Geophysical potential for wind energy over the open oceans

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Wind turbines continuously remove kinetic energy from the lower troposphere, thereby reducing the wind speed near hub height. The rate of electricity generation in large wind farms containing multiple wind arrays is, therefore, constrained by the rate of kinetic energy replenishment from the atmosphere above. In recent years, a growing body of research argues that the rate of generated power is limited to around 1.5 W m^{-2} within large wind farms. However, in this study, we show that considerably higher power generation rates may be sustainable over some open ocean areas. In particular, the North Atlantic is identified as a region where the downward transport of kinetic energy may sustain extraction rates of 6 W m^{-2} and above over large areas in the annual mean. Furthermore, our results indicate that the surface heat flux from the oceans to the atmosphere may play an important role in creating regions where sustained high rates of downward transport of kinetic energy and thus, high rates of kinetic energy extraction may be geophysical possible. While no commercial-scale deep water wind farms yet exist, our results suggest that such technologies, if they became technically and economically feasible, could potentially provide civilization-scale power.

wind power | geophysical generation limits | offshore wind | atmosphere–turbine interactions | storm tracks

Each wind turbine in a wind farm extracts kinetic energy (KE) from the mean flow and converts it into electricity. However, many studies have shown that individual turbines in a wind farm cannot be treated as independent and that the amount of electricity generated per turbine decreases as the turbine density and geographical area of the wind farm increases. As KE is extracted, the mean flow wind speed is reduced. This becomes particularly apparent in large wind farms with high turbine densities, where a multitude of wind turbines are arrayed in close proximity.

As KE is continuously removed from the atmosphere, the maintained rate of power generation in the wind farm is constrained by the extent to which KE can be restored to its free flow value over the wind farm area (1, 2). Previous estimates based on wind speed climatologies grossly overestimated wind farm power generation potentials as interactions between wind turbines and the atmosphere, and the resulting geophysical constraints on wind power generation were ignored (3–7).

Near-surface mean flow wind speeds are constrained by the amount of KE dissipated into the boundary layer, which forms in the lowest part of the atmosphere, and are governed by turbulent dissipation generated by surface drag, surface heat, and moisture fluxes. Operational turbines in current onshore and offshore wind farms extract KE primarily at heights between 30 and 120 m and are, therefore, predominantly entrained in the surface and boundary layer. Furthermore, each turbine poses an additional source of drag and an increase in near-surface dissipation of KE, which leads to a reduction of the mean flow wind speed. Therefore, sustaining high levels of power generation in a wind farm consisting of multiple turbines depends on whether the increased KE dissipation by the turbines can be compensated for by sources of KE, which contribute to the regeneration of the mean flow wind speed.

Near-surface KE is generated because of either near-surface pressure gradients or the downgradient transport of KE along wind speed gradients from the upper levels of the atmosphere. Both of these sources are ultimately driven by gradients in diabatic heating (8). In this manner, the energy cycle within the atmosphere imposes a limit on electricity generation by wind turbines, which acts at the scale of kinetic energy extraction (KEE) rates required to meet the primary power generation demands of the 21st century. Several studies argue that the rate of electricity generation by large wind farms may be limited to 1.5 W m^{-2} or less, even if the installed capacity of the wind farm greatly exceeds this threshold (2, 9–13).

The power generation potential of a large area wind farm is limited by the downward KE transport, but the extent to which this limit may be used depends heavily on the wind farm's geometric design and layout. Tight turbine spacing, the absence of turbine staggering, and suboptimal orientation of the wind turbines may further reduce the power generation potential of a wind farm below its geophysical limit. This has been the focus of multiple studies investigating the characteristics of individual turbine wakes and their superposition as a function of mechanical turbine characteristics, turbine positioning, the intensity of boundary-layer mixing, and boundary-layer stability (14–20). Furthermore, generated turbulence by the spinning turbine blades may also impact wake recovery (18, 21), although this effect is likely overestimated in mesoscale and coarser-scale numerical models parameterizing turbulent KE generation caused by turbine blades (18).

