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Interactive comment on "A simple explanation for the sensitivity of the hydrologic cycle to global climate change" *by* A. Kleidon and M. Renner

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We would like to thank the reviewer for his thoughtful comments on the manuscript. In the following, we provide a point-by-point response to each of the comments. The comments by the reviewer are included in italics.

Comment: *1. Discussion: I am not an expert on atmospheric physics, but I feel that it would be helpful if you reflected a bit more on whether any of the global assumptions you make does influence the result (i.e. the stated sensitivities of the hydrological cycle?) For example, neglect of atmospheric dynamics and spatial patterns, open water and* E_{opt} *assumptions. Can any differential effect of the two processes on the spatial climate pattern be expected (perhaps important for the precipitation projections in a geo-engineered climate)?*

Response: We agree that some discussion of the assumptions will help to interpret the robustness of the results. We provided a discussion in the manuscript in which the original model was published (Kleidon and Renner, 2013, HESS). In the revised version of this manuscript, we will provide a brief summary of this discussion. The main points are that there is an influence of large-scale motion in that it generates additional kinetic energy to mix near the surface, and that the estimates are somewhat affected by spatiotemporal variations because the expressions are slightly non-linear. We will elaborate on these aspects and place the discussion into a separate section.

Comment: *2. Pages 863 and 864 are difficult to follow, not least because it uses long sentences and a long list of process interactions. Can you provide some curve graph(s) showing what is told here, i.e. illustrating how the different sensitivities diverge under different assumptions (perhaps as a function of global mean temperature rise or using as example a stylized simple geo-engineering scenario)?*

Response: We will rewrite this section in the revision. We will also follow the suggestion of the reviewer and provide a new figure to illustrate the example of geoengineering described in this section of the manuscript. The new figure and the caption are included below.

Comment: *Title could reflect the two disparate processes under consideration here – that is, would you like to convey the main message that there is "a simple explanation for the sen- sitivity" (as suggested by the present title), or the (additional) message that there is sensitivity to both surface warming and altered solar radiative forcing.*

Response: We agree that there are more messages in the manuscript than what the title suggests and will slightly change the title following the reviewer's suggestion.

Comment: *Abstract: you mention two sensitivities, 2.2 and 3.2%/K; what is the combined sensitivity?*

Response: The value of 3.2 % K^{-1} represents the combined sensitivity to surface temperature and absorbed solar radiation. We will clarify this in the revision.

Comment: *Introduction: You may want to reflect this paper, which appears to derive a sensitivity of about 1%/K over land, though with a high standard deviation among GCMs (p. 3552, and Fig. 5 for spatial pattern): Heinke et al. 2012: A new dataset for systematic assessments of climate change impacts as a function of global warming. Geosci. Model Dev. Discuss. 5, 3533–3572.*

Response: Thanks for pointing out this paper, which deals with the climate sensitivity on land. One needs to be careful though to compare this estimate to the estimate provided in our manuscript. We perform a global analysis, which includes the assumption of a water surface, and that the system is closed, i.e. it does not exchange mass with the surroundings. On land, we would need to consider the effect of precipitation as well as its changes as this would result in an additional constraint by the water balance in the energy partitioning. This, in turn, would result in another term in the sensitivity, eqn. 7. This additional term would very likely affect the sensitivity. If, for simplicity, we assume that half of the land surface is dry, while the other half is not, this would roughly translate into an averaged sensitivity over land of half the sensitivity of an open water surface, which would be consistent with the mentioned sensitivity. This is, however, already describing an extension of our approach to land, which is beyond the point of our study. We will comment on this in the discussion that this approach needs to be extended to deal with the water balance constraints when applied to land.

Comment: *Introduction should explain in some more detail the two separated effects, as is done now in the first paragraph of section 3 (could partly be moved).*

Response: We feel that the explanation of the two effects is more meaningful after the expressions are introduced in section 2, in which the effects can be seen directly. We will, nevertheless follow the recommendation by the reviewer and add more explanation in the introduction regarding the two effects.

Comment: *page 856: line 19: did Bala et al. consider both effects?*

Response: Yes, Bala et al. did this indirectly. We will specify their findings in more detail in the revision.

Comment: *line 5: what is "maximum power"? Page 858 line 22: what is "Carnot limit"?*

Response: The Carnot limit and the maximum power limit are thermodynamic limits that express the extent to which the kinetic energy associated with convective exchange can be generated. We derived the expressions in detail in a closely related paper published in Kleidon and Renner (2013). Because this limit is rather important, we agree that some more explanation should be added to this manuscript. We will explain this in more detail in the revised version and add a brief derivation of these limits in an appendix.

