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

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Some changes have been made in response to my comments, but none of them address my main objections. I therefore still recommend rejection.

Much of the text consists in lengthy qualitative descriptions of how entropy is produced as a result of various energy transformations. These descriptions are correct, but unsurprising, since everything said follows immediately from basic thermodynamic principles. They also do not lead to any quantitative predictions.

The scientific core of the paper is a consideration of a simple model with two boxes. All radiative energy fluxes are assumed to be either given externally or determined by the temperature of the boxes. There is also a turbulent energy flux J between the boxes. A consideration of the energy budget then leads to an equation of the form

$$\Delta T = f(J), \tag{1}$$

where ΔT is the temperature difference between the boxes, and f is a decreasing function. This relation shows how an increased turbulent flux leads to a smaller temperature difference.

To close the problem we need one more equation that specifies how the turbulent transport depends on the temperature difference:

$$J = g(\Delta T), \tag{2}$$

where g is an increasing function. Solving the two coupled equations (1) and (2) gives the actual values of J and ΔT.

The function f describes the radiative fluxes and the energy budget, while g describes the turbulent flux. Thus, the two functions describe independent physical processes. But, of course, the turbulent flux affects the temperatures, and thereby indirectly the radiative fluxes, as a part of determining the state of the whole system.

Some information can be obtained from eq. (1) without using eq. (2). The temperature difference is maximal when there is no turbulent transport, i.e. $J = 0$ corresponds to $\Delta T = \Delta T_{max}$. Furthermore, the turbulent transport cannot be larger than what is required to equalize the temperatures, so $J = J_{max}$ corresponds to $\Delta T = 0$. Thus, ΔT must lie between 0 and ΔT_{max}, and J must lie between 0 and J_{max}.

Turbulent transport is in general a complex process that is difficult to describe. The author claims that this is not needed, and that J can instead be determined by maximizing the free energy production, subject to the Carnot constraint (the 'optimum principle'). If the ΔT is much smaller than the absolute temperature, this means that the product $J\Delta T = Jf(J)$ should be maximized. Further assuming that f is linear, this gives the solution

$$J = \frac{J_{max}}{2},$$

$$\Delta T = \frac{\Delta T_{max}}{2}.$$

The only support for the optimum principle is that it gives good agreement with observations. In the case of meridional heat transport in the atmosphere we have, according to the manuscript, $\Delta T_{max} \approx 60$ K, which gives the prediction $\Delta T \approx 30$ K. This should be compared to the observed value 20 K. I don't find this agreement very impressive, given that we know a priori that ΔT lies between 0 K and 60 K. Moreover, it is clear that many factors, for example the planetary rotation rate, affect the turbulent transport, and therefore the function g, without affecting the function f. Thus, changing the rotation rate will change the state of the system, while the proposed optimum solution remains the same.

The idea that you can determine the state of the system without knowing anything about the mechanisms of turbulent transport is scientifically unsound. This can clearly be seen in the case of vertical energy transport. Here, ΔT_{max} is the temperature difference given by a pure radiation balance. Defining $\Delta T = T_r - T_s$ and using the same notation and approximations as in the manuscript we have

$$\Delta T_{max} = \frac{1}{k_r}(R_s + R_{l,down} - R_{l,0}).$$

The prediction of the optimum principle is again

$$\Delta T = \frac{\Delta T_{max}}{2}$$

which is eq. (9) in the manuscript.

This result is different from the established theory, which says that the vertical temperature gradient is close to the adiabatic lapse rate. The mechanism is that the turbulent transport is negligible if the atmosphere is stably stratified, and increases very rapidly if the temperature decreases upward faster than the threshold for convective instability. Translating this to the box model used in the manuscript, this means that the function $g(\Delta T)$ in eq. (2) is essentially zero for $\Delta T < \Delta T_{conv}$ (where ΔT_{conv} is the threshold for convective instability), and increases very rapidly for $\Delta T > \Delta T_{conv}$. The solution of the problem is then essentially that ΔT equals the smallest of ΔT_{max} and ΔT_{conv}. Thus, if $\Delta T_{max} > \Delta T_{conv}$ (as in the real troposphere) the state is entirely determined by the mechanism of turbulent transport, which is ignored by the optimum principle.

The simple theory outlined above is a corner stone of climate science since many decades, and it is based on an clear physical mechanism. If you want to replace it by another theory, which lacks physical motivation, it is not enough to show that its prediction of ΔT agrees roughly with observations. You must explicitly compare it with the established theory, and show that it gives a better prediction.

The discussion of photosynthesis seems to imply that the evaporation somehow drives the photosynthesis. That is a strange idea, since increased evaporation is in general detrimental for plant growth. The text is not very clear on this, but in the reply to my previous comments the author rejects my comment that the main resistance to CO_2 transport is in the stomata, and is caused by the need to save water. He also states that "stomata play very little role in controlling evaporation rates".

Restricting water loss while at the same time allowing CO_2 to enter the leaves is the reason for the existence of the stomata. This can be seen in any text book, for example 'Plant Physiology', 3rd ed, Lincoln Taiz and Eduardo Zeiger, p. 59 (open source). A quick web search reveals similar statements in the abstract or opening paragraph of a large number of scientific articles. Here are two examples: "Almost all water used for plant growth is lost to the atmosphere by transpiration through stomatal pores on the leaf epidermis. By altering stomatal pore apertures, plants are able to optimize their CO_2 uptake for photosynthesis while minimizing water loss." (L.T. Bertolini et al, Front. Plant Sci., 2019, vol. 10, https://doi.org/10.3389/fpls.2019.00225). "In order for plants to function efficiently, they must balance gaseous exchange between inside and outside the leaf to maximize CO2 uptake for photosynthetic carbon assimilation (A) and to minimize water loss through transpiration. Stomata are the 'gatekeepers' responsible for all gaseous diffusion, and they adjust to both internal and external environmental stimuli governing CO_2 uptake and water loss. " (T. Lawson and M.R.Blatt, Plant Physiol., 2014, vol.164, pp 1556–1570.)

This means that the plants need to restrict the flux of CO_2 when access to water is limited. The facts that the water use efficiency is fairly constant across ecosystems, and that the energy efficiency of photosynthesis is far below the theoretical limit, imply that this regime of simultaneous water and CO_2 limitation is normal. The plants handle this by regulating the size of the stomata openings.