Individual turbine wake effects play an important role for wind farm optimization, but the total extracted power over a large area remains constrained by the efficiency of the vertical KE transfer from above the wind farm. It has been shown for onshore (22) as well as offshore (14) wind farms that boundary-layer stability may

Significance

Wind speeds over open ocean areas are often higher than those in the windiest areas over land, which has motivated a quest to develop technologies that could harvest wind energy in deep water environments. However, it remains unclear whether these open ocean wind speeds are higher because of lack of surface drag or whether a greater downward transport of kinetic energy may be sustained in open ocean environments. Focusing on the North Atlantic region, we provide evidence that there is potential for greater downward transport of kinetic energy in the overlying atmosphere. As a result, wind power generation over some ocean areas can exceed power generation on land by a factor of three or more.

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affect the vertical downward transport of KE within the boundary layer. In particular, these studies show that stable boundary layers impose the strongest constraint on vertical downward KE transport and therefore, wind power extraction. However, these changes in downward KE transport and wind power extraction have been found to be of the order of a few tens of percent. Furthermore, much larger sources of KE reside in the free troposphere, where wind speeds are higher because of the absence of friction.

In this study, we assess whether we can identify regions of the world where the large-scale downward KE flux from the free troposphere down to the lowest levels of the boundary layer may exceed the global onshore limit of downward KE transport of 1.5 W m^{-2}. In particular, we are interested in the wind energy potential over the open ocean, which remains largely unexplored. In these regions of the globe, mean surface wind speeds are, on average, 70% higher than on land and could, therefore, prove to be a viable source for wind energy technologies. However, it remains to be seen whether these regions of high wind speed indeed can sustain elevated generated power.

In the current body of literature, only two studies show global distributions of KEE, which indicate that large-scale vertical downward KE transport may regionally exceed 1.5 W m^{-2}; however, neither of these studies have focused on the open ocean potential, and their results provide conflicting estimates. While one study suggests that a similar limit may be imposed on KEE over the oceans as on land (figure S3B in ref. 11), another indicates that sustainable extraction rates may be up to three times as high (figure 2A in ref. 10). In this study, we contrast the open ocean large-scale limit imposed on maximum extraction rates by surface wind technologies globally to the onshore limit. Particular emphasis is given to the North Atlantic region because of its high geophysical potential and high unperturbed near-surface wind speeds. We further determine the dependence of the KEE rates on the geophysical limit as a function of wind farm area up to the spatial scales where the determined geophysical upper bound of KEE is sufficiently large to meet global primary power demands of ∼18 TW.

Results

The mean climatological surface ocean wind speeds are, on average, 70% higher than on land and highest within the midlatitude wind belts in each hemisphere (Fig. S1*A*). At these latitudes, the gradient in solar insolation during the winter months is largest, which leads to the formation of the westerly jets in the upper and middle troposphere. As a consequence, the downgradient transport of KE in these regions drives surface climatological wind speeds of up to 11 m s^{-1} in the North Atlantic and 13.5 m s^{-1} in the Southern Hemisphere. Assuming a uniform turbine surface density of one turbine per 1 km^2 (*Methodology* and *Supporting Information* have additional details), these high wind speeds would generate climatological mean rates of electricity at 60–80 W m^{-2} if one were to ignore the effects of turbine drag on the atmosphere (Fig. S2). Including drag forces, the maximum sustained power output decreases to 3–5 W m^{-2} (Fig. 1*A*) as the wind speed slows to nearly 50% of the free flow near-surface wind speed (Fig. S1*B*). Nevertheless, these extraction rates, which provide an estimate for the upper bound of the maximal sustained downward KE transport to the near surface, are remarkably high compared with the limit imposed on wind energy generation on land of around 1.5 W m^{-2}.

