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Hydrology and Earth System Sciences Discussions

Interactive comment on "Biological catalysis of the hydrological cycle: life's thermodynamic function" *by* K. Michaelian

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Complete response to Prof. Schymanski:

General Comments

In a preliminary response to Prof. Schymanski and the anonymous referee (Michaelian, 2011a), I clarified that my paper neither invokes, nor requires, the "maximum entropy production principle". The paper simply associates Onsager's principle (1931) of the coupling of irreversible processes, and the associated increase in entropy production, with the evidence (e.g. Zotin, 1984) for an increase in the amount of coupling of irreversible biotic processes over the history of life on Earth. The hypothesis of my paper

is that biological irreversible processes also couple with abiotic irreversible processes, in particular, that biology catalyzes the hydrological cycle. This coupling augments the global entropy production of Earth in its solar environment, in accordance with Onsager's principle. I also suggested in my preliminary response that the particular history of Earth with regard to entropy production would depend very much on particular initial conditions (even microscopic), the kinetics (dependent on the particular forces) and subsequent external perturbations (even microscopic). This dependence arises because the Earth system under the solar photon flux is non-linear and out of equilibrium (Prigogine, 1972).

Prof. Schymanski asks; 1) "What is the mechanism that selects for biota that contribute more to planetary entropy production over such that contribute less but invest more e.g. into reproductive success?"

We find historical evidence for the evolution of biota to ever more complex and interconnected systems. Examples are; the cell, ecosystems, and human society. Darwinian theory suggest that this is a result of evolution through natural selection of the individual. There is difficulty, however, with the explication of selection on a higher level, e.g. species, clade, ecosystem, biosphere, ecosphere, and this is generally attributed to some kind of "emergent" behavior of a complex many-body system. However, as known in physics, any kind of "emergent behavior" requires the dissipation of an underlying gradient, a thermodynamic potential. An "individual will to survive" does not fit the bill. Furthermore, Darwinists have conceived a type of force field, "natural selection", which apparently only applies to biota and hence assigns special uniqueness to living systems. However, we are fairly confident that we know and understand all the fundamental laws and forces of Nature and that they apply equally well to abiotic material as to biotic material. Why then don't we see evolution through natural selection in the abiotic world? The answer to this question, in my view, is that "We do see it, but we don't call it that!"

Take, for example, the case of a homogeneous fluid layer under gravity, heated from below and cooled from above. Above a certain Rayleigh number (e.g. at a certain heat gradient, other conditions being specified) this system will exhibit two distinct but coupled irreversible processes; conduction and convection of heat. Conduction is due to microscopic movement of the atoms around their equilibrium positions. This process starts immediately on application of the heat gradient. The second process, convection, takes a little more time to appear because a microscopic fluctuation large enough is needed to create a local density fluctuation sufficient to start the convection cell rolling (the initial microscopic density fluctuation becomes enlarged to macroscopic proportions through the driving dynamics (potential dissipation) due to the non-linearity in the system (Prigogine, 1972)). A thermodynamic analysis of this problem suggests that convection arises as an attempt to reduce the temperature gradient over the fluid layer. In thermodynamic terms, we say that convection sets in to augment the global entropy production of the system. A new species has appeared (the convection cell). The system is now more complex than the initial one since now there are two coupled irreversible processes operating. The transport of heat is increased and the system augments its entropy production in accordance with Onsager's principle. This is evolution through natural selection. It is not an analogy; rather it is the exact analog of what happens in the biological world. The convection problem is not analyzed on the basis of the "fitness" of the component irreversible processes, but rather on the basis of the global entropy production of the coupled irreversible processes (see for example Prigogine, 1967). It is this which gives thermodynamic legitimacy to the appearance of a new species (the convection cell) and an increase in complexity (in terms of coupled processes) of the system.

In direct answer to Prof. Schymanski's question: Those individuals, species, clades, ecosystems, etc. that have higher probability of arising and being selected (persisting) are those that most augment the entropy production of Earth in its solar environment, given the boundary conditions of Earth (the solar photon flux), the allowed kinetics (energy, momentum, angular momentum, etc. barriers) and given all pre-existing biotic and abiotic irreversible processes presently operating in the ecosphere (taken to be

