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Supplemental Information

Climatic Impacts of Wind Power

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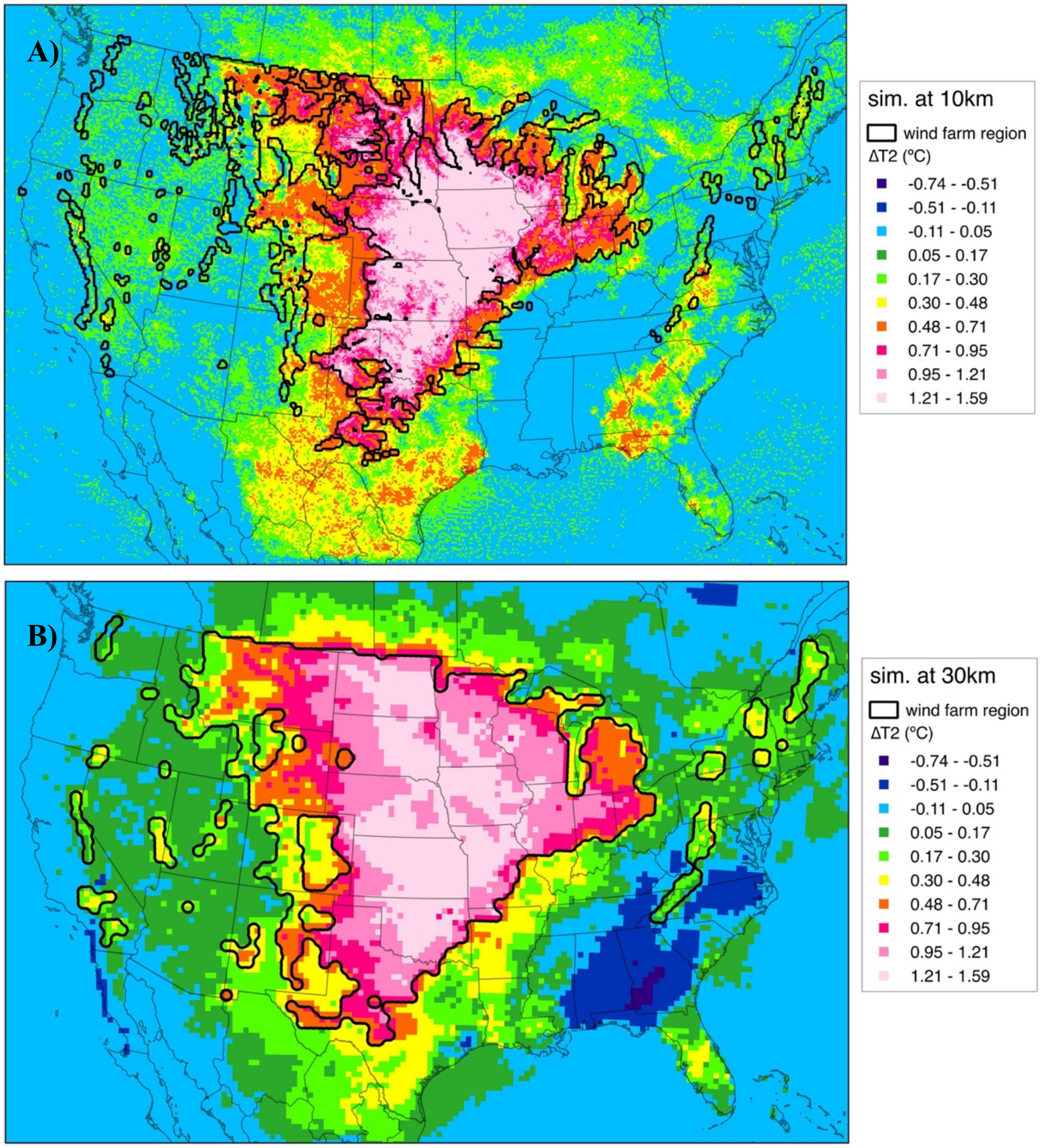

Fig. S1.

Annual mean 2-meter air temperature differences over 2012 resulting from the deployment of a turbine density of 3 MW km^{-2} into the *wind farm regions* (black outlined areas), simulated using **A)** 10 km horizontal resolution, and **B)** 30 km horizontal resolution. The wind farm regions are spatially different. Based on control conditions, the wind farm region in the 10 km simulation encompasses 27% of the Continental US (*i.e.* 2012 mean 80 meter wind speed greater than 7.6 m s^{-1}). The wind farm region of the 30 km simulation encompasses 31% of the Continental US land area, and is identified as the 2012-2014 mean 80-meter wind speed greater than 7.5 m s^{-1}.

