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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 thank the reviewer for the very positive and constructive comments on the manuscript. We reply to each of the comments in the following, with the comments by the reviewer in italic.

Comment: *This is an extremely interesting paper explaining with a very simple global energy balance method and an added assumption about the magnitude of convective exchange at the surface. Despite its apparent simplicity I had to read the paper more than once to comprehend the intricacies of the analysis and still I am not sure that my level of understanding is complete. Despite this, and despite the fact that I am not a boundary layer meteorologist, the paper is convincing and it is a stunning result that such a simple analysis yields the same results as the climate models. However,*

the explanation that is usually given as to why climate models present an increase in hydrological cycling of 2-3 % (of precipitation) instead of the 7% (Clausius Clapeyron) is very different and I will come back to that later.

Response: In the revision, we will try and make the approach as well as assumptions easier to follow.

Comment: *The assumption that the generation of convective motion is such that it maximizes a state of power. It is probably derived from thermodynamic principles, not familiar to many of the readers. This should be explained better, if not in the main text in an appendix. Also, it should be justified. I realize that some of this has been done in previous papers of the authors, but it should be reiterated in a concise fashion here nonetheless.*

Response: The maximum power state is a thermodynamic extremum state which allows for most dissipative activity by convective motion. We explained this in a closely related paper that was published earlier this year (Kleidon and Renner, 2013), and agree that we should provide more explanation to emphasize that this is a thermodynamic limit and not an arbitrary assumption.

In the revised version of the manuscript, we will include more explanation in the text and the appendix as suggested.

Comment: *It is unclear to me how equation (7) is derived, so a derivation would be in order. If* $E = E(T(R))$ *I get:* $dE/dT = (dE/dR)(deltaT/deltaR)^{-1}$*. If* $E = E(T(R), R)$*, I get:* $dE/dT = (dE/dR - deltaE/deltaT) * (deltaT/deltaR)^{-1}$*. Please provide the derivation.*

Response: To derive the temperature sensitivity of E, we first note that T_s is not the independent variable, but rather R_s and k_r, so that $E = E(k_r, R_s)$ and $T_s = T_s(k_r, R_s)$. However, we are interested in the sensitivity to T_s, as this is what is commonly reported from climate model simulations to greenhouse warming. So we want to make T_s our independent variable. Eqn. (6) ($T_s = T_a + R_s/(2k_r)$) relates these three variables to each other (with T_a being a function of R_s, as in the global energy balance, eqn. 2) so that we have three variables (T_s, R_s, and k_r), of which two are independent. In the physical world, this would be the greenhouse characteristics (k_r) and the solar radiative forcing (R_s), since surface temperature depends on solar radiation as well as the strength of the greenhouse effect. To evaluate dE/dT_s, however, we pick here T_s as the independent variable and can then use eqn. 6 to express R_s as the dependent variable which depends on k_r and T_s. This sounds a bit backward, but is mathematically sound and is simply attributable to the fact that we are interested in the sensitivity to surface temperature, which is not an independent variable. In this case, the derivative of E to T_s is given by

$$\frac{dE}{dT_s} = \frac{\partial E}{\partial T_s} + \frac{\partial E}{\partial R_s}\frac{\partial R_s}{\partial T_s} \quad (1)$$

Since $\partial R_s/\partial T_s = (\partial T_s/\partial R_s)^{-1}$, we can also write this as

$$\frac{dE}{dT_s} = \frac{\partial E}{\partial T_s} + \frac{\partial E}{\partial R_s}\left(\frac{\partial T_s}{\partial R_s}\right)^{-1} \quad (2)$$

for which the derivative $\partial T_s/\partial R_s$ can be directly calculated from eqn. 6. This above equation is eqn. (7) of the manuscript. In the revision of the manuscript we will make this derivation more explicit.

Comment: *Equation (12): misses 1/w for both terms on the right side of the equation.*

Response: Thanks for catching this error. This was merely a typing error, and the analytical expressions are not affected by it. We will correct this in the revision.

Comment: *Line 6,7 in Summary and Conclusions: what is meant by "reduced by a factor that results from the surface energy balance constraint". This is not clear.*

Response: By the reduction factor we refer to the factor $\gamma/(s+\gamma)$ in eqn. 8 of the sensitivity of E to T_s. This factor originates from the energy balance (and maximum

power) constraint and ensures that E is not unbound with much higher values for T_s, but converges to a upper limit of $R_s/2$.

We may also add that the proportionality of the sensitivity to the change in the slope ds/dT_s, rather than de_{sat}/dT_s, is due to the fact that the intensity of the water cycle does not depend on $e_{sat}(T_s)$, but rather on the difference of $e_{sat}(T_s) - e_{sat}(T_a)$, which is approximated in our model by the slope s. Hence, the sensitivity of the hydrologic cycle does not follow de_{sat}/dT, but rather ds/dT.

In the revision, we will provide a more detailed explanation of these aspects.

