Existence of Life and Creation of Atmospheric Environment

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1. Introduction

Geophysiology is a system approach to the Earth science. Lovelock and Margulis (1974) introduced the gaia hypothesis. It postulated the Earth to be a self-regulating system comprising the biota and their environment, with the capacity to maintain the climate and the chemical composition at a steady state favorable for life; Life and its environment evolve tightly as a single system. There is an active feedback loop in the system. Lovelock (1986) emphasized on the concept of geophysiology as follows: Perturbation of one will affect the other, and this in turn will feedback on the original change. At this time, biota respond by active feedback so as to oppose the change and to keep the system in homeostasis, or to make the system evolve toward a new steady state. The latter evolution is called homeorhesis. In homeorhesis, biota can adjust their operating points as the system evolves.

The system composed of the biota and the environment is vastly complex. It is very difficult to verify the geophysiological evidence in consequence of this complexity of the system. However, despite of this difficulty, some simplified approaches are recently tried for this problem by some investigators, e.g., Daisy World by Watson and Lovelock (1983), which studied the homeostasis resulted by the coupling process between albedo due to the colour change of the Daisy World and temperature of this world. Here, we also propose, with the use of a simplified model, that a geophysiological model can explain for the regulation of atmospheric CO₂ level.

The Earth's environment under the increase in solar luminosity has been studied by some investigators since Sagan and Mullen (1972). Owen et al. (1979) proposed that the amount of CO₂ is great enough to warm
the primitive Earth's surface so as to maintain its condition in homeostasis. However, through what process, or by what mechanism has it been regulated?

Our main motive for this work was to study whether it was simply chance that caused atmospheric CO\textsubscript{2} to decline while solar luminosity has been increasing at just such a rate as to maintain an equable temperature. Moreover, the following problems arouse our interest: why the mean surface temperature of the Earth is on the cool side of the optimum for biota, and why the concentration of CO\textsubscript{2} on the Earth's atmosphere is anomalously low?

Walker et al. (1981) proposed an abiological mechanism (hereafter, this is called Walker cycle) for the long-term stabilization of the Earth's surface temperature. It included a strong negative feedback mechanism in which the rate of weathering of silicate minerals, followed by deposition of carbonate minerals, depends on surface temperature, while the surface temperature, in turn, depends on the CO\textsubscript{2} partial pressure through the greenhouse effect. This mechanism might have operated early in the Earth's history. However, there is no doubt that current weathering of silicate rocks is biologically performed. Lovelock and Whitfield (1982) insisted that geological input and removal of CO\textsubscript{2} constitute only a few tenths of a percent of the biologically driven fluxes, and that the chemical weathering of rocks is monitored by the biota which maintain the high partial pressure of CO\textsubscript{2} in the soil through the biological oxidation mechanism of organic detritus. For the atmospheric CO\textsubscript{2} concentration, the Walker cycle predicted for the present a 100 or 1000 times higher concentration than what it is observed to be. Without biota significantly enhancing weathering rates, the Earth today would be uninhabitable, because an abiotic Earth would be over 30°C warmer than what it is today (Schwartzman and Volk, 1989).

Moreover, the abiological model has a weak point, to solve the homeostasis in the Earth's environment under the gradual increase of the solar luminosity, because external disturbances have great influences on the behavior of its solution: unexpected but common events on the Earth's history such as the rapid release of CO\textsubscript{2} by volcanoes, by metamorphism and by reduced land area exposed to weathering may bring about a new, warm, voluntary and discontinuous steady state from the former climate, and vice versa. To avoid this and to keep a constant condition on the Earth, the modified Walker model (e.g., Matsui and Tajika, 1989) proposed a huge storage of CO\textsubscript{2}, i.e., the existence of a continent as a stable and huge storage of CO\textsubscript{2}. However, this model cannot be accepted because of the scarcity and small sizes of continents in the Archaean. Continents seems to have appeared on the Earth barely 2.5-3 Gyr ago (e.g., Veizer,1988). Walker (1985) showed, with the use of the hydrothermal interaction model for the early
Earth’s stage, that the atmospheric CO$_2$ in the early stage reached 10 atm because there was no continent in those days. The silicate weathering model inevitably comes to the conclusion that our planet would have possessed a very thick CO$_2$-atmosphere of above a few bars during the half of its life because of the scarcity of continents (Matsui and Tajika, 1989). The existence of such a thick CO$_2$ atmosphere during almost 2 Gyr was never real on the Earth.

