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Self-organization and information for planets and ecosystems

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Contents

Abstract. Entropy is fundamental to describing open systems. It makes possible the distinction between non-equilibrium and equilibrium processes. The influx of negentropy is a measure of all physical and chemical processes occurring in a system. The entropy balance equation is a useful tool for the comprehensive description of an open system, as its application to planets and ecosystems illustrates. The entropy-information relationship established by the theory of information is applicable to self-organising systems provided their special features, particularly the presence or absence of memory, are taken into account.

1. Introduction

Among the many systems existing in nature, of special interest and importance are the complex macroscopic non-equilibrium systems which feature ordered structures in which 'order is created out of chaos' [1]. Such systems are numerous and diverse: hydrodynamic convection cells, vortices in the atmosphere and ocean, chemical reactions displaying time and space periodicity, lasers, living organisms and ecosystems [1 – 4]. The existence and evolution of such systems (especially the living systems) until recently were often regarded as incompatible with the second law of thermodynamics which states that the evolution of a closed system proceeds from order to chaos. Even not too long ago one could hear that 'Clausius and Darwin cannot both be right at the same time'. The need to describe such systems and predict their evolution stimulated a number of studies which laid the foundations of the theory of self-organization. Different approaches and names were used: the theory of self-organization or the theory of dissipative structures [1], synergetics [2], the theory of open systems [3], information dynamics [4]. And even though this theory is far from completion, the advances that have been made so far inspire hope for future progress in our understanding of the processes of self-organization. In particular, this theory helps to establish the linkage between physico-chemical and biological systems and processes. In this paper we discuss certain issues of the theory of self-organization, such as the role of entropy in open systems and the linkage between negentropy and information, and apply the results of this theory to the study of planets and ecosystems which are good examples of open non-equilibrium systems with numerous self-organizing structures.

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2. Entropy in open systems

All experiments and observations indicate that the existence of ordered structures in a system (with the exception of equilibrium crystal-like structures) is only possible when the system is open — that is, when the system exchanges energy and entropy with the environment, as well as matter or radiation. This exchange must be strong enough to place the system far from thermodynamic equilibrium, in the domain where the generalized thermodynamic flows exhibit a nonlinear dependence on the thermodynamic forces. While the description of equilibrium or near-equilibrium systems may be based on the equations of balance of mass, momentum and energy, the crucial role in the treatment of open systems belongs to the balance of entropy. This was noted as early as 1938 by R Emden who, having studied the process of heating of buildings, concluded that 'in the factory of Nature entropy is the general manager who determines the direction of processes and the performance, while energy is just the bookkeeper who settles the balance' [5]. Observing that a living organism gives away as much energy and matter as it receives, Schrödingerr asked himself what it lives by, and answered: "Living organisms feed on negative entropy" [6]. In any real system there always are irreversible dissipative processes going on (diffusion, viscosity, heat conduction, chemical reactions, phase transitions) associated with increasing entropy. The cause of irreversibility is the instability of the paths of interacting (colliding) atoms and molecules in phase space (see, for example, Ref. [4]). It is also important that atoms and molecules are complex quantum systems rather than rigid spheres as assumed in most models. The only function of state that behaves differently in irreversible and reversible processes is entropy: it increases in the former, and remains the same in the latter. The change in the entropy of an open system dS is the sum of the part coming from the environment dS_e and the entropy increase $dS_i > 0$ due to the internal dissipative processes [1, 3, 7–9]:

$$dS = dS_e + dS_i \qquad (dS_i > 0) . \tag{1}$$

In an open system the entropy flow may be directed inwards or outwards — that is, the term dS_e may have either sign, and the entropy of the system may be increasing or decreasing. However, the entropy of the system together with the environment always increases, in accordance with the second law of thermodynamics. If the system occurs in a steady state, the flow of entropy to the outside world $dS_e < 0$ compensates the production of entropy within the system dS_i, and so $dS = 0$. If we reverse the sign in the definition of entropy (negative entropy, or negentropy for short), we may say that there is a supply of negative entropy to the system which is consumed in dissipative processes and keeps the system in a non-equilibrium state. The inflow of negentropy in a steady non-equilibrium state is equal to the production of entropy in the system and serves as a measure of all dissipative processes taking place in the system. The entropy of non-equilibrium systems may be defined in such a way as to preserve its linkage with other thermodynamic parameters observed at equilibrium, and express it by the Gibbs formula [1, 3, 7–9]

$$dS = \frac{dE}{T} + \frac{p\,dV}{T} - \frac{1}{T}\sum \mu_i \, dN_i . \tag{2}$$