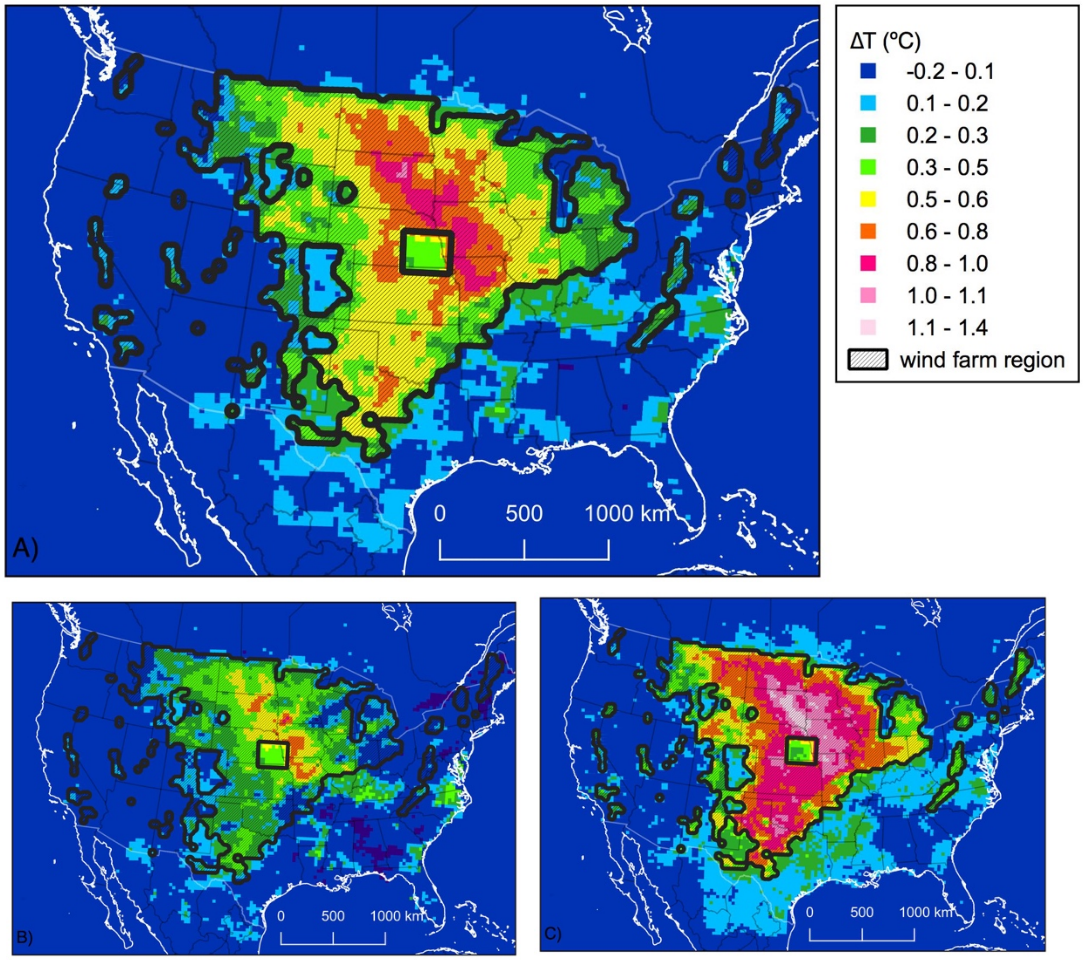

Fig. S2.

2-meter air temperature response to benchmark wind power deployment (0.5 MW_i km^{-2}), but with a 250x250km absence of wind turbines in southeast Nebraska and comparing the year 2014. This is in contrast to Figure 1 of the main text, where the Nebraska hole is not included and a 3-year (2012-2014) is shown. Maps are annual means over 2014 of perturbed minus control for 2-meter air temperatures, showing **(A)** entire period, **(B)** daytime, and **(C)** nighttime. The wind farm region is outlined in black. Mean values within the hole are noted in Table S1.