Particularly in the Southern Hemisphere, the KEE pattern shown in Fig. 1*A* is largely consistent with the pattern of KE dissipation into the boundary layer diagnosed for the preindustrial climate state (Fig. 1*B*). Areas of enhanced KEE coincide with regions where natural KE dissipation into the boundary layer is high. The near-surface KE dissipation is diagnosed as

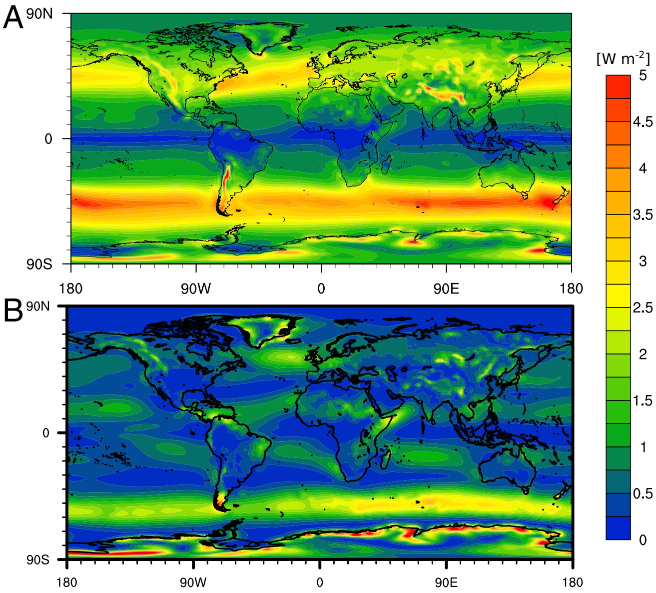

Fig. 1. (*A*) Climatology of kinetic energy extraction (KEE) rate for a globally homogeneous wind turbine density of one per 1 km^2, including turbine–atmosphere interactions. (*B*) Annual mean kinetic energy (KE) dissipation into the boundary layer for the preindustrial climate.

$\tau \times v_1$, where τ denotes the surface wind stress (units: newtons meter^{-2}) and v_1 is the wind speed of the first atmospheric model layer above the surface. Boundary-layer KE dissipation rates of 2.5 W m^{-2} are obtained over the Atlantic, and rates up to 4 W m^{-2} are found within the Southern Hemisphere wind belt, while overland dissipation rates remain below 1 W m^{-2} in most regions. Our estimates of KE dissipation rates due to drag are largely consistent with previous estimates obtained from the European Reanalysis 40 (ERA-40) dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis over the time period 1958–2001 (10). Therefore, increased rates of electricity generation seem plausible in regions where high near-surface KE dissipation is already sustained.

In the Northern Hemisphere, the North Atlantic is identified as a region with high potential for open ocean wind farm applications in terms of potential for increased downward transport of KE. Therefore, additional experiments were performed investigating the large-scale geophysical limit on wind farm power generation as a function of wind farm area ranging from 1.9 to 0.07 Mkm^2 in this region (Fig. 2*A*). For comparison, onshore wind farms of equivalent size were simulated in a region centered on Kansas (United States), where previous onshore wind farm studies have been performed (10, 12, 13). The determined scaling relations in terms of maximum KEE rates per area and generated power are summarized in Fig. 2 *B* and *C*, respectively. Spatial maps of climatological mean KEE are shown in Fig. 3 for the largest open ocean wind farm and in Fig. S3 for all other simulated wind farms.

It should be noted that all estimates given in this study provide an upper bound on KEE rates, which is solely determined by the sustained downward transport from the free troposphere to the near surface. Other geophysical factors, such as small-scale boundary-layer turbulent processes and individual turbine wake dynamics, may further limit open ocean wind power generation. Numerous turbulent flow studies (14, 16–20, 22) within small-scale wind farms have shown that small-scale atmospheric processes, such as the dynamics of individual turbine wakes, background boundary-layer mixing and stability, and small-scale

