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Earth System Dynamics Discussions

# *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

**Anonymous Referee #1**

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General comments

This paper investigates diurnal variations of turbulent heat fluxes and energy partitioning at the surface of the earth. The turbulent motion is assumed to produce a maximum rate of mechanical work by convective heat transport from the surface to the atmosphere through a Carnot-like cycle, and the surface temperature is assumed to be determined by the energy balance conditions in the radiation field. A key process assumed in this study is that part of the turbulent heat flux is stored in the heat engine, and this storage does not affect the atmospheric temperature (Ta) and the radiation thereof (k Ta). Under such assumptions, the turbulent heat flux at the surface can



be estimated to be a function of solar radiation (Rs), its daily mean (Rs,avg) and the ground heat flux (dUs/dt), and the estimated heat flux shows remarkable agreement with observations (Figure 3). This reviewer finds many parts of this paper interesting and provocative, and recommends an immediate publication of this paper. However, I have a few comments and suggestions that will be helpful to improve the quality and interpretation of the results before the publication of this paper.

Specific comments:

1. A "cold" heat engine?

The authors refer to the atmospheric engine with heat storage as a "cold" heat engine because of its lower efficiency compared to a usual heat engine without such storage (page 5, line 25). I have a different opinion on this point because the actual power of this engine is not very low for the following reason.

It is true that an increase in heat storage in the engine (dUa/dt > 0) results in lower power generation because the heat stored in the engine (Te $\approx$ Ts) is not transferred to the atmosphere with lower temperature (Ta), and thus cannot produce work according to the second law. This heat storage increase therefore results in a reduction in the power generation rate in Eq. (4). However, for the same reason of this heat storage, the reduction in the surface temperature against Jin is reduced when there is such heat storage increase (dUa/dt > 0). Thus, the optimum-state surface heat flux (Jopt) becomes larger when dUa/dt > 0, as is shown in Eq. (7). When we combine these two effects (negative and positive effects in the heat flux) together, and substitute Jopt (7) into (4), we get the optimum-state power generation rate, with the total energy balance condition (6), as

Gopt = Rs,avg/2 (Ts - Ta)/Ta. — (a)

This means that the large variation in Rs is cancelled out by the buffering effect of the heat storage, and Gopt is nearly constant over time, which is indeed identical to the steady-state generation rate found by Kleidon and Renner (2013). So the heat storage seems to act to regulate the rapid change in Rs (the driving force) to realize a nearly constant rate of power generation by storing heat in daytime and discharging heat in nighttime. I would therefore suspect a "buffering" effect of the heat engine with the heat storage rather than a "cold" heat engine. It may also be interesting to see if Gopt of the atmospheric system really shows such regulation by using the observed data (Rs, dUs/dt and Ts).

2. Figure 3 and its interpretation.

One of the most striking results of this paper is that the predicted Jopt shows remarkable agreement with the observed Jobs (Fig. 3). Also, one can see that Jopt (and Jobs) is generally smaller than Rs by a nearly constant value of about 50-100 W/m^2. This result can be explained directly from Eqs. (6) and (7) as

Jopt = Rs - Rs,avg/2 - dUs/dt $\approx$ Rs - Rs,avg/2. — (b)

The last approximation (dUs/dt $\approx$ 0) is written in the text as a limiting case (page 6, line 26). Eq. (b) clearly shows that the optimum-state turbulent heat flux should be Rs minus a constant value (Rs,avg/2 $\approx$ 80-100 W/m^2) for the most of the observation sites (Fig. 3A-D, F) where dUs/dt is nearly negligible. I think Eq. (b) captures valuable information on the turbulent heat flux at the optimum (maximum power) state, and may be explained in the results or discussions of this paper. The readers of this paper will then be able to use it as a diagnostic tool for future investigations on turbulent heat fluxes obtained from observations and GCM simulations.

I am somewhat skeptical about the region where Rs $\leq$ Rs,avg/2 and Jopt becomes negative (Fig. 3). This region implies a situation of "inverse" heat flux from the atmosphere to the surface, and convective motion as well as convective heat flux cannot occur in this situation. The validity of the assumptions used in this study becomes questionable (even G and D become negative) under such situation. I think this can be a cause of the failure in predicting Jobs in this situation, in addition to the effect of the



prevalent stable nighttime stratification in the boundary layer (page 8, line 6).

Technical corrections:

1. Page 1, line 21: "in by biases".

Just typo.

2. Figure 2

I cannot see what is the meaning of the rectangular boxes (blue) in Fig. 2B. Perhaps a range of standard deviation? It may be good to explain this in the caption. Also, the "minus" sign in "Rs - Rs,avg" should not be in the lowercase.

3. Figure 3

This figure should be made larger so that one can see the details of the results. Also, some of the arrows of Jobs and Jopt are not properly located for the corresponding lines and circles. It seems good to adjust them.

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