Here E is the internal energy, T is the temperature, p is the pressure, V is the volume, μ_i and dN_i are the chemical potential and the number of particles of the ith component of the system. From Eqn (2) under the assumption of local thermodynamic equilibrium (which holds for a very broad class of phenomena with the exception of shock waves), using the laws of conservation of mass and energy, we derive the equation of balance of entropy per unit mass $s = S/M$ [7–9]:

$$\frac{\partial(\rho s)}{\partial t} + \operatorname{div} J_s = \sigma_s , \tag{3}$$

where the flow of entropy consists of the conduction, convection and diffusion parts:

$$J_s = \frac{Q}{T} + \rho s \mathbf{v} - \sum \rho_k \mathbf{v}_k \frac{\mu_k}{T} , \tag{4}$$

and the production of entropy is

$$\sigma_s = Q \cdot \nabla\left(\frac{1}{T}\right) - \frac{1}{T}\prod : \nabla\mathbf{v} - \sum \rho_k \mathbf{v}_k \cdot \nabla\left(\frac{\mu_k}{T}\right) - \frac{1}{T}\sum \omega_{kl} A_{kl} , \tag{5}$$

where ρ is the density, $\mathbf{v}$ is the velocity, t is the time, $\prod$ is the tensor of viscous stress, Q is the heat flux, k denotes the kth component, ω_{kl} is the rate of the ith reaction of the kth component, A_{kl} is the chemical affinity, and $\prod : \nabla\mathbf{v}$ is the scalar product of the tensor of viscous stress and the tensor of field of velocities. The first term in Eqn (5) describes entropy production by heat conduction processes, the second by viscosity, the third by diffusion, and the fourth by chemical reactions and phase transitions. These terms are written in the general form; their particular expressions will depend on the degree of non-equilibrium — on whether, for example, the flows in the system are laminar or turbulent. On the other hand, from statistical physics we know that the entropy is the logarithm of the number of microscopic states compatible with the given (equilibrium or non-equilibrium) macroscopic state of the system [3, 7–10]:

$$S = k \ln \Delta\Gamma = -k \ln w , \tag{6}$$

where $\Delta\Gamma$ is the portion of the volume of the phase space available for the system in the given macroscopic state; $w = 1/(\Delta\Gamma)$ is the probability that the system occurs in the given volume, k is the Boltzmann constant. For the most simple physical system, a gas of one-atom molecules, classical continuous phase space may be converted into the a discrete space by splitting $\Delta\Gamma$ into the smallest cells whose size is defined from the quantum uncertainty principle and the condition of indistinguishability of particles in the statistics, $\Gamma_0 = h^{3N} N!$, where h is Planck's constant:

$$\Delta\Gamma = \frac{\prod_{i=1}^{3N} \delta p_i \delta q_i}{h^{3N} \cdot N!} . \tag{7}$$

If the temperature is measured in units of energy, the Boltzmann constant in Eqn (6) must be dropped, and S will be expressed in dimensionless units which define the number of microscopic states compatible with the given macroscopic state of the system. Equation (6) was derived under the assumption that all microstates are equiprobable; if we remove this restriction, in place of Eqn (6) we get

$$S = -\sum w_i \ln w_i = -\langle w_i \rangle . \tag{8}$$

The distribution function of probabilities for non-equilibrium states is different from the equilibrium canonical Gibbs distribution. One may assume that Eqn (6) and (8) are applicable to arbitrarily complex systems; then all the parameters that define the system must be regarded as the coordinates in the phase space. Of special importance is the entropy in systems where radiation interacts with matter. As demonstrated by Planck ([11], see also Refs [10, 12]), radiation, like matter, is characterized not only by the energy, but also by the entropy and temperature. The density of entropy of a beam of photons of frequency ν and intensity I_ν is

$$s_\nu = \frac{2k\nu^2}{c^3}\left[(1+y)\ln(1+y) - y \ln y\right] , \tag{9}$$

and the temperature of photons is

$$T_\nu^{-1} = \frac{k}{h\nu} \ln\left(1 + \frac{1}{y}\right) , \tag{10}$$

where $y = c^2 I_\nu / 2h\nu^3$. Equations (9) and (10) can be derived by considering the photons as particles obeying the Bose–Einstein statistics [10, 12]. The fluxes of energy and entropy of radiation across a unit area (f_r and f_s) are found by integrating I_ν and cs_ν with respect to frequency and solid angle:

