Planetary and Space Science 57 (2009) 491–497

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

On the homeostasis and bistability on a Gaian planet

Peter Nørtoft Nielsen, Peter Ditlevsen *

The Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen O, Denmark

ARTICLE INFO

Article history:
Received 3 April 2008
Received in revised form
5 September 2008
Accepted 15 October 2008
Available online 11 November 2008

Keywords:
Daisyworld
Gaia
Planetary habitability
Homeostasis
Climate–biosphere interaction

ABSTRACT

Geochemical disequilibrium of Earth's atmosphere is a sign of life. The fact that Earth's atmosphere is just right for life led Lovelock to propose the Gaia hypothesis: life itself regulates the environment on planetary scale in order to maintain habitability. This hypothesis is supported by the so-called Daisyworld parable, which illustrates a possible mechanism for such a self regulation. Here we revisit Daisyworld and challenge some of its conclusions from a closer examination of the model. We find that even within this simple, conceptual model of a Gaian planet there are regimes where climate is *less* homeostatic than on a dead planet. Furthermore, in other regimes, bistability between two climate states is found to exist due to the presence of life. This indicates that even if the Gaian stability might describe life in some planetary conditions, it need not be generic to all inhabited planets.

1. Introduction

As extra solar planets are discovered by the week, and even detecting the planetary atmospheric compositions is within reach, the search for signs of life is of renewed interest. On Earth, the habitability required for the planet's biota to thrive depends strongly on the friendliness of the environment. On the other hand, the planetary environment is influenced by the presence of the biota; the present state of the environment on Earth, such as the surface temperature, the atmospheric oxygen, carbon dioxide, and methane levels, are to a large extent governed by the biota. They would drift to a different state of geochemical equilibrium in the absence of a biota. Geochemical disequilibrium of the atmosphere is thus a sign of life. These observations led Lovelock to propose that the biota itself tends to create a state of homeostasis of the global environmental in a beneficial way for the biota itself. This is the Gaia hypothesis (Lovelock and Margulis, 1974), which we shall consider the "strong Gaia" hypothesis. The "weak Gaia" hypothesis is merely the statement that the biota and its global environment have a mutual influence on each other. A recent discussion of the Gaia theory is presented by Volk (2002), Kleidon (2002), Lenton (2002), and Kirchner (2002).

Watson and Lovelock illustrated the strong Gaia hypothesis by use of the imaginative Daisyworld model (Watson and Lovelock, 1983, hereafter denoted WL83). In Daisyworld, only two species exist: black daisies and white daisies. The surface temperature is governed by the balance between incoming and outgoing radiations, as on any other planet. The net incoming radiation, and in turn the temperature, depends on the planetary albedo, which is determined by the areal covers of black and white daisies. The growth rates of the two kinds of daisies depend on the temperature; thus there is a feedback between surface temperatures and the areal covers of the two different types of daisies. Watson and Lovelock found the results of these interactions to be a stability of the surface temperature with respect to external perturbations, here changes in solar luminosity: when the solar luminosity is increased, the planet should get warmer; however, on the inhabited Daisyworld the areal cover of black daisies falls off, and the areal cover of white daisies grows, in response to the increasing solar luminosity, thereby increasing the reflection; as a result, the temperature remains strikingly unaffected by the increasing solar luminosity. This is a classical homeostatic response of a system to an external perturbation.

The radiation balance itself, without a planetary albedo depending on the biota, sets the surface temperature through the radiative feedback: when the planet gets warmer, the outgoing long-wave radiation increases (as fourth power of temperature), leading to cooling and vice versa. This means that the temperature grows only with a power of $1/4$ of the solar luminosity. So, in order for the biota to be homeostatic, it should influence temperature in such a way that it increases less than the benchmark power of $1/4$ with increasing solar luminosity. That is indeed the case for the Daisyworld solution when both types of daisies are present. A closer examination of Daisyworld, however, shows that the situation is not quite as simple even for this constructed model. Stable solutions exist with only one kind of daisies present, which are not homeostatic in this sense. Furthermore, there are regimes in the external perturbation for

---

* Corresponding author. Tel.: +45 28750603.
E-mail address: pditlev@gfy.ku.dk (P. Ditlevsen).

0032-0633/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2008.10.010

which the temperature could actually jump between two different climate states due to the existence of multiple stable solutions, one with only white daisies present and one with only black daisies present. This could indicate that Gaian stability is not generic for inhabited planets.

2. Life and climate in Daisyworld

Daisyworld is a conceptual model planet with a very simple biosphere, consisting of only two plant species, namely black and white daisies. These daisies differ only in their colour and thus reflectivity properties. The growth rate of the daisies is determined by the surface temperature of their surroundings. Areas covered with white daisies have a higher albedo and therefore reflect a larger portion of the incoming radiation from the nearby Sun-like star than areas with bare ground. Likewise, areas covered with black daisies have a lower albedo and therefore reflect a smaller portion of the incoming radiation. Thus, the planetary albedo A, which is the global mean albedo, is controlled by the areal covers of white and black daisies, a_w and a_b, respectively. These are measured as fractions of the total planetary area, i.e. a_w, $a_b \in [0,1]$. We thus have

$$A = \sum a_i A_i = a_w A_w + a_b A_b + (1 - a_w - a_b) A_g,$$

where A_w, A_b and A_g denote the albedos of white daisies, black daisies and bare ground, respectively.

