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Estimating maximum global land surface wind power extractability and associated climatic consequences

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Abstract

The availability of wind power for renewable energy extraction is ultimately limited by how much kinetic energy is generated by natural processes within the Earth system and by fundamental limits of how much of the wind power can be extracted. Here we use these considerations to provide a maximum estimate of wind power availability over land. We use three different methods. First, we use simple, established estimates of the energetics of the atmospheric circulation, which yield about 38 TW of wind power available for extraction. Second, we set up a simple momentum balance model to estimate maximum extractability which we then apply to reanalysis climate data, yielding an estimate of 17 TW. Finally, we perform climate model simulations in which we extract different amounts of momentum from the atmospheric boundary layer to obtain a maximum estimate of how much power can be extracted, yielding 36 TW. These three methods consistently yield maximum estimates in the range of 17–38 TW and are notably less than recent estimates that claim abundant wind power availability. Furthermore, we show with the climate model simulations that the climatic effects at maximum wind power extraction are similar in magnitude to those associated with a doubling of atmospheric CO_2. We conclude that in order to understand fundamental limits to renewable energy resources, as well as the impacts of their utilization, it is imperative to use a thermodynamic, Earth system perspective, rather than engineering specifications of the latest technology.

1 Introduction

Several recent studies (Archer and Jacobson, 2005; Archer and Caldeira, 2009; Magdalena and Jacobson, 2009; Lu et al., 2009) propose that wind power can easily meet the global human energy demand while also having negligible impacts on the Earth system. Archer and Jacobson (2005) quantified 72 TW of wind power extraction potential over land utilizing only 13% of the most windy land areas. Lu et al. (2009) increased this land-based quantification to 125 TW using an increased land area, larger wind turbines, and additional wind velocity measurements. Even more recently, Magdalena and Jacobson (2009) stated that "should wind supply the world's energy needs, this parameterization estimates energy loss in the lowest 1 km of the atmosphere to be 0.007%", which seems to suggest that wind power can easily supply the current global energy demand with insignificant impacts.

These studies neglect energy conservation, nearly imperceptible at smaller scales but critical when quantifying wind power potential at regional to global scales, as recently shown by (Gans et al., 2010). The methodologies for calculating extractable wind power employed by these studies (Archer and Jacobson, 2005; Archer and Caldeira, 2009; Magdalena and Jacobson, 2009; Lu et al., 2009) also differ significantly with those of Keith et al. (2004) and Wang and Prinn (2010) and should not be confused. Wind turbine characteristics and wind velocity measurements are important when estimating the potential electricity output of a proposed wind farm but they do not allow the quantification of changes to global wind power availability or climatic impacts directly resulting from wind power extraction. Previous very large-scale estimates, such as those utilizing large expanses of land (e.g. Archer and Jacobson, 2005; Lu et al., 2009) or the global atmospheric boundary layer (e.g. Magdalena and Jacobson, 2009) for wind energy extraction cannot use the same methodology as small wind farm developments without resulting in overestimations. Kinetic wind energy, and thereby extractable wind power, is not infinite.

Here, we bound our estimates by the total rate of kinetic wind energy generated in the Earth system (Lorenz, 1955; Gustavson, 1979; Gans et al., 2010). Using 3 similar methods of increasing complexity, based on fundamental limits of kinetic energy generation and of extractability, we can estimate a range of wind power extractability potentials over all non-glaciated land surfaces. These estimates therefore represent a realistic range of the maximum wind power potential that cannot be exceeded by improving wind turbine technologies (e.g. increasing their height or blade length, capacity factor, between-turbine spacing) or wind velocity mapping methods while maintaining

energy conservation. Inevitably, this removal of wind power from the Earth system must result in climatic impacts, shown here to be linearly proportional to the amount of wind power extraction.