$$f_r = \int\!\!\int I_\nu \boldsymbol{\Omega} \; d\Omega \, d\nu , \tag{11}$$

$$f_s = \int\!\!\int cs_\nu \boldsymbol{\Omega} \; d\Omega \, d\nu , \tag{12}$$

where $\mathbf{\Omega}$ is the unit vector directed along the beam, and $\mathrm{d}\Omega$ is the differential of the solid angle. Differentiating Eqn (9) with respect to the time t and the coordinate r, we get [12]

$$\frac{\partial}{\partial t}(cs_\nu) = \frac{1}{T_\nu}\frac{\partial I_\nu}{\partial t}\,, \quad \mathbf{\Omega}\cdot\nabla(cs_\nu) = \frac{1}{T_\nu}\mathbf{\Omega}\cdot\nabla I_\nu\,. \tag{13}$$

Hence it follows that there is a simple connection between the transfer equation of the entropy of radiation and the conventional radiation transfer equation:

$$\begin{aligned}\frac{1}{c}\frac{\partial s_\nu}{\partial t} + \mathbf{\Omega}\cdot\nabla(cs_\nu) &= \frac{1}{T_\nu}\left(\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{\Omega}\cdot\nabla I_\nu\right) \\ &= \frac{1}{T_\nu}\left[B_\nu\varkappa_\mathrm{a} - I_\nu(\varkappa_\mathrm{a}+\varkappa_\mathrm{s})\right],\end{aligned} \tag{14}$$

where $\varkappa_\mathrm{a}$, $\varkappa_\mathrm{s}$ are the photon absorption and scattering coefficients, and B_ν is Planck's radiation function. Owing to the smallness of $1/c$, the derivatives with respect to t in Eqn (14) are, as a rule, negligible. In particular, in case of ideal blackbody radiation (then $T_\nu = T_r$ is constant) from Eqn (11), (12) it follows that the flux of energy into the hemisphere is

$$f_e = \sigma_\mathrm{B} T_r^4 \tag{15}$$

(where σ_B is the Stefan – Boltzmann constant), and the flux of entropy is

$$f_s = \frac{4}{3}\sigma_\mathrm{B} T_r^3 = \frac{4f_e}{3T_r}\,. \tag{16}$$

In a non-equilibrium system which contains matter and radiation at different temperatures (for example, molecules of the atmosphere and photons of sunlight) the entropy densities, fluxes and productions for matter (subscript m) and for photons (subscript r) add up [12]:

$$s = s_m + s_r; \quad J(s) = J(s_m) + J(s_r); \quad \sigma = \sigma_m + \sigma_r\,.$$

When photons interact with particles (absorption and scattering), the entropy production in a unit volume is [13]

$$\sigma_r = \int -\mathrm{div}(\mathbf{\Omega} I_\nu)\left(\frac{1}{T} - \frac{1}{T_\nu}\right)\mathrm{d}\Omega\,\mathrm{d}\nu\,. \tag{17}$$

For the blackbody radiation, from Eqn (17) we get

$$\sigma_r = -\mathrm{div}\, f_r\left(\frac{1}{T} - \frac{4}{3T_r}\right). \tag{18}$$

The first terms in Eqns (17), (18) describe the change in the entropy of matter, and the second terms that of photons.

The fact that even the entropy of the most non-equilibrium state (the beam of photons) depends on the same parameters as does the entropy of matter, $S(E, T, V)$ (recall that the chemical potential of photons is $\mu = 0$ [10]), once again justifies the extension of Eqn (2) to non-equilibrium states.

Let us now summarize the properties of entropy which determine its importance for non-equilibrium systems. First and foremost, entropy is the only function of state that behaves differently in irreversible and reversible processes: it grows in the former, and remains the same in the latter. The growth of entropy in the aggregate of irreversible processes defines the direction of time ('the arrow of time' [14]). The entropy is also a measure of disorder for a macroscopic state which may be realized through different combinations of microscopic states. Accordingly, the decrease of entropy indicates that the degree of order is increasing, and vice versa [3, 4]. Finally, the entropy characterizes the 'quality of energy': if the system receives the energy at a higher temperature, each particle or photon carries a larger amount of energy, and its impact on the system is stronger (this is especially clear when solar radiation hits a planet, which will be discussed later on). Another example is the case when only the free energy of the system, $F = E - TS$, performs mechanical or chemical work.

This point of view is not universally recognized. Some authors argue that since the entropy of the system is not conserved, it is not as important as the energy (see, for example, Ref. [15]). The mere fact that the entropy is not conserved, however, is not by itself a drawback: the increase or decrease of entropy indicates the nature of changes taking place in the system (ordering or disordering), while the magnitude of the change may serve as a quantitative measure of order. As a matter of fact, when we speak of 'energy consumption' we actually mean the consumption of negentropy, whereas energy comes and goes in different forms.

