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Daisyworld

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Abstract

In this thesis, the planetary model of daisyworld is studied. First of all we explain the Gaia theory. According to this theory, life and environment are seen as two parts of a coupled system. The environment has the variables Earth and regulation of temperature. They are too complex to be modeled mathematically, and therefore we consider a "Daisyworld" model. In this model the planet is covered by only two daisies (black and white) and the growth rate of daises, their local temperature and also the effect temperature is described using mathematical equations. Furthermore we consider the albedo effect on the temperature, the stabilization of the model and the relevancy of the model to the Earth.

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1 Introduction

Daisyworld is a planetary model which is suggested by James Lovelock and Andrew Watson to show the long-term effect of connection between biota and its environment. This model is presented in defence of the Gaia theory. The Gaia theory suggests that the Earth behaves like a single organism and the biosphere has a self-regulatory effect on the Earth's environment. There has been a lot of criticism on the Gaia theory and Daisyworld was presented to defend the Gaia theory. It is a suitable tool to understand the feedback loop which can control the climate system (temperature). Daisyworld illustrates that a self-regulated planet can exist without any need for foresight or planning on the organism.

This artificial world is made of two species of daisies, black or white daisies. The environment of the daisies is reduced to only one variable, which is temperature. The planet surface temperature is determined by the solar luminosity and the daisies albedo. We will see that this model is described in nonlinear equations. Both daisies have the same growth rate (β in section 3.2). The growth rate is a function of the local temperature. In this thesis we will study the stability of daisies population and the local temperature. We will observe the behaviour of these solutions by increasing the solar luminosity.

Moreover we will see that when the luminosity increases, the black daisies will grow less and the white daisies will grow more. Therefore the white daisies can maintain a better temperature balance. However there exists a negative feedback which cools down the Earth's surface. This happens when the black daisies increase in comparison with the white daisies. We conclude that however the white daisies tend to be eliminated, an effective homeostasis will be retained with black daisies (only one species).

2 Gaia hypothesis

The name of Gaia comes from the primal Greek goddess which personalizes the Earth. In its Greek version known as Mother Nature or Earth Mother [Lovelock (2009)].
The Gaia hypothesis also known as Gaia theory, was proposed by the English scientist, environmentalist James Lovelock and developed in the 1970s by the

American microbiologist and bacteriologist Lynn Margulis.
Gaia theory suggests that organisms are coupled with their inorganic environment on the Earth to form a self-regulating system, and claims that this whole system (which is called Gaia) provides a suitable chemical and physical environment for current life. So this theory tells us how the biosphere and the changes in the form of life have influence on the stability of global temperature, ocean salinity, oxygen in the atmosphere and other environmental elements. [Lovelock (1972), Wiman et al. (1990)]

The planetary homeostasis which has been influenced by living organism is observed in the field of bio-geochemistry. Moreover it is also studied in Earth system science, where the interactions between the atmosphere, hydrosphere, biosphere etc, is considered [Harris and Murton (2005)].

2.1 History Of Gaia

William Golding suggested to James Lovelock the word Gea as a name for this theory. He suggested this because Gea it is the first part of the words geology, geophysics and geochemistry [Lovelock (2009)]. James Lovelock called his proposition the Gaia hypothesis (or Gaia theory), this hypothesis has been supported by a number of theoretical experiments and brought out a lot of scientific predictions [Lovelock (1990), Volk (2004)].
In the eighteenth century, as geology build up as a modern science, the interconnection between geological and biological processes was carried out by James Hutton [Capra (1996)], and in the twentieth century, the Ukrainian geo-chemist Vernadsky suggested the theory of Earth's development. He was one of the first scientists to notice that the oxygen, nitrogen, and carbon dioxide in the Earth's atmosphere are outcomes or results of organic activities [Weart (2003)]. One of his theories was that living organisms could reshape the planet like any physical force. This vision was not accepted in the west [Weart (2003)].
James Lovelock presented in September 1965 a concept of the idea that a self-regulating Earth is in general controlled by living organisms, while he was working at the Jet Propulsion Laboratory in California to study the possibility of the life on Mars [Lovelock (1965, 1989)]. Lovelock published the Gaia Hypothesis in journal articles in 1972 and 1974 [Mcphie and Clarke (2015)]. It became well known in the book Gaia (1979) "A new look at

life on Earth" [Lovelock and Lovelock (2001)]. The Gaia hypothesis received lots of positive and negative attention, or in other words scientific and critical [Bittarello (2008)].

At first he called the theory the Earth feedback hypothesis. It was a way to express the combination of chemicals that include oxygen and methane and their concentration in the atmosphere of the Earth [Lovelock and Lovelock (2001)].
In 1971 microbiologist Dr.Lynn Margulis started to work together with Lovelock to trying to prove scientifically the primary Gaia hypothesis. She also dedicated the last of eight chapters of her book which called The Symbiotic Planet, to Gaia.

