Response to J.C. Bergmann "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 thank J.C. Bergmann (Bergmann, 2010) for his clear and thorough comment. He identified 2 mathematical derivations that required minor modifications and noted several interesting points. The calculations and text of the final manuscript will reflect these alterations with our noted changes/comments related to this comment noted below.

Clarifying our main message

Our study demonstrates the necessity of considering the generation rate of kinetic energy in the atmosphere when estimating maximum wind power extractability - reviewers and commenters do raise several interesting points but this main message remains the same. As our original title suggests, the methodologies and assumptions included in this study/manuscript were intended to provide an estimate of maximum global land surface wind power extractability. Additional processes could certainly be included that would change the realizable wind power potential on a global scale, but in our opinion, the main influences on wind power availability in the atmospheric boundary layer are adequately captured here. The original manuscript relied on a simple momentum balance model and general circulation model of T21 spectral resolution and 10 vertical layers to derive these estimates. Based on the general and referee comments, it would appear that our original intention should be substantiated further. To address this, an additional suite of general circulation model simulations at T21 and 20 vertical layers, T42 with

10 vertical layers, and T42 with 20 vertical layers have been completed and will be added to the final manuscript. The general agreement between all the estimates adds scientific substance to the estimates and analysis but is also more forthcoming about the range of resulting estimates. Should future estimates significantly exceed our range of estimates or exceed the global generation rate of kinetic energy in the atmosphere($\approx$ 900 TW by Kleidon, 2010), the estimate should be seriously reconsidered.

Extracted power to electricity conversion ratio

In reference to the conversion ratio of extracted wind power from the atmosphere to wind turbine derived electrical power - the Lanchester-Betz Limit (59.3%) is the maximum theoretical yet unrealizable limit (Lanchester,1915; Betz,1920) while the work of Garrett & Cummins (2007) suggests $\approx$ 33% is more appropriate. Given that Garrett and Cummins (2007) study the maximum extractable power from a confined tidal channel, it applicability is questionable here. As such, we agree with J.C. Bergmann that the actual conversion ratio between extracted wind power and potential conversion to electricity based on available research is unclear for such an extreme experiment. It seems most appropriate to emphasize this point in the final manuscript while also utilizing a conversion ratio of 60% from wind power extraction from the atmospheric system to the assumed mechanical wind turbine power and thereby electricity production.

Constant accelerating force ($\mathbf{F}_{acc}$)

We agree with Bergmann's initial reasoning, such that increased wind power extraction near the surface would result in an increased contribution of ageostrophic flow from higher altitudes. Bergmann (2010) states F_{acc} would increase as the drag force related to surface-based wind turbines increases, thereby increasing mixing of momentum from geostrophic flow which increases the ageostrophic component of the flow and increases power generation. We recognize that this effect has been shown experimentally (Cal et al., 2010) and with large-eddy simulations of extensive wind turbines (Calaf et al., 2010) but neither of these studies explore the possible feedbacks to ageostrophic flow contribution at the global scale.

We would clarify that the more long-term response of this phenomena would show that as the downgradient flow increases, the pressure gradient between the boundary layer near the wind turbines and the ageostrophic component above will be depleted, reducing the accelerating force and thereby reducing the geostrophic component of the wind velocity. These interactions would then result in a new steady-state of the atmosphere. Based on previous research that suggests the atmosphere is already operating at the maximum rate possible (Lorenz, 1960; Paltridge,1978), this new atmosphere would perform less work, making less wind power available for extraction. Given that approximately half the total atmospheric dissipation occurs in the atmospheric boundary layer (Peixoto & Oort, 1992), it does seem adequate to assume that the simple momentum balance model is capable of estimating extractable wind power near the surface within the 'estimate' context for which it was developed.

This also reinforces the need to use a general circulation model to explore the contributions of wind energy from higher-altitudes, accomplished here as a sensitivity analysis using a general circulation model of intermediate complexity (Fraedrich et al, 2005) which does capture the resulting changes in atmospheric dissipation (Fig. 1). As Bergmann himself stated in his conclusions, the possible dynamics resulting from these interactions are not well understood. As such, we think the most unbiased way to treat this is to assume a constant accelerating force (F_{acc}) while clearly stating the underlying assumptions, since these altered atmospheric dynamics might increase or decrease F_{acc}.

Parameter and coefficient clarification

The parameters used in the simple momentum balance model will be clarified (*e.g.* $F_{acc} = 1.1918 \cdot 10^{14} N$, mean 10-meter wind velocity = 0.7457m/s). Confusion over the symbols used in the simple momentum balance model, global climate model, and more general wind power terms will also be clarified - the symbols are indeed different and this will be corrected in the final manuscript (*e.g.* C_{ex} will now be C_{ext}, $\vec{v}$ in Eq. 10-13 will now be $\vec{v_L}$).