The climate of Daisyworld is represented by the mean surface temperature of the planet. The temperature T is controlled by the luminosity of the sun and the planetary albedo, through the overall energy budget of the planet:

$$\sigma T^4 = \frac{S}{4}[1 - A], \tag{1}$$

which balances the incoming short-wave solar radiation and the outgoing long-wave radiation. S is the solar luminosity at the orbit of the planet, i.e. the solar constant, and σ is the Stefan–Boltzmann constant. The factor $1/4$ is just the ratio of surface area to the cross-sectional area of the planet hit by sunlight. The greenhouse effect of the atmosphere is not considered, and simply assumed constant.

The local temperature T_i for the area covered by daisies of type i, where $i = w$ denotes white and $i = b$ black, will depend on how much sunlight is absorbed through the albedo of the daisies. Besides that, there will be a redistribution of heat through the atmosphere. This is modelled to depend linearly on the difference between the planetary and the local albedo:

$$T_i^4 = T^4 + q(A - A_i). \tag{2}$$

With this form, the radiative balance in (1) trivially holds, since $\sum_i \sigma a_i T_i^4 = \sigma T^4$. By definition we have $A_b < A_g < A_w$, and consequently $T_b > T_g > T_w$. The global temperature is thus naturally defined as the area weighted average of the fourth power of local temperatures.

The areal cover of daisies is governed by the following growth equation for each type of daisies:

$$\frac{da_i}{dt} = a_i \cdot [(1 - a_w - a_b) \cdot U(T_i) - \gamma]. \tag{3}$$

The growth of the areal cover of daisy of type i depends on the climate through the local temperature T_i. It is controlled through the growth rate function $U(T_i) = 1 - \mu(T_0 - T_i)^2$ times the available area of habitable ground, $(1 - a_w - a_b)$, and a constant death rate term $-\gamma a_i$. This closes the equations for Daisyworld. The model parameter values are listed in Table A1 in Appendix A. With the temperature set by the planetary albedo, the planetary albedo by the areal extent of daisies, and the growth of the daisies, in turn, by the surface temperature, a simple climate–biosphere feedback loop is established in Daisyworld.

3. Homeostasis of Daisyworld

We will follow the approach in the original presentation of Daisyworld. We examine the response in the planetary temperature to an increase in solar luminosity S, and compare the results to the homeostatic implications found in WL83.

We are looking for steady state solutions to (3), i.e. fulfilling $da_w/dt = da_b/dt = 0$. These solutions can be separated into four different types: the *abiotic* state $a_w = a_b = 0$ is easily recognized as a (trivial) solution. Assuming $a_w > 0$, $a_b = 0$ yields the *white-only biotic* solution, while taking $a_b > 0$, $a_w = 0$ yields the *black-only biotic* solution. Lastly, taking both $a_w > 0$, $a_b > 0$ gives us the *biotic* type of solution. To find the solutions, we will take $T_i = \sqrt[4]{T^4 + q(A - A_i)}$ and insert this into the governing equations (3)—T_i is then positive and real as long as $T^4 > q(A_i - A)$ which, using (1), can be shown to be fulfilled for the constants and parameters used here. Both the white-only and the black-only biotic fixed point solutions are then found as the zeros of a non-linear function in one variable, which we solve by numerical methods. The full biotic case can be reduced after a few manipulations to find the roots of a third order polynomial in T_b, from which the solution can be easily computed, see e.g. Saunders (1994) for further details. With the fixed points found, the stability of these are determined by a linear stability analysis: the Jacobian matrix for the system of equations (3) is easily derived, and the stability of a given fixed point is then characterized from the eigenvalues of the Jacobian matrix, evaluated in the fixed point.

An overview of model solutions is shown in Fig. 1, sketching the phase portrait for four solar luminosities S/S_0, S_0 being a

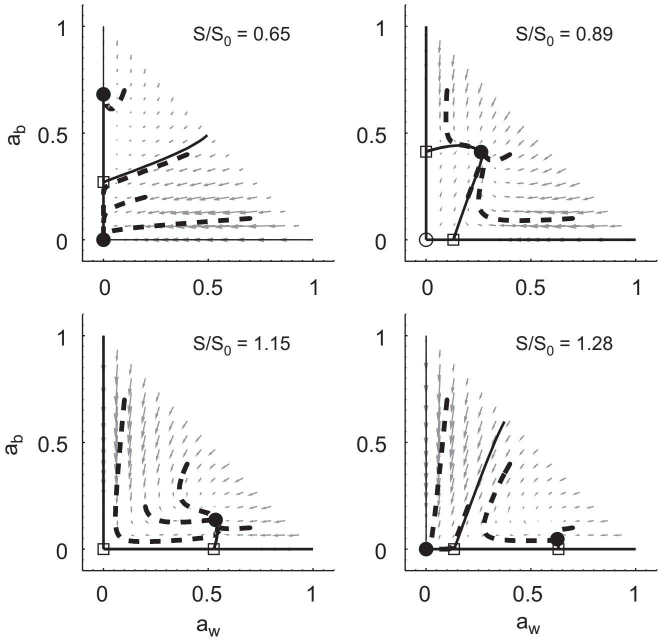

Fig. 1. Phase portrait for four values of luminosity. The grey arrows sketch the phase space velocity field. The steady states are indicated by markers: filled circles correspond to stable nodes, open circles to unstable nodes, and open squares to saddle points. Also shown are the trajectories for four random initial conditions (dashed lines), and the heteroclinic trajectories (solid lines).

reference luminosity. In each phase portrait, filled circles indicate stable fixed points, open circles unstable fixed points, and open squares saddle points (fixed point with one stable and one unstable eigendirection in phase plane). The abiotic solution is found in the origo of the phase plane, the white-only solutions on the horizontal a_w-axis, the black-only solutions on the vertical a_b-axis, and the biotic solutions in the remaining part of the phase plane. The arrows sketch the velocity field (da_w/dt, da_b/dt) in phase space, as given by Eq. (3). The solid lines connecting unstable fixed points or saddle points with stable fixed points are *heteroclinic trajectories*. These separate the phase plane into basins of attraction. The dashed lines sketch trajectories for four arbitrary initial conditions.

