Modelling greenhouse effect: an ecodynamic approach

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Abstract

The model described in this paper can be defined with the neologism "ecodynamic". The biosphere is defined as the geometric locus in which entropy decreases. The biosphere is in a steady state: it does not grow quantitatively but only in biodiversity (or at least it has grown in biodiversity from the origin of life up to recent millennia). Since the exchange of matter with the outside is practically negligible and, on the other hand, the Earth receives an enormous flux of energy from outside, the biosphere can be regarded thermodynamically as a closed system.

The "conditio sine qua non" for all this to continue is the absence of an adiabatic membrane around the planet. In other words, the greenhouse effect must not be allowed to prevent the flow of positive entropy into space.

The role of carbon dioxide and other "greenhouse" gases becomes determinant in this ecodynamic model, one reason being the great difference between the biological time of fossil formation and the fleeting historical time in which the fossils are being used. The space of the biosphere is defined as the spherical corona of the planet including the atmosphere and the ozonosphere, the oceans and the Earth's crust, but not reduced carbon which has effectively been treated as a waste by nature, relegated as it is to the bowels of the Earth, the biological dustbin.

If we examine the spatial model in more detail, we find that the boundary between the biosphere and the universe is open to the entry of flows of energy and matter. It receives more than $10^{24}$ joules of solar energy per year, an enormous quantity, and receives practically no matter, with the exception of
meteorites and atmospheric dust, a negligible quantity in relation to the mass of the Planet.

The same boundary is not open to the exit of flows of matter (with the negligible exception of space vehicles sent by man) because of gravitation, but is open to the exit of an enormous flow of degraded energy (positive entropy). The latter property is necessary for the maintenance of life. It is a fundamental negentropic condition that man can alter by dumping greenhouse gases into the atmosphere.

1 Introduction

Evolution implies a hierarchical trend towards increasingly complex living systems. The Second Law of Thermodynamics states that the universe, or each isolated section of it, tends towards maximum entropy. Statistical mechanics and kinetic theory tell us that maximum entropy implies maximum disorder in the framework of the constraints of the system. Hence when we think about evolution in this context (Boltzmann's H theorem) [1], we think of evolution towards increasingly disordered states of the system.

This idea is strikingly at variance with our knowledge of biology. Clearly the trend of living organisms is towards the creation of order where previously there was disorder: it is the trend to organize and self-organize. Life seems to contradict the Second Law of Thermodynamics. The solution to this apparent contradiction between biological and physical theory, underlined by Harold Morowitz², lies in the realization that the Second Law of Thermodynamics applies to systems close to equilibrium, whereas the surface of the Earth, the matrix of biological evolution, belongs to a different class of physical systems. Systems in equilibrium must be either adiabatic (isolated) or isothermal. However the biosphere is quite another type of physical system, in contact with various sources and sinks, and with matter and energy flowing through it from the sources to the sinks.

2 Theoretical Background

Let us consider the following flow diagram, due to Morowitz [2]

energy sources (sun) \(\rightarrow\) intermediate system (biosphere) \(\rightarrow\) sinks (outside universe)

Let us now consider the system divided in two parts:
1) source(s) + sink(s)
2) intermediate system(i)

According to the Second Law of Thermodynamics:

\[ dS_S + dS_i \geq 0 \]  \hspace{1cm} (1)
where $S_S$ is the entropy of source + sink and $S_i$ is the entropy of the intermediate system. The flow of energy from the source to the sink will always involve an increase in entropy:

$$dS_s > 0 \quad (2)$$

whereas the only restriction placed by the Second Law of Thermodynamics on $dS_i$ is that:

$$-dS_i \leq dS_s \quad (3)$$

so that the entropy of the intermediate system (in our case the biosphere) can decrease if there is an energy flow. A flow of energy provides the intermediate system (the Earth's surface) with quantities of energy for the creation of states far from equilibrium, that is, far from thermal death. The more the non equilibrium system is far from equilibrium, the more it is ordered. The ordered state of a biological system would decay, if left to itself, towards the most disorderly state possible. This is why work must continuously be done to order the system. As we have seen, this requires a hot source and a cold sink, the sun and outer space.

The surface of the Earth (intermediate system) receives a flow of energy from the sun source at 5800°C (temperature of the surface of the sun; the core of the sun is millions of degrees hotter) and returns it to the sink of outer space at 3°C. In this vast temperature range lies the secret of life and the possibility of work against entropic equilibrium, moving the living system away from equilibrium towards ordered, negentropic, alive states. The living system is maintained in a "steady state" as far as possible from equilibrium by the flow of energy $E$. Solar energy is distributed over its spectrum as follows (molecular changes induced in brackets):

- 0.02% far ultraviolet (ionization);
- 7.27% ultraviolet (electron transitions and ionization);
- 51.73% visible (electron transitions);
- 38.90% near infrared (electron and vibrational transitions);
- 2.1% infrared (rotational and vibrational transitions).