2 Estimation of wind power availability over land

Approximately 900 TW of kinetic wind energy is currently generated and dissipated in the global atmosphere (Lorenz, 1955) – this is a meteorological fact (Peixoto and Oort, 1992). Thermodynamic derivations show that this rate of wind power generation is the maximum value achievable by the Earth System given present-day radiative forcing gradients, demonstrated by simple theoretical considerations (Lorenz, 1960), box models (Paltridge, 1978; Lorenz et al., 2001), and general circulation models (Kleidon et al., 2003, 2006). Of the total wind power in the atmosphere, physics-based considerations fundamentally restrict the extraction potential of turbines to a decreased percentage of the initial flow (Lanchester, 1915; Betz, 1920; Garrett, 2007). Using these ingredients, we derive 3 different estimates of wind power availability.

2.1 Back-of-the-envelope estimate

A very simple estimate for global land-based wind power extraction potential in the atmospheric boundary layer is shown in Fig. 1 and briefly outlined as follows:

1. 45 000 TW ≈ differential solar heating results in atmospheric pressure differences which sets the air into motion, a process that is currently operating at its maximum rate of conversion (Lorenz, 1960);
2. 900 TW ≈ total wind power generation rate in the global atmosphere (Lorenz, 1955) is the upper limit available for wind power extraction (Gustavson, 1979);
3. 450 TW ≈ 1/2 of this wind power is dissipated in the atmospheric boundary layer (Peixoto and Oort, 1992);

4. 113 TW ≈ 1/4 of the global surface is non-glaciated land making it most accessible for extraction;

5. 38 TW ≈ 1/3 of the available power can be converted to mechanical power that drives the wind turbine as shown by Garrett (2007), an extension of previous studies from almost 100 years ago (Lanchester, 1915; Betz, 1920).

Note that this estimate is completely independent of wind turbine characteristics. The maximum land-based wind power extractability is not dependent on current engineering or technological limitations, but is instead completely dependent on wind power generation rates (Gustavson, 1979) and the unavoidable competition between wind power extraction and dissipation by natural processes such as turbulence.

2.2 Simple momentum model with reanalysis wind data

A simple momentum balance model was developed to refine the back-of-the-envelope estimate of maximum wind power extractability. To establish the limit of maximum extraction, we consider the momentum balance of the boundary layer in steady state as:

$$\frac{d(mv)}{dt} = F_{\mathrm{acc}} - F_{\mathrm{fric}} - M = 0 \tag{1}$$

where mv represents atmospheric momentum, F_{acc} is the rate of momentum generation by an acceleration force, $F_{\mathrm{fric}} = k \cdot v^2$ is the frictional force resulting from boundary layer turbulence with k being a friction coefficient and v being the wind velocity, and M is the rate of momentum extraction by wind turbines. F_{acc} is assumed to be constant, constrained by thermodynamic limits and currently operating at the maximum rate achievable as discussed by thermodynamic arguments (Paltridge, 1978; Lorenz et al., 2001) as well as climate model simulations (Kleidon et al., 2003, 2006).

The mean wind flow v is then given by:

$$v = ((F_{\mathrm{acc}} - M)/k)^{1/2} \tag{2}$$

The wind power in the boundary layer P_{tot} is given by:

$$P_{\mathrm{tot}} = F_{\mathrm{acc}} \cdot v \tag{3}$$

This power is partitioned into dissipation by natural boundary layer turbulence D_n and power extraction $P_{\mathrm{ex}}(M)$ by wind turbines:

$$P_{\mathrm{tot}} = D_n + P_{\mathrm{ex}}(M) \tag{4}$$

The expressions for these terms are:

$$D_n = F_{\mathrm{fric}} \cdot v = k \cdot v^3 \tag{5}$$

and

$$P(M) = M \cdot v = M \cdot ((F_{\mathrm{acc}} - M)/k)^{1/2} \tag{6}$$

The maximum power extraction from the system is obtained by:

$$\frac{dP_{\mathrm{ex}}}{dM} = 0 \tag{7}$$

yielding an optimum value of extracted momentum M_{opti}:

$$M_{\mathrm{opti}} = 2/3 \cdot F_{\mathrm{acc}} \tag{8}$$

The associated maximum power extracted is:

$$P_{\mathrm{ex,max}} = 2 \cdot (1/3)^{(3/2)} \cdot P_{\mathrm{tot}}(M = 0) \tag{9}$$

or about 38.5% of the original wind power in the absence of extraction. Of the extracted power, half is converted into wake turbulence with the other half available as mechanical power as previously derived for a tidal channel turbine (Garrett, 2007).