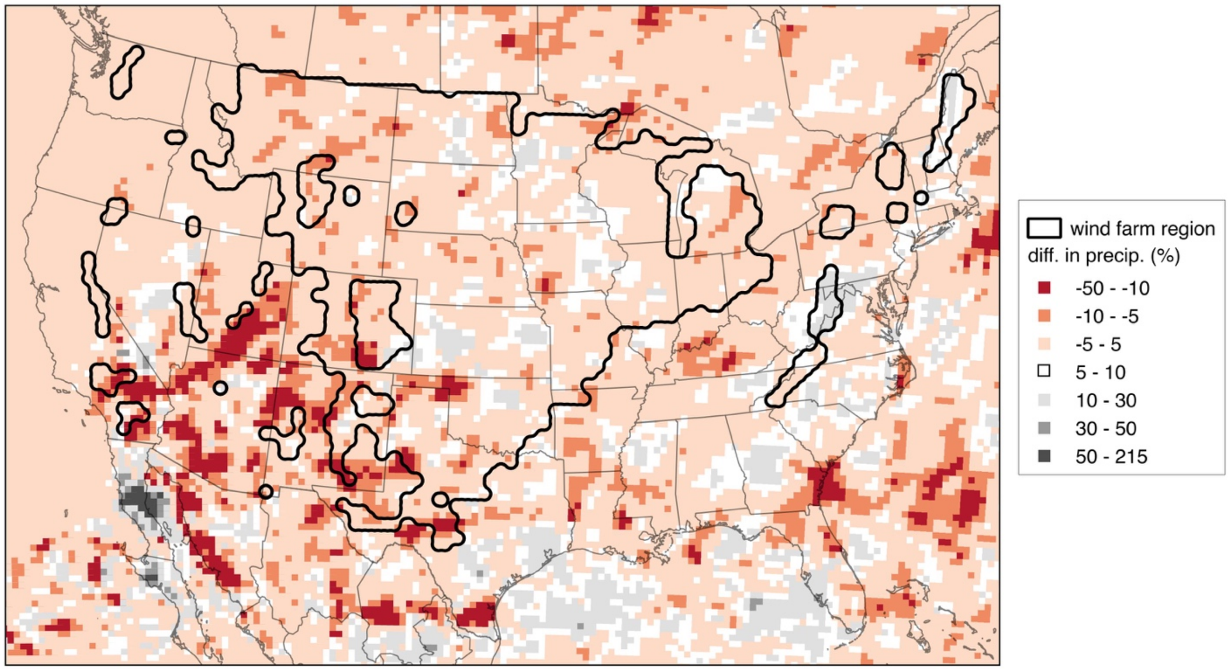

Fig. S3

Mean (2012-2014) precipitation differences between the *benchmark scenario* (0.5 MW km^{-2}) and the control. The black outlined area delineates the wind farm region. Overall, precipitation increased by 2% within the wind farm region.

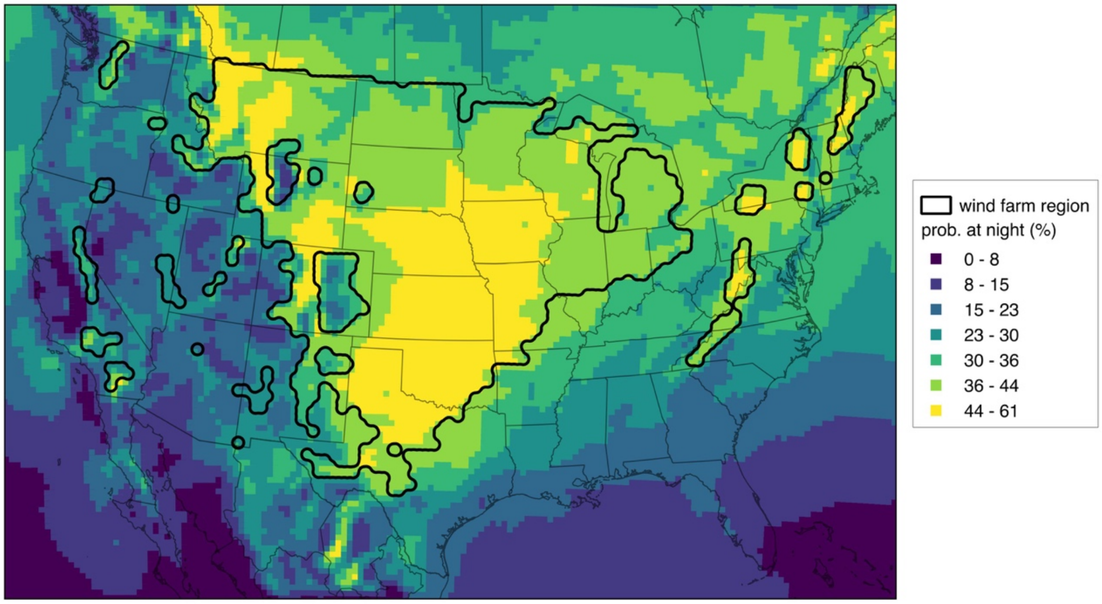

Fig. S4

Probability of the LLJ at night over the 3-year (2012-2014) period based on control conditions, defined as wind speeds greater than 12 m s^{-1} within 500m of the ground surface. The wind farm region is outlined in black.