2.2 Regulation of the salinity of the oceans and oxygen in the atmosphere

In the oceanic environments salinity stability is very important for many organisms and cells. They can not stand for a value more than 5% hence for a long time this stability remained about 3.4%. The salinity of ocean was a mystery because the balance of salt stream from rivers was unknown. Lately it was shown that the seawater circulation among the hot basaltic rocks can have effect on the salinity stability [Gorham (1991)].
For Earth's atmosphere, Gaia proved that by the existence of life the composition of Earth is retained at a dynamically steady state and atmospheric combination provide a condition that current life is shaped. All atmospheric gases apart from noble gases are made by living organism or processed by them [Lovelock (2009)].
But the stability of Earth's atmosphere is not the outcome of chemical equilibrium. Oxygen is in the long run combined with the gases and minerals of the Earth's atmosphere and crust and it was in small quantities circa 50 million years before the start of the Great Oxygenation Event [Anbar et al. (2007)]. Since the start of Cambrian period, the Oxygen concentrations in atmosphere is undulate between 15% and 35% of atmospheric content [Berner (1999)].

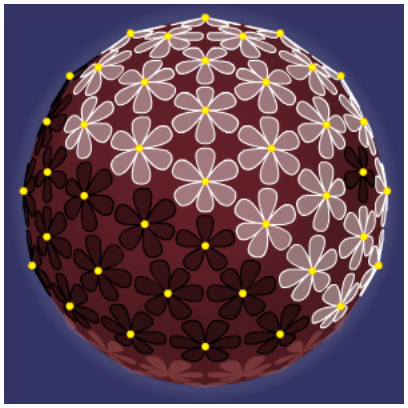
2.3 Regulation of the global surface temperature

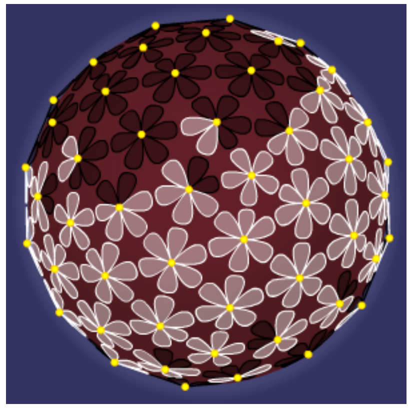
Scientists say that from the beginning of life on Earth the energy of sun is increased by 25% to 30% but the temperature of surface always stayed at a level of habitability [Owan et al. (1979)].
The Claw hypothesis, which has been inspired by Gaia, presents a feedback loop between The Earth's climate and ocean ecosystems [Charlson et al. (1987)]. Specifically it says that the change of climate is caused by di-methyl sulfide which is produced by particular phytoplankton, this can operate a stabilize temperature for Earth's atmosphere.
So the increase of human population and changes in the environmental activities such as reproduction of greenhouse gases causes the negative feedback in the environment, therefore Lovelock posed that these changes maybe causing the global warming [Lovelock (2009)].

2.4 Criticism to Gaia hypothesis

Gaia hypothesis was criticized by many of scientists such as Ford Doolittle, Richard Dawkins and Stephen Jay Gould. Whereas the hypothesis was supported by many non-scientists [Turney (2003)]. Many of the criticism was toward his book which called "A New Look at Life on Earth ".Lovelock replied to this criticism that "Nowhere in our writings do we express the idea that planetary self-regulation is purposeful, or involves foresight or planning by the biota" [Lovelock (2000)].
Stephen Jay Gould criticized that Gaia is a "metaphor", not a "mechanism" [Gould (1988)]. Moreover David Abram, an American philosopher and cultural ecologist, discussed that Gould has connived this fact that mechanism, itself, is a metaphor but this is a very common unknown metaphor. Lovelock replied that the relations between the diverse known mechanisms may not be always known and no single mechanism is responsible. This is accepted as a consequence in other fields of biology and ecology [Abram (1991), Smith (2012)].
Furthermore Lovelock explained that many of the criticism on the hypothesis is lack of understanding of non-linear mathematics and that is idealistic that all events can be explained by special causes. He also noted that many of his critics are biologists but Gaia hypothesis contains experiments outside of the field of biology Furthermore, he expressed that sometimes self-regulating nat-

ural phenomena is not mathematically interpretable [Lovelock and Lovelock (2001)].





3 Daisyworld

The Earth is too complex to be expressed mathematically, therefore Lovelock defined and constructed daisyworld model in mathematical form. In this model, many of the complexity has been ignored and only the fundamental relationships and characteristics are remained. The life on Earth is simulated with two kinds of daisies (black and white). Daisyworld shows that there is no need for the development of communication between species and planning, in order to attain planetary homeostasis.

First of all we define two concepts which can help us to understand the daisyworld model:

- Albedo: This means how an object can reflect the light, if Albedo 1 or 100% it is a perfect reflector and if Albedo 0 it is a perfect absorber [Webster (Webster)].

- Luminosity: This is the amount of light which is considerable in a unit of area [Hopkins (1976)].