We now use this estimated maximum efficiency of extraction and combine it with the wind power in the boundary layer as estimated from the European Centre for Medium Range Forecasting (ECMWF) ERA-40 reanalysis climate data (ECMWF, 2004). We use the surface wind stress as well as near-surface wind velocity components to compute natural dissipation D in the atmospheric boundary layer:

$$D = \boldsymbol{\tau} \cdot \boldsymbol{v} \quad (10)$$

where $\boldsymbol{\tau}$ is the wind stress and $\boldsymbol{v}$ is the wind velocity. We find that for the period 1958–2001, a mean of 513 TW of wind energy is dissipated globally in the atmospheric boundary layer, most of which is dissipated over the southern ocean (Fig. 2). This is consistent with the 450 TW approximation (50% of the total atmospheric dissipation) of the back-of-the-envelope estimate. Of these 513 TW, 89 TW is dissipated over non-glaciated land surfaces that would be most easily accessible for wind turbine installations. This is less than the 25% assumed in the back-of-the-envelope estimate (Fig. 1).

Using the simple momentum balance model and the land-based dissipation of the ECMWF ERA-40 data results in a maximum of 17 TW of mechanical wind power potential from the initial 89 TW of dissipation (Fig. 3). It shows how an overall increase in momentum removal (drag + extraction) corresponds to a decrease in boundary layer dissipation, with increased momentum removal beyond the maximum power extraction corresponding to a decrease in extracted power due to the reduced wind velocities.

2.3 Climate model simulations

In the third method we use a global climate model of intermediate complexity (Fraedrich et al., 2005; Lunkeit et al., 2007) and a methodology similar to the one used by Keith et al. (2004) to implement the effects of wind turbines. The climate model consists of a low-resolution atmospheric general circulation model with T21 spectral resolution, corresponding to a horizontal resolution of about 5.6° longitude by 5.6° latitude, ten atmospheric layers, a mixed-layer ocean model with prescribed oceanic heat transport, interactive sea-ice model, a simple land surface model, and prescribed ice sheets.

Boundary layer dissipation is parameterized by the commonly used surface drag parameterization of the form:

$$F_{\mathrm{drag}} = \rho(C_n|v| + C_{\mathrm{ex}}) \cdot \boldsymbol{v} \quad (11)$$

where ρ is the air density, C_n is the volumetric drag coefficient for natural turbulence (which depends on surface roughness and atmospheric stability among other factors) and $\boldsymbol{v}$ is the wind velocity. This model's reference manual provides a more detailed explanation of the drag parameterization (Lunkeit et al., 2007). The effect of momentum extraction by wind turbines is implemented by the additional drag coefficient C_{ex}. Natural dissipation by boundary layer turbulence D is given by

$$D = \rho C_n v^3 \quad (12)$$

while the extracted power by wind turbines is given by:

$$P_{\mathrm{ex}} = \rho C_{\mathrm{ex}} v^2 \quad (13)$$

A range of model simulations was conducted for different values of C_{ex}. The simulation with $C_{\mathrm{ex}} = 0$ represents the natural case in the absence of power extraction by wind turbines and is referred to as our control simulation. In total, 25 simulations were completed with different values of $C_{\mathrm{ex}} = [0.0001{:}10.0]$. All simulations were conducted for 30 simulated years with the first 10 years discarded from the analysis to exclude spin-up effects.

The control simulation of the climate model results in 551 TW of global boundary layer dissipation, of which 137 TW occurs over land (Fig. 4), nearly consistent with the two previous estimates. In comparison to the ECMWF data, wind dissipation over land is overestimated by 48 TW but the patterns agree reasonably well. The differences can in part be attributed to high interannual variability in the ERA-40 data and possibly due to the poor representation of topography due to the low spatial resolution of the model.