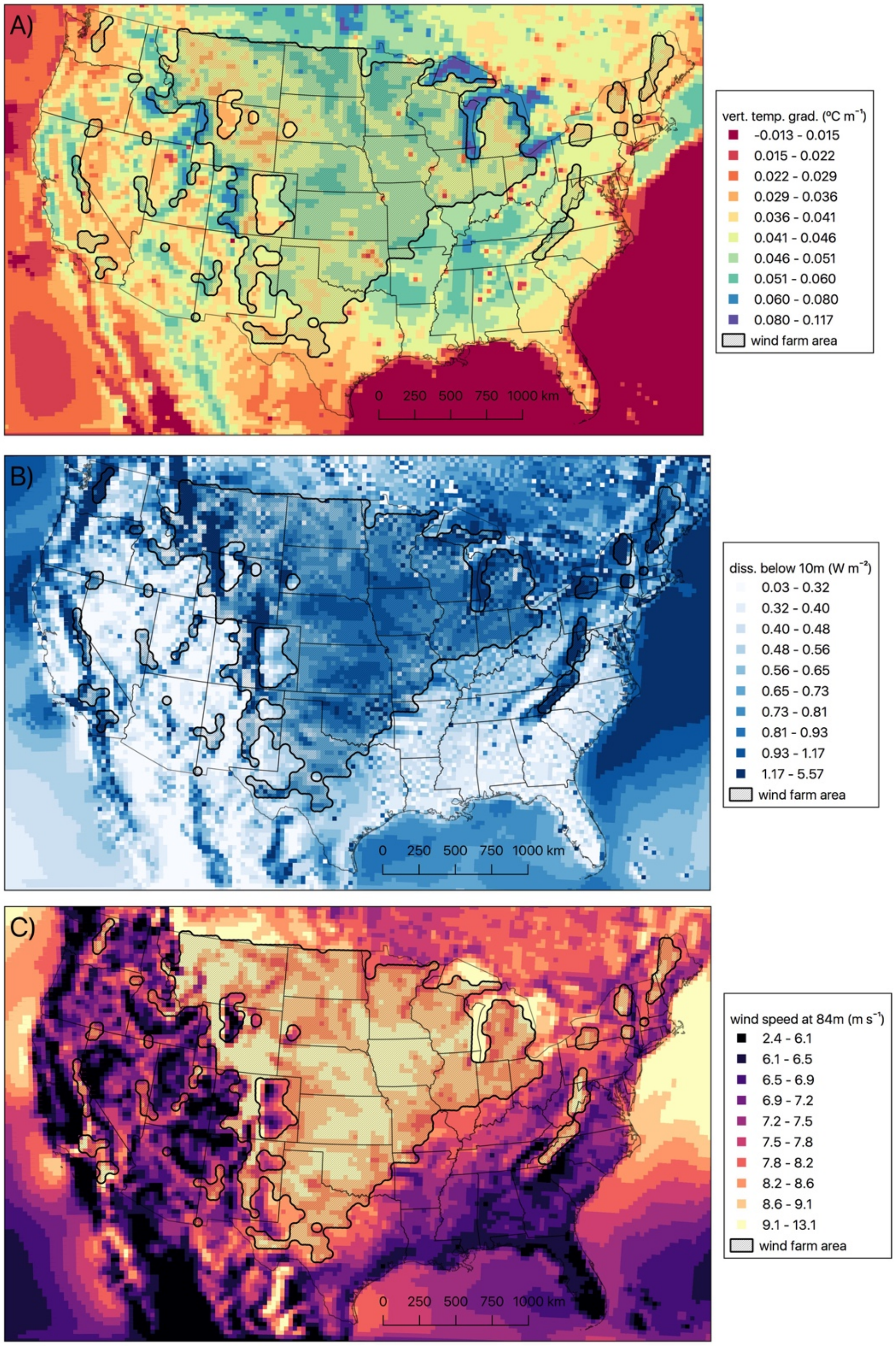

Fig. S5
3-year mean conditions at night of the control simulation to help understand the spatial pattern of nighttime warming (main text Fig. 1C), **A)** vertical gradient in virtual potential temperature between the lowest two model levels (0-56m, 56-129m), **B)** surface dissipation within 10m of the surface, derived as $\boldsymbol{\rho} u_*^2 \cdot (v_{10})$, where $\boldsymbol{\rho}$ is the air density, u_* is the friction velocity, and v_{10} is the 10-meter wind speed, **C)** 84-meter wind speed (hub-height of the wind turbines). Note, the spottiness in B&C corresponds to cities in the US Midwest and Southeast.

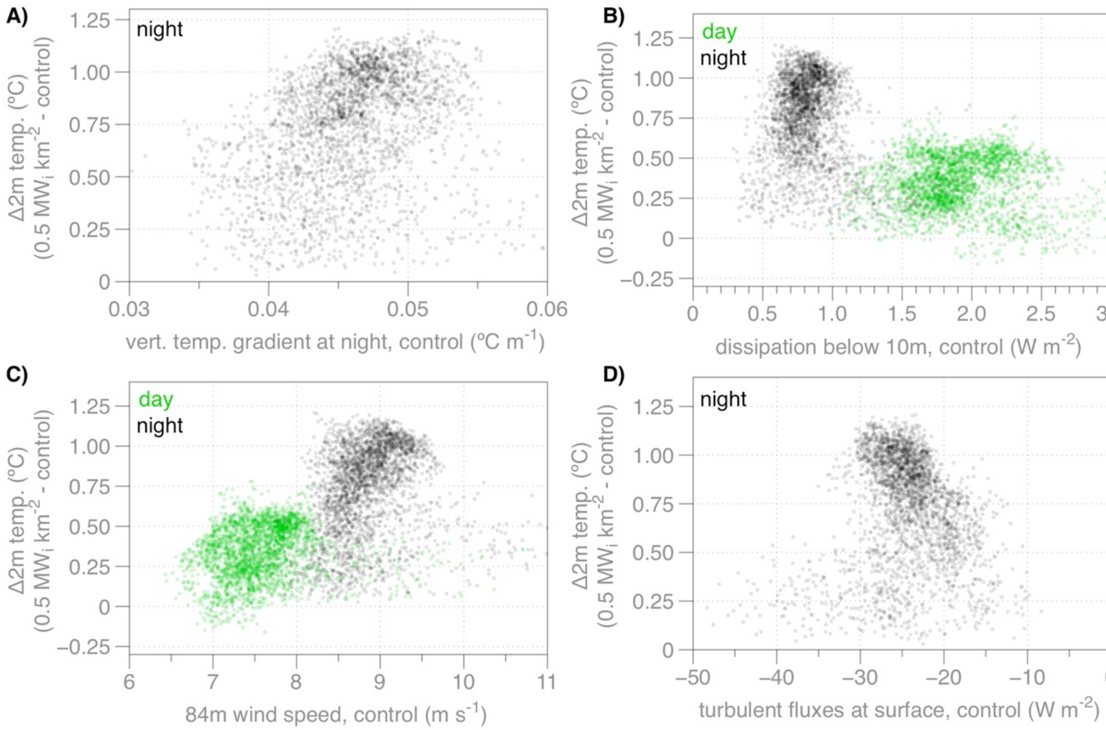

Fig. S6

Comparing 3-year means of control variables to differences in 2-meter air temperature between the benchmark scenario (0.5 MW_i km^{-2}) and the control for each grid point within the wind farm region. **A)** vertical temperature gradient between the lowest 2 model levels (0-56m, 56-129m), **B)** dissipation within 10m of the surface, derived as $\boldsymbol{\rho} u_*^{2} \cdot (v_{10})$, where $\boldsymbol{\rho}$ is the air density, u_* is the friction velocity, and v_{10} is the 10-meter wind speed, **C)** 84-meter (hub-height) wind speed, and **D)** turbulent fluxes (sensible heat flux + latent heat flux). 'Night' values in A,B,C correspond to the maps in Fig. S5.