This means that the equations of balance of mass, momentum and energy in the theoretical models of highly non-equilibrium systems must be supplemented by the equation of balance of entropy. Now the question is whether or not we overdetermine the system by doing so. After all, the system of equations of balance of mass, momentum and energy (or the simplified equation of balance of entropy instead of the latter [16]) usually employed in thermohydrodynamics is closed and allows expressing of the parameters of the fluid (density, velocity, and temperature) as functions of coordinates and time. We must remember, however, that this set of equations is closed with the aid of the empirical laws of Fourier, Fick and Newton, which express the thermal flux, the tensor of viscous stress, and diffusion flows in terms of the coefficients of heat conductivity, viscosity and diffusion, and the gradients of temperature, velocity and concentration of components. These laws only hold for small deviations from equilibrium. Far from equilibrium the flow of fluid becomes turbulent, the processes of transport and energy dissipation become much more vigorous, and their characteristics are hard to define [17].

The equation of entropy balance can be used for defining one of the characteristics of the flow — for example, the coefficient of turbulent mixing. The dissipative function $\Phi = T\sigma$, which defines the amount of energy transformed into heat in unit volume per unit time, is linked with the production of entropy.

It is difficult to calculate the production of entropy in complex systems; an exact method has only been developed for the ideal gas. If, however, we consider the equation of entropy balance, then for a steady system σ can be expressed with the aid of Eqn (3) in terms of the inflow of entropy into the system which can be measured experimentally. Later on we shall use the examples of a planet and an ecosystem to show how the description can be refined with the aid of the entropy balance equation. Also, information about the entropy and its production can be helpful for analyzing the stability of the system [3, 9, 14].

Of course, when we say that it is necessary to take into account the inflow of energy and entropy into the system, we should be aware of the fact that in any case the system is actually receiving a flow of photons, particles, or heat, which is characterized by two characteristics related to the quantity and quality of energy.

3. Negentropy and information

In order to better understand the role of negentropy in non-equilibrium systems, we must recall that direct linkage has been established between negentropy and information [18, 19].

The theory of information considers systems which are capable of registering and storing information. Entropy is defined for such systems in essentially the same way as in physics. An information system consists of N cells, each of which is associated with either zero or one; 2^N combinations (texts) are possible, the probability of each being $w = (2^N)^{-1}$. The entropy is defined by formulas (6) and (8), and is the measure of uncertainty: it gives the mean probability of any possible combination. It is convenient to express this information entropy in bits; with this purpose the physical entropy must be divided by $(k \ln 2) = 9.57 \times 10^{-24}$.

The quantity of information is equal to the decrease in the uncertainty (entropy) of the system [15], that is,

$$I_1 = S_0 - S_1 = -\Delta S = \Delta N . \tag{19}$$

This means that in the course of a certain process (experiment) the entropy of the system S_0 has reduced to S_1 — in other words, the system has received an amount of negentropy ΔN.

Assuming that the system after the experiment occurs in a cell of the phase space (that is, $\Delta\Gamma = 1, S_1 = 0$), from Eqn (15) it follows that

$$I_1 = S_0 , \tag{20}$$

this implies that the *a posteriori* information is numerically equal to the *a priori* information when and only when the entropy after the experiment has become zero — that is, the system has arrived at a certain particular cell. This is possible for an information system (for example, the coin falls heads up), and impossible in principle for the microstates of a physical system (if only its temperature is not equal to absolute zero). This must be made very clear, because many authors define information by Eqn (20), failing sometimes to indicate that the right-hand and left-hand sides of this expression relate to different times and conditions (before and after the experiment), and that a very strong constraint is imposed on the final state of the system. Besides, from the complete formula (19) we see that information is numerically equal to negentropy [15]. This means that when a system receives information, it loses some entropy or gains some negentropy. This maintains the steady state of the system, or keeps the processes of self-organization going. If the entropy of the system increases, then one may say that the system has received false information, which may result in a stress or even degradation of the system.

Equation (19) may be rewritten as

$$I_1 + S_1 = S_0 . \tag{21}$$

Hence we see that if the information after the experiment increases, then the entropy decreases by the same amount, and their sum remains constant and equal to the *a priori* entropy.