inclusive of the abiotic environment). This principle acts on all scales. However, since almost all irreversible processes on Earth are in some way coupled, it is difficult, if not impossible, to separate the system into parts. Therefore, in principle, there is a possibility of using this principle to predict which species, ecosystems, clades, biospheres, or ecospheres, have higher probability of appearance and survival, but in practice, at least at the lower levels, it is just as impossible to utilize as the principle of natural selection (of the "fittest"). However, the thermodynamic view has the advantage of avoiding the tautology by explaining biological evolution in terms of established physical thermodynamic law. It also accommodates selection on all levels, simply moving towards whatever possible couplings, or hierarchies of couplings, that leads to greater global entropy production of the Earth in its solar environment. The Darwinian view sees evolution as a bottom up process where the individual, with its "will to survive", takes precedent. The thermodynamic view sees evolution as a top down process in which the global entropy production of Earth in its solar environment, with its "tendency to augment", takes precedent. Such a thermodynamic view also provides new insights into the dynamics of the biosphere, ecosphere, etc., that otherwise may not have been recognized; for example, the hypothesis of my paper – that biology catalyzes the hydrological cycle – or to a new view of the problem of the origin of life in terms of its thermodynamic function (see Michaelian, 2011b). I have included two new paragraphs in the Introduction to the revised version of the manuscript which summarize the above and are aimed at addressing this question of Prof. Schymanski.

Prof. Schymanski asks; 2) "If maximisation of entropy production is the rule of the game and not maximisation of fitness as defined traditionally, why do plants not produce black carpets that simply absorb solar radiation and convert it directly to high entropy long-wave radiation?"

As noted in my preliminary response (Michaelian, 2011), "maximization" is not the correct word. Instead, there is a natural tendency of irreversible processes to couple, and when this happens it augments the global entropy production of Earth in its solar environment. Plants do produce black carpets. Boreal forests appear black under a mid-day sun. Plants are green no so much for a lack of absorption at these wavelengths, as for the fact that our eyes peak in sensitivity at green wavelengths. However, a non-living black carpet (organic or inorganic), even though initially absorbing well at all wavelengths is not as robust, efficient, nor pervasive, at producing entropy as are living biotic black carpets for the following reasons;

1) Non-living black materials eventually bleach (loose their absorbing characteristics) over time if left in the Sun. This is because UV wavelengths destroy (photolyse) the absorbing pigments. In living material, there are a number of mechanisms to prevent, repair, or replace, photo-damage to pigments.

2) Non-living materials do not have active roots to draw up water to help dissipate the high energy photons absorbed. Therefore, their temperatures, if left under the sun for some time, will rise, and their quasi- black-body emitted spectrum will be of shorter wavelength than that of living black materials such as, for example, living pine needles that use water and the water cycle to allow them to eventually dissipate the absorbed photon at a much lower temperature (that of the cloud tops).

3) Non-living black carpets don't have the same ability to grow and to spread into virgin areas as do living black carpets.

4) Inorganic black carpets would have trouble floating on the ocean surface due to generally higher densities of inorganic material compared with water.

The papers by Volk and Volk et al. address the maximum entropy production principle to which my paper is not concerned. I personally believe that the maximum entropy production principle will eventually be placed on a firm statistical mechanics foundation, as a probabilistic, rather than deterministic, principle but only if all the irreversible processes in the system are included.

Whenever I mention "entropy production" in the manuscript it is always in reference to

that of the Earth in its solar environment. For this system the definition of entropy production is not "nebulous" but is that given approximately by my equation (3) (old version, Eqs. (13) and (14) new version). All we need to calculate it is the spectrum of photons incident on, and the spectrum of photons reflected and emitted by, the Earth. The hydrological cycle helps to lower the temperature at which the approximately black-body spectrum is emitted by the Earth (for example, at -14°C at the cloud tops instead of about 14°C at the Earth's surface), implying an emitted spectrum of longer wavelength and thus greater global entropy production.

Table 3 (new version) shows that the amount of energy absorbed and dissipated in the ocean surface layer (1 mm thickness) under cloudy skies is only about 5% of that under clear skies. This is principally due to the absorption of infrared light from the Sun at the cloud tops. The amount of evaporation from this layer can be expected to be related to the amount of energy deposited. It is related to, among other factors, the temperature difference maintained between the ocean surface layer and the atmosphere (due to the dependence of saturation vapor pressure on temperature). The greenhouse effect has to do with the trapping of energy of much longer wavelength at the surface layer of Earth. Since the ocean surface and atmosphere at the surface will rapidly come to a new quasi-equilibrium temperature with more greenhouse gases in the atmosphere, and since evaporation rate is dependent upon temperature difference (between the sea surface and atmosphere) and not on absolute temperature, a greenhouse effect will not necessarily lead to an increase in the evaporation rate. The data to date on whether evaporation is increasing due to global warming is not definitive. See also my answer to the specific comments 9 and 16 raised by Prof. Schymanski below.

Specific Comments

1. As noted above, there are characteristics that make living black organic carpets more efficient and robust at entropy production than non-living black carpets. See my answer to this given above.

