Response to comment by J.C. Bergmann

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

We thank J.C. Bergmann for his time and effort in preparing his comment. Instead of responding in the same inflammatory dogmatic tone, we will instead focus on how to use Bergmann (2011) as a means to result in an improved final manuscript.

In summary, all of Bergmann's comments (hereafter Bergmann (2011)) were:

- focused on a few small mistakes, admittedly the fault of the authors (*e.g.* zonal-meridional mix-up on p. 438, inverted y-axis in the original v-wind plot, Fig. 6b)
- illustrating a fundamental difference in the intention of modeling (*e.g.* full-complexity (Bergmann) vs. as simple as possible to answer the question (Miller, Gans, Kleidon))

It would appear that Bergmann (2011) agrees with our overall premise — there is very little extractable wind energy from the jet stream and only with substantial climatic impacts.

> *"Physical reasoning reveals directly (without utilisation of numerical models) that no additional wind power can be gained and that the jets' resource must be very small" p.C249*

and then recognizes the ongoing discrepancy between extractable wind energy and undisturbed wind power density, noting

> *"Of course, the discrepancy [wind power density vs. wind energy extractability] is very pronounced in the extreme case of the upper-troposphere jet streams, which have a very small energy throughput in the undisturbed case." p.C244*

While these ideas concerning the jet stream as a renewable energy resource may be obvious to someone with a strong background in atmospheric science or meteorology, the lack of response by the entire scientific community to a scientifically peer-reviewed article stating potential extraction rates of 1000 - 10 000 W/m^2 (Archer and Caldeira (2009) Fig. 3) suggests this might not be so clear after all. Another potential option is that the topic is simply not of general scientific interest, but the Nature News article highlighting these findings directly conflicts with this idea too. That Nature article (Vance, 2009) further clarifies the details of the article by Archer and Caldeira (2009) with clear text stating "...jet streams, which taken together contain 100 times as much energy as humans use today" [*i.e.* 1700 TW], and a direct quote from the author, stating jet streams are "the highest concentration of renewable energy in large quantities."

Now, as a means to understand jet stream wind energy extraction without complex general circulation model simulations, we developed a simple model that captures the essential jet stream physics required to understand how a jet stream would respond to an additional drag on its flow. According to our manuscript's Abstract on p.436, "We first use a simple thought experiment of geostrophic flow to demonstrate why the high wind velocities of the jet streams are not asociated with a high potential for renewable energy generation." We do not refer to any simple model energy extraction rates within the Abstract or within the Summary and Conclusions because that was not our intention in its development.

This intention was recognized by reviewer Hasselmann (2011) p.C238-239 when he reiterates, "The analytical model provides a simple description of the basic dynamics of the jet stream, but is not closed, as the feedback of the energy extraction on the large scale pressure gradient that maintains the geostrophic flow must be parametrized. The problem is then closed through the extensive numerical simulations with the global climate model." As a simple model, we want to be able to derive it analytically, which would not be possible if we included turbine drag as a square dependence on velocity (stated as a deficiency by Bergmann on p.246). It also includes the replenishment term as the pressure gradient force F_0 (Bergmann p.C245 "MGK 2011 does not consider the processes of energy-replenishment to that reservoir"). Bergmann (2011) clearly desires a much more detailed simple model, but that is well beyond the scope of this paper as we have written it.

After the simple model is used to illustrate the difference between jet stream wind energy extractability and jet stream wind power density, along with the dependency of extractability of momentum diffusion into and out of the jet stream, the manuscript progressed to the parameterization and sensitivity analyses of a general circulation model. Bergmann (2011) is not satisfied with this parameterization either:

> *"A direct physical error is committed by considering KE-extraction equivalent to a quantity that is a force.... Thus, turbine drag is presented as friction-equivalent. Such conception is incorrect because friction is completely dissipative, so that no electric energy can be provided by a 'turbine' that is a frictional apparatus, and all extracted energy is fed into the transformation chain via turbulent kinetic energy (TKE) and subsequent viscous dissipation to heat... real turbines with good efficiency (little friction!) do not produce significant amounts of (additional) TKE. There is a general misconception in the wind energy meteorology 'community' that interprets turbine drag as friction-equivalent — in analogy to natural flow obstacles like trees — MGK2011 reproduces it!"*

Our goal in using the GCM is to assess the impact of an additional drag on the jet stream, both in its ability to remove kinetic energy from the flow, and to estimate how the resulting dynamics may alter the angle of the jet stream and thereby its subsequent extraction rate. Our parameterization of this 'jet stream technology' as a frictional-equivalent accomplishes this goal. We do assume that this additional conversion of kinetic energy conversion to heat is negligible within the intended accuracy of the GCM, as the additional effect would be through the direct removal of kinetic energy.

There is a wind energy study that does differentiate between drag and friction when modeling wind power (Baidya Roy , 2011). When comparing this noted study and our own, it is important to notice that fully resolving the change in turbulent kinetic energy (TKE) within the regional model can only be done with a vertical model resolution of 10s of meters and a full TKE-closure scheme. This is well beyond the intended use of our general circulation model. As frictional dissipation plays almost no role in atmospheric heating, along with the overarching assumption that jet stream wind energy extraction is simply not sensible from a energy or climate consequence at this time, more complex implementations within a more complex higher resolution GCM or regional model do not deserve consideration at this time.