A small fraction is fixed chemically by photosynthesizing organisms. This energy is the prime mover of biological transformations, including the main nutritional cycles. Global ecological processes are characterized by chemical cycles, such as the carbon and nitrogen cycles. The solar energy reaching the Earth is about $5.6 \times 10^{24}$ joules but the figure, $E$, normally accepted, after correction for albedo, is $3.93 \times 10^{24}$ joules.

The decrease in entropy (negentropy) in the biosphere depends on its capacity to capture energy from the sun and to retransmit it to space in the form of infrared radiation (positive entropy). If retransmission is prevented, in other words, if the planet were shrouded in an adiabatic membrane (greenhouse effect), all living processes would cease very quickly and the system would decay towards the equilibrium state, that is, towards thermal death. A sink is just as necessary for life as a source.

Morowitz underlines that all biological processes depend on the absorption of solar photons and the transfer of heat to the celestial sinks. The sun would not be a negentropy source if there were not a sink for the flow of thermal energy. The
surface of the Earth is at a constant total energy, re-emitting as much energy as it absorbs. The subtle difference is that it is not energy per se that makes life continue but the flow of energy through the system. The global ecological system or biosphere can be defined as the part of the Earth's surface that is ordered by the flow of energy by means of the process of photosynthesis.

The physical chemistry mechanism was elegantly described by Nobel Prize winner Albert Szent-György [3] as the common knowledge that the ultimate source of all our energy and negative entropy is the sun. When a photon interacts with a particle of matter on our globe, it raises an electron or a pair of electrons to a higher energy level. This excited state usually has a brief life and the electron falls back to its basic level in $10^{-7}$ - $10^{-8}$ seconds, giving up its energy in one way or another. Life has learned to capture the electron in the excited state, to uncouple it from its partner and to let it decay to its fundamental level through the biological machinery, using the extra energy for vital processes. All biological processes therefore take place because they are fueled by solar energy. It is this tension between photosynthetic construction and thermal degradation that sustains the global operation of the biosphere and the great ecological cycles [4].

The Second Law of Thermodynamics says that the universe or any other isolated system in the universe, tends towards maximum entropy, towards thermodynamic equilibrium understood as an absence of differences, or thermal death, in the terminology of Clausius[5]. We also know that statistical mechanics and kinetic theory show that maximum entropy means maximum disorder in the framework of the constraints of the system.

Boltzmann defined entropy, $S$, as follows:

$$S = k \ln W$$

where $W$ is the total number of microstates possible, in the framework of macroscopic constraints.

Let us now consider the entropy of a system that is not in equilibrium. The change in entropy when a system goes towards a state of non equilibrium is:

$$\Delta S = S_\alpha - S = k \ln \frac{W_\alpha}{W}$$

where $W_\alpha$ is a subset of possible states $W$; hence $\frac{W_\alpha}{W}$ is always less that one and the term $\Delta S$ is always negative. Hence the entropy of the state of equilibrium is maximum and the other states must have a lower entropy.

The non-equilibrium entropy function is expressed as:

$$S = S_{eq} + \Delta S$$

As the system tends to equilibrium, $\Delta S$ tends to zero.

Summing up:

- entropy is a maximum at equilibrium and there is therefore a natural trend towards maximum entropy or maximum disorder.
b) On the other hand, biological evolution implies a hierarchical trend towards increasingly complex and ordered forms of living systems. Now we know that this is only an apparent distinction. The entropy balance must be global and must include both the biological organism and the environment with which it continuously exchanges energy and matter. Hence biological organisms develop and live by virtue of the increase in entropy that their metabolism causes in their surroundings. The global change in entropy (system + environment) is positive, the entropy of the universe increases, the Second Law is not violated.

When bacteria are cultured in a glucose solution, one notices that part of the sugar causes entropy to decrease by being transformed into cell constituents, and part is transformed into carbon dioxide and water, contributing to an overall increase in entropy.

For open systems, it is necessary to combine the negative entropy produced inside the system with the positive entropy discharged into the environment, and calculate the total change in entropy. In this way we see that although disorder sometimes seems to degenerate into order, this is only a facet of the problem, the apparent order occurring at the cost of even greater disorder in the surroundings. Living systems therefore need a continuous flow of negative entropy from outside and a sink for an even greater amount of positive entropy. Ilya Prigogine calls these open systems "dissipative structures". The flow of energy causes changes in dissipative structures, which reorganize towards a higher level of complexity.

