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Interactive comment on "Diurnal land surface energy balance partitioning estimated from the thermodynamic limit of a cold heat engine" *by* Axel Kleidon and Maik Renner

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We thank the reviewer for the constructive and helpful review of our manuscript. In the following, we summarise the referee's comments in *italic*, provide our reply to each point, and suggest how we address these points in the revision.

Reviewer comment 1: *The authors frequently use the term "cold heat engine", which, honestly, was not known to me before. It seems that a cold heat engine is defined as a heat engine with some storage (P2L29), but a more precise definition may be given.*

Reply: We introduce this term here. To our knowledge it has not been defined before.

Our motivation to refer to our Eq. 4 as the Carnot limit of a "cold" heat engine is similar to a cold car engine in winter. When the car engine is still cold in winter just after it has been started, one needs to hit the gas harder to get the same power. Our expression captures this effect: The heat flux needs to be larger to get a certain power, because the term dU_a/dt reduces the effect of the heat flux on the power. As this is a storage effect similar to a cold car engine heating up, we think that the term "cold heat engine" nicely captures this storage effect.

In the revision, we will motivate and clarify the justification for the "cold" heat engine terminology in greater detail in the introduction and section 2.1.

Reviewer comment 2: *From Fig. 1 it seems that the heat engine discussed by the authors is confined to the radiative-convective layer with J_{out} being a flux into the free atmosphere above. However, combining Eqs 1,4,5 gives $J_{out} = R_{l,out} - R_{l,net}$, i.e. the cooling of the whole atmospheric column by thermal radiation. Thus, either it is assumed that there is no exchange between the radiative-convective layer and the free atmosphere, or the heat engine comprises the whole column. This needs to be clarified (in Fig.1 and/or the text introducing the heat engine).*

Reply: We apologise, as it appears that Fig. 1 is misleading in this respect. J_{out} does not actually go into the free atmosphere, but rather stays in the radiative-convective layer and is exported to above by net emission of longwave radiation. In other words, the radiative-convective layer is heated by the turbulent heat fluxes from the surface (J_{in}), and the cooling takes place not by a heat flux, but net longwave radiative cooling of the radiative-convective layer, and this cooling is represented by $J_{out} = R_{l,out} - R_{l,net}$, as you write.

We will clarify this aspect in the revision.

Reviewer comment 3: *Eq. 2 gives the entropy budget of the heat engine. However, $J_{out} = R_{l,out} - R_{l,net}$ (see above), and $R_{l,net}$ is the sum of thermal flux coming from the atmosphere (approx. $R_{l,out}$, say) and from the surface ($R_{l,surf}$). Thus, instead of*

J_{out}/T_a I would expect a term ($R_{l,surf}/T_s$) and something like $2R_{l,out}/T_a$ appearing in Eq. 2, representing both the import of entropy from the soil and the respective export from the atmosphere. It seems that $R_{l,surf}/T_s$ can be of the same order as J_{in}/T_s. The authors need to explain why the entropy import from the surface ($R_{l,surf}/T_s$) is not considered, in particular as J_{out}/T_a is used to obtain Eqs. 3,4,7.

Reply: Thank you for pointing this out. The important point that we did not describe well enough in the text is that the entropy budget expressed in Eq. (2) is the budget for thermal entropy, not for radiative entropy. This is an important distinction. What you describe as terms such as $R_{l,surf}/T_s$ represent terms of radiative entropy, i.e., it is entropy reflected in the composition of radiation, but not associated with heat (or thermal energy). As we deal here with convection and a heat engine, we must not include radiative terms as such, but only when radiation is absorbed and heats (adds thermal energy), or when the net emission of radiation cools (removes thermal energy). Radiative terms and radiative entropy production are typically much larger in the Earth system than non-radiative contributions (easily by a factor of 100). Yet, any form of motion is associated with the much smaller, but relevant thermal entropy terms.

In the revision, we will explain this important point.