Now from the theory of information let us go back to physics, and apply equations (19) and (21) not to the information systems but to arbitrary physical systems. In other words, let us assume that the inflow of negentropy into the system is equivalent to the inflow of information. In particular, if prior to the experiment the system was in a state of thermodynamic equilibrium, and after the experiment moved into a non-equilibrium state, then the acquired negentropy (information) may serve as the measure of deviation from equilibrium, also for systems with emerging ordered structures.

However, when applying the methods of information theory to physical systems, one must remember that, although the above formulae hold for any system, the information systems are much different from simple physical systems. The main distinction is that the former are capable of storing (remembering) the received information for a long enough period of time. Obviously, the information about the coordinates and momenta of gas particles at a given time or about the existence of convection cells in the gas does not survive a change in the external conditions, whereas the information in the memory of a computer or in the DNA molecule in a living cell will stay long after the external conditions change, and will be used in life processes and passed on to the next generation.

Another important distinction of information systems is that their memory cells have a sophisticated internal structure, and so the volume taken up by each cell in the phase space is greater by many orders of magnitude than the corresponding volume in the case of simple physical systems. In DNA, for example, the information cell is at least 10^{20} times as large as the smallest cell of the physical phase space defined by Eqn (7) [20]. This must be taken into account in calculating the information storage capacity of different systems. Neglecting this fact, as well as disregarding the distinction between memorized and non-memorized information, lead to erroneous estimates of the amount of information contained in an organism, ecosystem or biosphere [21].

In addition, information systems may arrive at the state with zero entropy, while for most physical systems (at $T \neq 0$) this is not possible, and therefore Eqn (20) is not applicable.

Finally, in the case of information systems it is possible to define not only the quantity, but also the quality (value) of information. This concept is very hard to formalize. The value of information has been defined as the gain obtained by the system because of reduced losses [22, 23], or as the increased probability of achieving the objective [24] upon reception of a given quantity of information. One may assume that more valuable information increases the probability of survival of the system — that is, increases its adaptation to the environment, and hence its life span. Of course, the gain and the objectives are different for different systems, and have to be defined specially for any system under consideration.

Facing such difficulties, some authors express doubt in the expedience of using the linkage between negentropy and information (see, for example, Ref. [20]). In spite of the above difficulties, however, this approach can be quite fruitful, since it permits application of the advanced methods of information theory to the study of physical systems.

Treating an open system as a system controlled not only by the input of energy, but also by the input of information, one can get a better understanding of the way the complex hierarchical systems evolve in the process of self-organization: the evolution of an information-controlled nonlinear system may take alternative paths towards higher complexity; as a result, the system can better adjust to the changing environment [4].

4. Entropy balance of planets

The governing role of entropy is vividly illustrated by the study of energy and entropy balance of the planets in the Solar System [13, 25–30]. For a planet one may disregard the loss and gain of mass, and in the energy balance only take into account the solar radiation absorbed by the planet, Φ_s, and the infrared radiation emitted by the planet Φ_p (for earth-like planets, where the heat generated in the core is negligible compared with the surface radiation):

$$B = \Phi_s - \Phi_p = f_s(1 - A)\pi r^2 - 4\pi r^2 f_p \,. \tag{22}$$

Here f_s is the incident solar radiation per unit area, $f_p \approx \sigma_B T_e^4$ is the infrared radiation emitted from a unit area of the planet's surface, T_e is the equilibrium temperature, A is the integral spherical albedo of the planet, and r is the radius of the planet; the factor of 4 in the last term takes care of the fact that the solar radiation falls on the cross-section of the planet, while the infrared radiation is emitted by the entire surface of the planet. Satellite measurements of radiation fluxes over many years indicate that the annual energy balance of the Earth is close to zero [27], which means that the planet gives off about as much energy as it receives (the deviation from zero is about ± 5 % from f_p when the Earth is at perihelion and aphelion). From Eqn (22) it follows that when the solar radiation increases (decreases), the planetary radiation increases or decreases accordingly, which ensures the overall stability of the climate on the planet.

What is then consumed in the planetary processes which involve enormous amounts of energy and matter? Let us show that these processes are driven by the negentropy received by the planet. Assume that the spectra of solar and planetary radiation are close to blackbody emission (this simplifying assumption is only made for convenience, and can be rejected). Then the inflow of entropy to the planet is

$$\Delta S = \frac{4}{3}\left(\frac{\Phi_s}{T_s} - \frac{\Phi_p}{T_p}\right) . \tag{23}$$

Since the temperature of solar radiation ($T_s = 5780$ K) is always much higher than the temperature of thermal planetary radiation ($T_p = 211-441$ K for the terrestrial planets, and even less for the rest), for any planet we have $\Delta S < 0$ — in other words, there always is an outflow of entropy from the planet, or an inflow of negentropy $\Delta S < 0$, which is used in all processes taking place on the planet [26].