The response in steady state areal covers of daisies, when varying the solar luminosity, is shown in Fig. 2. Here, the steady state areal cover of each of the two types of daisies are plotted as function of solar luminosity S for $0.5 \leqslant S/S_0 \leqslant 1.7$. Referring to the phase portraits in Fig. 1, this figure shows the projections of the fixed points onto the two axes that span the phase space. The four panels correspond to the different types of steady state solution as indicated: no daisies, white-only, black-only, and both types of daisies. In the upper right plot we see that for low solar luminosities, no black-only solution exists. This is because temperatures are too cold due to the low value of S. When increasing S, a saddle-node bifurcation is seen to occur, giving birth to a stable (the upper solid line) and a saddle point (the lower dashed line) black-only solution. At this point, a relatively large cover of warming black daisies is capable of making the planet warm enough for the plants to thrive, in spite of the low solar luminosity. As S is increased, the stable fixed point turns into a saddle point, as the full biotic solution is born. However, since the stable manifold coincides with the a_b-axis in phase space, it is possible for the system to reside in the state as long as no white daisies are introduced (i.e. all initial conditions $a_b > 0$, $a_w = 0$ will end up here, as seen in the upper right plot in Fig. 1). This state is maintained by a still smaller cover of black daisies as S increases. Eventually, S becomes too high for the black daisies to thrive and maintain temperatures within their limits, and the stable black-only state disappears. A similar bifurcation pattern is seen for the white-only solution in the lower left plot, only here the bifurcations take place as S is *decreased*. This change is simply due to the reversed effect of the white daisies on the planetary albedo, as compared to the black daisies. White daisies are favoured by high solar luminosities, since their colour can *cool* the planet to habitable temperatures, whereas black daisies are favoured by low solar luminosities, since they can *warm* the planet to habitable temperatures. The upper left plot shows that the stability of the abiotic solution changes as S varies and different steady states appear. The lower right plot shows that for a large range of S, a stable steady state exists where both white and black daisies can thrive together.

From the cover of daisies, the associated temperature T of the planet can directly be computed. The resulting bifurcation diagram is seen in Fig. 3, showing the steady state T as function of S. This figure shows the same bifurcations as in the plots of Fig. 2. The blue curve corresponds to the abiotic solution in the upper left plot in Fig. 2, the grey curves correspond to the white-only solution in the lower left plot in Fig. 2, the black curves correspond to the black-only solution in the upper right plot in Fig. 2, and finally the green curve corresponds to the full biotic solution in the lower right plot in Fig. 2.

The results shown in Fig. 3 are similar to those found by Watson and Lovelock, although not completely identical. A black daisy steady state is seen to exist in the interval $0.62 < S/S_0 < 0.70$ in Fig. 3 (solid black line). This solution is not found by the method used in WL83. This part of the black-only biotic solution is of particular interest since the response in steady state temperature to an increase in solar luminosity is actually a *larger* warming than for the abiotic solution, as will be discussed below. It should also be noted that both the lower, black-only saddle point branch and

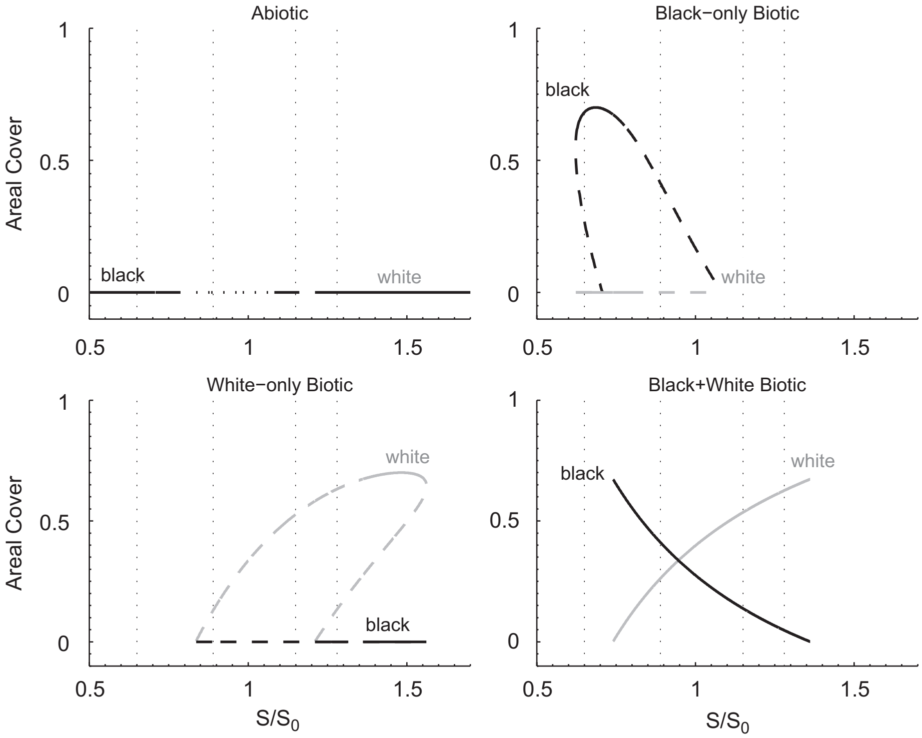

Fig. 2. Steady state areal cover of daisies as function of luminosity. Each panel corresponds to the indicated type of solution. The vertical, dotted lines indicate the phase portraits in Fig. 1.