3.1 Description of the model of Watson and Lovelock

Daisyworld is a mathematical model to give an impression of The Earth-sun system. It is an artificial world, presented by James Lovelock and Andrew Watson, that was published in 1983 to show the possibility of Gaia theory and introduced by two kinds of daisy (black and white), using them as a symbol for life [Watson and Lovelock (1983)].

White daisies reflect the light and black daisies absorb the light. This model describes the population of daisies and the surface temperature of planet as the sun's rays grow more strongly. The energy budget which calculates how many energy comes from sun to Earth's climate and how many is lost into space is here shown in the equation (6) [Watson and Lovelock (1983)].

The colour of daisies have effect on the albedo, in such a way that the black daisies absorb light and make the planet warmer but the white daisies reflect the light and make the planet cooler. So this rivalry between two daisies which is based on the Albedo makes balance in population of daisies and tends to result in a suitable planetary temperature.

For the first step of model, the daisyworld is too cold, the sun's ray is not strong enough to support any life and the surface is barren. As the luminosity of the sun's rays increases, the black daisies begin to grow and they absorb more light energy. They are able to increase the local temperature. Later as the surface heats up, the white daisies begin to grow in a competition with the black daisies in such a way that the population of two daisies reach an equilibrium and in a co act they put the surface temperature in order.

For the second step of the model, we see what happens if the sun's luminosity begins to increase. This means that the daisyworld surface becomes warm and this causes white daisies to grow more. They make the surface cooler because of their high albedo to reflect the light. Slowly the black daisies are replaced by white daisies and at end we see that the Daisyworld's surface temperature remains residential for life, as the sun's luminosity continuous to increase.

For the third step of model there is a continuous increase of sun's rays. the white daisies can not survive and at a determined luminosity their population decline. the barren surface of Daisyworld cannot longer reflect the sun's light and quickly becomes warmer and warmer. At this point of the simulation the sun's luminosity is programmed to decrease and to go back to its initial value. And at the end, the decrease of sun's ray causes a comfortable level which allows the white daises to grow again, resulting in a cooler planet [Watson and Lovelock (1983)].

3.2 The mathematical Equations for Daisyworld

The mathematical model for Daisyworld is represented by a group of equations, which show the relative growth of daisies.
In these equations α_b and α_w represent the surface of planet which is covered by black daisies and white daisies and x is a fertile soil that is not covered by either species.
the birth rate of the daisies on the fertile ground is β which is the same for both daisies. Moreover γ is the death rate per unit of time and p is the proportion of the planet's surface which is suitable for daisies to grow [Watson and Lovelock (1983)].

$$\begin{aligned} \frac{d\alpha_w}{dt} &= \alpha_w(x\beta - \gamma) \\ \frac{d\alpha_b}{dt} &= \alpha_b(x\beta - \gamma) \\ x &= p - \alpha_b - \alpha_w. \end{aligned} \tag{1}$$

The growth rate of daisies β_l is supposed to be a function of local temperature:

$$\beta_l = 1 - 0.003265(22.5 - T_l)^2. \tag{2}$$

This growth rate is a function of the temperature and this is zero when the local temperature is equal to $5°C$ and $40°C$, but its maximum value will be obtained when the temperature is $22.5°C$. The following equation show the effective temperature of planet(T_e) with the albedo and solar Luminosity:

$$\sigma(T_e + 273)^4 = SL(1 - A), \tag{3}$$

where σ is the Stefan Boltzman constant, S is a constant of units of flux, L is a dimensionless value of luminosity coming from the sun and A is the global albedo of planet.

The next equation is about the global albedo of surfaces which are covered by black daisies, white daisies and bare ground [Watson and Lovelock (1983)].

$$A = \alpha_g A_g + \alpha_w A_w + \alpha_b A_b, \tag{4}$$

with $\alpha_g = (1 - \alpha_w - \alpha_b)$ and A_b and A_w is the albedo of the planet covered by black daisies and white daisies.
We define the value of $A_g = 0.5$, $A_b = 0.25$ and $A_w = 0.75$ and we suppose that $A_w > A_g > A_b$. (i.e white daisies reflect more light than black daisies).

With the help of the variables defined above, the local temperature of two species would be fixed. If we then assume that the black daisies are warmer than the white daisies, we have:

$$(T_l + 273)^4 = q(A - A_l) + (T_e + 273)^4, \tag{5}$$

where q is a positive constant and shows the degree of sun's ray which are absorbed by the planet. Instead of T_l we can write $T_{(b,w)}$ which is the temperature of black daisies or white daisies. In the same way $A_{(b,w)}$ shows the albedo of the surface with black or white daisies (consider that $T_b > T_g > T_w$), the equation 5 can keep the balance of energy in the planet [Watson and Lovelock (1983)].

