Supplementary Materials for

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

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This PDF file includes:

Materials and Methods
Supplementary Text
Figs. S1 to S9
Table S1
References
Materials and Methods

Model description

The UMD–ICTP (University of Maryland–International Centre for Theoretical Physics) Earth System Model is used to conduct the experiments. The model consists of an Atmospheric General Circulation Model (AGCM), SPEEDY (Simplified Parameterizations, primitive-Equation DYNamics) (38), a physical land surface model, Sland (Simple land) (39), and a dynamic vegetation and carbon model, VEGAS (VEgetation–Global–Atmosphere–Soil) (40, 41). The model setup for the experiments of this study uses prescribed sea surface temperatures (SSTs) and is therefore considered to be a climate model. The atmospheric model, SPEEDY, is based on a hydrostatic spectral dynamical core (38, 42). The parameterized processes include short- and long-wave radiation, large-scale condensation, convection, vertical diffusion, and surface fluxes of momentum, heat, and moisture. In this study, the AGCM model SPEEDY is configured with 8 vertical (sigma) levels and with a spectral resolution of T30 (48×96), equivalent to a spatial resolution of 3.75 × 3.75 degrees. The dynamic vegetation model VEGAS simulates the dynamics of vegetation growth and competition among different plant functional types (PFTs), including broadleaf trees, needleleaf trees, cold grass, and warm grass. The dynamic vegetation model is coupled with the AGCM, allowing for the representation of the two-way interactions between vegetation and climate, which have rarely been taken into account in previous studies regarding wind and solar farm impacts. The model has participated in multiple model intercomparison projects (32, 33), and was shown to have skills comparable to other higher resolution models in simulating modern climate and multi-decadal variability in this region. In addition, the model setup used in this study has been validated against observational data for the Sahara region from the Climate Research Unit (21).

Parameterization of wind and solar farms

The large-scale wind and solar farms can directly modify land surface properties. Wind turbines can increase surface friction (roughness) and solar panels can decrease albedo (for typical low-efficiency photovoltaic cells installed in the desert). Therefore, in the model, their impacts can be parameterized by changing the model parameters representing surface friction and albedo, respectively. Whereas more sophisticated schemes exist for wind turbines such as TKE (turbulent kinetic energy) (14, 43), the advantage of such a simple parameterization is the simplicity of its implementation in the Earth System Model framework and the ability to capture the first order impacts.

The impact of wind farms is parameterized by an increase of the drag coefficient ($C_D$ value), which is directly linked to surface friction in the atmospheric model. The default $C_D$ value (0.0024) in the model is multiplied by 4, so that the resulting amplified $C_D$ value (0.0096) falls in the range of 0.005–0.013. This range represents a realistic wind farm scenario with an average turbine spacing of five to eight rotor diameters and a 100 m turbine hub height (17). Solar panels are parameterized based on the “effective albedo” concept (35). Effective albedo is used to describe how much incoming shortwave radiation is not absorbed by the land surface in the presence of a PV panel. It is defined as the sum of the reflectivity of the PV panel and of the percentage of harvested energy, divided by incoming shortwave radiation. Effective albedo enables the model to emulate
the solar panel impact through a surface albedo change. Assuming PV panels have a reflectivity of $\alpha_p = 0.1$ and a conversion efficiency of $\eta = 0.15$, the available shortwave radiation that a PV panel receives after reflection, $1 - \alpha_p = 1 - 0.1 = 0.90$, multiplied by 0.15 conversion efficiency gives the portion of the solar energy converted to electricity as $\eta (1 - \alpha_p) = 0.15 \times (1 - 0.1) = 0.135$. This ratio, $\eta (1 - \alpha_p)$, plus the reflectivity of the PV panel, $\alpha_p$, gives the effective albedo $\alpha_e = \alpha_p + \eta (1 - \alpha_p) = 0.235$. The solar panel from the example above will reduce the land surface albedo for sand from $\sim 0.4$ to 0.235 when installed in the Sahara, and thus affect the local climate.