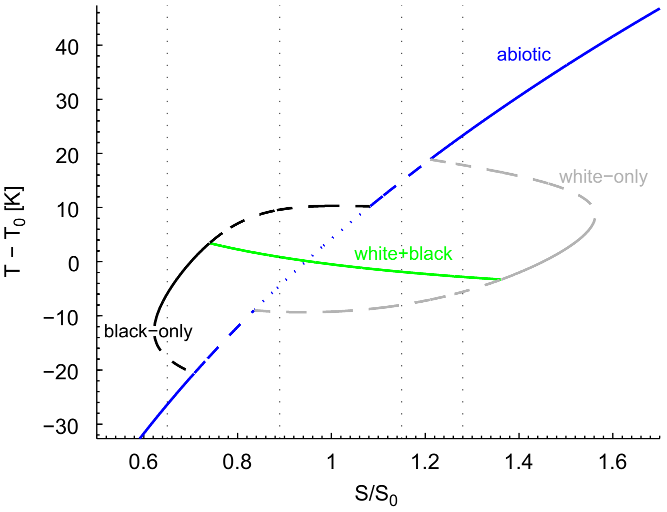

Fig. 3. Steady state temperature as function of luminosity. The vertical, dotted lines indicate the phase portraits in Fig. 1.

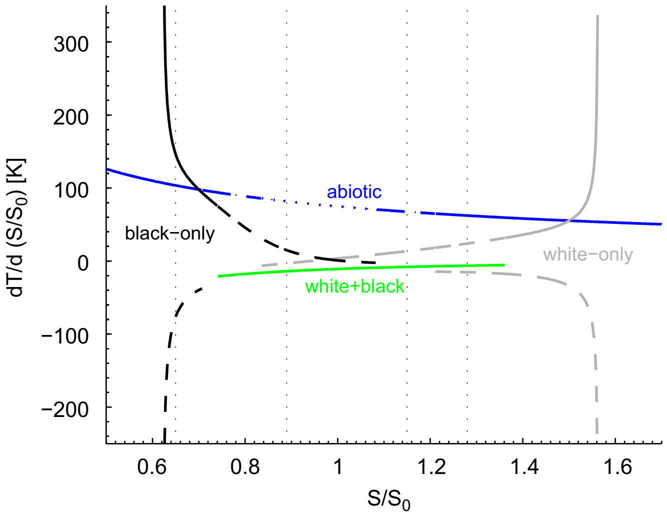

Fig. 4. Slope of steady state temperature as function of luminosity. The vertical, dotted lines indicate the phase portraits in Fig. 1.

the upper, white-only saddle point branch are not shown in WL83, but since the axis of the non-vanishing variable coincides with the unstable manifold in both cases (as opposed to the upper black-only and the lower white-only branches where it coincides with the stable manifold), these states are not habitable. This is also evident from the upper left plot and the lower right plot in Fig. 1, respectively. These results are similar to the ones found by different authors (Saunders, 1994; Weber, 2001). For the former, this should come as no surprise for the full biotic solution, since this also served as motivation for our approach. In the latter, a slightly simplified formulation of Daisyworld is solved analytically, with the long-wave radiation linearized; a similar bifurcation diagram is still found.

From the temperature curve as a function of solar luminosity $T(S)$ plotted in Fig. 3, it is now interesting to note the slope $\partial T/\partial S$. This is a good quantitative measure of homeostasis, since this exactly measures the response in temperature to changes in solar luminosity. The homeostatic effect on climate of the daisies is then immediately seen as the fact that the absolute value of the slope, $|\partial T/\partial S|$, is, for most values of S, smaller for the inhabited planet than for the life-less planet (which is $\sim T^{-3/4}$ from the outgoing radiation). This is the case for both the habitable black-only planet (upper black curve), the habitable white-only planet (lower grey curve), and the full biotic planet with both black and white daisies (green curve). For the latter, we see that $\partial T/\partial S < 0$, and the temperature actually *decreases* in response to the increasing solar luminosity. Fig. 4 shows the slope $\partial T/\partial S$ of the steady state solutions in the bifurcation diagram, Fig. 3, scaled by a factor of S_0, as function of solar luminosity. In this figure, the upper black curve corresponds to the upper black-only stable node/saddle point branch in Fig. 3, the lower black curve to the lower black-only saddle point branch, the blue curve to the abiotic branch, the green curve to the full biotic branch, the upper grey curve to the lower white-only saddle point/stable node branch, and finally the lower white curve to the upper white-only saddle point branch. The blue abiotic curve shows the $T^{-3/4}$-dependence for the life-less planet. The upper black curve is seen to lie above this scaling law for solar luminosities in the range $0.62 < S/S_0 < 0.70$. The planet inhabited by black daisies is thus climatically *more* sensitive to changes in solar luminosity than the life-less planet in this range of luminosities. For solar luminosities in the range $1.50 < S/S_0 < 1.56$ the upper grey curve also lies above the abiotic scaling law. In this range of solar luminosities the temperature on the planet inhabited by white daisies is therefore *also* more sensitive to changes in solar luminosity than the life-less planet. Although this is only valid for relatively narrow ranges of luminosities, this is nevertheless somewhat in contradiction with the notion of a purely homeostatic effect of the daisies on the climate of Daisyworld.