The equations below shows the whole energy and radiation which is emitted into space.

$$\begin{aligned} F &= \Sigma_l \alpha_l \sigma \cdot (T_l + 273)^4 \\ &= \Sigma_l \alpha_l \sigma (q(A - A_l)) + (T_e + 273)^4 \\ &= \Sigma_l \alpha_l \sigma q A - \Sigma_l \alpha_l \sigma q A_l + \Sigma_l \sigma_l \sigma \cdot (T_e + 273)^4 \\ &= \sigma q A \Sigma_l \alpha_l - \sigma q \Sigma_l \alpha_l A_l + \Sigma_l \alpha_l \sigma (T_e + 273)^4. \end{aligned} \tag{6}$$

If we assume that $\Sigma_l \alpha_l = 1$ and also $\Sigma_1 \alpha_l A_l = A$ then it will be equal to $F = \sigma(T_e + 273)^4$ [Watson and Lovelock (1983)].
Because of the fact that local temperature of black and white daises are always changing in the limit $22.5 \pm 17.5°$, we prefer to choose linear estimation to equation 5, For this purpose we have from the first order Taylor polynomial : $(1 + x)^\alpha \approx 1 + \alpha x$ for $\mid x \mid < 1$.

$$
\begin{aligned}
(T+273)^4 =&((T-22.5)+273+22.5)^4 \\
=&(273+22.5)^4.(\frac{T-22.5}{273+22.5}+1)^4 \\
=&(273+22.5)^4.(1+\frac{4}{273+22.5}(T-22.5)).
\end{aligned}
\tag{7}
$$

So we can apply the above equation to equation 5 for both T_l and T_e:

$$
\begin{aligned}
(273+22.5)^4.(1+\frac{4}{273+22.5}(T_l-22.5)) &= q(A-A_l)+(273+22.5)^4(1+\frac{4}{273+22.5}(T_e-22.5)) \\
1+\frac{4}{273+22.5}(T_l-22.5) &= \frac{q(A-A_l)}{(273+22.5)^4}+1+\frac{4}{273+22.5}(T_e-22.5) \\
T_l-22.5 &= \frac{q(A-A_l)}{(273+22.5)^4}+T_e-22.5 \\
T_l &= \frac{q(A-A_l)}{4(273+22.5)^3}+T_e.
\end{aligned}
\tag{8}
$$

then we have:

$$
T_{b,w}=q'(A-A_{b,w})+T_e, \tag{9}
$$

where $q'=\frac{q}{4(273+22.5)^3}$

So we assume that A is omitted in equation (3) and (5) therefore from equation 3 we can see that :

$$
\begin{aligned}
\sigma(T_e+273)^4 &= SL-SL(A) \\
SL(A) &= SL-\sigma(T_e+273)^4 \\
A &= 1-\frac{\sigma}{SL}(T_e+273)^4 \\
(T_l+273)^4 &= q(1-\frac{\sigma}{SL}(T_e+273)^4-A_l)+(T_e+273)^4,
\end{aligned}
\tag{10}
$$

Then we have:

$$(T_l + 273)^4 = q(1 - A_l) + (1 - q\frac{\sigma}{SL})(T_e + 273)^4. \quad (11)$$

If we put $q = 0$ in the above equation we observe that the local temperature is equal to the effective temperature and that this makes a perfect transfer between higher and lower temperature [Watson and Lovelock (1983)].

If we put $q = \frac{SL}{\sigma}$, we can see that in this case the temperatures are at steady state between local absorption and local radiation to space [Watson and Lovelock (1983)]. Now we take the value of q equal to $0.2\frac{SL}{\sigma}$. It can be seen that if we set $q > \frac{SL}{\sigma}$ then $q(\frac{\sigma}{SL}) > 1$ so $(1-q)(\frac{\sigma}{SL}) < 0$ therefore in the equation (11) if T_e increases then T_l has to be decreased and if T_l reduces then T_e has to be increased so the suitable amount for q is $0.2\frac{SL}{\sigma}$.

4 The steady state behaviour of model

The analysis of daisyworld model is not trivial because the equations of daisyworld are non linear system. The steady state solution of daisyworld is focused on two daisy states which shows homeostasis over a major range of solar luminosities [Watson and Lovelock (1983)].
So we consider the non zero steady state solutions of equation (1), then we see that:

$$\frac{\alpha_w}{dt} = \alpha_w(x\beta_w - \gamma) = 0$$
$$\frac{\alpha_b}{dt} = \alpha_b(x\beta_b - \gamma) = 0 \quad (12)$$

We denote the steady states with asterisks [Watson and Lovelock (1983)].