**Experimental setup**

The large-scale wind and solar farms in this study cover either just the Sahara desert or all the deserts of the world. The Sahara desert is defined in the model as the region within latitudes of 3.75N–30N and longitudes of 0–60E and with an annual mean precipitation from the control run less than 250 mm. The world deserts in the model are defined based on different conditions: (1) leaf area $< 2$ m$^2$/m$^2$; (2) annual near-surface air temperature $> 5$ °C; and (3) annual precipitation $< 500$ mm. The resulting model desert locations match fairly well with those in the real world.

For experiments involving a wind farm in the Sahara or the world’s deserts, we increased the surface drag ($C_D$ value) four-fold to simulate the wind farm effect. For experiments involving a solar farm in the Sahara or the world’s deserts, we set the surface albedo to 0.235 for 20% of the area of a model grid, assuming solar panels cover 20% of the land. This albedo of 0.235 corresponds to the effective albedo of a 15% conversion efficiency PV panel with a reflectivity of 0.1. The 15% efficiency chosen here represents the medium range of conversion efficiency of solar panels that are commercially available (44). A greater coverage of solar panels than the assumed 20% here would result in larger albedo change and thus stronger climate response. For experiments in which wind and solar farms are deployed together, both surface drag and albedo are modified accordingly.

To better understand how roughness and vegetation feedback produce climate changes, we carried out an additional factorial wind farm experiment in the Sahara, since wind farm impacts arise from changes in both roughness and albedo (albedo changes due to vegetation feedback). To separate the contributions from roughness and albedo, we compare the results of the standard wind farm simulation, which includes the effects of both roughness change and vegetation feedback, with the experiment that only includes the effect of roughness change in which vegetation feedback is disabled and the albedo is the same as the control run.

To investigate how impacts of solar farms depend on different conversion efficiency rates of the solar panel, we run solar farm experiments with alternative efficiency of 30% and 45%, representing a much higher efficiency than commercially available panels at present. The 30% and 45% efficiency solar panels correspond to effective albedos of 0.37 and 0.505, respectively. The results of these experiments are shown in Fig S6.

To investigate how climate impacts of wind farm would differ when installed with different spatial configurations (spatial extent, density, and location), we designed two pairs of wind farm experiments in the Sahara, referred to as the “checkerboard” and “quarter surface” types (Fig. S9). The two checkerboard wind farm layouts — which still cover the Sahara but whose coverage is half of the coverage of the original wind farm,
i.e., every other grid box — are expected to have smaller impacts. The four quarter-type wind farms, each of similar size, are located in different quadrants (northeast, southeast, southwest, and northwest) of the Sahara. The northwest quadrant farms produce significantly more precipitation than the other three quadrants, presumably due to the closeness to the Atlantic ocean and the Mediterranean sea. This suggests that the actual climate impacts of wind farms are determined not only by the imposed perturbation but also by the environmental conditions at a given location, such as the distance to the ocean, which provides the moisture source for the additional precipitation.

All experiments described above were run in the model for 100 years with a 100-year spin-up, driven by the observed SST data from 1901 to 2000. The averaged climate of the last 50 years of simulation in each experiment was used for the analysis.

**Supplementary Text**

**Estimate of electrical power generated by wind and solar farms in the Sahara**

To roughly estimate the power generated by the modeled wind infrastructure, we note that studies of the limits of wind generation suggest that an installed capacity of 1.0 W/m$^2$ is a safe limit to avoid substantial reductions in generation due to wind turbine wakes (45). The area of the Sahara desert is approximately $A = 9.2$ million km$^2$, which yields an installed capacity of 9.2 TW. Typical Capacity Factors for new wind farms in locations with a good resource (such as the Sahara) are around 0.35 (46), yielding an expected generation of about 3.2 TW. For solar infrastructure, we assume an annual average insolation of $S = 320$ W/m$^2$ for the Sahara (47). Assuming $\eta = 15\%$ conversion efficiency, $\alpha_p = 0.1$ panel reflectivity, and $\rho = 20\%$ area coverage by the panels, yields $S \times [\eta \times (1 - \alpha_p)] \times [\rho \times A] = 79$ TW of electrical power generation, averaged over a typical year. In comparison, the average rate of global consumption of energy is about 18 TW (48).