The sensitivity of wind power extraction over land is shown in Fig. 5. It is very similar to the simple estimate of Fig. 3. We find a peak of 36 TW of mechanical wind power potential over all non-glaciated land surfaces in the boundary layer in comparison to the 137 TW of boundary layer dissipation in the control simulation. This is nevertheless higher than the simple momentum balance model estimate due to the exchange of momentum between land and ocean which is reflected by the decrease in boundary layer dissipation over oceans (Fig. 5).

When we want to compare this number to the ECMWF estimate, we should correct the bias in boundary layer dissipation in the climate model by using the ratio of derived dissipation values. This allows us to estimate the maximum global land-based mechanical power as 36 TW·(89/137), to achieve a corrected climate model estimate of ≈ 23 TW.

3 Climatic impacts from wind power extraction

Global atmospheric motion will be affected by the extraction of momentum by large-scale wind turbine development. It has been previously suggested that the global human energy demand (17 TW in 2009, EIA, 2009) could be easily accounted for by large-scale wind power development (Archer and Jacobson, 2005; Archer and Caldeira, 2009; Magdalena and Jacobson, 2009; Lu et al., 2009). In stark contrast, our estimates suggest that 17 TW of wind power derived electricity would represent roughly 50% of the maximum land-based wind power possible with more severe climate effects.

We use the climate model simulations of Sect. 2.3 to demonstrate these climate effects. The control simulation was initially compared to an identical control simulation to estimate the variability within the climate model for the analyzed climatic variables and as such, there was no need for error estimation within the 25 simulations. To compare the magnitude of the climatic effects, we perform an additional model simulation using an identical control setup with a doubled atmospheric CO_2 concentration of 720 ppm. Area-weighted mean land values only changed slightly at the maximum wind power extraction ($C_{ex} = 0.10$) and the sensitivity to a doubled CO_2 concentration showed a typical magnitude of change ($CO_2 = 720$ ppm) as shown in Table 1. This is

to be expected since the primary cause for the expected climatic changes from wind power extraction (the decrease in atmospheric mixing and transport) are much less directly linked to surface temperature change than direct changes in radiative forcing due to elevated CO_2 concentrations.

To identify resulting climatic impacts, we take the area-weighted mean of the absolute value differences for monthly climatological means for 20 simulation years for all non-glaciated land grid points as: $\sum_n^1 |x_{\text{simulation}} - x_{\text{control}}|$, where x is the climatic variable under consideration. Values reflect the climatic impacts resulting from the decrease in boundary layer dissipation, at the maximum wind power extraction by 10% globally and 25% over land, in comparison to the CO_2 simulation decrease by 2% globally and over land. Absolute differences do not identify if a land point is warmer or wetter than the control simulation, but rather focus on how monthly climatic variables differ. Figure 6 shows the linear sensitivity response of 2-m air temperature, heat fluxes, precipitation, and surface thermal radiation to increases in momentum extraction. Previous studies have shown changes in climatic variables with wind power extraction (Keith et al., 2004; Roy and Pacala, 2004; Kirk-Davidoff and Keith, 2008; Barrie and Kirk-Davidoff, 2010) but this study directly relates changes in boundary layer dissipation to absolute differences in climate. As shown in Fig. 6, the magnitude change of precipitation and surface thermal radiation for the maximum wind power extraction simulation are similar in value to the elevated CO_2 simulation.

4 Conclusions

We estimate that at most, between 17–38 TW of mechanical wind power can be extracted from the atmospheric boundary layer over all non-glaciated land surfaces. This estimate is substantially less than previous estimates due to our consideration of the fundamental limits to wind power extraction and maintaining energy conservation within the Earth system. Although wind power extraction from a single turbine has little effect on the global atmosphere, many more will influence atmospheric flow and reduce the

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

extraction efficiency. Any extraction of momentum must also compete with the natural process of wind power dissipation by boundary layer turbulence.

These points reinforce the fact that wind power is renewable but finite. Our study focuses on the rate of wind power generation in the climate system rather than previous near-surface estimates that focused on measured wind velocities and engineering limitations (Archer and Jacobson, 2005; Lu et al., 2009; Magdalena and Jacobson, 2009). This consideration results in our estimate being significantly less than previous studies while also being independent of wind turbine size or layout.

