*C*). The top of each plot shows the percentage of data (not area-weighted) within each land or ocean bin. The bin upper and lower bounds are derived from the interquartile range (IQR), with the boxes representing the 25th, 50th, and 75th percentiles. The statistical relationships are provided in *SI Appendix, Supplement C*.

wind power is likely to become increasingly more expensive to utilize, so that the limit to wind power use derived here may, in fact, not be economically feasible to achieve. Installed capacities of 5–10 MW_i km^{-2} are common among present-day wind turbine deployments [the US average is about 3 MW_i km^{-2} (0.4–23 MW_i km^{-2}) from 161 operational and planned wind farms (27)], and yet these values are also close to the large-scale limit shown in Fig. 1. This finding suggests that a future increase in the deployment of wind turbines toward larger scales should probably proceed

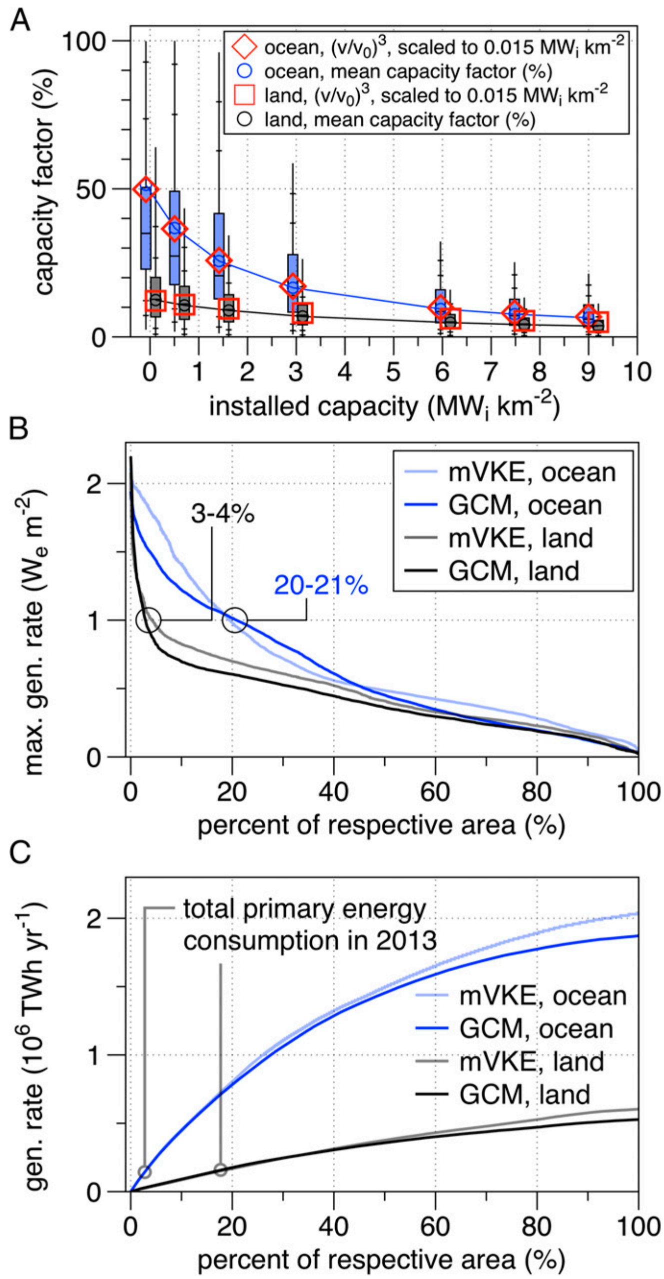

Fig. 4. Comparison of the implications derived from the mVKE and GCM approaches. *A* shows the sensitivity of the capacity factor of individual wind turbines to installed capacity for ocean (blue) and land (black). Also shown by the red symbols is a simple estimate of the capacity factor reduction predicted by the wind speed reduction as $(v/v_0)^3$. *B* shows the distribution of large-scale wind power limits per unit surface area across regions. *C* integrates the distribution shown in *B* to yield estimates for how much area would at a minimum be needed to yield a certain total electricity rate.

at installed capacities well below those currently used to mediate the detrimental effects of reduced wind speeds (also see ref. 28).

The second relevant aspect of these wind power limits is their spatial distribution (Fig. 2). Fig. 4*B* shows the distribution of area according to the wind power limit, showing that the mVKE estimate closely matches the distribution derived from the GCM estimate and that about 3–4% of land and 20–21% of ocean surfaces could, on average, generate more than 1.0 $W_e\ m^{-2}$. This electricity generation rate is considerably lower than 0.8–6.6 $W_e\ m^{-2}$ (with installed capacities of 3.5–24 $MW_i\ km^{-2}$) observed from much smaller wind farms operating on hilltops or in coastal arrays (29). When this distribution is integrated over area to derive electricity generation rates (Fig. 4*C*), it indicates that at least 18% of the windiest land areas (or 3% of the windiest ocean areas) would be needed to meet the current primary energy demand of 18 TW. Using lower installed capacities than those associated with the wind power limits, as described above, would imply that a greater area would be needed. Overall, the comparison indicates that the mVKE approach reasonably reproduces these insights from the GCM simulations as well.

Conclusion

We have shown that the large-scale limits to wind power generation can be derived from climatological conditions in a relatively simple and transparent way using the mVKE approach. The mVKE approach uses the momentum balance and accounts for the reduction of wind speeds, as well as how wind turbines can enhance the downward momentum flux to the surface. The resulting wind power limits estimated by mVKE (global: 0.59 $W_e\ m^{-2}$; land: 0.44 $W_e\ m^{-2}$; ocean: 0.64 $W_e\ m^{-2}$) agree well with the GCM estimates (global: 0.53 $W_e\ m^{-2}$; land: 0.37 $W_e\ m^{-2}$; ocean: 0.59 $W_e\ m^{-2}$), with 92% of the land estimates and 93% of the ocean estimates varying within a factor of 2. Because mVKE used only the climatic conditions of the control simulation, this finding suggests that full atmospheric dynamics are not necessarily required to describe atmospheric effects that set the limits to wind power use. The mVKE approach thus represents an approach that can be used with observations to yield more realistic large-scale wind power potentials that account for these critical, atmospheric effects.

We have illustrated that the relevance of this atmospheric perspective on wind power limits goes beyond the number of turbines and their technical specifications. In both the GCM and mVKE approaches, atmospheric effects explicitly shape the wind power limits. As shown in Table 1, there are numerous observation-based approaches that, by neglecting these atmospheric effects, drastically overestimate wind power limits by a factor of 10. Accounting for these atmospheric effects results in large-scale limits to wind power use in most land regions that are well below 1.0 $W\ m^{-2}$.

These much lower limits have practical relevance, because reduced wind speeds result in lower average electricity generation rates of each turbine. These lower per-turbine generation rates are also associated with higher generation rates per unit area ($W_e\ m^{-2}$) up to the wind power limit, and likely makes wind power less economical at progressively larger deployment scales. Because current values of installed capacity are close to those associated with the limits, this finding implies that the future expansion of wind power should not plan for installed capacities that are much above 0.3 $MW_i\ km^{-2}$ over areas larger than 10,000 km^2. We conclude that these atmospheric effects need to be considered in actual deployments and future scenarios of wind power at larger scales. Specifically, by understanding the basis of wind power limits and their associated atmospheric effects, we can bound future expansion scenarios by the wind power limit and aim to minimize these atmospheric effects to keep wind power economical and effective in reducing CO_2 emissions, thus counteracting global climate change.

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