Author response to D.B. Kirk-Davidoff "Interactive comment on 'Estimating maximum global land surface wind power extractability and associated climatic consequences' by L.M. Miller, F. Gans, and A. Kleidon"

L.M. Miller, F. Gans, and A. Kleidon

We appreciate D.B. Kirk-Davidoff's clear analysis of our submitted manuscript and sincerely appreciate several of the suggestions and comments he raised. Here we will respond to these points.

Rephrase back-of-the-envelope estimation method to a question

Yes. Our original 'back-of-the-envelope' estimate does make a number of assumptions that are not representative of the true complexities of the Earth System. As such, we agree that it is less an estimation method than a process hierarchy from incoming solar radiation to wind power dissipation in the atmospheric boundary layer over non-glaciated land. The resulting geographic dissipation shift with increased land-based kinetic energy extraction in the boundary layer suggested by D.B. Kirk-Davidoff indeed occurs in our general circulation model sensitivies (thereby indicating less than the control condition atmospheric momentum is available for extraction) and is not accounted for by the 'back-of-the-envelope.' We suggest renaming the 'back-of-the-envelope' to 'How to conceptualize the process hierarchy - a back-of-the-envelope estimate' as a more accurate descriptor of this part of the paper.

We do feel this 'How to conceptualize the process hierarchy?' question does deserve a place in the final manuscript. To illustrate this, we would highlight contrasting ideas to D.B. Kirk-Davidoff's stated assumption that "... no one is claiming that wind turbines could produce 300 TW of electrical power." In Santa Maria & Jacobson (2009), it is stated that "should wind supply the world's energy needs [12 TW], this parameterization estimates energy loss in the lowest 1km of the atmosphere to be $\approx 0.007\%$." A simple translation of this statement suggests $> 170{,}000$ TW of wind-derived electricity is continually available for extraction in the atmospheric boundary layer region. Jacobson & Archer (2010) stated something different in direct reference to this discussion manuscript, where under the assumption that 11.5 TW of electricity can sustain global energy demand, "...[the required wind turbine] power extraction at 100m amounts to $< 1\%$ (11.5 TW / 1700 TW) of the world's available wind power at 100m." We feel this confusion regarding wind power generation rates and the associated transfer processes validates this section's inclusion in the final manuscript.

Given all of this, it does seem critical to state the numerous simplifications that are included: wind power can be extracted where it is dissipated, no contribution of momentum from over the oceans or ice, no contribution of momentum from higher-altitudes, and there is no feedback on the generation rate of kinetic energy in the atmosphere. These will also be explicitly mentioned in the final manuscript text including, "Given these stated assumptions, the back-of-the-envelope estimate is only applicable as a first-order approximation of the processes related to wind power extraction from the atmospheric boundary layer." This clearly identifies our intention in devising it while also noting its severe limitations and applicability to an actual estimate of extractable wind power.

Simple momentum balance model is flawed - assumes a well-mixed boundary layer

No — we seem to have a difference of opinion regarding the initial assumptions. It is true that we used the 10-meter u- and v-wind velocities and the u- and v-surface stresses to estimate boundary layer dissipation of the ECMWF ERA-40 reanalysis data (ECMWF, 2004). Extrapolating the wind velocities to 80-meters would certainly increase the wind velocities but it would also decrease the influence of surface stress. Our primary intention of this study was to focus on the generation rate of kinetic energy in the atmosphere and how wind power extraction from the atmospheric boundary layer alters this generation rate.

Our simple momentum balance model is based on the assumption that the resulting estimate of ECMWF ERA-40 1958-2001 mean land dissipation of 89 TW is relatively proportional to dissipation in the atmospheric boundary layer as derived from a general circulation model (*e.g.* in this study: 71 TW with T21 spectral resolution and 20 vertical layers, 126 TW with T42 spectral resolution with 20 vertical layers). As also done in our general circulation model sensitivity simulations, we extract momentum from the entire atmospheric boundary layer — in application, this would be very difficult but it does alleviate any questions related to which wind turbine (*e.g.* hub height, rotor diameter, conversion efficiency) we chose to use for our estimates. Thus, we feel the simple momentum balance model is not flawed, but instead enables us to address the expected feedback of increased drag coefficients to changes in dissipation and extractable power from the entire atmospheric boundary layer. To estimate the extractability at a specific above-ground altitude (*e.g.* 80m) would certainly require model alterations but that was not our original intention.

Simple momentum balance model - drag exerted by the turbines makes the existing roughness elements irrelevant to the momentum balance of the wind farm

Not exactly. With very small frictional coefficients (*e.g.* $\kappa = 0.01$ where dissipation has decreased from 89 to 88.9 TW), the influence of surface roughness ($F_{fric} = \kappa \cdot v^2$ where v is the wind velocity), maintains the dissipation rate in the simple momentum balance model without wind turbines. It is true that with higher drag coefficients (*e.g.* $\kappa = 1000$ where dissipation has decreased from 89 to 18 TW with 34 TW of estimated extracted wind power) the influence of the simulated wind turbines is far greater than the influence of surface roughness. Thus, the frictional force F_{fric} maintains the model's boundary layer turbulence in conditions of little simulated wind turbine influence.

