ENERGY

Climate model shows large-scale wind and solar farms in the Sahara increase rain and vegetation

Yan Li[1,2,3]*, Eugenia Kalnay[1,4]*, Safa Motesharrei[1,4,5]*, Jorge Rivas†, Fred Kucharski[6], Daniel Kirk-Davidoff[1], Eviatar Bach[1,4], Ning Zeng[1,7]

Wind and solar farms offer a major pathway to clean, renewable energies. However, these farms would significantly change land surface properties, and, if sufficiently large, the farms may lead to unintended climate consequences. In this study, we used a climate model with dynamic vegetation to show that large-scale installations of wind and solar farms covering the Sahara lead to a local temperature increase and more than a twofold precipitation increase, especially in the Sahel, through increased surface friction and reduced albedo. The resulting increase in vegetation further enhances precipitation, creating a positive albedo–precipitation–vegetation feedback that contributes ~80% of the precipitation increase for wind farms. This local enhancement is scale dependent and is particular to the Sahara, with small impacts in other deserts.

Limiting global warming to 2°C is essential for mitigating excessive damages from climate change (*1*–*3*). Major global efforts and long-term policies are needed to attain the corresponding level of decarbonization (*4*–*6*). Renewable energy sources such as wind and solar power have become viable options (*7*) because of their abundant supply and wide availability on Earth (*8*, *9*). Extracting a small fraction of the solar and wind energy available on Earth would be more than enough to meet the total global demand of energy in all forms. This opens the possibility of powering the world entirely with wind and solar energy, which is possible and has been discussed in the literature (*9*–*13*).

To substitute for the fossil fuels that currently still dominate worldwide electricity generation, as well as transportation, heating, and industrial energy demands, more large-scale wind and solar farms would need to be installed throughout the world. The installed wind turbines and photovoltaic panels would cover the land and modify land surface properties (in particular, surface roughness and albedo, respectively) and, if large enough, could have unintended consequences on local and regional climate (*14*–*16*). Previous modeling studies have shown that large-scale implementation of wind and solar farms can produce significant climate change at continental scales (*10*, *17*). However, in those studies, vegetation is prescribed rather than dynamic—that is, either vegetation types and properties do not respond to the changing climate caused by the large wind and solar farms or the vegetation changes do not feed back onto climate. The lack of vegetation feedbacks could make the modeled climate impacts very different from their actual behavior (*18*, *19*), as vegetation dynamics [e.g., albedo, evapotranspiration, roughness, and leaf area index (LAI)] have been proven to play a key role in the land-climate interaction (*20*). Vegetation feedbacks can either enhance or suppress the initial climate changes triggered by land change (*21*, *22*).

In our study, we used a climate model with dynamic vegetation to investigate the climate impacts of large-scale wind and solar farms installed in the world's largest deserts. We primarily focused on the effect of such large wind and solar farms in the Sahara region (including the most arid parts of the Arabian Desert) and the neighboring Sahel region for several reasons: (i) The Sahara is the largest desert in the world and has a great supply of solar and wind energy. (ii) The Sahara is sparsely inhabited, and thus the development of wind and solar farms would have minimal competition for land surface area against natural and other human land uses, such as agriculture (*15*). (iii) The Sahel is a transition region between desert and wooded savanna and, as such, is highly sensitive to land changes (*18*, *19*, *23*). (iv) Both regions are near Europe and the Middle East, areas with enormous current energy demand, and sub-Saharan Africa, which has a large projected growth in energy demand (see supplementary text). (v) Massive investment in solar and wind generation could promote economic development in the Sahel, one of the poorest regions in the world, as well as provide clean energy for desalination and provision of water for cities and food production (*24*). The wind and solar farms simulated in this study would generate approximately 3 and 79 TW of electrical power, respectively, averaged over a typical year (see supplementary text).