**Feasibility of the transmission of electricity generated in the Sahara by wind and solar farms to other regions**

The export of electricity from the Sahara would require the use of long-distance electricity transmission systems such as High Voltage Direct Current (HVDC). HVDC can dramatically reduce the line losses in the transmission of electricity over long distances, and also has lower construction costs compared to Alternating Current (AC) lines (49). For example, according to Siemens¹, their Ultra High Voltage Direct Current (UHVDC) system at 800 kV has less than 3% line losses for every 1,000 kilometers with a transmission capacity of 10 GW over a single UHVDC link across transmission lengths of over 2,000 km. Their converter stations at the end of the line to convert to local AC systems have losses of approximately 0.7% of rated power.

As to the feasibility of the required long distance transmission systems, we compare already existing long-distance HVDC transmission distances in developing countries with those required for the export of renewable power from the Sahara. We first estimate the approximate distances that would be required to export energy from North Africa to Europe: the distance from Tunis, Tunisia to Rome, Italy is 601 km, Rabat, Morocco to

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Madrid, Spain is 770 km, and Algiers, Algeria to Paris, France is 1,347 km. With regards to supplying energy to Sub-Saharan Africa, the distance from Niamey, Niger to Lagos, Nigeria is 790 km, Agadez, Niger to Abuja, Nigeria is 881 km, Timbuktu, Mali to Abidjan, Côte d’Ivoire is 1,275 km, Khartoum, Sudan to Addis Ababa, Ethiopia is 990 km, and from Khartoum all the way to Nairobi, Kenya is 1,927 km.

For comparison, the following existing long distance HVDC projects were compiled from various sources. China alone already has over 20 HVDC lines, each over ~900 km in length, with a total length of over 28,000 km. The Jinping–Sunan and the Xiangjiaba–Shanghai HVDC transmission lines are each over 2,000 km. India has 9 HVDC lines each over 700 km long, including the 1,830 km Tamil Nadu line and the 1,728 km North-East Agra line. In Brazil, the Rio Madeira HVDC link, connecting Rondônia to São Paulo is composed of two sets of 600 kV DC lines of 3 GW capacity each over 2,375 km. Brazil completed two other 600 kV Itaipu HVDC lines each with a rated power of 3 GW and a total distance of 1,650 km as early as 1987, and Brazil began construction of the ~2,100 km Xingu–Estreito HVDC transmission line in 2017. As with other infrastructure, it is expected that as the scale of construction continues to grow, voltage and distance capacities will also increase. For example, in 2017 China began construction of the record-breaking 1100 kV ~3,300 km UHVDC Xinjiang–Anhui link, which will transmit 10–12 GW. At 1100 kV, this UHVDC link will significantly reduce line losses even further.

Furthermore, long-distance HVDC transmission lines have already existed in Africa for decades. For example, the 1,700 km Inga–Shaba Extra High Voltage (EHVDC) Intertie transmission line in the Democratic Republic of Congo was completed in 1982. The 1,420 km Cahora–Bassa HVDC transmission line from Mozambique to South Africa was completed in 1979. Other kinds of development projects on this scale of distance also already exist deep within the Sahara itself. Starting in the 1980s, Libya built ~2,800 km of underground pipes to supply the cities on the coast with ~6,500,000 m³ of freshwater per day from over 1,300 wells in the Nubian Sandstone Aquifer System located deep in the Sahara (50). These examples demonstrate that the long distance transmission required is technologically feasible and already in use, which allows the long distance transmission of renewable power to be economically viable.