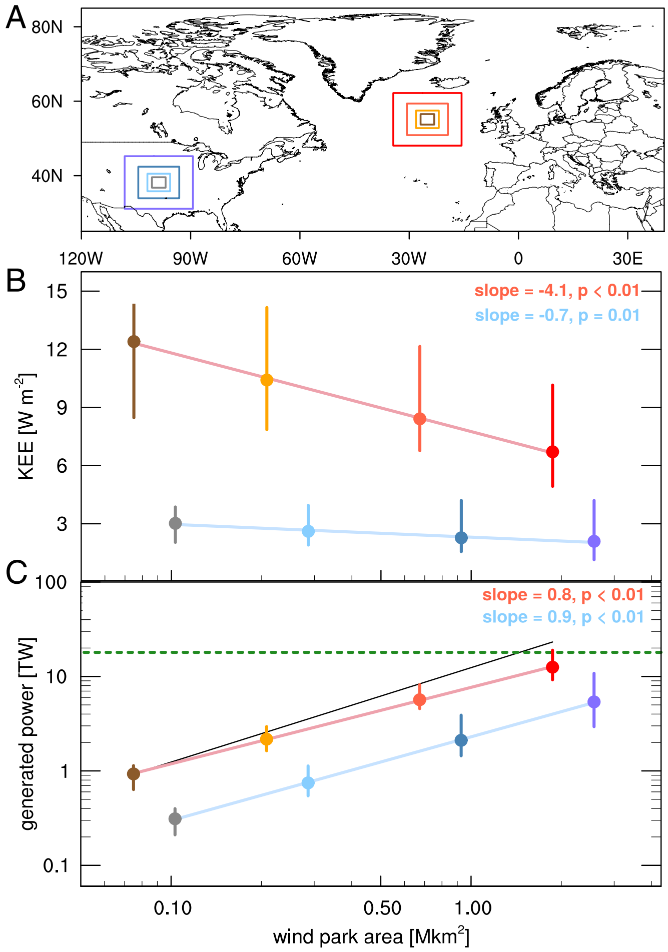

Fig. 2. (*A*) Map of wind farm locations. (*B* and *C*) Regional medians (●) and minimum–maximum ranges (lines) of annual mean kinetic energy extraction (KEE) in (*B*) watts meter^{-2} and (*C*) terawatts as function of wind farm area. Linear regression is fitted through the median KEE points against the common logarithm of the wind farm areas in the North Atlantic (salmon) and North America (light blue). Slopes and *P* values of fit are given. Precise KEE values and areas are in Table S1.

wind systems developing below the 100-km scale, may all impact the generated power along with the large-scale downward KE transport limit discussed here. For instance, a reduction of the interturbine spacing parameter to values determined by individual turbine wakes (additional details are in *Supporting Information*) reduces the extracted power over the Atlantic by 31% from the large-scale geophysical limit on KEE (Fig. S4).

In the annual mean, the atmosphere is able to sustain KEE rates at least three times as high over wind farms in the North Atlantic than over onshore wind farms. On land, the downward transport of KE may limit the power generation in onshore wind farms the size of Greenland (2 Mkm^2) to rates lower than what would be needed to power the current two largest energy-consuming countries: China, with a power consumption of 4.1 TW, and the United States, with a consumption of 2.9 TW in 2015 (https://yearbook.enerdata.net/). In contrast, the determined upper limit on power generation in the North Atlantic, on an annual mean basis, exceeds 10 TW.

In both cases, open ocean and onshore wind farms, the power generation and consequently, KE dissipation rate by wind turbines of at least 6.7 and 2.1 W m^{-2}, respectively, are at least twice as large as the near-surface KE dissipation into the boundary layer caused by drag within the respective regions (Fig. 3 and Fig. S3). Therefore, the total near-surface dissipation of KE is locally enhanced. However, globally, the total near-surface KE dissipation remains largely unaffected and oscillates around 336 TW in the mean (Fig. S5), which is within the range of previous estimates (1, 10, 23). This would suggest that increased rates of KE dissipation within each spatially constrained wind farm are compensated by equivalent decreases in near-surface dissipation of KE elsewhere.

In smaller area wind farms, even higher KEE rates than 6.7 W m^{-2} are sustained by the atmosphere as opposed to onshore wind farms, where KEE remains constrained to 2–3 W m^{-2}. As the wind farm area is decreased from 1.9 to 0.07 Mkm^2, the annual mean upper limit of extractable KE almost doubles, and values of up to 12.4 W m^{-2} are reached. Hence, our simulations suggest that, while KEE rates are limited on land for currently conceivable wind farm domain sizes and installed capacities, downward KE transport may not limit power generation for open ocean wind farms of equivalent size and installed capacity in the North Atlantic.