As discussed later, the isotopic data ($\delta^{13}$C/$\delta^{12}$C) assert that the ancient Earth was not abiotic but in a state of global biotic saturation since almost 4 Gyr ago. Carbon isotope records in sedimentary rocks indicate that photosynthesis must have been fully operated by microbial ecosystems for almost 4 Gyr, and that, strange enough, organic carbon would have always been regulated so as to be about one-fifth of the total carbon in the surficial compartment, by ecosystems (Schidlowski, 1988).

We investigated this regulation of the atmospheric CO$_2$ level which looks as to indemnify against the gradual increase of the solar luminosity, proposing quite another model from the Walker cycle. Our results indicated that the CO$_2$ level can be intensely regulated by the biological control and, as described later, the actuality of our hypothesis proposed here would be within the ample bounds of possibility even in the actual Earth’s history.

2. Model

Our model diagram is shown in Fig. 1. There are three boxes. Carbon or CO$_2$ in the biosphere can interact with that in the atmosphere-ocean sphere through photosynthesis and the formation of an organism (this rate is shown by C in the following), and also through respiration and decay (the rate is expressed by E). The biosphere interacts with rocks through burial (D). The atmosphere-ocean sphere exchanges carbon with rocks by means of vulcanism and weathering (G). It was assumed that, within the time step used in our calculation, the dissolution equilibrium of CO$_2$ is accomplished as fast as possible between rocks and ocean, and also between ocean and atmosphere. We also assumed that the biological activity $k$ is a parabolic function of a globally averaged surface temperature $T$ as shown in Eq.(1), where $T$ is estimated, in use of the expression by Walker et al. (1981) as in Eq.(2), under the consideration of a greenhouse effect due to CO$_2$ and H$_2$O, together with the dependence on incident solar flux $S$ (the ratio to the current value). That is,

$$k = C\{1 - a(T_1 - T)^2\}, \quad (1)$$
\[ T = 285 + 2(T_e - T_{e,0}) + 4.6(p/p_0)^{0.364} - 4.6, \]  \hspace{1cm} (2)

and

\[ T_e = S^{1/4}T_{e,0}, \]  \hspace{1cm} (3)

where \( T_e \) is the effective temperature, \( p \) the partial pressure of CO\(_2\) in the atmosphere, \( a \) and \( T_1 \) constants, and suffix 0 means the present condition. Equation(1), that is a peaked growth versus temperature curve, is a universal property of living things.

The faculty of biota was expressed by using the equation about the biological process including internal and mutual antagonism (Nicolis and Prigogine, 1977), because, most fundamentally, the biosphere and the atmosphere-ocean sphere seem to exchange carbon with each other through this principle, \( i.e., \) the mutual relationship between the resources and a consumer. This principle about biotic plenitude reflects the intrinsic property of life to proliferate exponentially to limits ultimately set by the availability of
critical resources. That is, it reflects the fact that biota blooms to limits determined by the resources.

In spite of the dependence of biological activity on many other factors, e.g., temperature (Eq.(1)), phosphorus and so on, the development of the biosphere in the Earth’s history is thought to be primarily controlled by this principle. Here, for example, phosphorus input from the continents may be a determinant of the maximum size of the Earth’s biomass in the present ocean. However, the scarcity and small size of continental areas during the early Earth’s stage suggest that this common idea about the phosphate cycling must not be applied throughout the whole Earth’s history (Schidlowski, 1988).