The fact that the energy balance does not completely determine the planetary processes can be illustrated with the following mental experiment. Assume that the Sun is replaced with a star of the same luminosity (which means that the solar constant remains the same, f_s), but with a lower radiation temperature T_s — that is, with the spectrum shifted towards the infrared. According to Eqns (22) and (23), the planet will be receiving the same amount of energy, but a smaller amount of negentropy. Then many processes on the planet will take a different course. Infrared photons, for example, cannot support biosynthesis, so the biosphere on the planet, if any, will be much different from what we have now. This is because the supply of negentropy characterizes the quality of the flow of energy coming to the planet [26, 27].

On the Earth, according to satellite measurements, $f_s = 1368$ W m^{-2}, $A = 0.29$, $T_s = 5778$ K, $T_p = 254$ K. Using these values, from Eqn (13), (14) we find that the inflow of negentropy to the entire planet is $\Delta N = 6.2 \times 10^{14}$ W K^{-1}, or, on average, $\Delta n = 1.22$ W m^{-2} K^{-1} per unit area [27]. A more detailed calculation with due account for space and time variations gives $\Delta N = 6.8 \times 10^{14}$ W K^{-1}, $\Delta n = 1.25$ W m^{-2}K^{-1} [30]. This large inflow of negentropy is used primarily for maintaining the thermal balance of the planet: the photons interact with the particles of the atmosphere and the surface, the increase in the entropy of matter and radiation being

$$\Delta S_1 = \int \left[-\frac{\operatorname{div} f_s + \operatorname{div} f_p}{T} + \frac{4}{3}\left(\frac{\operatorname{div} f_s}{T_s} + \frac{\operatorname{div} f_p}{T}\right)\right] \mathrm{d}z \,, \tag{24}$$

where z is the height above the surface of the planet.

Since the atmosphere is much more transparent for solar photons than for infrared photons, the established and maintained distribution of temperature with respect to altitude is such that the temperature near the surface $T_0 = 288$ K is much higher than the equilibrium temperature $T_e = 254$ K at an altitude of a few kilometers, from where the infrared photons go into space. The fact that T_0 is higher than T_e (the so-called greenhouse effect) ensures the existence of liquid water and the biosphere on the Earth. Calculations using formula (24) reveal that about 70% of the negentropy coming to the Earth is used for maintaining the thermal regime on the planet [27].

About 25% of the negentropy is spent on the evaporation of water [27], mostly from the surface of the oceans; the water vapor rises up in the atmosphere to build clouds, which are carried by the wind over the land. The rainfall supplies water to the vegetation. This so-called hydrologic cycle turns around about 5×10^{14} tonnes of water per year.

From these estimates (which have to be further refined) it follows that the entire dynamics of the atmosphere and ocean, including all flows of mass and heat, tsunami, hurricanes and the like, involves no more than 5% of the negentropy coming to the Earth [27]. This fits in well with the estimates made by climatologists, according to which the kinetic energy of atmosphere and ocean constitutes about 2 to 4% of the solar energy absorbed by the planet. Having considered these estimates, E Lorentz (who, incidentally, discovered the first strange attractor in the course of his studies of convection) pointed to the importance of explaining the low efficiency of the 'atmospheric thermal engine' [31]. The entropy balance on the planet offers a simple explanation: most of the negentropy received is spent on maintaining the thermal regime and on the evaporation of water, and only a few percent is left for the dynamics. On Venus, where there is no water, a much greater share of negentropy goes into the dynamics of the atmosphere.

On Venus the inflow of negentropy is $\Delta N = 4.0 \times 10^{14}$ W K^{-1}, and $\Delta n = 0.88$ W m^{-2} K^{-1}, on Mars $\Delta N = 9.9 \times 10^{13}$ W K^{-1} and $\Delta n = 0.69$ W m^{-2} K^{-1} [26].

The opinion expressed in Ref. [32] and elsewhere is that the information concerning solar irradiation and the temperature on the surface of Venus obtained by space probes is either wrong, or points to the violation of the entropy balance on the planet. The calculation of entropy balance using Eqn (23) indicates that these fears are unfounded [26].

In this way, all processes on planets (including biospheric processes on the Earth) operate at the expense of the inflow of negentropy. This inflow arises because the temperature of solar radiation which brings the energy to the planet is about 6000 K, whereas the temperature of the outgoing infrared radiation which carries away about the same amount of energy per unit time is much less. In other words, the outgoing radiation carries away a much larger amount of entropy, which compensates the production of entropy in all dissipative processes taking place on the planet.