$$x^*.\beta_b^* = \gamma.$$

$$x^*.\beta_w^* = \gamma. \quad (13)$$

$$x^*.\beta_b^* = x^*.\beta_w^*. \tag{14}$$

From the equation (14) we have for steady state growth parameter of black and white daisies :

$$\beta_b^* = \beta_w^*. \tag{15}$$

The equation below is obtained from equation (2) so:

$$\begin{aligned}
\beta_b^* &= 1 - 0.003265(22.5 - T_b^*)^2 \\
\beta_w^* &= 1 - 0.003265(22.5 - T_w^*)^2 \\
1 - 0.003265(22.5 - T_b^*)^2 &= 1 - 0.003265(22.5 - T_w^*) \\
(22.5 - T_b^*)^2 &= (22.5 - T_w^*)^2.
\end{aligned} \tag{16}$$

$$T_b^* - 22.5 = 22.5 - T_w^*. \tag{17}$$

From equation (9) we obtain:

$$\begin{aligned}
T_b^* - T_w^* &= q'(A - A_b) + T_e - q'(A - A_w) - T_e \\
&= q'(A - A_b - A + A_w).
\end{aligned} \tag{18}$$

$$T_b^* - T_w^* = q'(A_w - A_b). \tag{19}$$

And from equation (19) we get:

$$\begin{aligned} T_b^* &= T_w^* + q'(A_w - A_b) \\ &= 2(22.5) - T_b^* + q'(A_w - A_b) \\ 2(T_b^*) &= 2(22.5) + q'(A_w - A_b). \end{aligned} \tag{20}$$

$$\begin{aligned} T_w^* &= T_b^* - q'(A_w - A_b) \\ &= 2(22.5) - T_w^* - q'(A_w - A_b) \\ 2(T_w^*) &= 2(22.5) - q'(A_w - A_b). \end{aligned} \tag{21}$$

$$T_b^* = 22.5 + \frac{1}{2}q'(A_w - A_b). \tag{22}$$

$$T_w^* = 22.5 - \frac{1}{2}q'(A_w - A_b). \tag{23}$$

Now we can easily see that steady state with this assumption that $\alpha_b > 0$ and $\alpha_w > 0$, exists and that it is stable for a large range of initial values, where we supposed that T_w^* and T_b^* are both constant [Watson and Lovelock (1983)] .
We can show that a steady state exists and that it is stable for a large range of parameters, so for this purpose we integrate the equations.
From the differentiation of equation (11) it would be seen:

$$\begin{aligned} (T_l^* + 273)^4 &= q(1 - a_l) + (T_e^* + 273)^4 \times (1 - \frac{q\sigma}{SL}) \\ 0 &= 0 + 4(T_e + 273)^3 . \frac{dT_e^*}{dL}(1 - \frac{q\sigma}{SL}) + (T_e^* + 273)^4 . \frac{q\sigma}{SL^2} \\ 0 &= 4(T_e^* + 273)^3 . [\frac{dT_e^*}{dL}(1 - \frac{q\sigma}{SL}) + (T_e^* + 273) . \frac{q\sigma}{4SL^2}] \\ \frac{dT_e^*}{dL} &= \frac{-q\sigma(T_e^* + 273)}{4SL^2(1 - \frac{q\sigma}{SL})}. \end{aligned} \tag{24}$$

We can see that the steady state planetary temperature T_e^* will decrease when we have increase in solar Luminosity [Watson and Lovelock (1983)].

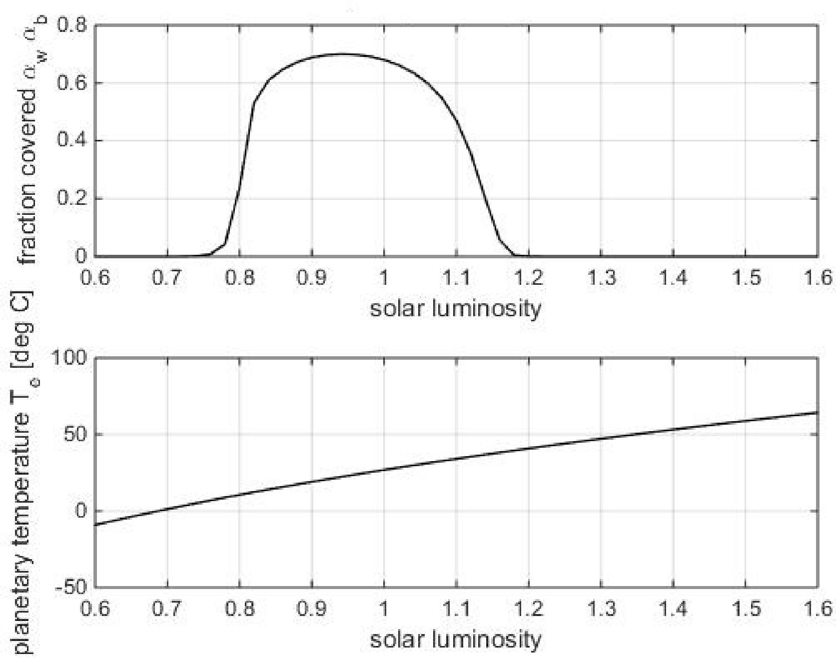


Figure 1a: shows the growth of neutral daisies (with albedo 0.5) as the luminosity increases.

4.1 Analysis of Model

The analysis of the daisyworld model is shown in four Figures for specific cases.