Because of the finite resource (i.e., carbon), an increase in biota is yielded, most basically, at the sacrifice of this resource in the atmosphere-ocean sphere. On the contrary, death of the consumer brings an increase in the resource. Under the finite resource, development of the biosphere is under the strong control of this principle. These are strict facts in the real world. According to Nicolis and Prigogine (1977), this is a sort of biological antagonism. Photosynthesis is thought to be carried out basically according to this principle. Introduction of this principle into our problem has a deep meaning that the faculty of biosphere, that is, to be alive or to be competent for regulation, should be strongly reflected in this process. This process is shown in the first term on the right-hand side of Eq.(4) or (5). Thus, our proposed system constructs a mathematical system composed of a set of non-linear equations as follows:

\[
dx_b/\!\!\!dt = k x_a x_b - D x_b - E x_b, \tag{4}
\]

\[
dx_a/\!\!\!dt = -k x_a x_b + G x_r + E x_b, \tag{5}
\]

and

\[
dx_r/\!\!\!dt = D x_b - G x_r, \tag{6}
\]

where \( t \) is time, and \( x_b, x_a, \) and \( x_r \) indicate the amount of carbon in the biosphere, atmosphere-ocean, and rocks, respectively.

The procedure used to obtain the solutions was as follows: for a fixed value of \( S \), initial values of \( x_a, x_b \) and \( x_r \) were set at the previous steady state values; the equations were integrated forward in time until a steady state was reached; the value of \( S \) was incremented and the procedure was
repeated. Calculations were performed for various values of the parameters. Some of these results are shown in Figs. 2 to 7. In these figures, the distribution of carbon (%) for each sphere of influence and temperature is plotted as a function of $S$. In the figures, $P_0$ gives a measure of the ratio of the amount of CO$_2$ circulating in the cycle shown in Fig. 1 to the total CO$_2$ existing on the Earth’s crust. Here $P_0$ is expressed by the percentage of the current amount of atmospheric CO$_2$ (0.0003 bar) to the total CO$_2$ cycling through the system shown in Fig. 1. For instance, $P_0 = 0.001$ means that 30 bar of CO$_2$, i.e., about one half of the total CO$_2$ existing on the Earth’s crust, is assumed to be circulating within the cycle shown in Fig. 1. Similarly, $P_0 = 0.01$ corresponds to 3 bar, and $P_0 = 0.1$ to 0.3 bar.

3. Results

Although the partition of CO$_2$ between atmosphere and ocean is thought to be mainly decided by the acidity of the ocean, the historical curves about the changes in this acidity are still not evident. So, we parameterized tentatively this by introducing the partition coefficient PH1 as follows: from the time corresponding to the factor 0.7 of the current solar flux to the time of the factor 0.85 of the current one, i.e., from 4.5 Gyr ago to 2.25 Gyr ago if a linear increase in solar luminosity is assumed, the share of atmospheric CO$_2$ decreases linearly with time from PH1 toward the factor 0.1 of the total amount of CO$_2$ existing within the ocean-atmosphere system following the change in acidity of the ocean. Discontinuities appearing at $S = 0.85$ in the figures are due to this assumption. However, as known easily, the assumption concerning the change in acidity of the ocean does not affect our results (and conclusion) at all. As the standard case, PH1= 1.0 was used in the following calculations.

Figure 2 shows that, within the solar flux range tolerable for life ($S < 0.96$) in which biota can control freely the amount of the atmospheric CO$_2$, the minimum operating point about temperature (MOP) is set up for biota and its environment, independent of variation in temperature dependence of the biological activity (the cases a and b). The reason why this MOP state was set up will be presented later in Concluding Remarks. In the following, we consider the case a as a standard.

