Review of "Working at the limit: A review of thermodynamics and optimality of the Earth system" by Kleidon

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This manuscript proposes that both the horizontal and the vertical energy transport in the atmosphere, the evaporation and the biological productivity in the Earth system are determined by a simple optimality priciple. This principle is that the turbulent energy transport between two regions with different temperatures is obtained by maximizing the associated generation of free energy.

I find this hypothesis implausible, and the support for it given in the manuscript is weak. I therefore recommend rejection.

Detailed comments:

1. Let's consider a simple system with two boxes, similar to the one used in the manuscript. The temperature difference between the boxes is ΔT, and the energy transport from the warm box to the cold box is J. The equilibrium temperature in each box is determined by a combination of external energy fluxes and the transport J, so that a larger transport cools the warm box and warms the cold one. Assuming a simple linear relation (as also done in the manuscript), this is described by the equation
$$\Delta T = \Delta T_0 - c_1 J. \tag{1}$$
Here ΔT_0 is the temperature difference that would result from the external fluxes in the absence of transport between the boxes. We also define J_0 as the transport that would be required to equalize the temperatures, so that $\Delta T = 0$:
$$J_0 = \frac{1}{c_1} \Delta T_0.$$
We can regard the two states $(\Delta T, J) = (\Delta T_0, 0)$ and $(\Delta T, J) = (0, J_0)$ as extremes. A realistic state should be intermediate between them,

but to determine it we need to know how J depends on ΔT. Assuming that the transport is driven by the temperature difference, the simplest possible relation is

$$J = c_2 \Delta T. \tag{2}$$

The equilibrium state of the system is then

$$\Delta T = \frac{1}{1 + c_1 c_2} \Delta T_0, \tag{3}$$

$$J = \frac{c_1 c_2}{1 + c_1 c_2} J_0. \tag{4}$$

Thus, if $c_1 c_2 \ll 1$ it is close to one extreme, and if $c_1 c_2 \gg 1$ it is close to the other one.

Equation (1) is used in the manuscript to determine the temperature response to both the horizontal and the vertical atmospheric transport. The external fluxes are then the vertical radiative fluxes, and the coefficient c_1 (which corresponds to $2/b$ in eq. (11)) describes the Planck feedback, i.e. how much the temperature needs to change for the long-wave radiation to space to change by a prescribed amount.

In the manuscript, eq. (2) is not used directly to determine the transport. Instead, J is chosen so that the generation G of free energy is maximized, subject to the constraint of the Carnot efficiency. Using eq. (3) in the manuscript, we have

$$G = \frac{\Delta T}{T_{\mathrm{w}}} J,$$

where T_{w} is the temperature of the warm box. We then substitute J from eq. (1) and maximize G, neglecting possible variations of T_{w}, as also done in the manuscript. This determines ΔT, and by using eq. (1) also J:

$$\Delta T_{\mathrm{max}} = \frac{1}{2} \Delta T_0,$$

$$J_{\mathrm{max}} = \frac{1}{2} J_0.$$

Thus, the solution is exactly half way between the two extremes mentioned above.

Clearly, the optimization principle is equivalent to the choice $c_2 = 1/c_1$ in eq. (2). However, no motivation is given in the manuscript for why this particular choice should be universally valid. In fact, the external fluxes and the transport between the boxes are usually independent physical processes. This certainly true in the cases considered in the manuscript, with the external fluxes given by Planck's law and the transport by the turbulent dynamics in the atmosphere, and it is easy to imagine changes that would affect one but not the other. For example, a faster planetary rotation should decrease the horizontal transport in the atmosphere without affecting the radiative fluxes, thus decreasing c_2 while leaving c_1 unchanged.

In the absence of physical motivation, the only support for the choice $c_2 = 1/c_1$ comes from the agreement with observations. However, in the case of horizontal transport in the atmosphere, the agreement is not very convincing. According to Fig. 8, J is approximately $(2/3)J_0$, rather than $(1/2)J_0$. This very approximate agreement in only one data point could well be a coincidence, and if there is a fundamental reason for it, this is not given in the manuscript.

In the case of vertical energy transport in the atmosphere, no direct observations of this are given. Instead the energy transport is translated into evaporation by using the psychrometric constant, and the evaporation compared to observations. However, the theoretical prediction is first combined with a precipitation dataset to account for water limitation, and it is most likely the precipitation data that are mainly responsible for the seemingly good agreement in Fig 3b.

2. In the section about photosynthesis, the rate of CO_2 assimilation (usually called GPP, 'gross primary production') is obtained by multiplying the estimated evaporation by a typical value of the water use efficiency (WUE). Thus, no optimality assumption for the photosynthesis itself is involved. Instead, the result is a 'by-product' of the rate of evaporation obtained by using the optimality assumption for the vertical transport in the atmosphere.

   The agreement with data is not surprising, given that WUE is known to vary only moderately, and that the evaporation estimate is constrained by precipitation, but is hard to see what this proves. There is hardly a direct causal relation, since excessive evaporation is typically detrimental to the plants, while a surplus of water is simply transported away as run-off. From the text the idea seems to be that the downward transport of CO_2 is governed by the same dynamics as the upward transport of water vapor, and that GPP is therefore another 'by-product' of the optimality assumption for the vertical transport in the atmosphere.

However, the main resistance to CO_2-transport is not in the lower atmosphere, but in the stomata of the plants, and it is caused by the need to save water. Thus, CO_2 limitation and water limitation are two sides of the same coin, and increasing turbulent transport in the atmosphere is unlikely to increase GPP. The most natural explanation for the agreement seen in Figure 12 is that both the theoretical estimate and the real GPP are limited by the precipitation. This adds nothing to the common knowledge in the field.