In Figure 1a, we have reaction for only one species daisy and the daisy albedo is the same as the ground (for albedo 0.5), therefore absence or presence of daisies does not make any difference to the temperature. In Figure 1b, we observe only the growth of black daisies. Here, only one species and the changes in homeostasis temperature is considered.
Figure 1c shows the reaction for only white daisies, with increasing and decreasing of luminosity. Figure 1d shows the behaviour of the complete model

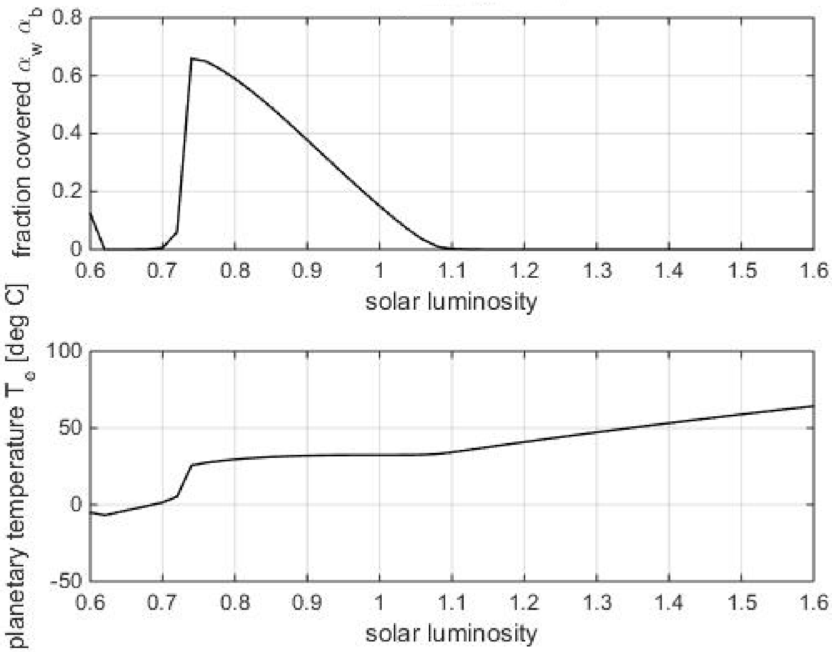


Figure 1b: Shows the growth of black daisies (albedo 0.25) as the luminosity increases.

which presents the stable region of two species of daisies, furthermore we consider the decreasing of effective temperature when the luminosity is increasing [Watson and Lovelock (1983)].
Therefore in Figure 1a,1b,1c,1d, the steady state T_e and also the areas which are covered by black and white daisies, has been shown as the luminosity increases or decreases [Watson and Lovelock (1983)].

For each of the four cases we have integrated the model to steady state with attention to time-dependent solution and this procedure is repeated. For this purpose the initial values of α_b and α_w are set at the previous steady state or, if they are zero then they would be equal to 0.01. Furthermore in the first step the value of luminosity L is fixed and will be incremented for the next steps [Watson and Lovelock (1983)].

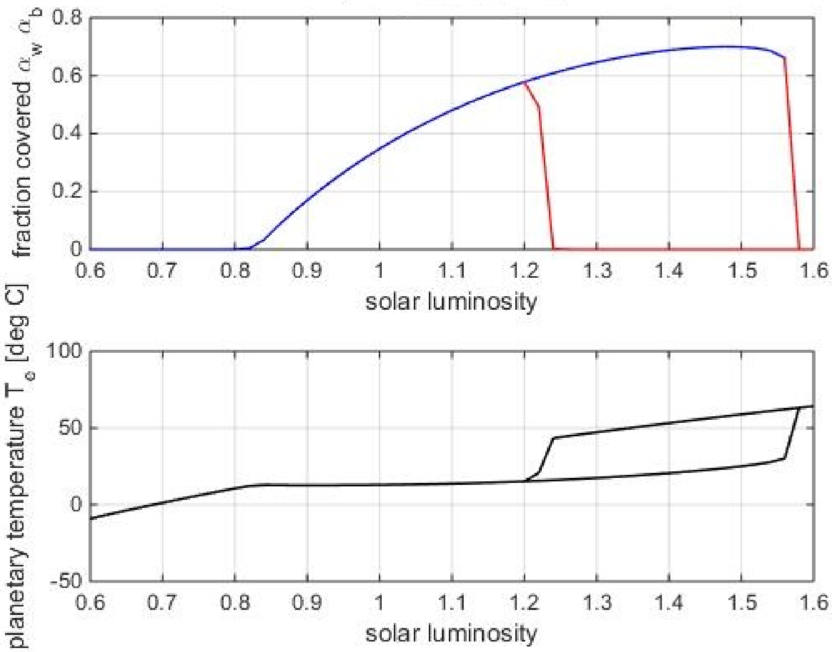


Figure 1c: shows the growth of white daisies (with albedo 0.75) as luminosity decreases or increases.

4.2 Feedback loop in daisyworld

As we know, white daisies are cooler than black daisies. Both daisies have the same growth rate but the albedo of each daisy has the ability to change the local temperature on the planet of the daisies.