Figure 3 indicates that, independent of the magnitude of $P_0$, the Earth’s surface temperature was set close to the MOP condition. As discussed later, the independence of our results on $P_0$ plays a very important role in the establishment of the bio-regulating system on the Earth. Figure 3 also shows that the more $P_0$ increases, the more our eco-system will be impossible for survival, owing to the enormous amount of CO$_2$ for the bio-system to control under a given activity.
Fig. 2. Temperature change of the Earth for the gradual increase in solar luminosity $S$ (abscissa), for variation in temperature dependence of biotical activity $k$. In Case a minimum activities appear both at $5^\circ$C and at $40^\circ$C, and in Case b at $10^\circ$C and $45^\circ$C, which are also written with arrow heads beside ordinate. $C = 0$ means the life-deleted condition. At the dot mark drawn at the end of each solid line, our eco-system is destroyed suddenly and a jump toward the temperature state for $C = 0$ case occurs. Case b can survive longer than Case a, owing to a shift of the biological activity toward higher temperature range. $G = 1$, $D = E = 10$. 
Figure 4 shows that, independent of PH1 and of $P_0$, our eco-system could ingeniously regulate the amount of CO$_2$ in the atmosphere-ocean system against the change of the solar luminosity and keep the Earth’s environment in homeostasis. Until the insolation reached the intolerable point, $S = 0.96$, the CO$_2$ level in the atmosphere-ocean system was regulated significantly at just such a rate as to maintain an equable temperature, i.e., the same MOP states as shown in Fig. 2 or 3. As Fig. 5 also shows, this regulation of CO$_2$ level in the atmosphere-ocean system is a universal phenomenon, independent of the various values in transportation rates. Even if $S$ exceeds 0.96, our eco-system still makes every effort, though now almost fruitlessly, in order to lower the atmospheric CO$_2$ level by increasing the carbon in rocks and biosphere against the increase in the solar flux.

Figures 4 and 5 also explain the reason why there was a smaller size of the biomass on the Earth in the past than in the present. As described later, this was surely due to the result of an atmospheric CO$_2$ level regulation against an increase in the solar luminosity, apart from the problem of evolution. Strangely enough, the start of the break down of the MOP state coincides with the epoch of drastic prosperity of life on the Earth’s surface, i.e., the start of the Cambrian. This implies that, by adding carbon to the biomass, the Earth’s eco-system must have been opposing an increase in the solar luminosity. Although our main purpose of presenting Fig. 5 is to inves-
Fig. 4. Distribution of carbon in each sphere for an increase in solar luminosity \( S \). In spite of changes in values of \( PH1 \), the distribution of carbon in each sphere is ingeniously regulated for all the cases, so as to maintain the same homeostasis as in the standard (Case a) of Fig. 2. \( B \), \( AO \), and \( R \) indicate the biosphere, atmosphere-ocean, and rocks shown in Fig. 1, respectively. As in Figs. 2 and 3, our eco-system is destroyed at the end of each line.
Fig. 5. Same as Fig. 4 but for various changes in transportation rates G, D, and E. Although the various values are taken to those, the same environment as the standard case in Fig. 2 is created in every case.

Investigate the influences of various values of parameters on our bio-regulating model and not to simulate the real data on the Earth, the case for the solid lines is, if anything, thought to be near the actual distribution rate.

Figure 6 shows the dependence of results upon biological activity $C$. As expected, the more active, the more the temperature decreased and the more our eco-system survived, owing to the prompt removal of CO$_2$ from the atmosphere.

As shown in Fig. 7, we investigated the effects of potential biotical activity on regulation, $r$. In this case, the biotical activity $C'$ is defined as follows in the place of $C$ in Eq.(1):
Fig. 6. Same as Fig.2 but for variation in biological activity rate $C$.

\[ C' = C_\text{10} \frac{S-S_0}{S_\text{L}-S_0} \log r, \]

and with this $C'$ the following $k$ is used in the place of Eq.(1):

\[ k = C'\{1 - a(T_1 - T)^2\}. \]

We assumed that at $S = S_0 = 0.74$ biota had come into action and after $S = S_\text{L} = 0.97$, with continuity, $C'$ is fixed to be equal to $C$. Here, $r$ gives the relative ratio of potential biotical activity at $S = S_0$ to that at $S = S_\text{L}$. By the use of $r$, we can parameterize tentatively the temporal development of the biotical activities for regulation or the biological evolution for the ability of regulation. As indicated for the case of $r = 1/1$, by a solid line in Fig. 7, if the potential biotical ability for regulation remained constant, our Earth's environment must have been intensely controlled by biota so as to be in homeostasis from the early Earth's ages. However, as seen in the case
Fig. 7. The averaged temperatures of the Earth's surface adjusted to the dim Sun, when the sizes of biological activity enlarge by degrees with ratios described in the figure within a certain period of time, from 4 Gyr to 0.4 Gyr, which is shown by an arrow head marked with a.