Comment: *What is not clear to me: does an increase in radiation also lead to an increase in the greenhouse term (first term in equation 7), or does this term increase due to other mechanisms? Please clarify better the mechanisms behind this in the text.*

Response: Yes, an increase in absorbed solar radiation increases both terms in eqn. 7. An increase in R_s results in an increase in T_s (cf. eqn. 6), and hence an increase in s. This affects both factors in the expression for E_{opt} (cf. eqn. 4), the term $s/(s+\gamma)$ increases as well as $R_s/2$. An increase in the greenhouse effect reduces the value of k_r, increases T_s (eqn. 6), alters the term $s/(s+\gamma)$ but leaves $R_s/2$ unaffected. In this sense, the first term in eqn. 7 is not a "greenhouse" term, but rather the direct effect of surface temperature change.

We will extend the explanation of eqn. 7 in the revised manuscript.

Comment: *Finally, coming back to the increase in the intensity of the hydrological cycle not being 7% per degree K but 2-3% in climate models (measured in terms of rainfall increase): this is often explained differently. One starts by explaining that the atmosphere can hold more water because atmospheric temperature increases as well, at least in the lower parts. (This is not possible in this model here, because T_a is constant. However, as the gradient $T_s - T_a$ increases one would expect that if T-stratification where to be taken into account T_a would increase in the lower atmosphere* *and hold more water). The fact that this does not lead to 7% more rainfall is explained by the inability of the atmosphere to radiate away the additional energy that is released when condensating this additional atmospheric moisture. This effect is strengthened by the reduced emissivity of an atmosphere with higher CO2 content. I would like the authors to reflect on how this presumed mechanism fits into their scheme of things. Is there a relationship between this explanation and theirs.*

Response: This is indeed an important point and we will include a discussion of the common explanation in the revised manuscript. We agree with the reviewer's explanation that the atmosphere would hold more vapor in our model because of the increase in T_s.

As the reviewer describes, the common explanation for the hydrologic sensitivity starts at the atmospheric energy balance (e.g. Allen and Ingram, Nature, 2002; Allan et al., Surv. Geophys., 2013). Surface warming results in a perturbation of this energy balance, and accounts for the extra release of latent heat, $\lambda\Delta P$, which needs to be balanced by a change in radiative cooling of the atmosphere to space, ΔR_{toa}, the change in radiative fluxes from the surface, ΔR_{srf}, and a change in the sensible heat flux, ΔH:

$$\lambda\Delta P = \Delta R_{toa} - \Delta R_{srf} - \Delta H \tag{3}$$

where the term ΔH is often neglected because H is quite a bit smaller than the latent heat flux. The common explanation for the lower sensitivity of the precipitation to surface warming argues that the additional release of latent heat, $\lambda\Delta P$, is constrained by the ability to radiate away the additional heat by the term $\Delta R_{toa} - \Delta R_{srf}$.

This energy balance is, of course, indirectly also obeyed in our model even though we do not explicitly mention it. First, we consider a steady state, so that $\lambda\Delta P = \lambda\Delta E$, or, $1/P \cdot dP/dT_s = 1/E \cdot dE/dT_s$. We also consider a sufficiently opaque atmosphere in the thermal radiation regime, so that all radiation to space is emitted from the atmosphere. In this case, changes in the greenhouse effect do not change the radiative temperature

of the atmosphere, hence, $\Delta R_{toa} = 0$. The change in surface thermal radiation, ΔR_{srf}, corresponds to ΔR_l in our model. For changes in the greenhouse effect, this term, however, does not change, because the maximum power constraint results in an equal partitioning among R_l and $H + \lambda E$, no matter how strong the greenhouse effect is. Hence, the overall changes in the atmospheric energy balance reduce to

$$\lambda\Delta P = -\Delta H \tag{4}$$

This implies that the weak, 2.2 % K^{-1} increase in the strength of the hydrologic cycle simply results from the reduction of the sensible heat flux. This interpretation is identical to what we found for the changes in the surface energy balance: Changes in the greenhouse effect result in surface warming, but this surface warming merely affects the partitioning between sensible and latent heat, but does not affect the magnitude of the turbulent heat fluxes.

The changes in the atmospheric energy balance are different if the surface temperature change was caused by changes in solar radiation. If absorbed solar radiation increases by ΔR_s, then the global energy balance requires that $\Delta R_{toa} = \Delta R_s$, so that the radiative temperature T_a must increase. The partitioning of energy at the surface changes as well. At a state of maximum power, the additional heating of ΔR_s results in an equal increase in radiative and turbulent fluxes of $\Delta R_{srf} = \Delta R_s/2$, and of $\Delta(H + \lambda E) = \Delta R_s/2$. In addition, surface temperature increases, which alters the partitioning between H and λE. Hence, in this case, all four terms are going to change

$$\lambda\Delta P = \Delta R_{toa} - \Delta R_{srf} - \Delta H \tag{5}$$

which is quite different to the case above in which only the partitioning between sensible and latent heat was affected.

Overall, this is a quite different explanation of the hydrologic sensitivity, yet it is simple, consistent with the atmospheric energy balance, and predicts the right value of the sensitivities.

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