4. Bistability of a modified Daisyworld

We will now turn to a modified version of Daisyworld, as also described in WL83. In this second Daisyworld, the darkening effect of the black daisies is changed to a whitening effect, mimicking the formation of convective clouds over the warm, black surface. From the original to the modified version of Daisyworld only A_b is increased; model equations and all other model parameters are left unaltered, see Table A1 in Appendix A. Higher local temperature at areas covered by black daisies is still assumed; as a consequence, the albedo A_b appearing in (2) is assumed *not* to increase in this modified version, but all other appearances are. Watson and Lovelock found that only black daisies could flourish in such a world, still with a homeostatic effect on climate. As we shall demonstrate below, it is indeed possible for white daisies to thrive in this version, leading to bistability of Daisyworld for a range of solar luminosities.

Following the same procedure as above, Fig. 5 shows the phase portrait for four values of S. Solving for steady state daisy populations when varying the solar luminosity yields the results in Fig. 6. From these, the bifurcation diagram in Fig. 7 is generated, showing the steady state temperature as function of solar luminosity. Focussing on Fig. 7, we see that the full biotic stable node branch in the unmodified Daisyworld (green curve in Fig. 3) has disappeared in the modified Daisyworld; only a saddle point branch exists in a narrow interval of S. Also, the saddle-node bifurcation associated with the black-only solution is seen to be oriented in the same way as the saddle-node bifurcation associated with the white-only solution. We note that only the abiotic solution and the lower, stable black-only solution are found by the methods used in WL83. For the black-only solution, the upper branch is unstable. For the white-only solution, the upper, saddle point branch is not habitable, with the same reasoning as above. However, it is indeed possible for a system comprising only white daisies to reside in the lower, saddle point/stable fixed point branch. Hence, it obviously seems problematic to claim that the white daisies fail in this modified version of Daisyworld, because they are “distinctly less fit” than black daisies, as is stated in WL83. White daisies could indeed thrive well in the modified Daisyworld; the outcome in WL83 is a mere result of the procedure used to solve the system. Furthermore, we see in Fig. 7 that for a range of solar luminosities, $1.36 \leqslant S/S_0 \leqslant 1.50$, both the white-only steady state and the black-only steady state are stable (as well as the abiotic state), as is also seen in the lower left plot in Fig. 5. The system is thus *bistable*. This means that transitions between the two biotic states are possible if the system is subjected to suitable perturbations. A jump between the two biotic states is associated with a change in temperature of up to ~9 K. Such transitions between states would surely be a non-homeostatic phenomenon in Daisyworld. This is discussed in greater detail in the following section.

Finally, let us observe the slope of the temperature curves as function of solar luminosity. Fig. 8 shows the slope $\partial T/\partial S$ of the steady state solutions in the bifurcation diagram in Fig. 7, scaled by a factor of S_0, as function of solar luminosity. Once again, the general

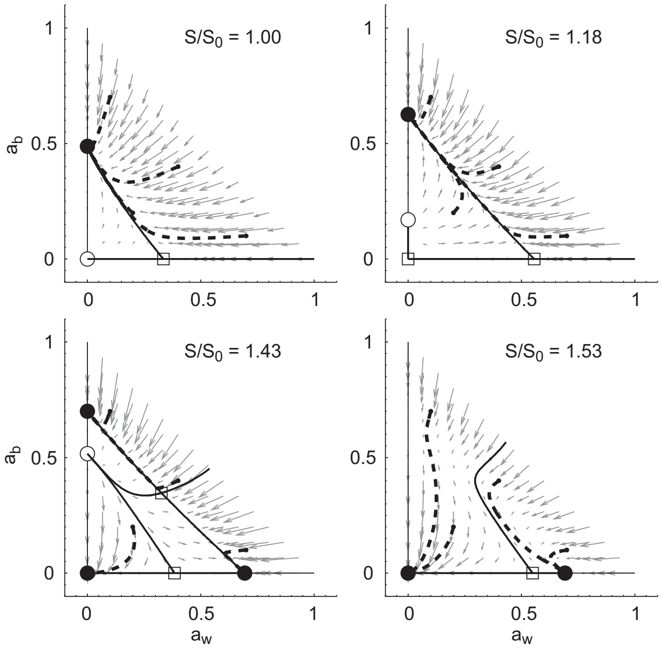

Fig. 5. Phase portrait of the modified Daisyworld for four values of luminosity. The grey arrows sketch the phase space velocity field. The steady states are indicated by markers: filled circles corresponds to stable nodes, open circles to unstable nodes, and open squares to saddle points. Also shown are the trajectories for four random initial conditions (dashed lines), and the heteroclinic trajectories (solid lines).

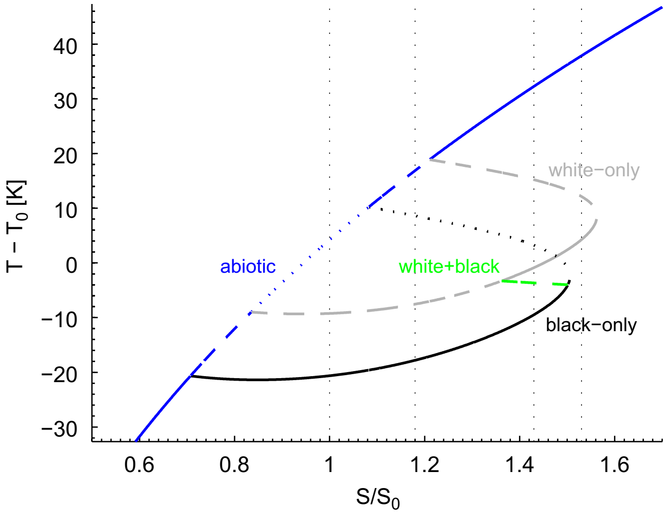

Fig. 7. Steady state temperature as function of luminosity for the modified Daisyworld. The vertical, dotted lines indicate the phase portraits in Fig. 5.