2. Evapotranspiration increases entropy production with respect to abiotic dissipation in the absence of water, simply because abiotic surfaces heat up considerably under the Sun while biotic systems do not due to the latent heat of evaporation of water. When the water vapor condenses at the cloud tops, it does so at a significantly lower temperature than at which it absorbed the solar energy, and thus releases the same energy but with greater entropy.

3. Both winds and agitation of the surface water by zoo-plankton increase the evaporation from the surface. Since I have been unable to relocate the reference to zooplankton, I have left this sentence out of the revised manuscript. I believe that it comes from the book "Traces of Bygone Biospheres" by A.V. Lapo.

4. The free energy in the photons from the Sun that ends up in biomaterial (i.e. the product of photosynthesis, the breaking and making of chemical bonds) is a very small fraction of the total free energy available in sunlight. Gates (1980) estimates it at about 0.1%. Most of the free energy available in sunlight captured by biota goes into the evaporation of water. The only quantitative analysis of optimization that I am aware of suggests that the transpiration rate is maximized in plants, not the photosynthetic rate (despite many unsubstantiated remarks to the contrary in the literature). The two do not appear to be directly coupled as Prof. Schymanski suggests (see Wang et al., 2007).

5. See my response to Prof. Schymanski's second question above in General Comments.

6. Ok.

7. Suspended minerals generally have their atoms bound by ionic or metallic bonds, not by the strong covalent bonds of organic materials. There are thus no strong collective electronic excitations (e.g. sigma and pi) in the visible and UV wavelengths. They instead are individual electronic excitations that decay radiatively. Collective covalent excitations can decay radiationlessly through normal mode coupling (vibrations)

to surrounding water molecules. Inorganic substances are thus generally less effective photon dissipaters. For example, 1) there are few sunscreens based on inorganic materials, 2) the surface of the Moon is very hot under the midday sun. Suspended minerals also have the tendency to settle rapidly to the bottom of the water body while organic materials float on the surface due to generally lower densities than water.

8. If the biosphere is not heating up, and not growing in size (energy being stored in organic chemical bonds) then the total energy entering the biosphere must be equal to that leaving it, however the biosphere is defined. Of course, this is only a very good approximation. I have opted for using the word "ecosphere" in the new version of the text when I refer to biotic plus abiotic, and reserve the term "biosphere" to refer to only the biotic.

9. Clouds absorb more strongly longwave radiation (infrared) than shortwave radiation. This long-wave radiation therefore does not get absorbed on the ocean surface, and thus the organic material, which absorbs in the visible and UV, has a much greater effect on surface heating under clouds (although, of course, the total energy absorbed is significantly reduced under clouds). Prof. Schymanski's question concerning the effect of clouds on evaporation rate is very interesting but very difficult to answer. Local clouds certainly reduce local evaporation by cooling the surface (this has been confirmed in numerous studies) but the effect on global evaporation has not, to my knowledge, been studied. Here I give a few indications suggesting that a partially clouded Earth may, counter-intuitively, be beneficial for global evaporation;

a) Clouds produce wind currents that help to mix atmospheric layers and thus reduce relative humidity directly over the wet surface.

b) The condensation of water vapor into clouds reduces the absolute amount of water vapor in the atmosphere, meaning reduced humidity at the surface.

c) Clouds bring water to inland regions which allows plants to grow and thus increment land evapotranspiration and thus the size of the water cycle over land.

However, the important question within the context of the hypothesis presented in my manuscript is not the evaporation rate, but rather the global entropy production rate under a partly cloudy sky as compared to a clear sky. This is a much more complex issue because we have to take into account all irreversible processes operating in the biosphere. For example, even Lambertian reflection of light produces entropy. Most importantly, however, the potential for entropy production is biased towards dissipation in the visible and UV regions so strong absorption by clouds in the infrared will have a reduced effect on entropy production. Finally, as the referee noted, clouds are a necessary part of the hydrological cycle and without them there would be no plants growing on land, and therefore less global photon dissipation. These are very complex issues and this manuscript only begins to address them. I have re-written the paragraph containing the reference to clouds to reflect these complexities.

10. See my response to point 2.

11. The ideal gas assumption for photons is not only relevant for black-body radiation. An ideal gas assumption for photons simply means that they do not interact with one another. This is relevant when photon densities are low or when the photon beam is expanding, as, for example, the radiation emanating from the Sun's surface. However, I have completely re-written this section, using instead an expression due to Planck for the entropy flow. This is in response to Profs. Gorshkov's and Makarieva's comments, as well as to that of an anonymous referee who pointed out the reference to the formula by Planck. Prof. Schymanski is correct in surmising that what I call "efficient dissipation" is simply greater entropy production; greater absorption of photons from the sun and a greater shift towards longer wavelengths of the light leaving our planet. I have more carefully defined this in section 2 of the revised manuscript.