Comment: *line 19: which "key characteristics"?*

Response: As the key characteristics we refer to the global evaporation rate as well as poleward moisture transport by the large-scale atmospheric circulation. We include this more specific description in the revised manuscript.

Comment: *Page 859 line 8: more than 70% of the strength of the hydrological cycle: what does "strength" mean here (at the beginning you should define what you mean with hydrological cycle and its strength).*

Response: With strength we refer to the magnitude of the evaporation rate, which in the steady state balances precipitation. We will provide a definition of this term in section 2.

Comment: *p. 864 line 20: what is meant by "reduced" hydrological cycle, reduced global precipitation? Can you point to your relevant equations here, from which one might deduct the 6.4% and 5.8% change? It is not absolutely clear how these numbers relate to a 2% strengthening per K warming stated in other studies (see also above comment on abstract).*

Response: Yes, we refer to a reduced strength as a hydrologic cycle with a lower rate of evaporation (or precipitation). The changes were derived from the sensitivities for a surface warming of 2 K. If this warming results from changes in the greenhouse, then this would result in a 2 K * 2.2% K^{-1} = 4.4% increase in evaporation. On the other hand, when geoengineering by solar radiation management attempts to undo this warming by reducing solar radiation, this would result in a reduction of -2 K * 3.2% K^{-1} = -6.4%. Hence, in this scenario, the warming would be undone, but evaporation would be reduced by 4.4% - 6.4% = -2%. This lack of compensation in the sensitivities is quite an important point. In the revision, we will make this description clearer, including the illustration with an additional figure (as already described above). The same considerations were applied to the convective mass exchange.

Comment: *Conclusions: Is it possible to add something on the applicability of this simple model for specific research questions (maybe on geo-engineering)?*

Response: Absolutely. We will extend on the conclusions on geoengineering and elaborate on potential extensions of this approach to other aspects of climate change (e.g., the extension to land).

Figure Caption: Illustration of the effects of greenhouse changes and solar radiation changes on evaporation. The sensitivity of evaporation to a surface warming of $\Delta T = 2$ K by an elevated greenhouse effect results in an increase of $1/E \cdot \partial E/\partial T_s = 2.2\%$ K^{-1} (the first term on the right hand side of eqn. 7), resulting in a change from point A to B (blue line). A geoengineering response aimed at compensating this increase in surface temperature by reducing solar radiation would change evaporation at a rate of $1/E \cdot dE/dT_s = 3.2\%$ K^{-1} (both terms on the right hand side of eqn. 7), resulting in a change from point B to C (red line). Hence, while the geoengineering response may undo differences in surface temperature, it cannot compensate changes in the hydrologic cycle at the same time.

Interactive comment on Earth Syst. Dynam. Discuss., 4, 853, 2013.

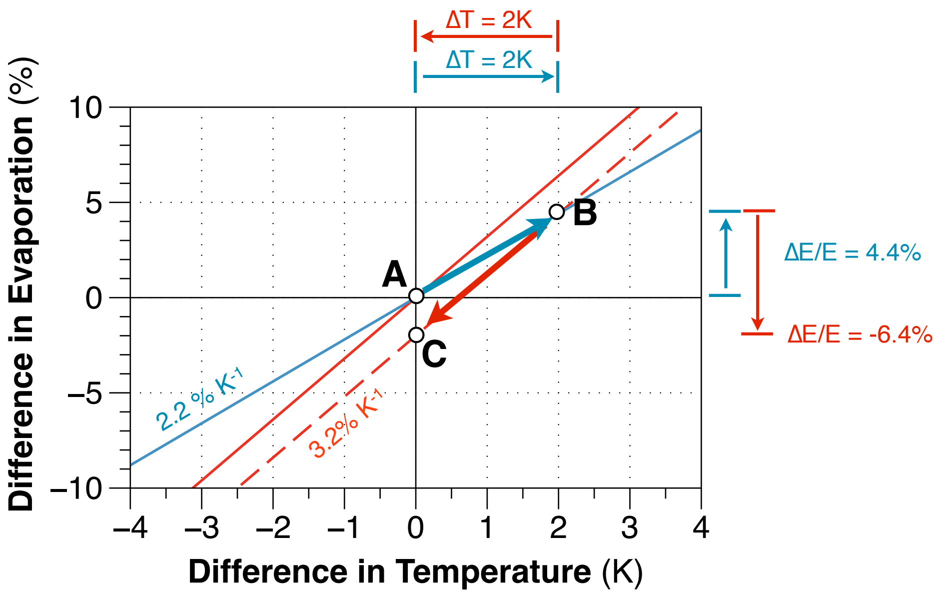

Fig. 1. Illustration of the effects of greenhouse changes and solar radiation changes on evaporation. See text above for explanation.