Our results show that the effects of the large-scale wind and solar farms in the Sahara are most significant locally—i.e., at or near the locations of wind and solar farms—with limited remote impacts (Fig. 1). The wind farm causes significant regional warming on near-surface air temperature (+2.16 K), with greater changes in minimum temperature than maximum temperature (+2.36 versus +1.85 K) (fig. S1). This asymmetric temperature impact has been reported in both empirical (*16*) and modeling studies (*14*, *25*). The greater nighttime warming takes place because wind turbines can enhance the vertical mixing and bring down warmer air from above to the lower levels, especially during stable nights (*14*, *26*). Wind farms also increase precipitation as much as +0.25 mm/day, averaged over areas with wind farm installations, which results in the doubling of precipitation compared with the control experiment (0.24 mm/day), particularly in the Sahel region, which features an average increase of +1.12 mm/day (table S1). This is because the increased surface friction reduces wind velocity and the associated Coriolis force, which leads to a more dominant pressure gradient force toward the Saharan heat low that is enhanced by the warming induced by wind farms. This produces surface convergence and upward motion as well as moisture convergence and higher humidity (figs. S3 to S5). The increase in precipitation, in turn, leads to increases in vegetation cover fraction (+0.084), LAI (+0.50 m^2/m^2), and root carbon (+0.08 kgC/m^2) that further reduce surface albedo (figs. S2 and S5). These changes together trigger a positive albedo–precipitation–vegetation feedback (*21*, *22*). Additionally, the recovered vegetation increases evaporation, surface friction, cloud cover (fig. S3), and consequently, precipitation. The increased evaporation, which partially compensates the increased net surface solar radiation, also plays an important role in local precipitation enhancement (*21*). A slight cooling is observed in the wetter Sahel region because recovered vegetation increases evaporation and decreases sensible heat flux. As expected, the increased drag at the surface due to wind turbines reduces wind speed by ~36% (fig. S1).

Impacts of solar farms on temperature and precipitation are markedly similar to those of wind farms in terms of spatial patterns. This is because solar panels directly reduce surface albedo and thus trigger a similar positive albedo–precipitation–vegetation feedback to that of wind farms, and this feedback leads to temperature and precipitation increase. The resulting warming is stronger in maximum temperature

[1] Department of Atmospheric and Oceanic Science, University of Maryland, College Park, MD 20742, USA. [2] Department of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA. [3] State Key Laboratory of Earth Surface Processes and Resources Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China. [4] Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742, USA. [5] Department of Physics, University of Maryland, College Park, MD 20742, USA. [6] Earth System Physics Section, Abdus Salam International Centre for Theoretical Physics, Trieste I-34100, Italy. [7] LASG, Institute of Atmospheric Physics, Chinese Academy of Science, Beijing 100029, China.
*Corresponding author. Email: yanli.geo@gmail.com (Y.L.); ekalnay@umd.edu (E.K.); ssm@umd.edu (S.M.) †Independent researcher.

(+1.28 K) than in minimum temperature (+0.97 K) because albedo reduction mainly affects net radiation during daytime (fig. S1). Compared with the control experiment, a 50% increase in precipitation (+0.13 mm/day) is observed in solar farm locations in the Sahara, and an increase of +0.57 mm/day is recorded in the Sahel (table S1). Unlike the wind farm experiment, the solar farm experiment produces very little change in wind speed (fig. S1).

When wind and solar farms are deployed together in the Sahara, changes in climate are enhanced. The precipitation in the Sahara increases from 0.24 mm/day in the control run to 0.59 mm/day in the case of combined wind and solar farms, a ~150% increase, whereas the temperature increase (+2.65 K) is only slightly larger compared with that for the solar farm alone. Although the absolute amount of precipitation change averaged over the entire Sahara is low from these experiments (up to +0.35 mm/day for the combined wind and solar farms), it should be emphasized that the precipitation impact is not uniform across space. The most substantial precipitation increase occurs in the Sahel, with a magnitude of change between +200 to +500 mm/year (table S1), which is large enough to have major ecological, environmental, and societal impacts.