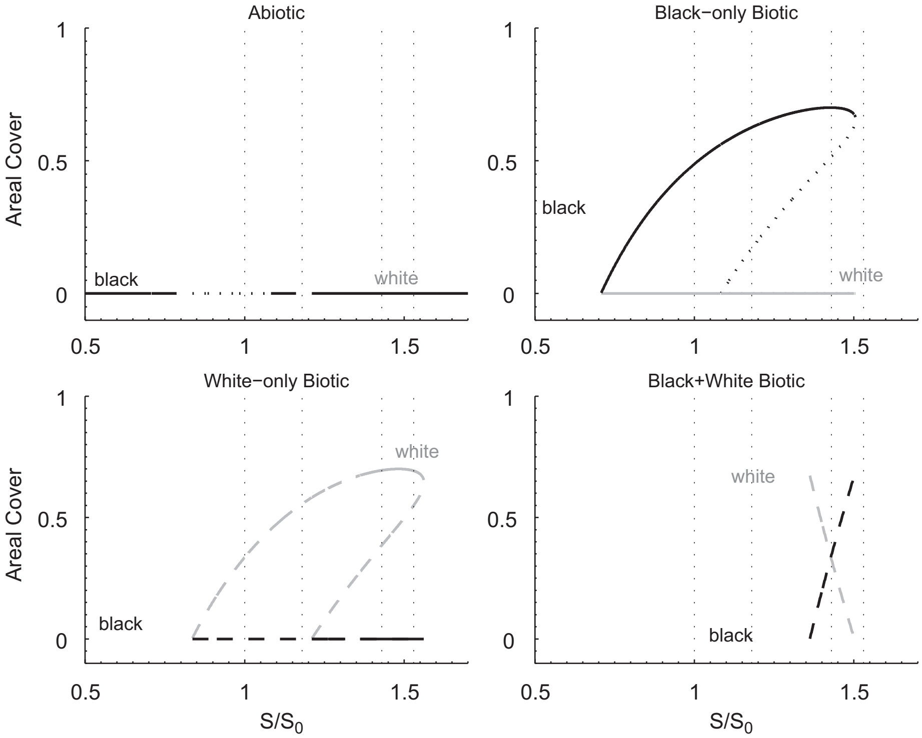

Fig. 6. Steady state areal cover of daisies as function of luminosity for the modified Daisyworld. Each panel corresponds to the indicated type of solution. The vertical, dotted lines indicate the phase portraits in Fig. 5.

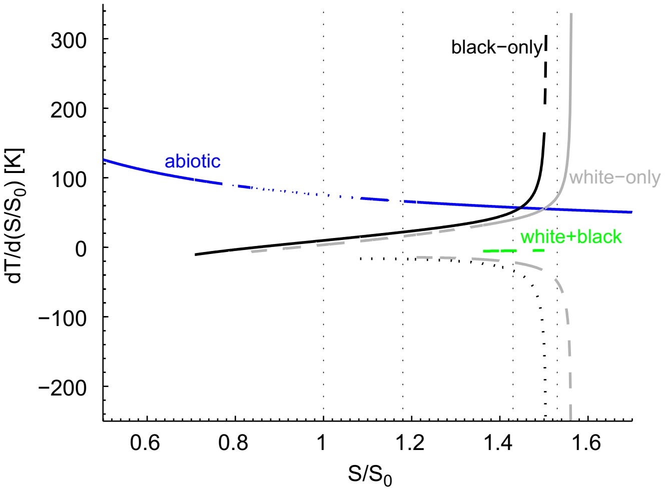

Fig. 8. Slope of steady state temperature as function of luminosity for the modified Daisyworld. The vertical, dotted lines indicate the phase portraits in Fig. 5.

picture is that the norm of the slopes of both biotic curves are smaller than the norm of the slope of the abiotic curve. This supports the homeostatic effect of the biosphere as suggested by Watson and Lovelock, although once again narrow ranges of solar luminosities do exist for which the biotic slopes are larger than the abiotic slope.

5. Noise-induced transitions

The modified Daisyworld has both a stable white-only and a stable black-only steady state for luminosities $1.36 \leqslant S/S_0 \leqslant 1.50$. This biotic bistability makes transitions between inhabited states of the planet possible for luminosities within this range. Transitions can be induced by noise from both internal and external short-term processes that have not been directly included in the model.

We can envisage this by introducing natural fluctuations in the daisy populations. Let us assume a luminosity of $S/S_0 = 1.43$ in the following. We now leave the formalism in WL83 by adding some noise to the governing equations (3). We model these fluctuations by a Langevin equation, perturbing the governing equations by a white noise term:

$$\frac{\mathrm{d}a_i}{\mathrm{d}t} = a_i \cdot [(1 - a_w - a_b) \cdot U(T_i) - \gamma] + \sigma\eta_i(t). \tag{4}$$

Here, the noise η is assumed to be (normal) Gaussian distributed, and the intensity is taken to be $\sigma = 0.003$. A realization of this perturbed system is shown in Fig. 9. In the upper part, the areal cover of daisies a_w and a_b are plotted as function of time, and below, the resulting temperature T as function of time is sketched. This transient model run was performed by numerical integration of the white-noise perturbed governing equations using a fourth order Runge–Kutta scheme for the deterministic drift term, and adding the stochastic noise term in the Ito sense. For $t < 450$, the planet is dominated by black daisies, and T fluctuates around the equilibrium state $T \approx 286$ K. At $t \approx 450$, the transition takes place, and for $t > 450$, the planet is dominated by *white* daisies, with T fluctuating around the equilibrium state $T \approx 295$ K. In Fig. 10, the corresponding trajectory in phase plane is sketched. The grey line shows the trajectory $(a_w(t), a_b(t))$. Also shown are the contour lines of the temperature as function of a_w and a_b, and the steady state solutions. The system is initiated from the black-only steady state in the upper left part of phase plane, and ends up in the lower right part close to the white-only steady state.