12. The question raised by Prof. Schymanski here has been answered in the response to his second question under General Comments. I would say that, due to organic life, the surface of Earth has indeed organized spontaneously into a highly dissipating structure (note the emphasis on dissipation, not absorption).

13. I meant to emphasize the fact that in the upper 10 microns of the sea surface zooplankton are found in densities of up to 10 times that of greater depth. The text has been reworded to emphasize this as a high density region, not to exclude larger zooplankton, or zooplankton at other depths.

14. Ok, this is now noted in the revised version.

15. A partial answer has been given in point 7 above. Attenuation due to particulate scattering (inorganic material absorbs little in the UV and visible) is at least an order of magnitude less than that due to absorption on dissolved organic material and chlorophyll in turbid costal waters (Liew, 2002). Therefore, I maintain that it is valid to use the absorption coefficients for costal turbid waters as a surrogate for the ocean surface skin layer. This reference has been included to support the revised text.

16. Tables 1 and 2 (now tables 2 and 3) show that, on a cloudy day, only 5% of the energy is absorbed in the ocean skin surface layer (1 mm thickness) compared to that absorbed on a clear day. Clouds have high albedo over all wavelengths and absorb strongly infrared light. Therefore, clouds certainly do have the effect of reducing the down-welling longwave radiation from the Sun (here "longwave" is taken to mean from 700 -10000 nm). The down-welling radiation in this wavelength region is always lower on a cloudy day than on a clear day. Earth's emitted radiation averages at wavelengths of around 14,300 nm. This upwelling radiation is, as the Prof. Schymanski states, absorbed and approximately one half re-emitted downwards by the clouds. This tends to keep the surface warm at night, for example. The greenhouse effect is related to the trapping of energy (> 14,300 nm) at the surface and this radiation is therefore both upwelling and downwelling with a net upwelling component overall. It keeps the surface somewhat warmer but also the atmosphere warmer and so does not necessarily increase evaporation rates (see my last paragraph under General Comments). We loose about 80% of the down-welling incident radiation due to cloud albedo and absorption (Gates, 1980). A very high humidity clear atmosphere would absorb all infrared and cause approximately 50% of the infrared radiation from the Sun (700-10000 nm) to be

eventually emitted back into space by the atmosphere, and therefore not available for surface absorption. I have sent Prof. Schymanski a scan of the relevant Gates figure.

17. Prof. Schymanski is correct. There is no evidence to support the statement that gymnosperms came later than angiosperms in the evolutionary history of Earth. Gymnosperms and angiosperms are now thought to have evolved separately from petridosperms (Soltis). However, it is true that gymnosperms tend to displace angiosperms in late successional stages. I have corrected the text. Prof. Schymanski correlates CO_2 uptake directly with water loss, presumably through the opening of the stoma. However, as mentioned earlier, under ideal conditions transpiration is maximized by a plant, not CO_2 uptake (Wang et al., 2007).

18. If the only function of the pigments was to protect the photosynthetic system from damage then I do think it would be quite a selective disadvantage (speaking in Darwinian terms) to produce so many different pigments that have no overlap with any of the absorption peaks of the photosynthetic system. The view presented in my manuscript, that life is an irreversible process coupled to other irreversible processes, both biotic and abiotic, requires a disassociation from the notion of "selection of the individual based on fitness", whatever "fitness" is supposed to mean (see my comments in response to point 9 above) . I am not suggesting that pigments provide "a selective advantage for increasing evaporation", but rather "an entropy production advantage for dissipating high energy photons". Evaporation is part of this process. The "complicated photosynthetic apparatus" is need for growth and spread of the organic molecules. Only the organic pigments and a water flow system are needed for dissipation. As pointed out above, "any black stone" cannot float on the ocean surface, cannot draw up water to reduce the temperature of the eventually emitted radiation, cannot spread into virgin areas, and will eventually bleach under UV radiation. This is not science fiction; but rather a new view of life and evolution requiring a paradigm change in our evolutionary thinking. I have received ample critical analysis and in response I have presented arguments and evidence in its favor. I can only hope that it receives a

just scientific consideration.

19. Photon absorption, by definition, implies further dissipation. This has been explained in more detail in the revised text.

20. I thank Prof. Schymanski for this final comment. It makes me believe that he remains open to the suggestion of an important thermodynamic role for plants and animals in connection with the hydrological cycle, and this is the main point of my article.

I have included all technical corrections suggested. I sincerely thank Prof. Schymanski once again for his very through and thoughtful review. His insightful remarks and criticisms have certainly helped to improve my manuscript.

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