Maximum Entropy Production and Resistance to Heat Transfer in the Earth-Atmosphere System

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Abstract

To seek the thermodynamic basis for the well-known Maximum Entropy Production (MEP) principle has recently received considerable attention in the scientific community. However, a little success has been achieved in the reconciliation between the MEP and the currently existing physical laws. In fact, the MEP is not a fundamental physical principle, because it is not consistent with the minimization of energy expenditure rate (MEE) principle that has been supported by observations for water flow on the ground surface. A fundamental physical principle should be able to explain observations from different areas. To resolve the inconsistence, Liu (2014), based on observations from different geological systems, proposed a new thermodynamic hypothesis that states that *a nonlinear natural system that is not isolated and involves positive feedbacks tends to minimize its resistance to the flow process through it that is imposed by its environment.* He also shows that the MEP is actually a by-product of the minimization of heat transfer resistance in the Earth-atmosphere system under a relatively restrictive condition. This communication further derives that previous result *in the more general case* for the Earth-atmosphere system. The consistence between the thermodynamic hypothesis of Liu (2014) and Darwin's evolution theory is also briefly touched on. All these support the validity of the hypothesis of Liu (2014).

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Introduction

Optimality principles refer to that state of a physical system is controlled by an optimal condition that is subject to physical and/or resource constraints. One of the most well-known optimality principles is the Maximum Entropy Production (MEP). The MEP principle, initially proposed by Paitridge (1975), has been shown to be useful for predicting behavior of the Earth-atmosphere system. The MEP principle states that a flow system subject to various flows or gradients will tend towards a steady-state position of the maximum thermodynamic entropy production (Nieven, 2010).

The thermodynamic basis for the MEP has been a subject of active research in the literature (Paltridge, 2009; Dewar, 2003, 2005; Martyushev et al., 2006). The reconciliation between the MEP and the currently existing physical laws has not been successful (Paltridge, 2009). As a matter of fact, the MEP is not really a fundamental physical principle, because it is not consistent with the minimization of energy expenditure rate (MEE) principle that has been supported by observations for water flow on the ground surface (e.g., Rodriguez-Iturbe et al., 1992), as indicated by Liu (2014). A fundamental physical principle should be able to explain observations from different areas. This inconsistence calls for the development of a more precise understanding of fundamental physical laws within the context of thermodynamics.

To resolve the inconsistence, Liu (2014), based on observations from different geological systems, proposed a new thermodynamic hypothesis: "*a nonlinear natural system that is not isolated and involves positive feedbacks tends to minimize its resistance to the flow process through it that is imposed by its environment."* The hypothesis specifies the conditions under which the optimality occurs for flow processes in geosystems. Especially, for a system involving multiple flow processes, only the driving process (that is imposed by its environment) is subject to resistance minimization. Liu (2014) also shows that the MEP is actually a by-product of the minimization of heat transfer resistance in the Earth-atmosphere system in which heat transport is the driving flow process. His development was under the condition that convective heat transport rate is a power function of temperature difference between the low- and high-temperature regions on the Earth surface (Clausse et al. 2012).

The objective of this communication is to further demonstrate that the MEP is a direct result of the minimization of heat transport resistance, or the maximization of heat conductivity *in the general case* for the Earth-atmosphere system. The consistence between the thermodynamic hypothesis of Liu (2014) and Darwin's evolution theory is also briefly touched on. All these support the validity of the hypothesis of Liu (2014).

MEP and the heat transport conductivity in the Earth-atmosphere system

Under steady-state flow conditions, the entropy production in the Earth-atmosphere system is given by (Paltridge, 1978; Ozawa et al., 2003):

$$S' = \int_A \frac{dQ}{T} = Q\left(\frac{1}{T_L} - \frac{1}{T_H}\right) = Q\frac{\Delta T}{T_{av}{}^2[1-\left(\frac{\Delta T}{T_{av}}\right)^2]} \qquad (1)$$

where S' is the entropy production rate, A is the boundary (Earth surface), Q is heat flow through the boundary, T_L and T_H are average Earth surface temperatures in the low and high temperature regions, respectively, T_{av} is the average temperature in both high and low temperature regions, and $\Delta T = T_H - T_L$. (Heat flows from the high-temperature region to the low temperature region.) The above equation represents the fact that the entropy production by some processes associated with turbulence is completely discharged into the surrounding system through the boundary under steady-state conditions (Ozawa et al., 2003).

Since $(\Delta T / T_{av})^2$ is generally on the order of 1-2% and T_{av} can be reasonably determined based on global solar heat current and Earth surface radiation into space only (Clausse et al., 2012), Eq. (1) can be rewritten as

$$S' \approx Q\frac{\Delta T}{T_{av}{}^2} \qquad (2)$$

where T_{av} is considered a well constrained parameter that does not depend on Q and ΔT.

There are two heat transfer mechanisms between the low- and high-temperature regions on the Earth surface, conduction and convection. The former is relatively small compared with the convection and therefore is ignored here for the simplicity (e.g., Clausse et al. 2012). (Inclusion of the conduction will not alter the final conclusion.) Under the steady-state fluid flow condition, fluid with temperature T_H from the high-temperature region flows to the low-temperature region. At the same time, the same amount of fluid with temperature T_L flows from the low-temperature region to the high-temperature region. As a result, the net heat flow rate between the two regions is given by

$$Q \propto Q_{fluid}\Delta T \qquad (3)$$

where Q_{fluid} is the fluid flow rate between the two regions.