Solar power projects in North Africa and the Middle East are already underway. Examples include: Dubai’s Al Maktoum Solar Park (Phase 1 (13MW) completed 2013, Phase 2 (200 MW) completed 2017, and Phase 3 (800 MW) due 2020; Abu Dhabi’s Shams solar plant, Phase 1 (100 MW) completed 2014; Saudi Arabia’s Al-Aflaj 50 MW solar plant; Kuwait’s Shagaya solar project (50 MW); and Morocco’s Noor solar plant (580 MW), phase 1 (160 MW) completed 2016 (Morocco already has a transmission link to Europe) (51, 52). Saudi Arabia recently announced a plan to install 200 GW of solar power by 2030, at a projected cost of 200 billion USD (i.e., at an

average cost of $1 per Watt). Investments on this scale would likely lead to further reductions in the costs of both photovoltaics and transmission infrastructure.

In assessing the comparative costs, one also has to take into account that with renewables, there is the one-time cost of transporting the generation infrastructure to the location of generation, whereas with the current system of fossil fuel-based generation, in addition to the one-time cost of transporting the generation infrastructure to the location of generation, there is the continuous cost of transporting the stream of fuels (coal, oil, and gas) to the generation plants. For coal and nuclear, there is also the additional cost of transporting the waste for disposal, and the energy required for processing and disposing of the waste.

Costs should also be compared to benefits. Today, the Sahel region is the poorest region on the planet. It is also the region with the fastest rate of population growth, and with the highest forecast for its future absolute population growth (53, 54). With massive investment in solar and wind generation, the region could not only meet its own rapidly growing electricity needs, but it could also become a major electricity exporter to other regions in Sub-Saharan Africa, providing needed earnings to fund the internal economic development of this very poor region. If these investments in wind and solar power production were to also increase local precipitation and vegetation growth through similar vegetation feedback mechanisms involved in the Green Sahara (55), this could provide these regions with increased agricultural production. Moreover, the availability of massive amounts of clean, renewable energies could help greatly with desalination and transport of seawater, as well as recycling and reuse of consumed freshwater. These processes, which can alleviate the problems associated with water scarcity (such as famines), are currently employed only in few places around the world because they are energy intensive, and therefore expensive. Improved availability of freshwater, in turn, will bring positive societal, economic, environmental, ecological, and health impacts. The interconnected nature of these factors renders the Sahara as an ideal testbed for research on the Human–Climate System and Food–Energy–Water Nexus.

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Table S1. Precipitation changes averaged over the Sahara wind farm locations and averaged over the whole Sahel region. Sahel region is defined as the rectangular land area with latitudes from 10N to 20N and longitudes from 20W to 30E.