Temperature and precipitation climatic impacts maps and discussion should be included

Yes. The climatic impacts attributed to very large-scale boundary layer wind power extraction are primarily advective effects as previously illustrated by Kirk-Davidoff & Keith (2008). We are including the suggested maps (Fig. 1) here that will also be included in the final manuscript. Increased vertical mixing from simulated wind turbines in the boundary layer results in the entrainment of higher-altitude air and an associated 2-meter temperature response. This vertical mixing also influences the cloud formation process, especially noticeable by changes in convective precipitation and solar radiation at the surface. For reference, the rate of maximum wind power extraction is also included to relate wind power extraction regions to climatic impact regions. As also noted by D.B. Kirk-Davidoff, the wind power extraction shows the primary influence of the large-scale circulation on extractable wind power, previously noted by Barrie & Kirk-Davidoff (2009).

Suggestion to explore model sensitivity to increased vertical resolution in the boundary layer

We did greatly enhance the simulation estimates by including multiple spectral resolutions (T21,T42) and vertical levels (10,20) but as a proxy for potentially extractable wind power, the atmospheric boundary layer dissipation between vertical resolutions changed very little ($< 1\%$). We would agree that a high drag coefficient over a deep boundary layer would maximize wind power extraction related climate impacts. Our intention to explore the effect of boundary layer height by altering the vertical resolution, where the experimental drag is applied to the lowest atmospheric model layer and over all non-glaciated land grid cells equally, did not result in a significantly different result (Fig. 1 & 2). We would encourage a similar regional climate model study where the number of vertical levels and their prescribed drag coefficient can be more intricately parameterized.

Author Overview

D. B. Kirk-Davidoff has a well-founded perspective on modeling wind power and we sincerely appreciate his comments and suggestions. We will explicitly state the numerous simplifications and assumptions that are included in the process hierarchy, illustrated as a back-of-the-envelope estimate. We agree with D.B. Kirk-Davidoff that an estimate for extractable wind power derived this way includes many dynamics that would not be present and we will state these clearly while also noting the added understanding and complexity of the simple momentum balance model and general circulation model simulations. We have illustrated why our application of the simple momentum balance model is not flawed because of our stated assumptions but this will also be further clarified. We agree that some maps of climate impacts from wind power extraction are necessary to reinforce the impacts to the global climate while also noting that the extreme nature of this study suggests that a similar 'real-world' scenario will never be realized. Finally, we intend to include a suite of 4 sensitivity analyses of 13 simulations of varied spectral and horizontal resolutions. This suggestion by D.B. Kirk-Davidoff is appreciated, as it will further clarify our intention to provide a suite of estimates, all thermodynamically consistent regarding realizable wind power potentials and direct climatic consequences from wind power extraction.

References

[Barrie & Kirk-Davidoff(2009)] Barrie, D., and D. Kirk-Davidoff, (2010) Weather response to management of a large wind turbine array, *Atmospheric Chemistry and Physics*, **10**, pp. 769–775.

[ECMWF, (2004)] European Centre for Medium Range Forecasting: The ERA-40 archive, (2004) European Centre for Medium Range Forecasting.

[Jacobson & Archer (2010)] Jacobson, M., and C.L. Archer (2010) Comment on Estimating maximum global land surface wind power extractability and associated climatic consequences, by L.M. Miller, F. Gans, and A. Kleidon (Earth Syst. Dynam. Discuss., 1, 169-189, doi:10.5194/esdd-1-169-2010, 2010), *Earth Syst. Dynam. Discuss.* **1**, C84–C85.

[Kirk-Davidoff & Keith(2008)] Kirk-Davidoff, D., and D. Keith, (2008) On the climate impact of surface roughness anomalies, *J. Atmos. Sci.*, **65**, pp. 2215-2234.

[Peixoto and Oort, (1992)] Peixoto, J.P. & Oort, A.H. (1992) Physics of climate. *American Institute of Physics*.

[Santa Maria & Jacobson (2009)] Santa Maria, M.R.V., and M.Z. Jacobson, (2009) Investigating the effect of large wind farms on energy in the atmosphere, *Energies.*, **2**, pp. 816–838.

[World Wind Energy Association (2008)] World Wind Energy Report, (2008) World Wind Energy Association 2009. Bonn, Germany.