On subannual timescales, considerably stronger limits on KEE may be imposed because of the downward KE transport throughout the troposphere. During late spring and summer (May to August), sustainable KEE rates drop to 20% of the annual mean (Fig. 4). Furthermore, we find the seasonality of open ocean wind energy applications to be amplified compared with onshore wind farms at similar latitude (Fig. S6). In particular, the seasonal variability shows that the elevated power generation potential for open ocean wind power applications is largely seen throughout autumn until early spring (September to April) in the Northern Hemisphere. During this time period, sustainable extraction rates are up to seven times as high in the North Atlantic than on land. Despite the given strong seasonally varying geophysical limit imposed by the atmosphere, we still find that even the

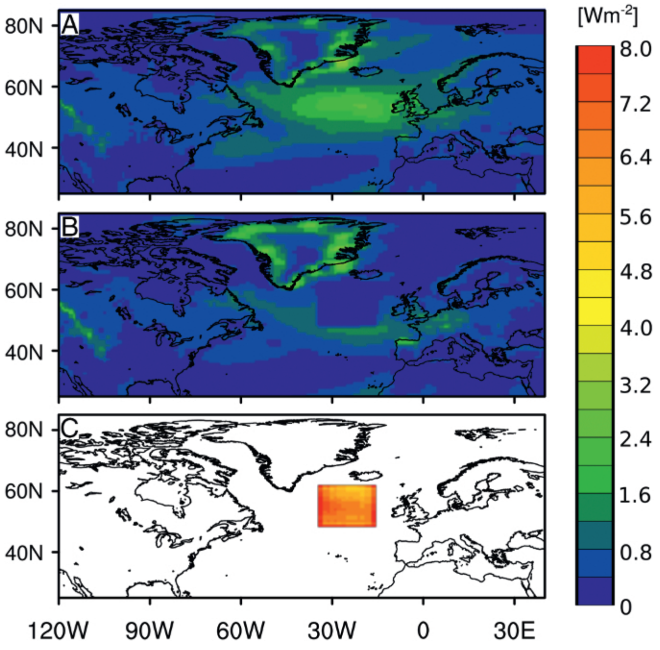

Fig. 3. Annual mean near-surface kinetic energy (KE) dissipation caused by drag (*A*) in the preindustrial climate and (*B*) for the largest simulated wind farm in the Atlantic with an area of 1.9 Mkm^2. (*C*) Kinetic energy extraction (KEE) within the largest wind farm in the North Atlantic. KE extracted by wind turbines is partially compensated for by a reduction in KE dissipation into the boundary layer caused by surface drag. Surplus energy extracted locally is compensated for by a regional decrease of KE dissipation into the boundary layer outside the wind farm.

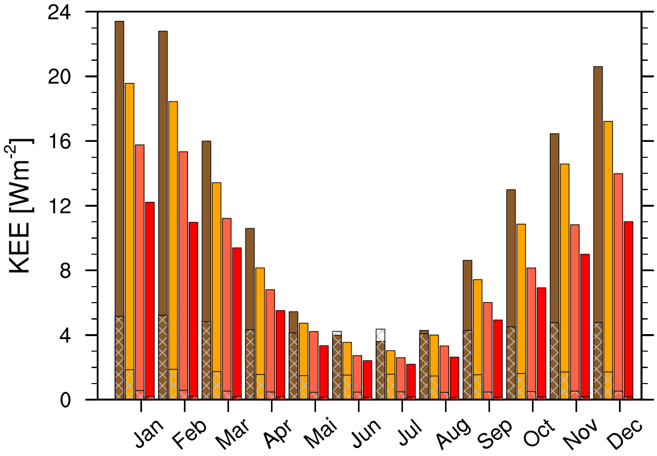

Fig. 4. Seasonal variability for open ocean wind farms in the North Atlantic. Colors correspond to different wind farm areas as shown in Fig. 2*A*. Wind farm areas increase as color changes from brown to red tones. Gray hatching indicates rate of Kinetic energy extraction (KEE) required to meet monthly mean electricity demand of the European Union (0.3–0.4 TW) scaled to wind farm size.

smallest wind farm considered in this study would generate sufficient electric power to meet the demand of the European Union in 2015 (24) almost all year round (10 of 12 mo) if it were operated at the geophysical limit. On land, the stronger geophysical limit imposed by the reduced downward transport of KE reduces this time period to 4 mo of the year.