Such processes and phenomena on the Earth as the greenhouse effect, the hydrologic cycle of water, the global circulation of the atmosphere and oceans, are essentially dissipative structures supported by the supply of negentropy and making up the global self-organizing system whose characteristic is the climate of the Earth.

These days the radiation balance of the Earth is routinely monitored by satellite-borne instruments. These results can be used for calculating the supply of negentropy to the planet, which may serve as a measure of the planetary processes. This will be useful for refining the parametrization of dissipative functions of the atmosphere and oceans, and for studying the evolution and stability of the climate [28 – 30].

5. Inflow of entropy in the description of ecosystems

By definition, an ecosystem is the totality of living organisms which populate a certain territory, together with the environment with which they exchange matter, energy and information (see, for example, Ref. [33]).

We know that organisms, to say nothing of ecosystems, are extremely complex hierarchical systems. Because of this many authors have voiced doubts in the representability of such systems by theoretical models. It has been demonstrated, however, that theoretical models of ecosystems and the biosphere are becoming more and more advanced, and yield very interesting results (see, for example, Refs [34 – 36]).

The first question in the study of an ecosystem is how its biomass B and the mass of detrite (deteriorating organic matter) D change with the time. If the biomass does not decrease with the time, one may assume that the ecosystem is doing well. For B and D one may write the following equations:

$$\frac{\mathrm{d}B}{\mathrm{d}t} = P_{\mathrm{p}} + \sum P_i - R_{\mathrm{a}} - M\,, \tag{25}$$

$$\frac{\mathrm{d}D}{\mathrm{d}t} = M - R_{\mathrm{h}}\,. \tag{26}$$

Here t is the time, P_{p} is the yield of photosynthesis, P_i are the flows of nutrients from the soil, R_{a} is the autotrophic respiration of plants, M is the rate of decay of the biota, R_{h} is the heterotrophic respiration (the rate of deterioration of the detrite).

For the problem in question it is sufficient to consider only the biomass of the plants (phitomass), which in most ecosystems constitutes from 95 to 98% of the biomass. Under certain simplifying assumptions, the terms in Eqns (25) and (26) are described by empirical or semi-empirical relations. For example, the description of photosynthesis involves the incident photoactive solar radiation (in the spectral range from 0.4 to 0.7 cm), the concentration of carbon dioxide CO_2 in the atmosphere, the air and soil humidity, the temperature of air and soil, the foliage index (the ratio of foliage area to plot area). Different models use different approximations, and any attempt at improving the description gives rise to numerous new parameters (see, for example, Refs [34 – 36]).

Theoretical description of an ecosystem may be refined by supplementing Eqns (25) and (26) with the equation of entropy balance [24, 25]. Let us write it in the stationary form (averaging over the year or over the period of vegetation if the latter is shorter), placing the upper limit of integration in the atmosphere above the vegetation layer, and the lower limit in the soil beneath the plant roots:

$$\int J(s)\,\mathrm{d}A = \int \sigma(s)\,\mathrm{d}V\,, \tag{27}$$

$$J(s) = \frac{f_{\mathrm{s}}}{T_{\mathrm{s}}} - \frac{4}{3}\,\sigma_{\mathrm{B}}\left(\varepsilon_{\mathrm{s}} T_{\mathrm{s}}^3 - \varepsilon_{\mathrm{a}} T_{\mathrm{a}}^3\right) - \frac{1}{T_{\mathrm{s}}}\left[LE - c_{pw} T_w r + Q + \sum_k J_k(m_k)\mu_k\right]. \tag{28}$$

Here V is the volume of the system, ε_{s}, ε_{a} are the radiation coefficients of plants and atmosphere near the upper boundary of the system, T_{s} and T_{a} are the corresponding temperatures, L is the heat of evaporation, E is the rate of evaporation, c_{pw} is the heat capacity of water, T_w and r are the temperature and the rate of rainfall, and Q is the turbulent flow of heat into the atmosphere.

One can measure the components of the entropy flow in Eqn (28) (combining the results of ground-level and satellite measurements for higher reliability [28]), calculate the flow, and use Eqn (27) for finding the rate of entropy production, which is the measure of all physico-chemical processes in the system and is linked with the productivity, which is the most important characteristic of the system. This may help to ascertain the form of some functions which enter equations (25) and (26) in the absence of the comprehensive model of the system.