When the planet is cool, the growth of black daisies increases so they warm up the planet and their population increases rapidly and tend to increase the local temperature (negative feedback). For the positive feedback the white daisies grow with the increase of sun's ray and their high albedo can reduce the local temperature, therefore we have increase in the population of white daisies. We can conclude that the daisies cause the temperature variation on the planet. we see that when a certain kind of daisies are more favorite than another, we have a temperature feedback [Watson and Lovelock (1983)].

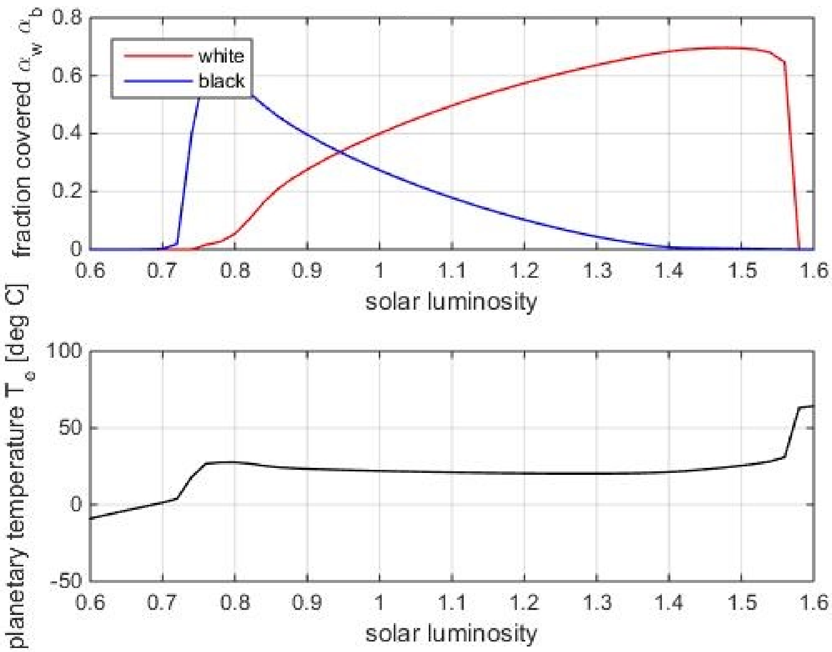


Figure 1d: shows complete model white and black daisies as luminosity increases.

Now we focus on what happens if we make a change on negative feedback so we contrive to make that black daisies cause a cooler planet.

Due to a suitable change the clouds appear on daisy world. We suppose that clouds, made by rising air, can appear over black daisies. With this assumption the black daisies don't cause the increase of the temperature anymore. Therefore, when there are more black daisies, there will be more clouds and it will be cooler, this assumption is showed in Figure 2.
Under this new condition the white daises will be eliminated, because in a competition with black daisies they can not survive anymore. With this change of direction there exists no more white daisies but the black daisies are still able to homeostasis [Watson and Lovelock (1983)].

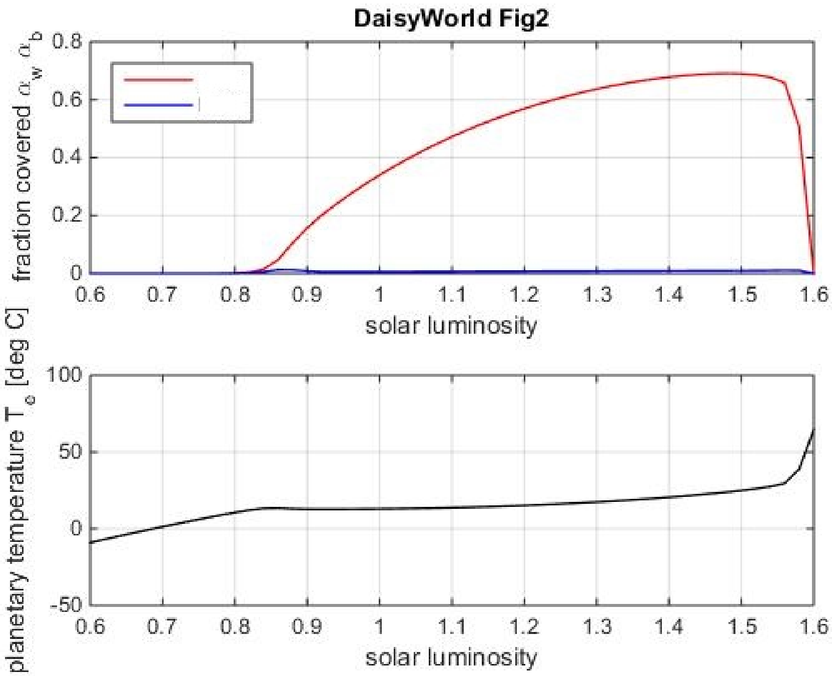


Figure2: shows the steady state output derived for complete model when clouds appeare

5 Conclusion and Relevance to the Earth

Now considering the relationship between the Daisyworld and the Earth, we can observe that the biota by producing of greenhouse gases have effect on the Earth's temperature. Recently the increase of atmospheric CO_2 is considerable. To determine the mean temperature of the Earth, suppose that the only effect of life on Earth is reduction of CO_2 and we observed that the existence of biota causing limit in the temperature. Hence this decreasing tend to the barren area, and we will also see a decrease of biological activity over the whole Earth, whereas for increasing of temperature we have the opposite effect [Watson and Lovelock (1983)].