of $r = 1/1000$, if the biological ability was too weak in the early ages, until $S$ reached to 0.84 the Earth's environment is out of biotical control. We can see from Fig. 7 that the greater the biotical ability at $S = S_0$, the longer the Earth's environment can maintain the MOP state (MOP is explained in Section 4 in detail). Figure 7 is in good agreement with some data asserting that the early Earth might have been rather warmer than in the present (e.g., Knauth and Epstein, 1976). Our results suggest that evolution of the biotical ability for regulation may have affected largely the Earth's early environment.

4. Concluding Remarks

It should be stressed that our model does not assume any such explicit feedback mechanism as in the Walker cycle: Only the assumption that temperature influences the biotical activity is required, namely, Eq.(1), which is a universal property of life.

Existence of our proposed bio-controlling system on the Earth from an early stage, not long after the Earth's formation, is not a matter for specula-
tion in the least. There is sufficient evidence that photosynthesis must have existed as a biochemical process for almost 4 Gyr. Recently, from a 3.8 Gyr isotopic record of life $^{13}$C/$^{12}$C ratio in sedimentary rocks as an indicator for the principal carbon-fixing reaction of photosynthesis, Schidlowski (1988) pointed out that the biological control of the terrestrial carbon cycle must have been established very early and was in full operation when the oldest sediments were formed, and also, that over almost 4 Gyr photosynthesis has been an important agent in the geochemical transformations of the Earth's surface. Moreover, his results derived very puzzling conclusions. First, from the long-term near constancy of the $^{13}$C/$^{12}$C ratio over almost 4 Gyr, organic carbon has always been about one-fifth of the total carbon in the surficial compartment throughout the ages. As Schidlowski also said, this means that the ancient Earth could have been in a state of global biotic saturation. Prolific prokaryotic communities probably bloomed to limits ultimately set by the availability of critical resources.

Our results were obtained on the basis of carbon cycling, only relating to organic carbon production. In reality, bio-regulation for carbon cycling must have been much more effective than in our results. This is so, for CaCO$_3$ in the sea has been mostly produced by marine biota in the present and also in the past (Broecker, 1974). Besides our present model, through the control of productivity of CaCO$_3$, marine biota would have strongly regulated the atmospheric CO$_2$ from the early Earth’s stage. As for the changes in the atmospheric CO$_2$, concentration happened in the ice age, Knox and McElroy (1984) proposed the model in which the production of CaCO$_3$ links closely with an activity of the marine biota. A similar process to this may have been expanding in the past. Regulation due to biota would have been stronger than that in the model of organic production only. Introduction of such an effect into our model was the next subject to solve.

The remaining carbon, excluded from our proposing cycle, would circulate making use of the hydrothermal interaction between the ocean-atmosphere sphere and the sea floor at first (Walker, 1985), and produce a large amount of inorganic carbonate rocks. However, it should be emphasized that as soon as carbon appears in the atmosphere-ocean sphere, in the form available for biota, our eco-system starts to control it, and hereafter, carbon enters under the control of our bio-regulating system. Thus, again, carbon must have been redistributed into each sphere of influence so as to maintain homeostasis in the Earth's environment, i.e., so as to keep the amount of atmospheric CO$_2$ nearly invariant in order to hold a temperature constant as compared with the former undisturbed state. Whatever disturbances may happen to our system, our proposing mechanism still keeps our environment in the similar homeostasis, because, as indicated in Fig. 3, homeostasis in our en-
environment is never disturbed by a variation in the magnitude of $P_0$.