Reviewer comment 4: *Eq. 7 gives an estimate for J_{in} derived from optimization based on the second law. However, using Eqs. 1,5 to replace dU_a/dt and dU_s/dt in Eq.7 (or replacing dU_s/dt in Eq. 5 by J_{opt} with dU_a/dt as described in Sec. 2.4) shows (if I'm not wrong) that J_{opt} is not equal J_{in}. Thus, while J_{opt} results from utilizing the second law it seems not to be consistent with energy conservation (the first law) within the same model framework (Eqs 1,5). If the conclusion (and the approach taken) that the turbulent fluxes optimize the heat engine constrained by energy conservation holds, this surprises me. What is the explanation (perhaps it is trivial)?*

Reply: Thank you for pointing out this discrepancy. It actually points out an error in Eq. 1 when dealing with the atmospheric energy budget. It has to do with the term

$R_{l,net}$, i.e., the net radiative cooling of the surface. In the optimisation, the outcome of $J_{in} = J_{opt}$ results in $R_{l,net} = R_{s,avg}/2$. This net emission of radiation at the surface may be absorbed within the radiative-convective layer, or it may pass this layer to higher levels, depending on the optical thickness/absorptivity of the layer. If it is re-absorbed, then it adds a radiative heating term to Eq. 1, and it adds a radiative heating term to the entropy budget (Eq. 2). However, as this radiation is absorbed at the prevailing physical temperature in the atmosphere, rather than the potential temperature associated with adiabatic motion, it is likely to be absorbed closer to T_a than to T_s. So it adds a term $R_{l,net}/T_a$ to the entropy budget. When combining the entropy budget with Eq. 1 to replace J_{out}, the terms involving $R_{l,net}$ drop out, resulting in no change in Eq. 3 and 4. If it passes the layer without being re-absorbed, then it does not affect Eqns. 1 - 4.

We therefore suggest to change the formulation in section 2.1 slightly in the revision and refer to dU_e/dt instead of dU_a/dt in Eq. 1, i.e., the heat storage change inside the engine, rather than the lower atmosphere. The reason for this renaming is that section 2.1 deals with the derivation of the limit in the presence of heat storage changes, and it is only afterwards that radiation and other aspects are introduced. Also, the term $R_{l,net} = R_{s,avg}/2$ in the case of maximum power is actually quite small. We would add this discussion to an Appendix.

Reviewer comment 5: *The difference between J_{opt} and J_{in} (as explained above) is given by $R_{l,net} - R_{l,out}/2$ (again, I hope that I'm not wrong). In Fig 3, although it is hard to judge, this difference seems to be relatively large, and larger than the difference between J_{opt} and J_{obs}. If so, this surprises me too. Perhaps, the authors may like to compute this J_{in} (consistent with energy conservation constraint), compare it with J_{opt} (J_{obs}), and discuss the result in the context of the optimization concept.*

Reply: Actually, as explained in the previous comment, $R_{l,net} = R_{s,avg}/2$ in the optimised case, so that the expression $R_{l,net} - R_{l,out}/2$ is actually zero, so that there is actually no discrepancy between J_{opt} and J_{in}. So we do not think that we need to explain something here (except, perhaps, that we do not reproduce the slight diurnal variation in $R_{l,net}$ with our approach).

Reviewer comment 6: *I do not understand Fig 2a: A more comprehensive explanation may be given in the text: e.g. what defines the particular shape of the atmospheric heat storage change (pink area).*

Reply: We apologise for not explaining this in more detail. What is shown by the pink area is the typical change of the temperature profile in the lower atmosphere. It warms during the day with an adiabatic lapse rate (i.e., the linear decrease with height shown by the dashed line), while at night, the lower atmosphere cools, and often it cools more near the ground, resulting in a night-time inversion (shown by the other dashed temperature profile).

In the revision, we will provide this explanation in the text in comprehensive form.

Reviewer comment 7: $R_s- > R_{s,ave}$.

Reply: Thanks, we will adjust this in the revision.

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