Our simulations show that both the wind and solar farms in the Sahara contribute to increased precipitation, especially in the Sahel region, through the positive albedo–precipitation–vegetation feedback. This positive feedback is established through different mechanisms for wind and solar farms. For wind farms, the higher surface roughness strengthens low-level convergence, leading to precipitation increase in the Sahara (*27*). For solar farms, the decreased albedo associated with solar panels (i.e., the lower effective albedo of solar panels compared with the sand in the Sahara) results in more absorption of solar radiation and, hence, surface warming, which leads to low pressure at the surface, as well as convergence, rising motion, and consequently, more precipitation (*23*, *28*). The precipitation increase induced by either wind or solar farms, in turn, increases vegetation cover and LAI, leading to further reduction in albedo and increase in roughness, both of which help organize the moisture convergence that drives the change in precipitation. These friction–precipitation–vegetation feedbacks (wind farms) and albedo–precipitation–vegetation feedbacks (wind and solar farms) are known as the Sud (*27*) and Charney mechanisms (*23*, *28*), respectively. To quantify the contribution of these two mechanisms, we carried out additional wind farm experiments in which both mechanisms are present that can separate the climate changes induced by the initial roughness and the subsequent albedo changes due to vegetation feedback (Fig. 2). We found that for the temperature change, roughness and vegetation feedback contribute almost equally (+1.00 versus +1.16 K). The roughness-induced warming occurs because wind reduction weakens the near-surface vertical turbulence transport (*29*). In contrast, for precipitation change, 80% of the increase (+0.20 mm/day) comes from vegetation feedback, whereas roughness plays only a secondary role, except as an initial trigger. These results suggest that the absence of vegetation feedback in the model (*18*, *19*) would considerably underestimate the temperature and precipitation impacts of the large-scale wind farms in the Sahara.

Although wind and solar farms both enhance precipitation in our experiments, solar farms will not necessarily always increase precipitation through albedo changes. The direction of precipitation change is largely determined by the sign of the albedo change before and after a solar farm is installed. More specifically, it depends on the conversion efficiency of the solar panel and the background environment albedo. The precipitation increase in our solar farm experiments is due to the relatively low conversion efficiency of the panels (15%, typical current conversion efficiency for photovoltaic panels), which results in albedo decrease (*30*). However, if solar panel efficiency and the associated effective albedo are high enough to lead to an albedo increase relative to the background environment (as, for example, a 45% efficiency would), the climate impact would be surface cooling with precipitation suppression (fig. S6), similar to the impact of overgrazing in the desert (*23*). Assuming an intermediate conversion efficiency higher than 15% for solar panels (e.g., 30% efficiency) results in