There were a several instances where the comment by Bergmann can help improve the final manuscript:

- "All mass-related quantities in the subsequent equations are formulated in this sense as 'quantity per unit mass' , but the text does not specify this and treats the symbols as representing the quantities themselves." — Agreed. This will be clarified in the final submitted version of the manuscript

- the contradictory use of 'meridional' and 'zonal' on page 438 — this is our mistake and it will be corrected

- "On page 440, lines 18,19, the text states 'natural dissipation of momentum at the edges of the jet stream.' Momentum cannot be dissipated." — Yes. We will correct this in the final manuscript and closely read the entire manuscript to identify other potential inconsistencies related to this statement.

- "It is evident that the undisturbed jets are located in zones of equatorward meridional flow, which is counter-pressure gradient!" — Yes - true as presented. We accidentally reversed the signs for negative winds (northerly) and positive winds (southerly) in Figure 6b of the discussion manuscript. This will be corrected in the final manuscript and is included here for consistency (Fig. 1). To verify that Bergmann (2011) and this revised plot are now in agreement, we verified this plot against Peixoto and Oort (1992) for the pressure gradient (Fig. 7.10a on page 146) and meridional wind component (Fig. 7.17 on page 157) as well as Dima et al. (2005) and found it to be consistent. Thus, we would state that the undisturbed jets are located in zones of poleward meridional flow, representing down-gradient flow, while the natural friction and turbine-induced drag act opposite the pressure gradient. We apologize for the confusion this caused throughout Bergmann (2011).

- Bergmann (2011) perceived a possible imbalance in the global mass balance due to increased poleward transport resulting from jet stream wind energy extraction:

  > *"MGK 2011 (the discussion paper) is completely right in emphasizing that (additional) drag on the jet stream necessarily leads to (additional) down-gradient, i.e. poleward*

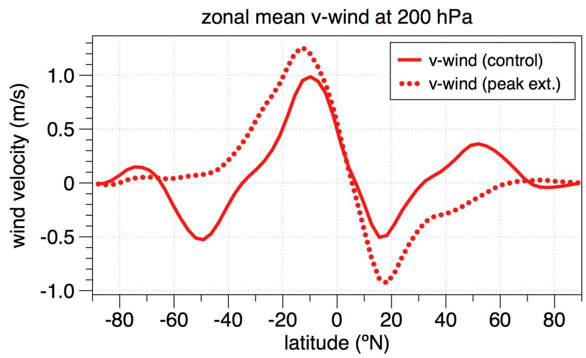

Figure 1: Zonal annual mean of the wind fields at 200 hPa for the meridional (v) wind component. The solid line represents the control simulation while the dotted line shows the simulation with peak rates of kinetic energy extraction.

> *flow. However, additional poleward flow in upper troposphere is only possible if there is the same amount of lesser poleward flow in the ABL below (mass conservation!). That is only possible if ABL winds are weakened (of if other layers' equatorward flow in upper troposphere is intensified, which, however, cannot happen by energy extraction). ... Model results from Table 1 show large monotone reduction of natural dissipation that exceeds jet-stream extraction by a factor of 22 in the ABL and by a factor of 40 in the free troposphere, so that the ABL 'gains' power relative to the free troposphere. That model result is in contradiction to the basic analysis presented [in previous critical comments by Bergmann (2011)]."*

Yes and no. We recognize that the dynamics resulting from jet stream wind energy extraction (increased poleward transport of upper-atmospheric air) must also result in an increase in a mass transport in the opposite direction. Figure 2 shows area-weighted differences in v-wind for the 200 hPa and 1000 hPa level. This indeed shows the missing 'gains' referred to by Bergmann (2011) above and indeed is the result of energy extraction. This does not mean that the total wind energy is increasing at 1000 hPa, and again using Table 1 values referred to above, ABL dissipation decreases from the control (584 TW) to peak extraction (419 TW) and in the free atmosphere for the control (635 TW) and peak extraction (358 TW). This is in support of our discussion paper's conclusions and contradicts part of the above-quoted statement.

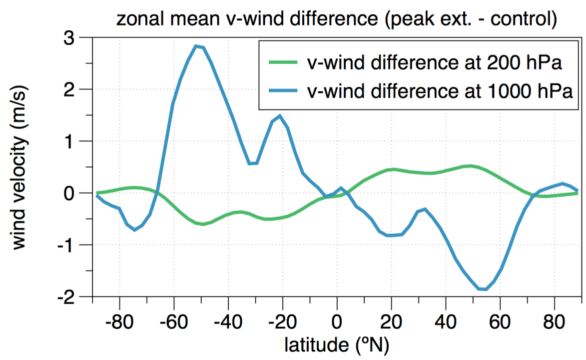

Figure 2: Mean differences between the peak extraction simulation and the control for two atmospheric levels

Regarding other concerns related to the general circulation model:

> *"Due to lack of specialised knowledge on modelling issues, the present author [J.C. Bergmann] cannot go into details of the circulation model applied in MGK 2011. ... In regards to the impacts, specified detailed statements should only be made on the basis of models, which explicitly consider complete jet physics."*

Bergmann (2011) is not giving us a position to respond to here. We would state that any model result derived from perturbing existing atmospheric dynamics so severely as to totally remove the jet streams from the climatic mean should be suspect, and reinforces our use of the simple thought experiment to understand how the jet stream might respond to an increased drag. Our intention in noting some of the climatic consequences of jet stream wind energy extraction was used to reinforce the connection between altering atmospheric circulation patterns and the difference in climate variables such as 2-meter air temperature and precipitation. Assessing the jet stream physics within the general circulation model we utilized are beyond the intended scope of the paper. We are confident that using a different general circulation model to simulate jet stream wind energy extraction will also result in proportionally small energy extraction compared to the disruption to atmospheric dissipation differences while also being directly related to dramatic differences in common climate variables.

References

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