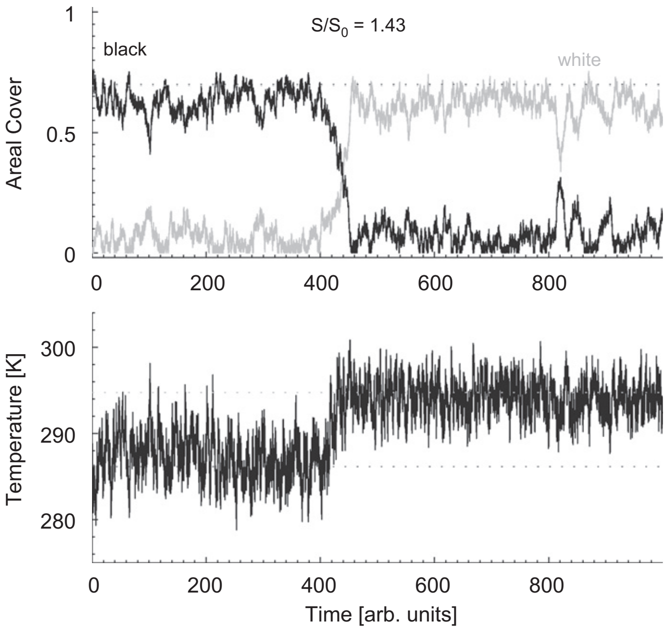

Fig. 9. A realization of the perturbed governing equations for the modified Daisyworld using a Gaussian white noise for $S/S_0 = 1.43$. Top: areal cover of white daisies (solid grey) and black daisies (solid black) as function of time. Also shown, with dotted lines, are the steady state one-species areal covers. Bottom: temperature as function of time. Also shown, with dotted lines, are the steady state single-daisy temperatures.

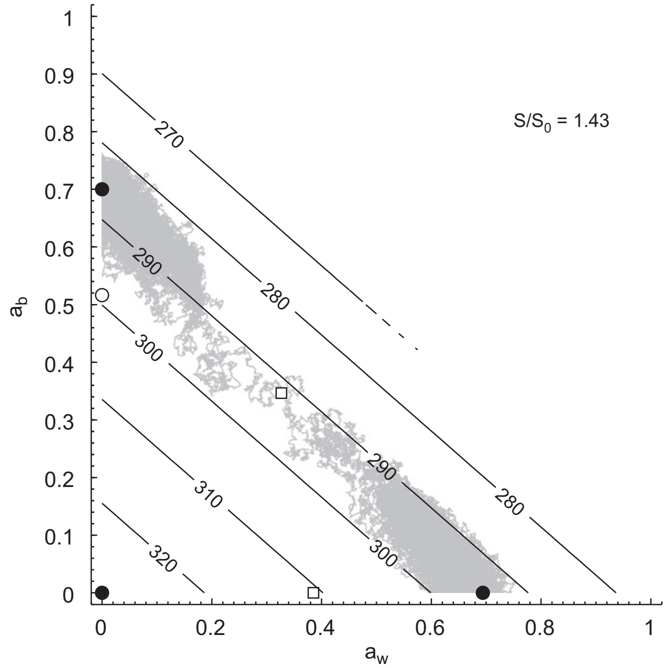

Fig. 10. Phase plane trajectory of the noise-induced transition in the modified Daisyworld for $S/S_0 = 1.43$. Also shown are the contour lines of the temperature (in K) and the steady states.

As seen in Fig. 9, before the transition occurs, the cover of black daisies fluctuates around a value slightly less than the steady state value. This is because the cover of white daisies fluctuates around a value *larger* than the steady state at zero, since the noise cannot perturb the value below this value, only above, and this influences the growth of black daisies negatively (vice versa *after* the transition). Also, the transition is seen to be more prominent in a_w and a_b than in

T, as measured by the signal-to-noise ratio. Referring to the trajectory shown in Fig. 10 and the corresponding phase portrait in the lower left plot in Fig. 5, this is better understood. The heteroclinic trajectories that connect the biotic saddle point with the two stable biotic nodes lie along the slowest eigendirections of both the saddle point and the two stable nodes. This is why the transition takes place along these heteroclinic trajectories; when the system is perturbed it will, so to speak, be dragged onto this line and then slowly forced away from the saddle point towards one of the stable nodes, since a stable steady state is approached along the slowest eigendirection. For the transition to occur, the noisy perturbations must overcome the slow forcing away from the saddle point. This path between the two stable biotic nodes is seen to be nearly parallel to the contour lines of temperature T, which is therefore only changed modestly during the transition, whereas a_w and a_b change appreciably.

In any realistic system the dynamics will be perturbed in a sense described by the noise. The noise could be initiated on the level of the biosphere, e.g. by variations in nutrient cycles, thereby perturbing daisy growth, or by the introduction of a new species with a different trait (Lenton, 1998). The transition could as well be initiated on the climatic level, i.e. in the existing limiting growth factor of the model: a change in the temperature by some new, external factor that could drive the system into a different state. In any case, the above is surely a non-homeostatic effect of life on climate on Daisyworld.