The decreasing of Biological activity will result in the decreasing of CO_2. To neutralize these changes, CO2 should be increased. Hence we will see a temperature stabilization system for the Earth, like the one that we have seen in Daisyworld. We can conclude that the mechanisms, mentioned above, can have a role in the regulation of temperature and other environmental variables [Watson and Lovelock (1983)].

6 Appendix

```
function [alpha_w, alpha_b] = DaisyWorld(L_vec, albedo, fig_num)
% Watson & Lovelock Tellus 1983
% Fig 1A [alpha_w, alpha_b] = DaisyWorld(0.6:0.02:1.6, [0.50, 0.50, 0.50], '1A');
% Fig 1B [alpha_w, alpha_b] = DaisyWorld(0.6:0.02:1.6, [0.25, 0.50, 0.25], '1B');
% Fig 1C
%   Lvec = [0.6:0.02:1.6, 1.6:-0.02:0.6]
%   [alpha_w, alpha_b] = DaisyWorld(Lvec, [0.75, 0.50, 0.75], '1C');
% Fig 1D [alpha_w, alpha_b] = DaisyWorld(0.6:0.02:1.6, [0.75, 0.50, 0.25], '1D');
% Fig 2  [alpha_w, alpha_b] = DaisyWorld(0.6:0.02:1.6, [0.75, 0.50, 0.80], '2');

% Input:L_vec 1 by N  range of solar luminosities []
%      albedo 1 by 3  albedo of white, background and black []
%      fig_num  1 by 1  string of figure number in Watson & Lovelock 1983
%Output:alpha_w 1 by N  fractional area covered by white daisies []
%       alpha_b 1 by N  fractional area covered by black daisies []


% function dw implements equations 1-7 of Watson & Lovelock
function dalpha = dw(~, alpha)
    A = (1 - alpha(1) - alpha(2))*Ag + alpha(1)*Aw + alpha(2)*Ab;
    Te = -273 + (S*L*(1-A)/sigma)^(1/4);
    Tw = qp*(A - Aw) + Te;
    Tb = qp*(A - Ab) + Te;
    Bw = 1 - 0.003265*(22.5 - Tw)^2;
    Bb = 1 - 0.003265*(22.5 - Tb)^2;
    dalpha = [alpha(1)*((p - alpha(1) - alpha(2))*Bw - gamma); ...
               alpha(2)*((p - alpha(1) - alpha(2))*Bb - gamma) ];
end
```

```
% parameter values from legend of Figure 1D
S = 9.17*10^5; sigma = 5.67032*10^-5;
gamma = 0.3; p = 1.0; qp = 20.0;
Aw = albedo(1); Ag = albedo(2); Ab = albedo(3);

% initialize variables
NL = length(L_vec); t_final = 10;
L = L_vec(1); [~, alpha] = ode45(@dw, [0, t_final], [0.5, 0.5]);
alpha_w = zeros(NL, 1); alpha_b = zeros(NL, 1);
alpha_w(1) = alpha(end, 1); alpha_b(1) = alpha(end, 2);
for i_L = 2:NL, % loop over L the solar luminosity
L = L_vec(i_L); init_val = [max(alpha_w(i_L-1), 0.01), max(alpha_b(i_L-1), 0.01)];
[t, alpha] = ode45(@dw, [0, t_final], init_val);
   alpha_w(i_L) = alpha(end, 1); alpha_b(i_L) = alpha(end, 2);

%     figure(1); clf; set(gcf, 'DefaultLineLineWidth', 1);
%     plot(t, alpha(:,1), 'r', t, alpha(:,2), 'b'); grid
%     title('DaisyWorld'); ylabel('alpha'); xlabel('time [au]')
end
% calculate planetary temperature T_e
A = (1 - alpha_w - alpha_b)*Ag + alpha_w*Aw + alpha_b*Ab;
Te = -273 + (S*L_vec'.*(1-A)/sigma).^(1/4);

figure(2); clf; set(gcf, 'DefaultLineLineWidth', 1);
subplot(2, 1, 1);
if (albedo(1) == albedo(3)),
    plot(L_vec, alpha_w + alpha_b, 'k'); grid;
end
if (albedo(1) ~= albedo(3)),
    plot(L_vec, alpha_w, 'r', L_vec, alpha_b, 'b'); grid
    legend('white', 'black', 'Location', 'NorthWest');
end
title(strcat('DaisyWorld Fig ', fig_num));
ylabel('fraction covered \alpha_w \alpha_b'); xlabel('solar luminosity')

subplot(2, 1, 2);
plot(L_vec, Te, 'k'); grid
ylabel('planetary temperature T_e [deg C]'); xlabel('solar luminosity')
```

```
end
```

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