Given that only 0.03 TW of wind-derived electricity was produced in 2008 (World Wind Energy Association, 2008), there is still substantial wind power development possible with relatively minor climatic impacts. However, future plans for large-scale wind power development must recognize the finite potential of the Earth system to generate kinetic wind energy. Future plans must also accept that the human appropriation of wind power must be accompanied by a climatic effect.

Our estimation methods are certainly extreme, but they nevertheless provide critical understanding of the limits of wind power in the climate system and how it can serve human energy requirements. Faced with the present-day global energy demand of 17 TW and a predicted change to 16–120 TW by 2100 (EIA, 2009; IPCC, 2007), extreme calculations such as this will provide the maximum power potentials and possible climatic effects of different forms of renewable energy sources planned to fulfill future human energy requirements. This in turn helps to prioritize which renewable energy resources are likely to be successful in meeting the future global human energy demand. More complex modeling studies can help refine our estimates and climatic impacts, but the presence of a maximum in wind power extractability and the associated climatic consequences from this extraction are fundamental.

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Table 1. The mean climatic variables of all non-glaciated land points for the control simulation (C_{ex} = 0.00 and CO_2 = 360 ppm), C_{ex} = 0.10 for peak wind power extraction, and an atmospheric CO_2 = 720 ppm simulation are shown. The associated climatic variables have the following units: temperature in °C, heat flux (latent + sensible) in W/m^2, precipitation in mm/day, and surface radiation in W/m^2.

C_{ex}	2 m air temp	heat flux	precip.	surf rad.
0.00	8.54	40.49	2.79	75.16
0.10	8.65	40.02	2.80	74.72
CO_2	2 m air temp	heat flux	precip.	surf rad.
360	8.54	40.49	2.79	75.16
720	10.73	41.44	2.94	70.74

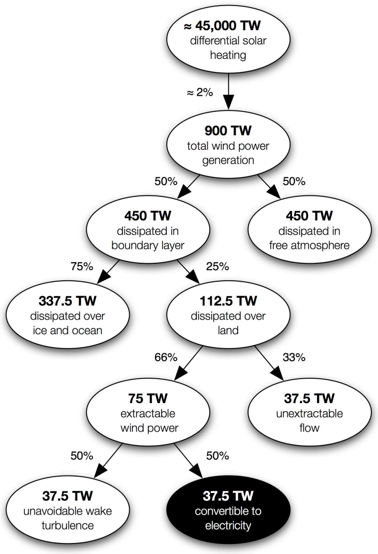

Fig. 1. The conversion processes between differential solar heating and extractable wind power over the land in the Earth system is shown. According to Lorenz (1960), only ≈ 2% of the differential solar heating of the Earth is converted to kinetic wind energy. This differential solar heating results in ≈ 900 TW of wind power generation and dissipation in the global atmosphere (Lorenz, 1955) and is the maximum available for potential extraction (Gustavson, 1979). Approximately 50% of this wind power is dissipated in the atmospheric boundary layer (Peixoto and Oort, 1992) and in steady-state, the dissipation rate of wind power must equal the generation rate (Lorenz, 1955). About 25% of the global surface is non-glaciated land and is most accessible for wind power development. For maximum power extraction, 33% of the wind flow must be permitted to pass through the turbine, while of the remaining 66%, 50% is unavoidably lost as wake turbulence and 50% can result in turbine mechanical power (Garrett, 2007). In this simple estimate, assuming a 100% conversion efficiency from mechanical power to electrical power, a maximum of 37.5 TW of electricity can be produced from wind power extraction from the boundary layer over all land surfaces.