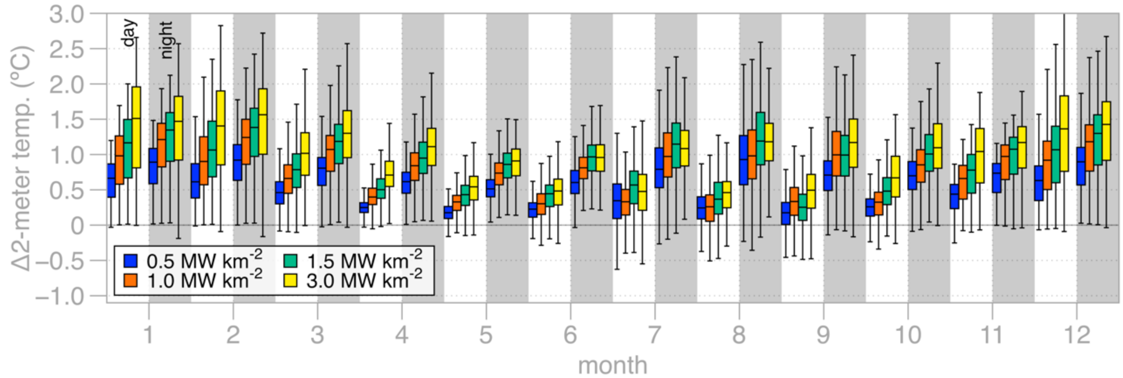

Fig. S7

Day and night 3-year monthly mean 2-meter air temperature differences over the wind farm region between the various turbine densities and the control simulation. The blue box-whisker plot data is the same at in Fig. 1D. The vertical line extent encompasses 1.5-times the interquartile range and the box represents the 25th, 50th, and 75th percentiles.

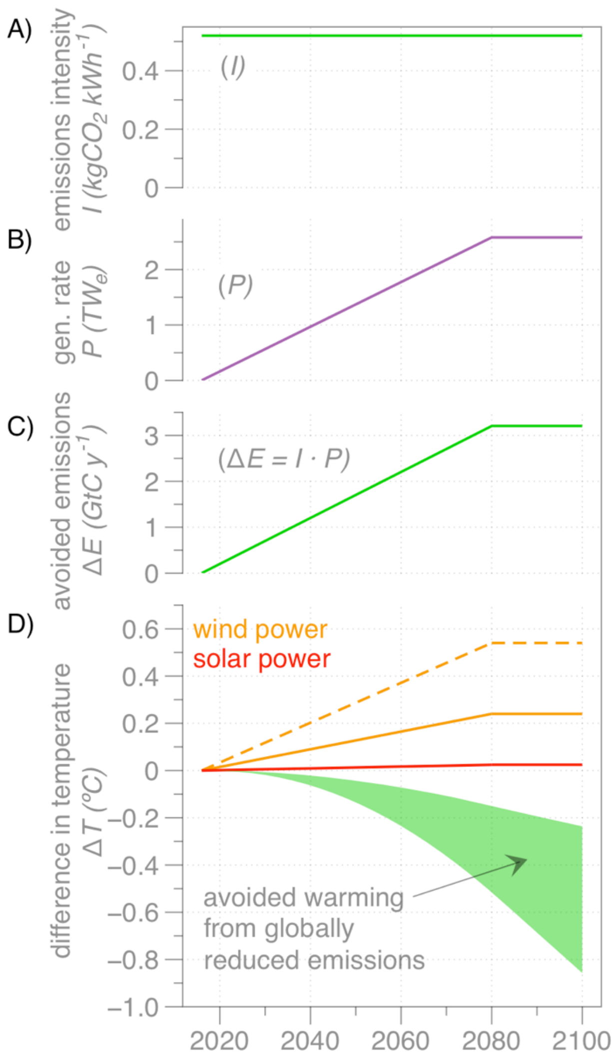

Fig. S8
Companion plot to Fig. 4 of the main text. Climate warming impacts compared to climate benefits of reduced emissions. (**A**) Static global emissions intensity, reflecting the present-day. (**B**) A scenario in which power output, *P*, from a zero-emissions renewable increases to 2.6 TW_e by 2080 and is constant thereafter. (**C**) Avoided emissions computed as $\Delta E = I \times P$, and (**D)** the resulting 2-meter temperature differences within the wind farm region (dotted lines) and the Continental US (solid lines). Values for wind power linearly scaled from the 0.46 TW_e *benchmark scenario* of the main text*,* while values for solar are derived from[18]. The green area shows the avoided Continental US warming if all global electricity emissions were zero in 2080, with the range estimated from the min- and max-values within the emissions-to-climate impulse response function.

