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

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I thank Prof. Gorshkov for his remarks on my manuscript. Prof. Gorshkov presents an equation for the approximate entropy production of the Earth, his equation (1), and suggests that the only variable that life can affect in this equation is the albedo A, since "the effective planetary temperature is determined by the distance of Earth to Sun" (actually, the albedo must also be taken into account in determining the effective temperature, e.g. Earth versus Moon). However, the approximate equation of Prof. Gorshkov for the entropy production of Earth is not valid since it fails to take into account the frequency transformations between the incident and outgoing radiation. A more accurate equation (although also an approximation) for the entropy production of Earth was given in my article, Eq. (3). This equation, originally conceived by Boltz-

mann [1] and later articulated by Ulanowicz and Hannon [2], suggests that instead of merely reflecting light, life transforms the light spectrum; pushing the incident solar spectrum out to much longer wavelengths (the outgoing radiation does not fit well a black-body spectrum, e.g. the red-edge of vegetation). It is the difference in intensities (outgoing minus incident) integrated over all wavelengths (or frequencies) which must be used to determine the global entropy production of Earth. The effect of life cannot be determined from a simple measure of the ratio of reflected to incident radiation averaged over an arbitrary wavelength region (e.g. visible). As I suggest in the article, life's thermodynamic role is to transform the incident solar spectrum by constructing organic molecules which, in water, absorb strongly in the high frequency regions and dissipate this energy into the low frequency regions. The global entropy production is the result of this non-equilibrium organization (coupled with other abiotic organizations, e.g. water cycle) under the imposed photon potential generated by the hot Sun and cold outer space.

Prof. Gorshkov suggests that life, by extending cloud cover over land, has increased the planetary albedo by about one third and thus "rather than increasing the entropy production rate life diminished it by a considerable magnitude on a global scale." As mentioned above, albedo is not the only relevant variable for determining the global entropy production of Earth. In any case, it seems improbable that Prof. Gorshkov has sorted out all the factors contributing to planetary albedo. Life, by maintaining Earth's surface temperature within the range suitable for liquid water (and even for helping to retain water on Earth [Lovelock, 3]) contributes enormously to the very low albedo measured over oceans. Ocean albedo (and integrated day-night ocean surface direct radiation) is further reduced by life in the surface microlayer [4]. Life also appears to have adjusted the gases of our planetary atmosphere in such a manner so as to reduce absorption and reflection, leading to a window of transparency over the most intense region of the solar spectrum [3]. Desert and rocky surfaces without life generally have high albedos, while climax conifer forests have very low albedos. Clouds are also an unavoidable part of the life catalyzed water cycle, which in itself produces an important

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amount of entropy. Planetary albedo, and its relation to entropy production, is a complicated issue, however, if Prof. Gorshkov's conclusions were correct, then life would be the only known irreversible process occurring in the Universe that does not contribute to entropy production (and in fact, he says, reduces it). This, of course, is in contradiction to the second law of thermodynamics. Onsager [5] and Prigogine [6] have shown that the global entropy production always increases when different irreversible processes couple.

I can appreciate the more general information theoretic approach over thermodynamics; however, when dealing with physical non-equilibrium situations, information only has meaning in how it can help catalyze Nature's incessant effort to distribute extensive thermodynamic variables over ever more microscopic degrees of freedom (entropy production). In contrast to Prof. Gorshkov′s assertion, I believe that evolutionary processes ARE determined by the laws of thermodynamics [7]; of course with the proviso that here "thermodynamics" is taken to mean "non-equilibrium thermodynamics", or better still, "quantum statistical mechanics".

It may be that the rate of information production on Earth has been increasing in time, but my paper is not concerned, per se, with how Earth's surface is organizing itself, but rather with what is the effect of this organization (biology) and its coupling to other non-equilibrium organizations (e.g. water cycle) on the entropy production of Earth in its interaction with its solar environment. I suggest that Earth over time has become ever more a black-body radiating at an ever lower temperature, i.e. augmenting its global entropy production in its interaction with its solar environment.

Finally, I acknowledge the wisdom of Prof. Gorshkov, for even though our respective views appear diametrically opposed, he has the grace to acknowledge the limited state of our understanding on these topics and welcomes this discussion.

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