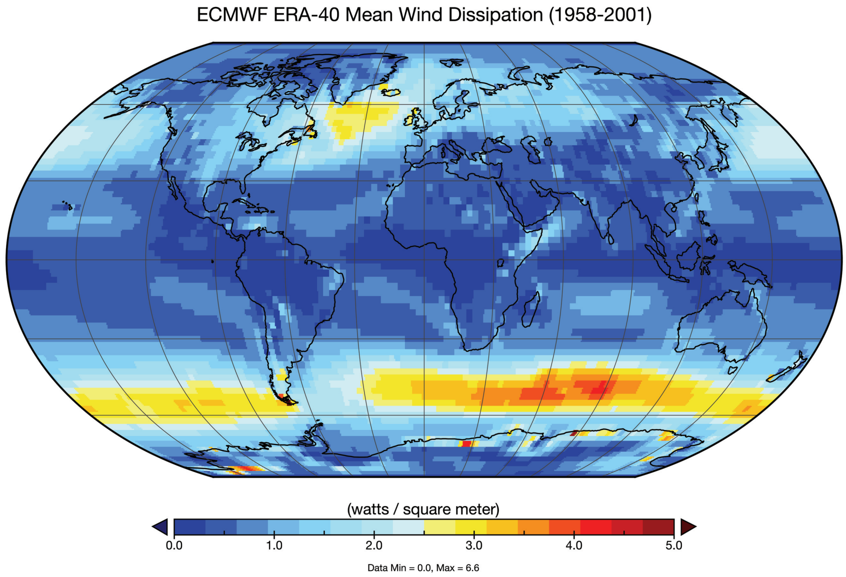

Fig. 2. Global distribution of boundary layer wind dissipation as a proxy for wind power from ECMWF ERA-40 reanalysis data.

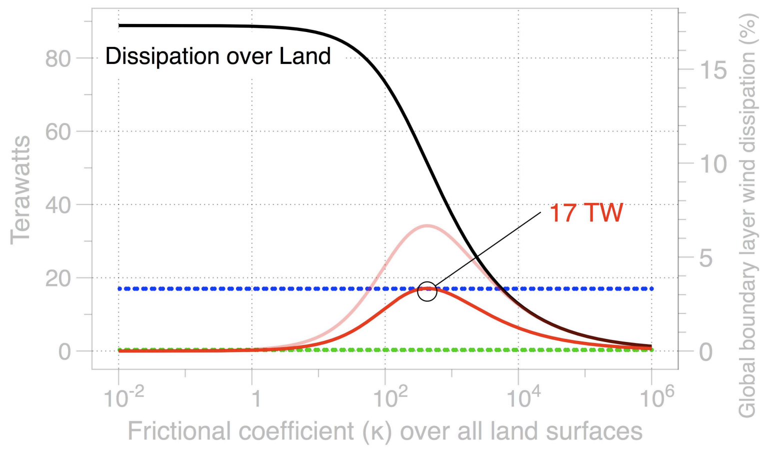

Fig. 3. The relationship between an increased frictional coefficient (κ) to changes in wind dissipation over land, extracted wind power (light red), and mechanical power that drives the wind turbine (dark red) is shown for the simple momentum balance model. For reference, the dashed blue horizontal line shows the estimated 17 TW of global energy demand in 2009 (EIA, 2009) and the dashed green horizontal line indicates the estimated 0.03 TW of global electricity production by wind turbines in 2008 (World Wind Energy Association, 2008).

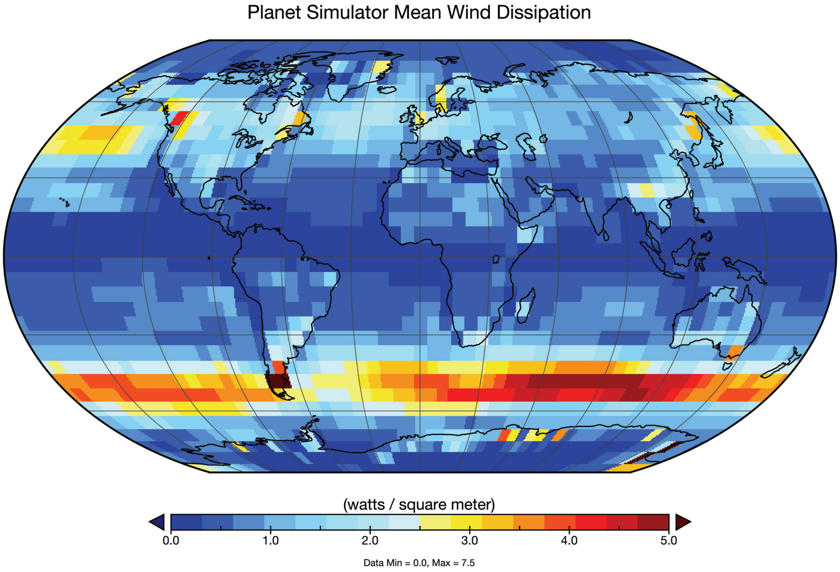

Fig. 4. Global distribution of boundary layer wind dissipation as a proxy for wind power simulated by the climate model.