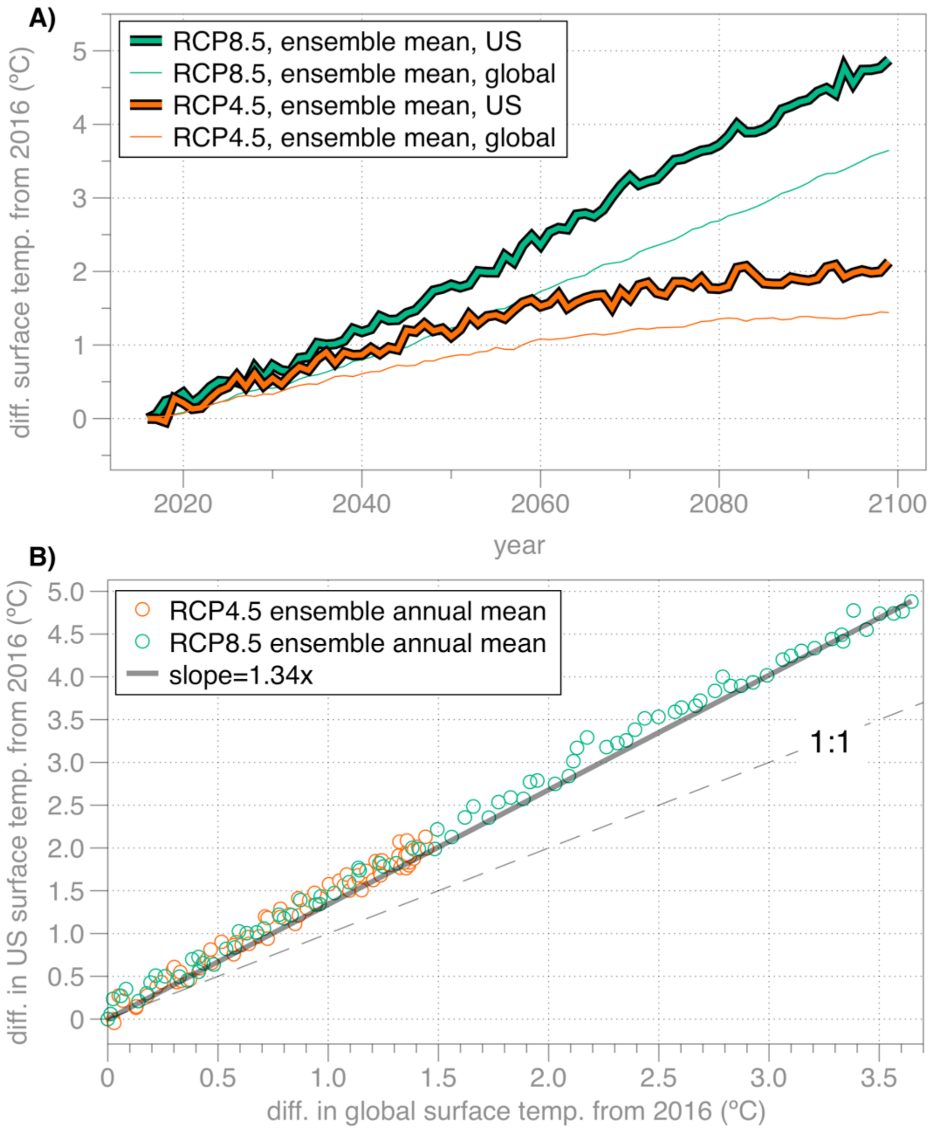

Fig. S9

To estimate the US warming from the global warming estimates from the emissions-to-climate impulse response function, we use the RCP4.5 and RCP8.5 ensemble mean data of Karmalkar et al. (2017); **A)** surface temperature data from 2016 over the Continental US and globally, **B)** using 2016 as the baseline temperature, comparing the difference in global surface temperatures and US surface temperatures. We used the statistical relationship in (B) to rescale the estimates of avoided global warming to estimates of avoided US warming in Fig. 5D.

Table S1. 2-meter air temperature response within the 'hole' region during 2014. Values identified as '0.5 MW_i km^{-2}; no hole' correspond to the original model setup and accompanying Fig. 1, while the '0.5 MW_i km^{-2}; hole' correspond to the results shown in the above Figure. Values within parentheses note the temperature difference from the control.

	control	0.5 MW_i km^{-2}; no hole	0.5 MW_i km^{-2}; hole
all	11.63ºC	12.44ºC (+0.81ºC)	12.02ºC (+0.39ºC)
day	16.86 ºC	17.40ºC (+0.54ºC)	17.25ºC (+0.39ºC)
night	6.39 ºC	7.48ºC (+1.09ºC)	6.78ºC (+0.39ºC)

Table S2.

