

## Title

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## Authors

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**A Turbine parameterization**

Pressure (hPa)

Percent change in world wind speed (%)

Jet streams (4,553 TW)  
World (5,728 TW)  
Land (1,829 TW)  
50% 2030 demand (20 TW)

**B Surface roughness parameterization**

Pressure (hPa)

Percent change in world wind speed (%)

World (5,728 TW)  
Land (1,829 TW)  
50% 2030 demand (20 TW)

**C Turbine parameterization**

Pressure (hPa)

Percent change in world water vapor (%)

Jet streams  
World  
Land

Fig. 5. Comparison of heights and morphologies of globally averaged percent of deepened reduction averaged over one year from (A) the turbine momentum sink parameterization presented here to (B) the latitude (333) surface roughness parameterization. In both cases, the world is covered with an 1.146 Gbillion (billion, world), 324.5 million (green, land), or four million (red, 50% of 2030 power demand) turbines. The turbine height is 100 m, and the turbine spacing is 0.04 km<sup>2</sup> each. A jet stream axis is also shown in (A) for 931 million (black) 5-MW vapor mass mixing rate in vertical profile as presented in the world (Simulation B) (land, 0% and sea, 4% × 5° horizontal resolution. Numbers in parentheses are installed wind power in (A)

plane, the GAT01-GCMM01 global model ((20), (21)) is used to estimate saturation flux and fixed wind power potentials. The model is modified so that the turbine is an elevated momentum sink, when the kinematic viscosity is calculated from the wind is determined from a turbine power curve at the instantaneous model wind speed. The treatment of turbines developed is conceptually similar to that in ((22), (23)) but differs as follows: (i) It assumes each wind turbine occupies multiple vertical atmospheric layers rather than one layer, (ii) it is applied to numerous wind farms worldwide simultaneously rather than one local farm, (iii) it is applied in a global model where momentum extraction feeds back to global dynamics rather than a limited-area model with only regional feedbacks, and (iv) it accounts for energy conversion due to both the electricity used and turbulent dissipation of kinetic energy. In addition, the new treatment allows distributed wind turbines in a grid cell to extract energy from four points on a staggered Arakawa C grid, thereby impacting five cells simultaneously, rather than from the center of the cell, affecting only that cell.

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## and credentials

More relevant for practical applications, the FWP of four million turbines at 100 m in three different configurations is quantified here to determine if this number is sufficient for powering half the world's all-purpose power demand in a 2030 clean-energy economy (10).

**Author contributions:** M.Z.J. and C.L.A. designed research; M.Z.J. and C.L.A. performed research; M.Z.J. contributed new reagents/analytic tools; M.Z.J. and C.L.A. analyzed data; and M.Z.J. and C.L.A. wrote the paper.

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Jacobson and Archer

# The Structure of a Scientific Article

total power in that region (100 TW) multiplied by the fraction that could interact with wind turbine rotors ( $<0.3$ ), the fraction in the range of turbine cut-in and cut-out speeds (0.75), and the fraction converted from kinetic to electrical energy (0.5). These factors were all accounted for in time and space in the simulations here. The large difference highlights the importance of using physical calculations.

The SWPP over land outside Antarctica here was approximately 72 TW (Fig. 24 and Fig. S3C). Based on the high-resolution global-SWPP calculations here, another approximately 8 TW was available offshore at depths  $<200$  m, giving a land plus coastal SWPP estimate of 80 TW. Like with the global case, the land-SWPP curve (Fig. 24) shows a linear portion at low turbine penetrations. Beyond approximately 185 TW of installed power, diminishing returns set in. However, the full land-SWPP was not obtained until approximately 1,500 TW ( $11.3 \text{ W/m}^2$ ) of installed power. The result here suggests that bottom-up approaches for calculating wind power potentials over land are justified for  $<185$  TW installed power.

The land-SWPP is not much lower than the 125 TW of onshore power from a study (25) that assumed a fixed percentage energy loss due to turbine interference but not increasing competition for wind with increasing turbine penetration. Results from (25) fall near the linear "global-no extraction" curve in Fig. 24, well above the land-SWPP.

Another study (26) estimated the world land plus coastal potential based on wind sounding and surface data at 100 m. Similarly, ref. 25 estimated a land potential of 78 TW, a density factor of 20% or higher. Both studies accounted for local variations with mean annual wind speeds before extraction of 7 m/s and did not account for increasing competition. The two offsetting factors caused their results to be similar to the SWPP (72 TW) and the land plus near-shore estimate (approximately 80 TW) found here.