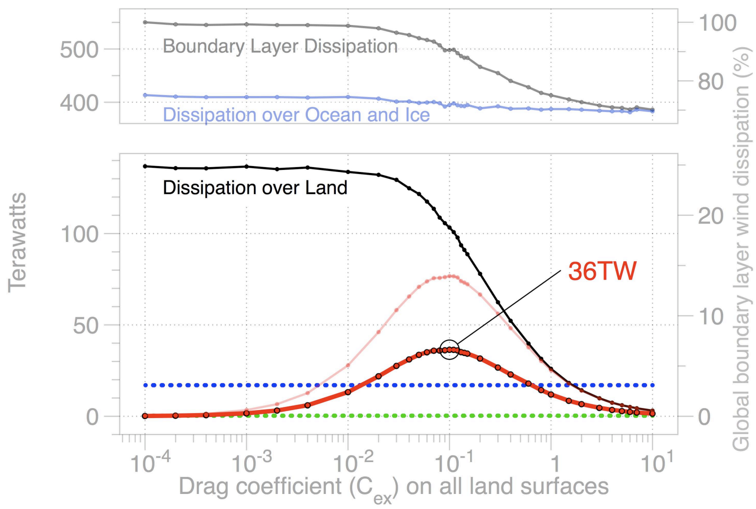

Fig. 5. The sensitivity to an increased drag coefficient (C_{ex}) to changes in wind dissipation, extracted wind power (light red), and mechanical wind power (dark red) is shown for general circulation model simulations. For reference, the dashed blue horizontal line shows the estimated 17 TW of global energy demand in 2009 (EIA, 2009) and the dashed green horizontal line indicates the estimated 0.03 TW of global electricity production by wind turbines in 2008 (World Wind Energy Association, 2008).

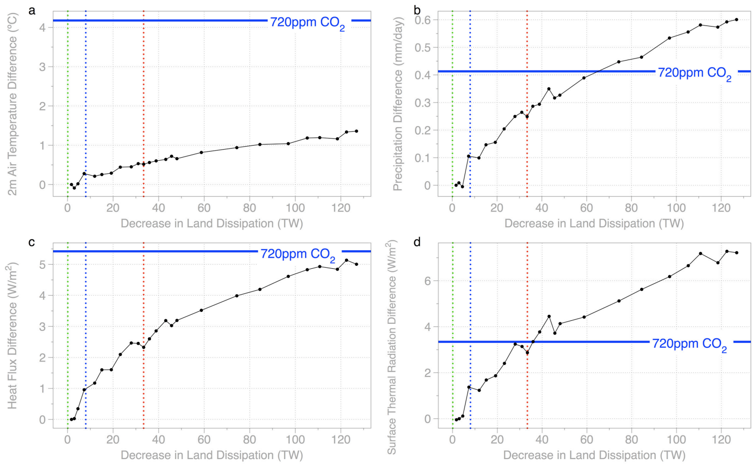

Fig. 6. Simulated absolute differences in climatic variables over all non-glaciated land for **(a)** 2-m air temperature, **(b)** precipitation, **(c)** latent + sensible heat flux, and **(d)** surface thermal radiation, resulting from increasing land-based wind power extraction compared to the control simulation. A simulation with an atmospheric CO_2 concentration of 720 ppm is shown as the horizontal blue line. The climatic difference is shown in relation to the decrease in land dissipation. The vertical green dotted lines represent the estimated 0.03 TW of electricity produced by global wind turbines in 2008 (World Wind Energy Association, 2008). The vertical blue dotted lines represent the 17 TW of estimated global energy demand in 2009 (EIA, 2009). The vertical red dotted lines represent the peak mechanical wind power based on general circulation model simulations.