Values used for the comparison in Fig. 3. Specifics of the reference and the analysis period are noted on the left, as well as the simulation data from our benchmark scenario at the Texas location (100.2ºW, 32.3ºN). Average day and night values were calculated for the observations to allow for a comparison to the simulation data (day = solar shortwave down > 1 W m^{-2}; night = solar shortwave down < 1 W m^{-2}).

		December - February						March - May					
		DAY			NIGHT			DAY			NIGHT		
Reference	Analysis Period	avg.	10:30	13:30	avg.	22:30	1:30	avg.	10:30	13:30	avg.	22:30	1:30
Zhou et al., 2013; Table 7 QA1 values, ΔT, ºC	(2009,2010,2011) -(2003,2004,2005)	0.11	0.41	-0.20	0.22	0.16	0.27	-0.11	-0.22	0.01	0.29	0.25	0.32
Zhou et al., 2013; Table 7 QA1 values, ΔT, ºC	2010-2003	0.14	0.68	-0.41	-0.01	0.05	-0.07	0.42	0.23	0.61	0.29	0.30	0.28
Xia et al., 2015; Table 2, ΔT, ºC	(2010,2011,2012,2013,2014)-(2003,2004)	0.18	0.28	0.07	0.26	0.28	0.23	-0.25	-0.39	-0.11	0.40	0.26	0.53
average weighted by obs. years		0.14			0.20			-0.10			0.34		
this study, simulated at TX location (ΔT), ºC	(2012,2013,2014)-(2012,2013,2014)	0.48			0.65			0.22			0.60		
this study simulated at TX location, control, ºC	2012,2013,2014	10.30			5.41			22.87			14.58		
this study, simulated at TX location, 0.5 MW/km^2, ºC	2012,2013,2014	10.78			6.05			23.08			15.18		

		June - August						September - November					
		DAY			NIGHT			DAY			NIGHT		
Reference	Analysis Period	avg.	10:30	13:30	avg.	22:30	1:30	avg.	10:30	13:30	avg.	22:30	1:30
Zhou et al., 2013; Table 7 QA1 values, ΔT, ºC	(2009,2010,2011) -(2003,2004,2005)	0.17	-0.18	0.52	0.35	0.46	0.24	-0.04	-0.03	-0.04	0.40	0.43	0.37
Zhou et al., 2013; Table 7 QA1 values, ΔT, ºC	2010-2003	1.52	0.84	2.20	0.67	0.70	0.64	0.12	0.18	0.05	0.47	0.59	0.35
Xia et al., 2015; Table 2, ΔT, ºC	(2010,2011,2012,2013,2014)-(2003,2004)	-0.26	-0.38	-0.13	0.42	0.38	0.45	-0.02	0.05	-0.08	0.27	0.37	0.17
average weighted by obs. years		0.15			0.42			-0.01			0.35		
this study, simulated at TX location (ΔT), ºC	(2012,2013,2014)-(2012,2013,2014)	0.34			0.86			0.29			0.54		
this study simulated at TX location, control, ºC	2012,2013,2014	35.47			27.89			24.06			16.11		
this study, simulated at TX location, 0.5 MW/km^2, ºC	2012,2013,2014	35.82			28.75			24.35			16.64		

		Annual					
		DAY			NIGHT		
Reference	Analysis Period	avg.	10:30	13:30	avg.	22:30	1:30
Zhou et al., 2013; Table 7 QA1 values, ΔT, ºC	(2009,2010,2011) -(2003,2004,2005)	-0.04	-0.03	-0.04	0.25	0.28	0.22
Zhou et al., 2013; Table 7 QA1 values, ΔT, ºC	2010-2003	0.49	0.42	0.56	0.26	0.31	0.20
Xia et al., 2015; Table 2, ΔT, ºC	(2010,2011,2012,2013,2014)-(2003,2004)	-0.09	-0.11	-0.06	0.33	0.32	0.34
average weighted by obs. years		0.01			0.29		
this study, simulated at TX location (ΔT), ºC	(2012,2013,2014)-(2012,2013,2014)	0.33			0.66		
this study simulated at TX location, control, ºC	2012,2013,2014	23.17			16.00		
this study, simulated at TX location, 0.5 MW/km^2, ºC	2012,2013,2014	23.51			16.66		