The biosphere is a special kind of system. It is a closed system that exchanges energy but not matter and is in contact with a permanent and practically infinite heat source (the sun) and with a cold sink (outer space), also permanent and practically infinite, to which it gives up its degraded heat. The biosphere is a steady state system because the source and sink are fixed and the flows from the source to the sink are constant in time so that the parameters of the system (temperature, pressure, and so forth) are practically independent of time. This makes life possible and is the reason why large changes induced artificially by man in periods that are brief on the scale of biological time, are so dangerous. The difference between a system in equilibrium and one in a steady state is that the latter exchanges energy and/or matter with external sinks. The stationary state and non equilibrium states are not characterized by maximum entropy.

One last point: the steady state is one in which the flow of energy maintains the system as far as possible from equilibrium. The biosphere, a steady state system far from equilibrium, is in a necessary rather than accidental state, unless greenhouse effect destroys everything.

3 The ecodynamic model

The model is concerned with interactions between biophysical constraints and the global environment. The epistemological bases of the model are derived from the mixing of environmental physical chemistry (mainly thermodynamics) with systemic ecology. The starting point is Boltzmann's statement, that the struggle
for life is not the struggle for matter and energy, that are substantially constant in
time, but the struggle for negative entropy supplied by the sun.
In other words, the model underlines the peculiar capacity of the biosphere to
decrease the entropy of the planet by capturing solar energy. This is done by
photosynthesis, in the broad sense of "making things with light", storing energy
in the organization of living organisms and decreasing the entropy of the
biosphere with the help of radiation from an external source. These statements
are summarized in Schrödinger's phrase that life feeds on negative entropy.
Negative entropy is therefore taken as a precondition for life, and biological
evolution, in turn, can be read as the history of negative entropy on the Earth.
This type of model is described by the word "ecodynamic". For spatial
coordinates, the biosphere is defined as the geometric locus in which entropy
decreases or the geometric locus of photosynthesis. Within this space, time
modulates structures and forms by virtue of negative entropy stored as
information. The biosphere is in a steady state: it does not grow quantitatively but
only in biodiversity (or at least it has grown in biodiversity from the origin of life
until fairly recently). Since the exchange of matter with the outside is practically
negligible and, on the other hand, the Earth receives an enormous flux of energy
from outside, the biosphere can be regarded as a closed thermodynamic system.
This means that matter cannot leave (this is why wastes are such a problem
today) or be exchanged, whereas energy is exchanged with the rest of the
universe by virtue of the existence of a source (the sun) and a sink (celestial
space). In this closed system, the negative entropy flux permits the creation of
dissipative structures, complexity, new information, biodiversity (even cultural
diversity) and relations stored in the energy-matter system. The closed system
biosphere is composed of a multitude of open systems: living organisms.
As we have seen, the "conditio sine qua non" for all this to continue is the
absence of an adiabatic membrane around the planet. In other words, the
greenhouse effect must not be allowed to prevent the flow of positive entropy
into space.
The role of carbon dioxide and other "greenhouse" gases becomes determinant in
this ecodynamic model, one reason being the great difference between the
biological time of formation of fossil fuels and the fleeting historical time in
which the fossil fuels are being used. This is why the model regards fossil
deposits (oil and coal) as external to the space of the biosphere. The bags in
which the fossils are stored are regarded as external to the closed system. The
space of the biosphere is defined as the spherical corona of the planet including
the atmosphere and the ozonosphere, the oceans and the Earth's crust, but not
reduced carbon which has effectively been treated as a waste by nature, and
relegated to the bowels of the Earth, the biological dustbin.
If we examine the spatial model in more detail, we find that the boundary
between the biosphere and the universe is open to the entry of flows of energy
and matter. It receives more than $10^{24}$ joules/year of solar energy, an enormous
quantity, and receives practically no matter, with the exception of meteorites and
atmospheric dust, a negligible quantity in relation to the mass of the planet.
The same boundary is not open to the exit of flows of matter (with the negligible
exception of space vehicles) because of gravitation, but is open to the exit of an
enormous flow of degraded energy (positive entropy), the necessary condition for the maintenance of life and for negative entropy. Man can alter this situation by dumping greenhouse gases into the atmosphere. This is why the increase in carbon dioxide touches a vital ganglion of our planet, and is a critical change from the ecological point of view.

The boundary between the spherical corona and the centre of the Earth is open to outward flows of matter (minerals, fossils) and energy (geothermal energy). It is not open to the inward flow of energy because of the higher temperature of the centre of the Earth. In the past this compartment received enormous quantities of matter (reduced carbon produced by primordial photosynthesis).

We have described a typical ecodynamic model, the protagonists of which are the carbon cycle, photosynthesis, energy flows and entropy. It is like a beautiful intricate antique toy in the hands of a spoilt child, the human consumer of today.

References

[5] Rudolf Clausius must have tormented himself over the final destiny (death) "of the whole of Creation"; for a reconstruction of the intellectual iter of the Prussian scientist from the first formulation of the Second Principle to this "cosmological" version, see M. Guillen, "Five Equations that Changed the World", Little, Brown & Co., London 1995, chap. 5.