By definition, the heat conductivity between the two regions, K_H, can be obtained from Eq. (3):

$$K_H \propto \frac{Q}{\Delta T} \propto Q_{fluid} \qquad (4)$$

Note that fluid flow between the low- and high- temperature regions is induced by the temperature difference $\Delta T = T_H - T_L$, or

$$Q_{fluid} = f(\Delta T) \qquad (5)$$

The temperature difference results in fluid density differences, and consequently fluid pressure differences (through gravity) between the two regions. The latter gives rise to the fluid flow. At this point, we do not need to know details of function *f*, such as a power function (Clausse et al. 2012). It is adequate to know that Q_{fluid} is a monotone increasing function of the temperature difference. It is easy to understand physically that a larger temperature difference corresponds to a larger fluid flow rate. In fact, it is how the positive feedback comes to play in the system.

Eqs. (2) to (5) yields the entropy production as

$$S' \propto Q\Delta T \propto Q_{fluid}\Delta T^2 = f(\Delta T)\Delta T^2 = F(\Delta T) \qquad (6)$$

Clearly, function *F* is a monotone increasing function of the temperature difference because *f* is a monotone increasing function. From Eq. (6), we have

$$\Delta T = F^{inv}(S') \qquad (7)$$

where superscript *inv* refers to inverse function. The function F^{inv} is the inverse function of *F*. Again, F^{inv} should also be a monotone increasing function when *F* is a monotone increasing function.

A combination of Eqs. (4), (5) and (7) results in

$$Q_{fluid} = f(F^{inv}(S')) = G(S') \qquad (8)$$

and

$$K_H \propto G(S') \qquad (9)$$

where function *G* is obviously a monotone increasing function, because both *f* and F^{inv} are monotone increasing functions. By the nature of a monotone increasing function, *S'* and K_H should reach their maximum values at the same time. This again proves that the MEP in the Earth-atmosphere system is not the fundamental physical principle, but a by-product of the maximizing K_H (or minimizing resistance to heat flow between the low- and high-temperature regions.)

Consistency of the hypothesis of Liu (2014) with Darwin's Evolution Theory

It is of interest to note that the hypothesis of Liu (2014) is consistent with Darwin's evolution theory, although the latter is for animate phenomena. For a given time, biological creatures always exhibit some physical and behavioral variations in different levels (e.g., individuals in a community, organisms, DNA and genes). These variations result from random mutations that are changes in the genetic sequence. Mutations are either harmful, neutral, or in some cases beneficial to the organism. The beneficial mutations will be inherited and harmful ones will be rejected by most individuals in the next generation. In this way, nature rewards those individuals better adapted to their environments with survival and reproductive success; this process is called natural selection.

Table 1 shows that similarity exists between some key elements of Darwin’s evolution theory and the proposed hypothesis. Natural perturbation in fluid and medium properties, although not explicitly mentioned in the hypothesis, is well known to exist for all the geological flow systems. This perturbation may be small in many cases, but serves as the seed to generate flow patterns with the minimum flow resistance. Thus, “natural perturbation” corresponds to “mutation” in Darwin’s theory.

Table 1 Similarity of some key elements of Darwin’s evolution theory and the hypothesis

Darwin’s evolution theory	**Proposed hypothesis**
Mutation	Natural perturbation
Inheriting beneficial mutations	Positive feedback
Natural selection	Minimum flow resistance

For a geological flow system, if the perturbation results in a slight change in the corresponding flow pattern that reduces the flow resistance. This slight change will be “remembered” such that it is enhanced in the next moment to further reduce the resistance, which is a result of positive feedback mechanism. This is how the fingering in unsaturated flow system or the flow channels in a river basin is formed. (Note that a negative feedback tends to reduce the perturbations.) Thus, the positive feedback mechanism is very similar to the procedure for the next generation to inherit beneficial mutations. Finally, the process to achieve the minimum flow resistance in a geological system is obviously comparable to the natural selection process to make the next generation to be better adapted to its environment.

Concluding remarks

To seek the thermodynamic basis for the well-known Maximum Entropy Production (MEP) principle has recently received considerable attention in the scientific community. However, a little success has been achieved in the reconciliation between the MEP and the currently existing physical laws. In fact, the MEP is not a fundamental physical principle, because it is not consistent with the minimization of energy expenditure rate (MEE) principle that has been supported by observations for water flow on the ground surface. A fundamental physical principle should be able to explain observations from different areas. To resolve the inconsistence, Liu (2014), based on observations from different geological systems, proposed a new thermodynamic hypothesis that states that *a nonlinear natural system that is not isolated and involves positive feedbacks tends to minimize its resistance to the flow process through it that is imposed by its environment.* He also shows that the MEP is actually a by-product of the minimization of heat transfer in the Earth-atmosphere system under a relatively restrictive condition. This communication further derives that previous result *in the more general case* for the Earth-atmosphere system. The consistence between the thermodynamic hypothesis of Liu

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