The use of information in various forms is one of the basic features of living systems [20, 22, 23]. In the first place, these open self-organizing systems feed on the information (negentropy) coming from the environment: plants use the radiation involved in photosynthesis, animals consume the food. This is the non-memorized information of the same type as that which maintains the stationary state of any open system. In addition, any organism features an information system based on DNA molecules with the involvement of RNA and proteins, which receives, creates, stores, transfers and uses the information for coordinating the numerous synthesis processes which take place in every cell, and the processes in the organism as a whole aimed at maintaining homeostasis and growth, as well as ensuring transfer of information to the offspring. This memorized information ensures the concerted progress of all life processes, and the advancement of the organism and the ecosystem.

Let us get a numerical estimate of the average inflow of information to the ecosystem. As demonstrated above, the mean inflow of negentropy to the Earth per unit area is $\Delta n = 1.22$ W m^{-2} K^{-1}. Accordingly, the inflow of information is $I = 1.27 \times 10^{19}$ bit cm^{-2} s^{-1}. Assume that this flow falls on a green leaf capable of photosynthesis, and that the number of cells on the surface of the leaf is about 10^8. Then the flow of information is $I \approx 1.3 \times 10^{11}$ bit s^{-1} per cell. This supply of non-memorized information is used in all processes, including photosynthesis, respiration, and transpiration, maintaining the temperature of the plant.

Now let us estimate the amount of information used directly for photosynthesis, the process which is essential for the existence of the biosphere. According to published data, the total primary production of biosphere on land and in the sea is about $(4-5)\times10^{14}$ kg year^{-1} of dry matter [33, 37]. Accordingly, the global power of photosynthesis is $(7-9)\times10^{21}$ J year^{-1}, or $(2.3-2.9)\times10^{14}$ W. Dividing this value by the mean temperature of the Earth's surface, 288 K, we find that the supply of negentropy which ensures the global production of phitomass is $N=(0.8-1.0)\times10^{12}$ W K^{-1}, which corresponds to the supply of $I=(0.9-1.0)\times10^{35}$ bit s^{-1} of information. Dividing this by the area of the Earth's surface, we get $(1.8-2.0)\times10^{16}$ bit cm^{-2} s^{-1}. Assuming that one square centimeter of green leaf has about 10^8 cells, we find that in the course of photosynthesis the cell processes information at the rate of 2×10^8 bit s^{-1}, which is the speed of a personal computer. It is interesting to observe that plain rainfall in the gravity field of the Earth is associated with an energy of the same order as that involved in the most sophisticated process of photosynthesis, which is another proof of the important role of the quality of energy [27].

Let us once again emphasize that the estimate of the quantity of information is just the first step in the study of an information system; it is much more important to assess its quality. According to some estimates, for example, the human organism contains 1.3×10^{27} bits of information (mainly in the protein molecules), whereas the DNA molecules carry just 3×10^{23} bit, but this information is the most valuable since it makes up the genome [23]. The arguments developed above confirm the importance of negentropy and information in the studies of ecosystems and the biosphere.

6. Conclusions

Let us summarize the main points. Entropy plays a major role in the description of open systems, and especially of self-organizing systems, since it is the only function that permits the distinguishing of equilibrium and non-equilibrium processes. The inflow of negentropy is the measure of all physico-chemical processes taking place in the system. The steady state of any non-equilibrium system is maintained by the inflow of negentropy. For a complete description of an open system the equations of balance of mass, momentum and energy must be supplemented by the equation of entropy balance, which describes the quality of the energy supplied to the system and the production of entropy in physico-chemical processes taking place in the system.

The linkage between information and entropy, found in the theory of information, is helpful in describing self-organizing systems, with due account for the systems capable or incapable of memorizing information, the volume of the phase space of the information cell, and the ability or inability of the system to arrive at a state with zero entropy.

All physico-chemical processes on planets feed on the inflow of negentropy which arises because the temperature of the incident solar radiation is much higher than the temperature of the infrared radiation leaving the planet. A mental experiment in which the Sun is replaced with a star of the same luminosity but with a different spectrum reveals that a complete description of the processes taking place on the planet is not possible without due account for the balance of entropy. The equation of entropy balance can be used for calculating the share of negentropy used in various processes on the planet, finding the dissipative characteristics, and studying the stability of the system.

In the studies of ecosystems, the use of the entropy balance equation with values of the negentropy measured with the aid of ground-level and satellite instruments allows one to assess the production of entropy which is a measure of all the physico-chemical processes taking place in the ecosystem, which otherwise would be very hard to find because of the difficulties associated with the construction of an adequate model of the ecosystem.

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