If only 50% of land-based wind was available at locally viable locations (21), the feasible wind resource for counting near the surface would be approximately 40 TW.

"The discussion section is the authors' opportunity to give you their opinions...[and] draw conclusions about the results."

Drag from blade rotation also creates turbulence in the form of small-scale vortices that can enhance mixing. This mechanism has been suggested by ref. 27 to explain why wind turbines decrease downwind surface temperatures during the day, when the lapse rate is generally unstable, and slightly increase them at night, when the lapse rate is generally stable but winds at hub height are stronger. However, blade-generated turbulence under neutral conditions is observed to be transported and dissipate downwind in a spiral motion (28), with greater turbulence intensity above the turbine centerline than below (28, 29). While such turbulence reduces mean wind speeds in the wake, it also increases the downward transport of faster winds from aloft into the wake. Blade-generated turbulence is transported vertically due to shear turbulence generated by the velocity deficit in the wake and ambient turbulence rather than on its own (28). As such, blade-generated turbulence decreases substantially between its peak above the centerline and surface and little may get to the surface, as indicated by at least some measurements and high-resolution modeling (figure 1 of ref. 29). This result may differ under very unstable conditions. Even when blade-generated turbulence reaches the ground, it may largely be offset by reduced shearing stress below the turbine caused by reduced wind speed in the wake, resulting in little net surface turbulence, consistent with the aforementioned measurements (29). Both the reduced wind

hydrogen (10). Fig. 2B shows that the power output of four million turbines increases with decreasing wind turbine spacing. When turbines are packed at an installed density of  $11.3 \text{ W/m}^2$  into three sites worldwide, the power output is too low (approximately 1.6 TW—Table 1 and Fig. S3F) to match power demand. At eight locations ( $5.6 \text{ W/m}^2$  installed), the output improves to approximately 4 TW (Fig. S3E) but is still far below demand. However, when turbines are spread away from the poles, and in all (0.11  $\text{W/m}^2$  installed), the output (Fig. S3D), much more than needed, is an installed density of approximately 0.11  $\text{W/m}^2$  to spread turbines evenly across such can have installed densities of 5.6–11.3  $\text{W/m}^2$  with a 5.6–11.3  $\text{W/m}^2$  density within and between farms is accounting for higher model resolution).

## Discussion

It is well known that spreading turbines in a farm increases the farm array capacity by reducing interference of one turbine with the next (11, 12). The results here suggest that staggering farms themselves geographically, improves the overall power output. In other words, the power potential of a fixed number of turbines (HWPP) increases with increased spreading of farms.

The addition of surface wind turbines reduced horizontal wind speeds in their wake, the most and below and above the wake centerline to a lesser extent (Fig. 1A). The reduction in wake wind speed reduced shearing stress below and increased it above the wake centerline, consistent with large-eddy simulation results (18). Greater shearing stress above the wake increased subgrid-scale turbulent kinetic energy (TKE) there, increasing the downward transport of horizontal momentum from above to the turbines. Downward transport of horizontal momentum to a turbine wake was also increased in the model by subgrid-scale thermal turbulence and grid-scale gravity waves when they were present. Lesser shearing stress below the wake decreased TKE and downward momentum fluxes near the surface, as in ref. 18. Evaporation rates are proportional to both surface wind speed and surface shearing stress, and both decreased in all surface turbine simulations, reducing evaporation and water vapor (e.g., Fig. 1C). These calculations were all made with the model resolving the bottom kilometer with 15 vertical layers, including five layers intersecting turbine rotors.

Drag from blade rotation also creates turbulence in the form of small-scale vortices that can enhance mixing. This mechanism has been suggested by ref. 27 to explain why wind turbines decrease downwind surface temperatures during the day, when the lapse rate is generally unstable, and slightly increase them at night, when the lapse rate is generally stable but winds at hub height are stronger. However, blade-generated turbulence under neutral conditions is observed to be transported and dissipate downwind in a spiral motion (28), with greater turbulence intensity above the turbine centerline than below (28, 29). While such turbulence reduces mean wind speeds in the wake, it also increases the downward transport of faster winds from aloft into the wake. Blade-generated turbulence is transported vertically due to shear turbulence generated by the velocity deficit in the wake and ambient turbulence rather than on its own (28). As such, blade-generated turbulence decreases substantially between its peak above the centerline and surface and little may get to the surface, as indicated by at least some measurements and high-resolution modeling (figure 1 of ref. 29). This result may differ under very unstable conditions. Even when blade-generated turbulence reaches the ground, it may largely be offset by reduced shearing stress below the turbine caused by reduced wind speed in the wake, resulting in little net surface turbulence, consistent with the aforementioned measurements (29). Both the reduced wind