Having shown the enhanced power generation potential of wind energy technologies in the North Atlantic, we also assessed potential climate impacts for each of the simulated wind farms. We find that the enhanced power generation rates in the Atlantic may come at the expense of exerting large nonlocal climate impacts. Climatological mean changes in 10-m wind speed remain constrained to the wind farm area, whereas significant changes in surface temperature are generated outside open ocean wind farms (Fig. 5 and Fig. S7). Changes are particularly strong north of the Arctic Circle, where a cooling of surface temperatures down to -13 K is obtained regionally. These large changes in surface temperature were driven by a dynamical sea ice feedback (Fig. S8) caused by induced changes in the near-surface wind field by wind farms exceeding an area of 0.1 Mkm^2.

Furthermore, sizable changes in the near-surface 950-hPa wind speed caused by giant wind farms in the North Atlantic may affect onshore wind energy installations in the United Kingdom, France, and Western Europe in general. However, these impacts are likely to be scale- and deployment-dependent and remain to be assessed in future studies on how enhanced wind resources in the Atlantic may be used. We only find moderate changes induced in surface precipitation, and these were not found to be statistically significant in our simulations (Fig. S7).

Discussion of KEE Rates

Our findings indicate that more wind energy may be extracted in the North Atlantic than over land for equivalent wind farm domains and turbine densities. These findings, therefore, support previous findings indicating a relative increase in maximum KEE over the oceans (10) rather than globally uniform extraction rates between land and ocean (11). We also find that the additionally induced drag of wind turbines can locally increase the near-surface dissipation of KE beyond the reference climate surface dissipation. However, a direct evaluation of these numerical estimates of KEE over the oceans is nontrivial.

The Community Earth System Model (CESM) compares well against observations in terms of its 10-m wind speed climatology (25) and interannual variability (Fig. S6*B*). The model also seems to simulate realistic KE dissipation rates caused by drag compared with KE dissipation in the reanalysis (10). Furthermore, on-land estimates of sustainable KEE caused by downward KE transport are consistent with previously published numerical estimates (9) on continental scales. However, for individual wind farm simulations, our simulations indicate that higher KEE rates may be attainable over land in subcontinental wind farms than previously published (2, 12). However, while their estimates were obtained for similarly sized wind farms (0.02–0.3 Mkm^2), simulations were performed for much shorter time periods: 10 d in January of 2006 (12) and May to September of 2001 (2). While we cannot compare our results on submonthly timescales (12), we find similarly low extraction rates when restricting our analysis to May to September (2) only (Fig. S9 and Table S2). Therefore, while there seems to be agreement among studies at large spatial scales, disagreement seems to persist at scales of individual wind farm sizes of the order of 100,000 km^2 and smaller. For additional evaluation, an understanding of the dominant processes driving the downward KE flux through the troposphere into the boundary layer is required, which may vary spatially and seasonally.

The key difference between simulated onshore and open ocean wind farms seems to be that, over the Atlantic, the simulated wind farms ranging in scale from 70,000 km^2 to 1.9 Mkm^2 impact the downward KE transport throughout the free troposphere, while over land, the overlying free troposphere remains largely unaffected by wind farms the size of Greenland (Fig. 6). The location and seasonality of increased power generation rates in the open ocean wind farms suggest that these are tied to the midlatitude storm track in the North Atlantic, which is characterized by the frequent generation and propagation of baroclinic