<table>
<thead>
<tr>
<th>Unit: mm/day</th>
<th>Control Sahara</th>
<th>Control Sahel</th>
<th>Wind farm Sahara</th>
<th>Wind farm Sahel</th>
<th>Solar farm Sahara</th>
<th>Solar farm Sahel</th>
<th>Wind + Solar Sahara</th>
<th>Wind + Solar Sahel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>0.24</td>
<td>2.23</td>
<td>+0.29</td>
<td>+1.12</td>
<td>+0.13</td>
<td>+0.57</td>
<td>+0.35</td>
<td>+1.34</td>
</tr>
</tbody>
</table>
**Fig. S1.** Impacts of wind and solar farms in the Sahara on (A–C) maximum near-surface air temperature, (D–F) minimum near-surface air temperature, and (G–I) surface wind speed. Columns 1 to 3 show the impacts of wind farms, solar farms, and wind and solar farms together, respectively. Only areas with changes significant at 95% by the t-test are displayed on the map. Black dots on the map denote the location of wind/solar farms. The number after $\Delta$ shows the change in climate averaged over areas covered by wind farms. The average values from the control run (i.e., baseline) over the Sahara wind/solar farms locations are 299.46 K for mean temperature (Fig. 1), 303.49 K for max temperature, 295.56 K for min temperature, and 5.09 m/s for surface wind speed.
**Fig. S2.** Impacts of wind and solar farms in the Sahara on (A–C) albedo, (D–F) vegetation cover fraction, and (G–I) net shortwave radiation at surface. The average values from the control run (i.e., baseline) over the Sahara wind/solar farms locations are 0.34 for albedo, 0.35 for vegetation cover fraction, and 194.52 W/m$^2$ for net shortwave at surface.
Fig. S3. Impacts of wind and solar farms in the Sahara on (A–C) evaporation, (D–F) sensible heat, and (G–I) deep cloud cover. The average values from the control run (i.e., baseline) over the Sahara wind/solar farms locations are 0.23 mm/day for evaporation, 49.89 W/m$^2$ for sensible heat, and 16.01% for deep cloud cover.
**Fig. S4.** Impacts of wind and solar farms in the Sahara on (A–C) surface pressure and surface wind field, (D–F) geopotential height and wind field at 850 hpa, and (G–I) moisture convergence. Note all changes for moisture convergence are shown on the map, including both significant and non-significant changes. The average values from the control run (i.e., baseline) over the Sahara wind/solar farms locations are 961.58 hPa for surface pressure, and 1517.81 m for geopotential height at 850 hPa.
Fig. S5. Impacts of wind and solar farms in the Sahara on (A–C) relative humidity, (D–F) leaf area index (LAI), and (G–I) root carbon. The average values from the control run (i.e., baseline) over the Sahara wind/solar farms locations are 29.92% for relative humidity, 0.64 m²/m² for leaf area index, and 0.095 kgC/m² for root carbon.
Fig. S6. Impacts of solar farms of varying PV panel solar conversion efficiencies (15% (A,D), 30% (B,E), and 45% (C,F)) in the Sahara on temperature and precipitation. Note that the impacts on regional climate from the 30% efficiency solar farms (B,E) are not significant (at the 95% level) but are shown here for display purposes. For 15% (A,D) and 45% (C,F) PV efficiencies, only significant changes are plotted, while white blank areas represent non-significant changes (at the 95% level).
Fig. S7. Impacts of wind and solar farms in the world’s deserts on near-surface mean temperature and precipitation. Rows 1 to 3 show the impacts of wind farms (A, B), solar farms (C, D), and wind and solar farms together (E, F). Only areas where changes are significant at 95% by the t-test are displayed on the map. Black dots on the map denote locations of wind farms/solar farms. The number after Δ at the bottom shows the changes in climate averaged over areas covered by wind/solar farms. The average values from the control run (i.e., baseline) over the global wind/solar farms locations are 249.64 K for mean temperature, and 0.55 mm/day for precipitation.
**Fig. S8.** Impacts of wind and solar farms in the world’s deserts on (A–C) albedo, (D–F) vegetation cover fraction, and (G–I) net shortwave radiation at surface. The average values from the control run (i.e., baseline) over the global wind/solar farms locations are 0.29 for albedo, 0.46 for vegetation cover fraction, and 188.99 W/m² for net shortwave at surface.
Fig. S9. Impacts of checkerboard (A, B) and quarter (northwest, northeast, southwest, southeast) layouts for wind farms in the Sahara. Wind farm locations are denoted by a “dot” and non-wind farm grid boxes by a “cross”. The two checkerboard wind farm layouts cover the Sahara but with half the density of the full wind farm. The four quarter type wind farms are each of similar size but located in different quadrants of the Sahara (northeast, southeast, southwest, and northwest). The number after ∆ shows the change in climate averaged over areas covered by wind farms. The results show that the northwest wind farm induces the largest precipitation and temperature changes.
References and Notes


30. Materials and methods are available as supplementary materials.