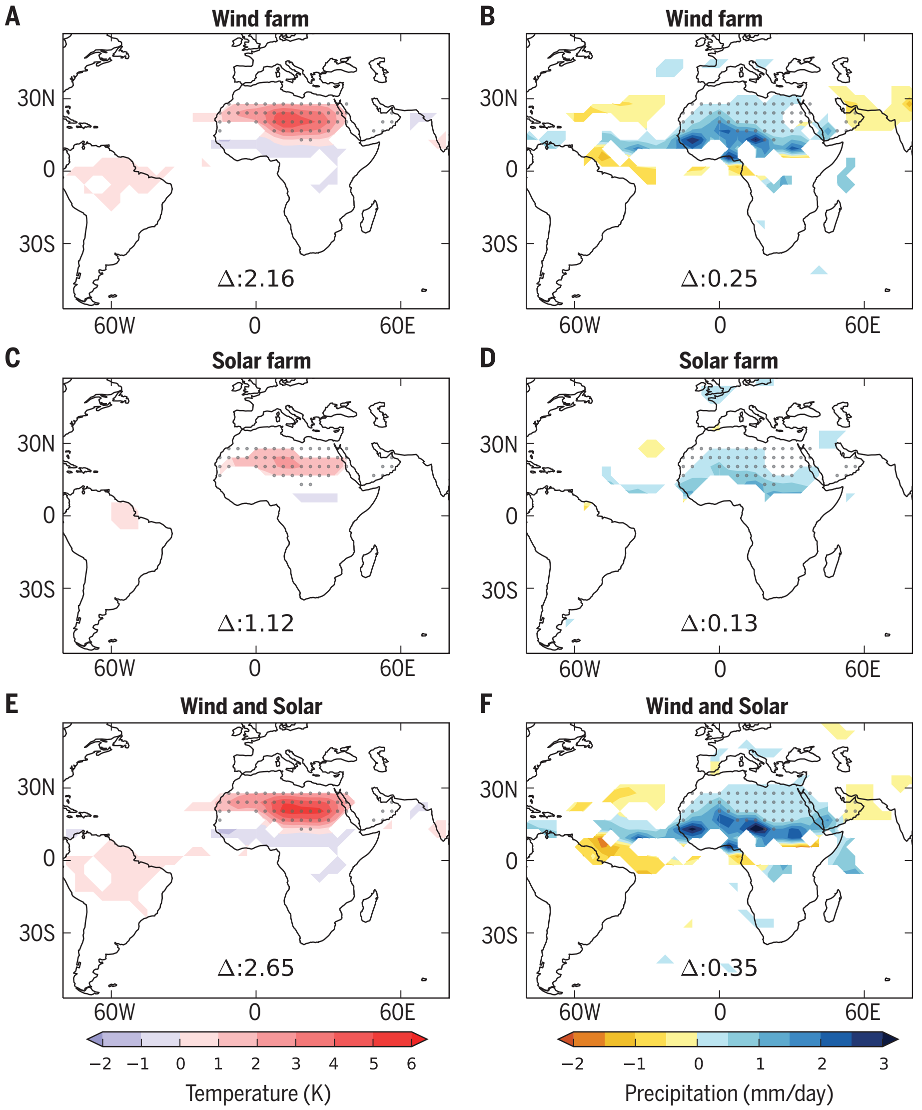

Fig. 1. Impacts of wind and solar farms in the Sahara on mean near-surface air temperature (kelvin) and precipitation (millimeters per day). The impacts of wind farms (**A** and **B**), solar farms (**C** and **D**), and wind and solar farms together (**E** and **F**), respectively, are shown. Only areas where changes are significant at the 95% confidence level (*t* test) are displayed on the map. Gray dots denote the location of wind and/or solar farms. At the bottom of each plot, the number after Δ represents the changes in climate (in either kelvin or millimeters of precipitation per day) averaged over areas covered by wind and solar farms.

negligible albedo change and, thus, insignificant climate impacts (fig. S6).

In this study, we used a model running at a relatively coarse spatial resolution to simulate the impact of wind and solar farms. However, the model has been shown to be capable of capturing the large-scale impacts from changing albedo, roughness, and vegetation responses (*20*–*22*, *31*) and has skills comparable to those of other higher-resolution models in simulating modern climate and multidecadal variability in this region in multiple model intercomparison projects (*32*, *33*). Still, uncertainties remain in the magnitude of climate response and the strength of vegetation feedbacks. The complexity of a global model also limits its ability in capturing the impacts on synoptic and mesoscale weather processes. It is not clear if all of our findings are directly applicable to wind and solar farms with a size much smaller than the model grid. Nevertheless, the temperature impacts of wind and solar farms in our study (i.e., the warming effect of wind farms and the albedo-dependent impact of solar panels) are consistent with those reported in studies conducted at the local scale (*34*, *35*). For the precipitation change, the impact is more uncertain due to its region-specific and scale-dependent nature. We addressed these uncertainties by designing additional experiments (*30*). We found that expanding the wind and solar farms from the Sahara to the world's other deserts does not significantly increase the climate impact (fig. S7). The most significant impact is still concentrated in the Sahara and the surrounding regions, whereas the impact is not significant in many other deserts, due to their scattered geographical distributions, smaller sizes, and weaker changes in albedo (fig. S8). Even in the Sahara, the wind and solar farms impacts also depend on their specific location and spatial distribution, with uneven impacts when deployed with different spatial configurations (i.e., the "checkerboard" and "quarter" wind farm experiments represented in fig. S9). Therefore, to assess the impacts of smaller-scale wind and solar farms installed at specific locations, further studies are required, especially those using more advanced global and regional climate models with higher spatial resolutions (*25*).

Our results obtained from experiments performed with a climate model suggest that, for installations of wind and solar farms with current conversion efficiency in the desert at a scale large enough to power the entire world, the impacts on regional climate would be beneficial rather than detrimental, and the impacts on global mean temperature are still small compared with those induced by CO_2 emission from fossil fuels (*3*, *10*). If carefully planned, these farms could also trigger more precipitation, largely because of a previously overlooked vegetation feedback. This highlights that, in addition to avoiding anthropogenic greenhouse gas emissions from fossil fuels and the resulting warming, wind and solar energy could have other unexpected beneficial climate impacts when deployed at a large scale in the Sahara, where conditions are especially favorable for these impacts. Efforts to build such large-scale wind and solar farms for electricity generation may still face many technological (e.g., transmission, efficiency), socioeconomic (e.g., cost, politics), and environmental challenges, but this goal has become increasingly achievable and cost-effective (*36*) (supplementary text). These results indicate that renewable energy can have multiple benefits for climate and sustainable development and thus could be widely adopted as a primary solution to the challenges of global energy, climate change, and environmental and societal sustainability (*4*).