Wind turbine drag

Wind turbine drag is now quadratic with wind speed in the global climate model.

Wind power extraction

Extracted wind power now has a cubic dependence on velocity.

Atmospheric boundary layer dissipation

The disappearance of atmospheric boundary layer energy dissipation will be clarified for Fig. 3 & 5 in the original manuscript. This requires clarification on the part of the authors but is not directly wrong as stated by Bergmann (2010). In reference to the global climate model, after the peak extraction of boundary layer wind power, the increase of drag (*e.g.* wind turbines) in the lowest atmospheric layer causes a progressive shift in atmospheric dissipation to the next-higher vertical layer (also suggested by Chris Garrett, pers. comm.). This suggests that a new atmospheric boundary layer is present at a higher altitude than the atmospheric boundary layer of the control simulation. This explains how the highest drag coefficient ($C_{ext} = 1.0$) results in a dissipation near-zero in the control-region atmospheric boundary layer (Fig. 2). The text and associated plots will be clarified in the final manuscript.

Climate impacts

The statement by J.C. Bergmann (2010) that "The author cannot comment on the climate-change computations because it is not evident whether, respectively how the climate model incorporates ABL physics," is very strongly phrased, but also difficult to effectively respond to. It is our opinion that using this particular general circulation model of intermediate complexity does force us to make sacrifices such as the lack of full ocean dynamics and a simplified land-surface scheme, but as a benefit, it allows us to model many different types of sensitivity analyses (*e.g.* T21 vs. T42, 10 vs. 20 vertical layers). The comparison of these 52 sensitivity analyses also allows us to identify problems with the calculations between different model configurations (*e.g.* vertical resolution) while also performing such extreme scenarios where all non-glaciated land surfaces experience an additional drag coefficient.

Climatic impacts resulting from wind power extraction have been substantiated with measurements (Baidya Roy & Traiteur, 2010), regional models (Baidya Roy & Traiteur, 2010; Calaf et al., 2010), and global climate models (Keith et al, 2004; Kirk-Davidoff & Keith, 2008; Barrie & Kirk-Davidoff, 2009; Wang & Prinn 2010). These impacts are not related to the heat released from wind power derived electricity use but instead, induced by changes to the atmospheric dynamics.

Any global general circulation model must simplify ABL physics. Our initial expectations of altered atmospheric dynamics (*e.g.* entrainment of higher-altitude air with typically higher potential temperature increasing the 2-meter air temperature, decreased atmospheric dissipation with increased kinetic wind energy extraction, variations between the simulated mean and absolute differences of several climatic variables) have been verified in the simulations. A different model will lead to different results, as can be seen by comparing our results with those of Keith et al., (2004), Kirk-Davidoff and Keith, (2008), and Wang and Prinn (2010), while also illustrating the overall consistency. We conclude that for this particular application, the general circulation model with the incorporated atmospheric boundary layer physics is appropriate.

Authors conclusions

We sincerely appreciate J.C. Bergmann's clear and concise comment. We also recognize his focus on the importance of atmospheric boundary layer (ABL) energetics to the global estimate of wind power extraction near the surface. By approaching the global estimate from a top-down (atmospheric wind power generation rate to extractable wind power) rather than bottom-up (wind turbine characteristics, wind velocity, and air density to extractable wind power) perspective, we are primarily concerned with the generation rates of wind power in the global atmosphere and the associated response to wind power extraction. Additionally, this study explores how these generation rates are altered with additional drag in the atmospheric boundary layer. Our estimate is just that, an estimate, as by definition any model is a simplification of reality. In this case though, because of thermodynamic constraints on the conversion of solar radiation to wind and further thermodynamic constraints related to wind power extraction, we have clearly identified how extractable wind power does not infinitely increase with the spatial scale of wind turbine installations.

Through this comment response, and the resulting changes to the original manuscript, we hope that we have eased the main concern of J.C. Bergmann — the contribution of kinetic and potential wind energy above the ABL has been adequately included in the general circulation model sensitivities. His other comment points have also helped us to view our manuscript from a different perspective which we sincerely appreciate. The final manuscript will be substantiated by these contributions, allowing us to reinforce the fact that to quantify a global land-based estimate of near-surface wind power, the inclusion of the generation rate and its dependencies is critical.