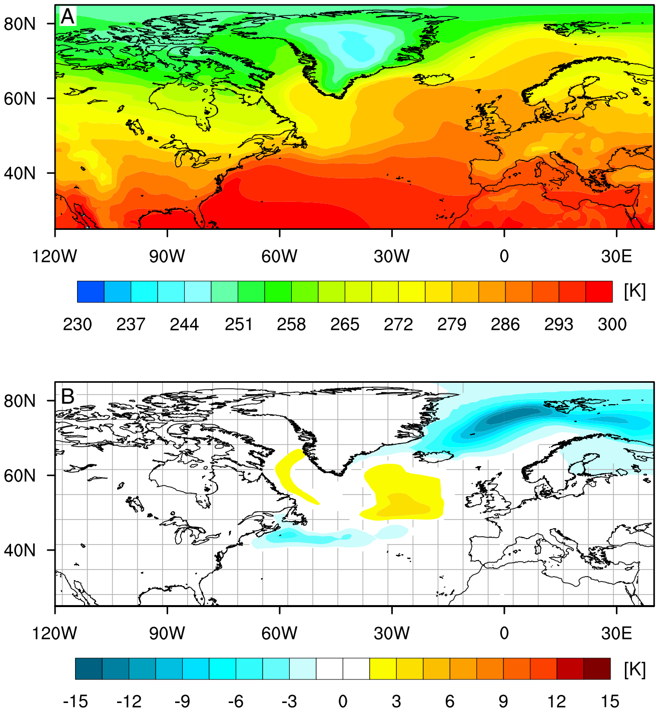

Fig. 5. (*A*) Preindustrial surface temperature climatology. (*B*) Absolute mean difference in surface temperature between the simulation with the largest open ocean wind farm situated in the North Atlantic and the climatological mean. Surface temperature changes for other wind farm simulations and changes in surface precipitation and 10-m wind speed are shown in Fig. S7. All changes in surface temperature over the ocean are at the 95% significance level.

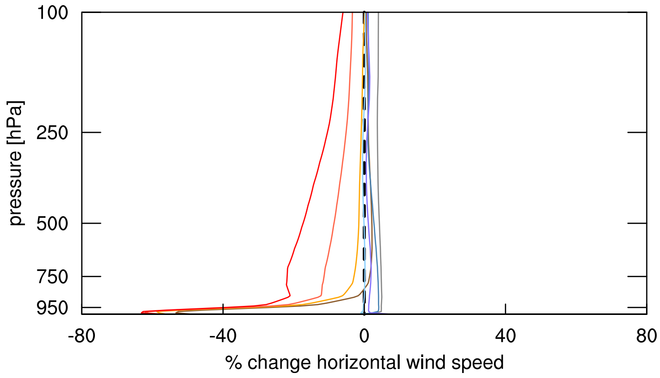

Fig. 6. Vertical profile of the climatological mean change in horizontal wind speed averaged horizontally over the four central points of each wind farm in the North Atlantic and North America. Differences were determined between each wind farm simulation and the preindustrial climate over the 50-y analysis period. Colors correspond to wind farms shown in Fig. 2*A*. Colors in the brown and red spectrum correspond to ocean wind farms, and colors in the blue spectrum correspond to onshore wind farms of varied domain size.

eddies. These eddies are the main driver of the accelerated near-surface winds and induce a strong coupling of the low-level winds to the upper-level jet stream (26). It is well-known that eddy generation is driven by the pronounced meridional temperature gradients during the winter months in combination with diabatic heating along the North American East Coast (27). From there, the eddies propagate westward to the Barents Sea in the Arctic. The northward tilt in the storm track is thought to be caused by the Rocky Mountains (28).

Therefore, baroclinic eddies constitute a source for near-surface KE along the storm tracks, which could provide an explanation for the far higher KEE rates sustained in the Atlantic. Furthermore, it would explain the extension of the reduction in horizontal momentum driven by near-surface drag over the oceans throughout the entire troposphere (Fig. 6). Also, ref. 29 showed that surface heat fluxes may additionally enhance baroclinicity in addition to the meridional temperature gradient. During the cold winter months, the ocean heats the atmosphere in the midlatitudes by 93 W m^{-2} on average. However, surface heat fluxes on land are small. Therefore, the surface heating from the ocean may play an additional role in sustaining increased downward transport of KE through the troposphere. Indeed, we find a narrowly constrained relationship between surface heat flux and maximum sustained KEE rates in our simulations (Fig. S10), which holds even in the tropics and subtropics, where meridional temperature gradients are small.