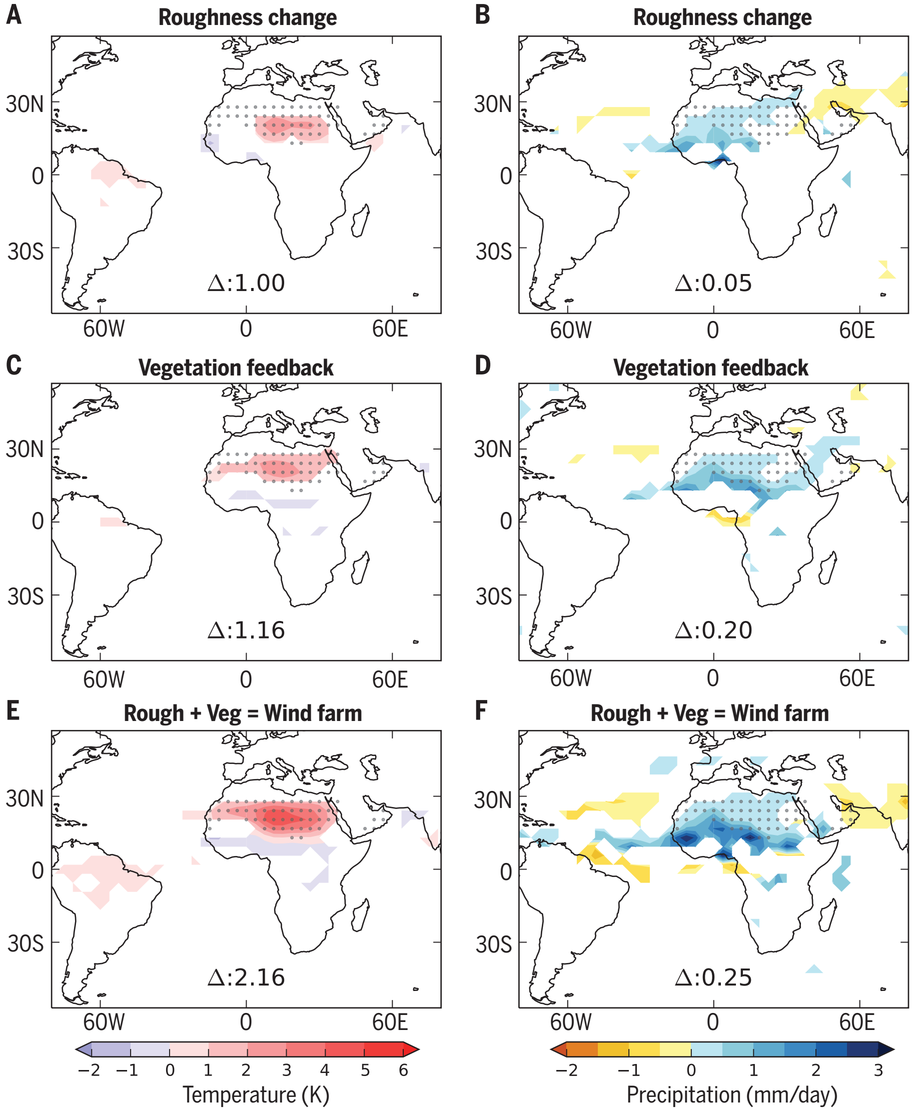

Fig. 2. Relative contributions of roughness change (Rough) and vegetation feedback (Veg) in the climate impacts of wind farms in the Sahara. Contributions in the temperature (**A**, **C**, and **E**) and the precipitation (**B**, **D**, and **F**) impacts are shown. The wind farm impact is produced by the initial roughness of wind turbines and the subsequent albedo changes due to vegetation feedback. At the bottom of each plot, the number after Δ represents the changes in climate (in either kelvin or millimeters of precipitation per day) averaged over areas covered by wind farms.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/361/6406/1019/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S9
Table S1
References (*38–55*)

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Science

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More energy, more rain

Energy generation by wind and solar farms could reduce carbon emissions and thus mitigate anthropogenic climate change. But is this its only benefit? Li *et al.* conducted experiments using a climate model to show that the installation of large-scale wind and solar power generation facilities in the Sahara could cause more local rainfall, particularly in the neighboring Sahel region. This effect, caused by a combination of increased surface drag and reduced albedo, could increase coverage by vegetation, creating a positive feedback that would further increase rainfall.

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