6. Earth and Daisyworld

In Daisyworld, the interaction between life and climate operates through albedo properties of different species and their influence on the planetary albedo. On Earth, plants and micro-organisms certainly have the ability to change the albedo, at least locally. Rainforest has an albedo close to 0, compared to typical bare soil albedo of about 0.2. Fresh snow has an albedo of about 0.8–0.9. If organisms like red algae grow on the surface of a glacier, the albedo is less than 0.5. On the other hand it has been proposed that sulphate aerosols emitted by oceanic micro-organisms can lead to enhanced cloud formation. Cloud albedos can be as high as 0.9, while the albedo of ocean water can be as low as 0.1–0.2 (Oke, 1992; Ahrens, 2006).

The simple coupling between life and climate in Daisyworld, being a conceptual model, is of course not responsible for the main features of Earth's climatic evolution over geological timescales, and cannot solve the Faint Young Sun Paradox on its own (the puzzle of high temperatures on early Earth known from evidence of liquid water, despite an up to 30% fainter young Sun). The planetary albedo is heavily controlled by a range of other quantities, most importantly clouds, extent of ice and snow, land–ocean distribution, etc. Also, to a first order, the temperature of the planet is not only determined by the planetary albedo, but also by the strength of the greenhouse effect, as determined by the content of greenhouse gases in the atmosphere; this is again directly related to the biota. A more realistic—but still simple—climate–biosphere model should take such issues into account. A more likely solution to the Faint Young Sun Paradox is through increased levels of greenhouse gases in the early Earth's atmosphere. Methane producing bacteria could have been responsible for the increased greenhouse effect (Kasting and Catling, 2003). A negative feedback loop between surface temperatures and weathering rates of silicate rocks, and thus the global carbon cycle, could as well have played a role (Walker et al., 1981).

7. Conclusions

Daisyworld serves as a conceptual model in support of the strong Gaia hypothesis. The model was constructed to illustrate a generic stabilizing coupling between biota and planetary environment. The stability works through the homeostasis maintained by life. However, even in the Daisyworld model, biotic solutions exist which are less homeostatic than the bare radiative Stefan–Boltzmann cooling. Furthermore, in the modified Daisyworld, where the black daisies create a reflective cloud cover, bistable solutions exist due to the presence of the biota. This could imply occasional catastrophic jumps between a black Daisyworld and a white Daisyworld with corresponding jumps in temperature. This kind of behaviour might not be in conflict with fluctuations in life on Earth as it is incompletely reconstructed from the geological records.

The Daisyworld model is a useful and an inspiring way of thinking of the biota and the planetary environment as an integrated entity. This thinking should guide us in the pursue of habitability conditions and potential life on other planets. However, the strong Gaian view might be too wishful thinking (Kirchner, 2002). The findings here indicate that strong couplings between biota and climate are not generically stabilizing.

Appendix A. Model parameters

Model parameter values in Daisyworld are given in Table A1.

Table A1
Model parameter values in Daisyworld

Parameter	Description	Value
σ	Stefan–Boltzmann constant	$5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$
S_0	Daisysun solar constant	$3.668 \times 10^{3}\,\mathrm{W\,m^{-2}}$
γ	Death rate of daisies	$0.3\,\mathrm{s^{-1}}$
T_0	Optimal temperature for daisy growth	$22.5\,^{\circ}\mathrm{C}$
μ	Temperature sensitivity for daisy growth	$3.265 \times 10^{-3}\,\mathrm{K^{-2}\,s^{-1}}$
A_w	Albedo of white daisies	0.75
A_b	Albedo of black daisies	0.25[a]
A_g	Albedo of bare ground	0.50
q	Heat redistribution coefficient	$2.067 \times 10^{9}\,\mathrm{K^{4}}$

[a] For the modified Daisyworld a value of 0.8 for A_b is used, except in Eq. (2) where a value of 0.25 is used. The values are equivalent to the ones used in WL83.

References

Ahrens, C.D., 2006, Meteorology today. In: An Introduction to Weather, Climate and the Environment, eighth ed. Thompson, Brooks/Cole, United States.

Kasting, J.F., Catling, D., 2003. Evolution of a habitable planet. Annual Review of Astronomy and Astrophysics 41, 429–463.

Kirchner, J.W., 2002. The Gaia hypothesis: fact, theory and wishful thinking. Climatic Change 52, 391–408.

Kleidon, A., 2002. Testing the effect of life on Earth's functioning: how Gaian is the Earth system? Climatic Change 52, 383–389.

Lenton, T.M., 1998. Gaia and natural selection. Nature 394, 439–447.

Lenton, T.M., 2002. Testing Gaia: the effect of life on Earth's habitability and regulation. Climatic Change 52, 409–422.

Lovelock, J.E., Margulis, L., 1974. Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis. Tellus 26, 2–9.

Oke, T.R., 1992. Boundary Layer Climates, second ed. Routledge, New York.

Saunders, P.T., 1994. Evolution without natural selection: further implications of the Daisyworld parable. Journal of Theoretical Biology 166, 365–373.

Volk, T., 2002. Toward a future for Gaia theory, an editorial comment. Climatic Change 52, 423–430.

Walker, J.C.G., Hays, P.B., Kasting, J.F., 1981. A negative feedback mechanism for the long-term stabilization of Earth's surface temperature. Journal of Geophysics Research 86, 9776–9782.

Watson, A.J., Lovelock, J.E., 1983. Biological homeostasis of the global environment: the parable of Daisyworld. Tellus 35B, 284–289.

Weber, S.L., 2001. On homeostasis in Daisyworld. Climatic Change 48, 465–485.