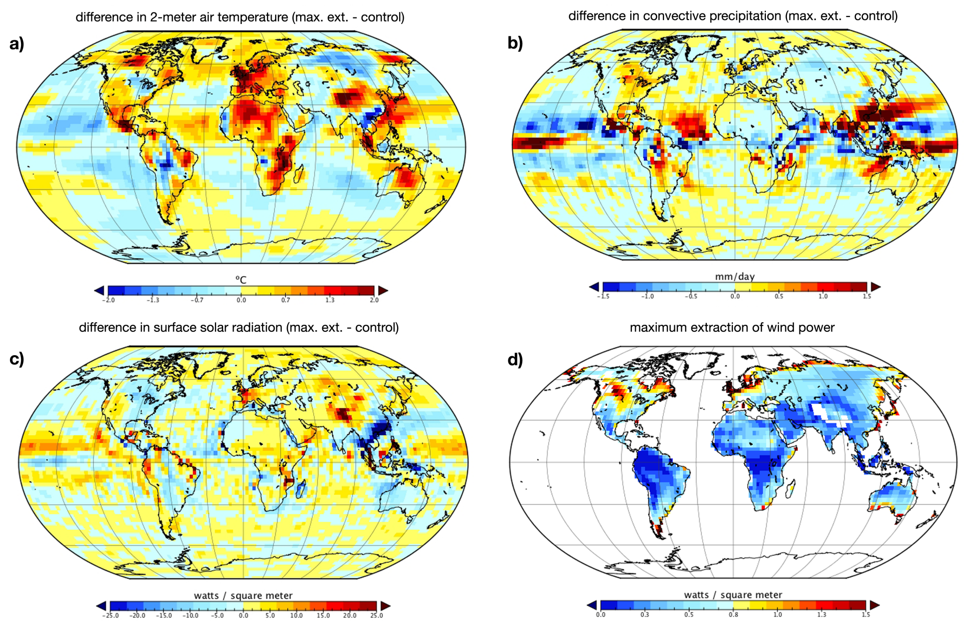

Figure 1: The extraction of wind power from the atmosphere has a direct impact on atmospheric dynamics, shown here as a difference between a T42 resolution, 20 vertical level simulation of maximum wind power extraction and a T42 resolution, 20 vertical level simulation with no wind power extraction (control) for **a)** 2-meter air temperature, **b)** convective precipitation, and **c)** incoming solar radiation at the Earth surface. Figure **d)** shows the maximum extraction of wind power when all non-glaciated land grid points are parameterized with the same increased drag coefficient, used to simulate wind power extraction from the lowest model layer and in this case, extracting a mean of 34 TW of mechanical power.

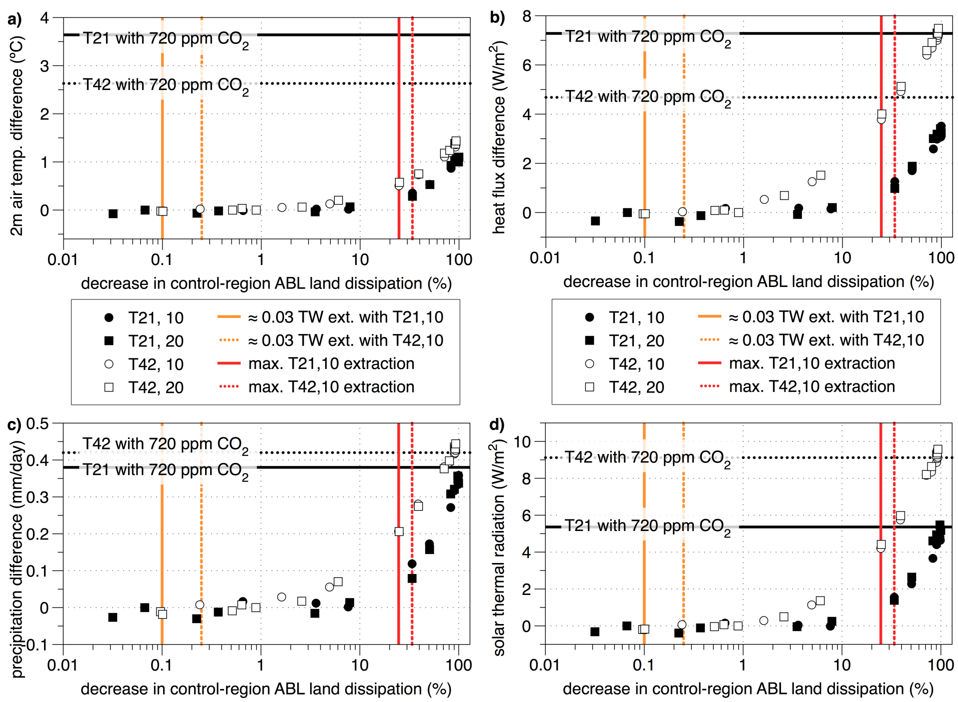

Figure 2: Simulated absolute differences in climatic variables over all non-glaciated land for a) 2-meter air temperature, b) sensible + latent heat flux, c) precipitation, and d) surface thermal radiation, resulting from increasing land-based wind power extraction compared to the control simulation. For comparison, simulations with an atmospheric CO_2 concentration of 720ppm are shown for a T21 simulation with 10 vertical levels (horizontal solid black line) and a T42 simulation with 10 vertical levels (horizontal dashed black line). For reference, the maximum wind power extraction (vertical red lines) and estimated 0.03 TW of electricity production in 2008 (World Wind Energy Association (2008)) from the general circulation model configurations (vertical orange lines) is also shown. The climatic differences are shown in relation to the decrease in control-region atmospheric boundary layer (ABL) land dissipation estimated by the respective model configuration.