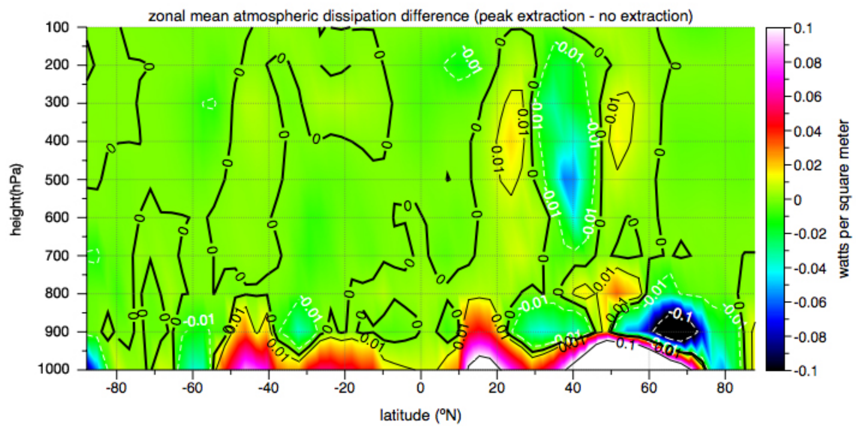

Figure 1: For a 20-year mean simulation with T42 spectral resolution and 20 vertical levels, the difference in wind dissipation between the peak wind power extraction ($C_{ext} = 0.01$) and no extraction ($C_{ext} = 0.00$) is especially apparent in the northern hemisphere. This reinforces previous research by Bergmann (2010) and Calaf et al (2010) which suggests that wind turbines in the atmospheric boundary layer will result in changes to the adjacent free atmosphere. Our simulations show this effect as increased dissipation within the region of wind power extraction in the boundary layer and a decrease in dissipation at higher altitudes adjacent to these regions.

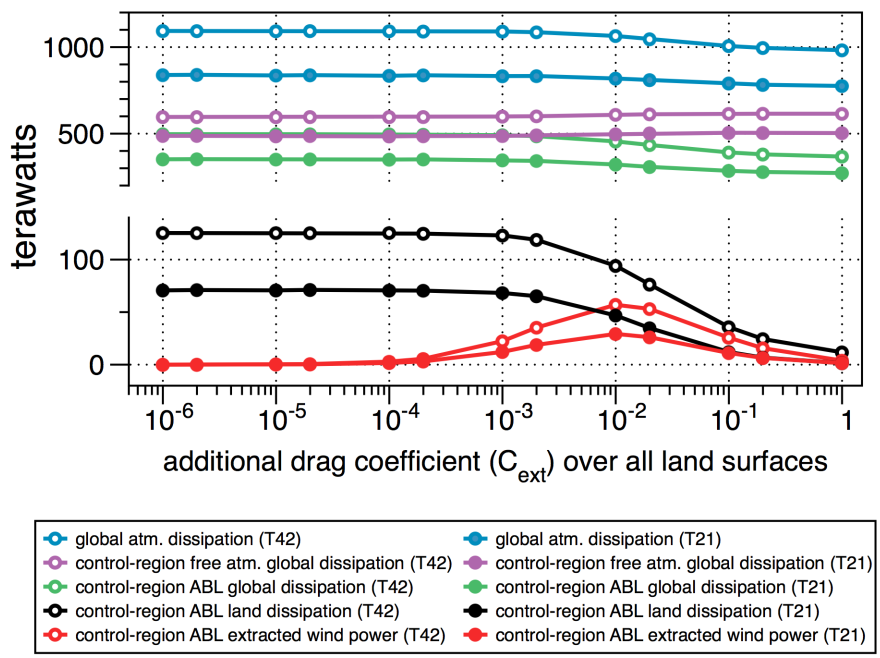

Figure 2: A sensitivity analysis of T21 and T42 spectral resolution and 10 vertical levels were completed to show the variability present in the model results related to dissipation and wind power extraction. Similar sensitivities were also completed with 20 vertical levels with very similar results (not shown). Overall, T21 with 10 vertical levels shows that total atmospheric dissipation decreased from 838 TW to 819 TW with a peak extraction of 29 TW. T42 with 10 vertical levels also shows a total decrease in atmospheric dissipation from 1094 TW to 1065 TW with a peak extraction of 57 TW.. Both sensitivities show corresponding decreases in the control-region atmospheric boundary layer (ABL) over land to additional drag: T21 = 70.7 TW (control) to 46.8 TW (peak), T42 = 125.0 TW (control) to 94.1 TW (peak). We attribute the differences between the T21 and T42 model resolutions to differential radiative forcing effects and the model parameterization of surface drag / topography. All these dissipation values are in general agreement with previous estimates (Peixoto & Oort, 1992; Li et al., 2007).

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