A more detailed mechanistic attribution of the relative contribution of individual processes and dynamic and thermodynamic drivers to vertical KE transport throughout the troposphere is beyond the scope of this study and will be subject to additional research.

Conclusions

Previous research has shown that onshore wind energy resources deployed at large spatial scales are limited by the energetics of the atmosphere. In particular, the downward KE flux through the troposphere seems to play an increasingly important role in constraining the efficiency of ever-growing wind farms with installed capacities exceeding actual extracted power. The pursuit of optimal power generation has pushed technological limits of material science and engineering in the last half-century and led to the construction of ever taller, larger, and more powerful turbines operating not only on land but also, in shallow coastal waters up to a depth of 40–50 m.

As wind energy technologies advance into coastal waters, the question of how much more energy may be obtainable farther out over the open oceans remains largely unknown. Climatological mean wind speeds are, on average, 70% higher over the Earth's oceans than on land. However, high wind speeds only translate into elevated potentials for wind power generation if the increased near-surface drag exerted by the wind turbines can be sustained (at least partially) by the local downward KE flux over the wind farm area.

This study focuses on the spatial and temporal variability of the large-scale geophysical limit imposed on wind energy power generation by the vertical downward transport of KE from regions of high wind speed in the free troposphere down to the near surface. We find that, over some ocean areas, downward transport of KE from the free troposphere may be sustained at levels several times greater than may be sustained over land.

Furthermore, we show that the upper limit of sustained wind power generation seems sufficiently large for giant wind farms, with an accumulated area of ~ 3 Mkm^2, to generate the current global primary energy demand of 18 TW in the annual mean. However, on seasonal timescales, wind energy resources in the North Atlantic drop to 20% of the annual mean during summer. Nevertheless, we find that the sustainable generated power is still maintained at a rate similar to the electric power consumption of the European Union of 0.35 TW (annual mean) in 2015.

However, estimates for smaller-sized wind farms remain uncertain because of insufficient model resolution and an incomplete mechanistic understanding of the underlying physical drivers sustaining elevated downward KE transport over the analyzed regions. Furthermore, extracting KE in vast amounts over the open ocean induced considerable changes in surface temperatures inside the wind farms of 2.4 K (Fig. 5 and Fig. S7). Moreover, even stronger changes in surface temperature of up to -13 K are simulated in the North Atlantic Ocean and the Barents Sea.

Therefore, while this study highlights the potential for open ocean wind technologies in the North Atlantic, it also illustrates the need for additional research addressing: (*i*) the dominant mechanisms of downward KE transport in the region of interest, (*ii*) the limits of wind power generation at finer spatial scales, and (*iii*) the potential climate effects exerted by wind farms given their location, turbine specifications, and size. Furthermore, the extent to which the open ocean potential may be used is likely to be strongly dependent on factors, such as sociopolitical and economic constraints as well as technical ingenuity required to construct, maintain, and operate potential wind energy technologies under such remote and harsh conditions, with wave heights frequently exceeding 3 m in the monthly mean (30). Nevertheless, even in the relative calm of summer, the upper geophysical limit on sustained wind power in the North Atlantic alone could be sufficient to supply all of Europe's electricity. On an annual mean basis, the wind power available in the North Atlantic could be sufficient to power the world.

Methodology

All simulations are performed with the CESM, version 1.2.2 (31). The model is run in its fully coupled ocean configuration under preindustrial conditions at a horizontal resolution of 0.9° in the atmosphere and $\sim$1.0° in the ocean. The default settings of the B_1850_CN model configuration (32) were used in our simulations. Each simulation was run for 100 y, and the last 50 y, by which time our simulations had equilibrated, were used in our analysis.

Using momentum conservation at each turbine, which was prescribed to operate at the Betz limit (i.e., KEE efficiency $\epsilon = 59\%$), the vertically integrated rate of KEE was computed at each longitude and latitude. As this paper is focused on the large-scale geophysical limit imposed on the vertical transport of KE through the troposphere to the near surface, our parameterization of wind turbines was built to ensure maximization of near-surface drag. A more detailed discussion of the wind turbine parameterization is presented in *Supporting Information*, including Fig. S11.

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