References: The numbers connect to the citations included at the end of the article.

speed and small turbulence change near the surface due to turbines contributed in the model to reducing surface evaporation. Uncertainties in the treatment of turbulence still exist due to both the coarse horizontal resolution of the model and the simplification of no turbine-rotor generated turbulence.

Reduced evaporation reduced evaporative cooling of the surface, first warming the surface. However, because evaporated water vapor normally recondenses in the atmosphere to form clouds, releasing latent heat there, the reduction in water vapor reduced latent heat release in the air, cooling the air due to a deficit of this process. Because water vapor contributes to air pressure, reducing water vapor also reduced globally averaged air pressure by approximately 0.3 and approximately 0.1 hPa in the global (Simulation B) and land (I) cases, respectively. Because water vapor is a greenhouse gas, reducing it increased thermal-radiation escape to space, cooling the surface further. However, less water also reduced cloudiness, increasing solar radiation to the surface during the day but increasing outgoing thermal-IR at night, thus causing a slight warming at night, as observed (27, 30). The net effect of all five changes (air cooling due to lower atmospheric latent heat release, ground warming due to lower surface water evaporation, air and ground cooling due to a reduced water vapor greenhouse effect, ground warming due to reduced daytime cloudiness, and ground cooling due to reduced nighttime cloudiness) was a globally averaged surface-air temperature decrease in 15 out of the 16 surface-turbine simulations. This result is expected because water vapor is known to cause net warming of the atmosphere, so reducing it should cause cooling (31). Temperature results, though, are still uncertain, particularly due to the uncertainty of clouds and the transient nature of the simulations and could change over longer simulations because full temperature responses take decades to realize. A certain benefit of the slower winds, though, is the reduction in wind-driven soil dust; sea spray; and spore, pollen, and bacteria emissions, reducing human exposure to small particles that penetrate deep into the lungs.

Globally distributed turbines decreased zonal winds; however, they increased meridional winds in the pole-ward direction in both hemispheres (Fig. S4A and B). The pole-ward transport of air increased the pressure gradient between the poles and Equator by approximately 15–25 hPa, supporting the contention that the atmosphere responded to the increased dissipation of kinetic energy by increasing some of its available potential energy via enhanced pole-to-equator pressure gradients. Reduced water vapor partial pressure at low latitudes contributed slightly to the enhanced pressure gradient.

Global warming increases temperatures at the poles more than lower latitudes. The temperature gradient reduction could reduce global near-surface wind resources in the future although ocean wind resources over the last 25 years have increased in the global average according to multiple datasets (32). Higher water vapor due to future warming will also likely offset reduced water vapor due to wind turbines.

Jet-stream turbines reduced mean wind speeds at altitudes above and below them, but increased boundary-layer wind speeds (Fig. 1C). Like in the surface case, turbines decreased zonal wind speeds substantially (Fig. S5A), but increased meridional wind speeds (Fig. S5B), moving air pole-ward at 10 km but equator-ward near the surface in both hemispheres, following the respective pressure gradients (Fig. S5C). Lower surface pressure in the tropics through midlatitudes caused air to rise, expand, and cool adiabatically, decreasing temperatures at all altitudes (Fig. S5D) and increasing both cloud liquid below 5 km (Fig. S5E) and cloud ice above that. Enhanced cloudiness increased precipitation, and both, together with net divergence, decreased water vapor in the tropics and subtropics and increased it toward the poles (Fig. S5F). Compressional heating over the poles increased temperatures there, but the net effect of jet stream turbines was surface cooling by  $>1 \text{ K}$  (Fig. S5F), as cold air advection from the Poles prevailed near the surface. Interestingly, the higher boundary-layer wind speeds (Fig. 1C and Fig. S5A) increased evaporation there, but enhanced condensation of that vapor decreased column vapor at low latitudes (Fig. S5F).

The reference section lists the sources the authors used in their research. "Use these citations as recommendations for other articles you can refer to for additional background reading."

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