For instance, let us suppose that there was CO$_2$ of 12 bar in the atmosphere-ocean system in the early Archaean, before our bio-controlling system appears. By the bye, most of the remaining CO$_2$ of about 50 bar is in the form of inorganic carbonate rocks, and a larger part of CO$_2$ in the atmosphere-ocean system (12 bar) would exist in the air, owing to the high acidity of the early Earth’s ocean: For instance, the abiotic model of Walker, *i.e.*, the hydrothermal interaction cycle described above, estimates a very thick atmosphere composing of CO$_2$ of about 10 bars, in the case of a scarcity of continents (Walker, 1985). However, once our proposed system is established on our planet shown in Fig. 3, the MOP state would appear by and by on the Earth. The case of $P_0 = 0.0025$ corresponds to this case. Thus, about one-fifth of the carbon within the Earth crust would circulate in the organic carbon cycle proposed, so as to regulate the amount of the atmospheric CO$_2$ in order to maintain our environment in homeostasis. This inference is in accord with the records of carbon isotopes that organic carbon has always been about one-fifth of the total carbon in the surficial compartment over almost 4 Gyr. Thus, the existence of such a regulation is conceivable enough even throughout the real Earth’s history extending to the present time.

Here, we must stress again that the above mechanism does universally take effect, independent of its scale, if only the bio-regulating system such as presented here, is existing on our planet. One should also recall the fact that, as described above, the ancient Earth was never abiotic but in a state of global biotic saturation since its early stage.

In Fig. 8, we proposed one model for the transition of carbon (or CO$_2$) on the Earth, which is in harmony with the carbon isotopic data. Before the ocean was created, all the carbon was in the atmosphere in the form of CO$_2$ gas. Once the ocean was formed, atmospheric CO$_2$ would have gradually dissolved into the ocean, with an increase in the pH of the sea. The partition of CO$_2$ between the atmosphere and the ocean strongly depends upon the pH of the ancient ocean. As soon as life appeared on our planet about 4 Gyr ago, the bio-regulating system for the carbon cycle would have been in full operation. From the early stage, the ratio of organic carbon to carbonate carbon was fixed as 1 : 4, as indicated by the isotopic data.

In the early stage, carbonate rocks would have been produced by the abiotic hydrothermal interaction of the ocean-atmosphere sphere with the sea floor, as pointed out by Walker (1985). However, carbon must have been gradually fixed as CaCO$_3$ which was produced in the cells of sea life, together with the intensification of photosynthesis in the Earth’s early times, because speed of calcification of micro-organisms such as algae increases linearly with intensification of photosynthesis (Okazaki and Setoguchi, 1988). Increase of
continental area which had happened some 25 Gyr ago would have also accelerated the CO₂ fixation into CaCO₃ in the cells of marine biota, owing to supply of cations through silicate weathering of land. Today, above 95% of carbonate rocks originate from life.

As summary, we can conclude as follows: (a) until the incident solar flux reaches the intolerable solar flux point \((S < 0.96)\), biota attempt co-existence with the Earth’s environment through the setting of their operating point to the MOP, regulating the atmospheric CO₂ level appropriately. On the contrary, if the operating point of biota rises and sets at a higher temperature, the atmospheric CO₂ will decrease in due time. In consequence, if things go wrong, temperature will decrease to the point to which biota would be incompatible. This conflict between the CO₂ level and the

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Fig. 8. One transition model for carbon on the Earth.
biological activity is the reason why biota prefer and keep the MOP, i.e., the cool side of the optimum for the biota, and its corresponding Earth’s surface temperature in homeostasis; (b) when the solar flux reaches the intolerable point for biota, i.e., $S = 0.96$ according to our result, even an amount of the atmospheric CO$_2$ nearly equal to zero is too large to maintain the MOP condition. Our bio-regulating system must resist the increase in solar flux by lowering the atmospheric CO$_2$ level. However, as described above, the appropriate level of the CO$_2$ reserved for the bio-regulation against the increase in solar radiation is now too low to preserve the MOP condition. After this, although biota do their best so as to lower the CO$_2$ level in the atmosphere and to survive as long as possible by transporting carbon into the biosphere and the rocks, the increasing solar flux will overcome the effort of biota in due time. This will be the ruin of our bio-regulating system, certainly. This sad prediction is in good accordance with that of Lovelock and Watson (1982). According to our present model calculation, our eco-system would now be on the way to ruin, having already left the MOP state in former days, i.e., some six hundred million years ago or so, which, strange enough, coincides with the epoch of the drastic prosperity of life on the Earth’s surface.

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