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Habitable zone for Earth-like planets in the solar system

S. Franck*, A. Block, W. von Bloh, C. Bounama, H.-J. Schellnhuber, Y. Svirezhev

Potsdam Institute for Climate Impact Research (PIK), PO Box 60 12 03, 14412 Potsdam, Germany

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Abstract

We present a new conceptual Earth system model to investigate the long-term co-evolution of geosphere and biosphere from the geological past upto 1.5 billion years into the planet's future. The model is based on the global carbon cycle as mediated by life and driven by increasing solar luminosity and plate tectonics. As a major result of our investigations we calculate the "terrestrial life corridor", i.e. the biogeophysical domain supporting a photosynthesis-based ecosphere during planetary history and future. Furthermore, we calculate the behavior of our virtual Earth system at various distances from the Sun, using different insolations. In this way, we can find the habitable zone as the band of orbital distances from the Sun within which an Earth-like planet might enjoy moderate surface temperatures and CO_2-partial pressures needed for advanced life forms. We calculate an optimum position at 1.08 astronomical units for an Earth-like planet at which the biosphere would realize the maximum life span. According to our results, an Earth-like planet at Martian distance would have been habitable up to about 500 Ma ago while the position of Venus was always outside the habitable zone. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The extraterrestrial life debate spans from the ancient Greek world of Democritus over the 18th century European world of Immanuel Kant to the recent discoveries of extrasolar planets. Concerning the search of life in our planetary system, Schiaparelli's observation of a system of canali on the Martian surface in 1877 was the beginning of an epoch to reveal planetary conditions relevant to life with the refinement of observational techniques. The detection by Mc Kay et al. (1996) of the chemical biomarkers and possible microfossils in a meteorite from Mars called ALH 84001 (a meteorite found in 1984 in Antarctica) has stimulated research in the newly emerging field of astrobiology. Mars holds great interest for exobiology and presently stands center stage in the plans to explore the inner solar system for signs of past or present life. Already now, it can be stated that the search for extraterrestrial life will be one of the predominant themes of science in the 21st century.

The histories and fates of the three terrestrial planets Venus, Earth, and Mars suggest that a combination of distance from the Sun, planetary size, as well as geological and perhaps biological evolution will control the habitability of a planet. Earth-like planets cannot remain habitable if they are too much closer to the Sun than Earth's orbit, because of too high temperatures and loss of water by photodissociation. On the other hand, an Earth-like planet which is too much distant from the Sun would have permanent surface temperatures below the freezing point of water and therefore would not be habitable.

Therefore, the habitable zone (HZ) around the Sun is defined as the region within which an Earth-like planet might enjoy moderate surface temperatures needed for advanced life forms. Usually, this definition is equivalent to the existence of liquid water at the planet's surface. Such a definition was introduced by Huang (1959, 1960) and extended by Dole (1964) and Shklovskii and Sagan (1996). Hart (1978, 1979) calculated the evolution of the terrestrial atmosphere over geologic time at varying distances. He found that the HZ between runaway greenhouse and runaway glaciation is surprisingly narrow for G2 stars like our Sun: $R_{\text{inner}} = 0.958$ AU, $R_{\text{outer}} = 1.004$ AU. A main disadvantage of these calculations is the neglect of the negative feedback between atmospheric CO_2 content and mean global surface temperature discovered later by Walker et al. (1981). The implementation of this feedback by Kasting et al. (1988) provided the interesting result of an almost constant inner boundary but a remarkable extension of the outer boundary. Later on, the calculations

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* Corresponding author. Tel.: +49-331-288-2659; fax: +49-331-288-2660.

E-mail address: franck@pik-potsdam.de (S. Franck).

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of the HZ have been improved and extended to other main sequence stars (Kasting et al., 1993; Kasting, 1997; Williams, 1998). A comprehensive overview can be found in the proceedings of the first international conference on circumstellar habitable zones (Doyle, 1996). Kasting et al. (1993) give two different estimates for the outer boundary of the HZ: the "1st CO_2 condensation" limit and the "maximum greenhouse" limit. For the present time the values are 1.37 AU and 1.67 AU, respectively.

In the present paper we want to investigate the possibilities of existence of life on an Earth-like planet at various distances from the Sun. Our method is based on the Earth system science approach (Franck et al., 1999, 2000) that calculates the past and future evolution of a dynamic Earth under the influence of an increasing solar luminosity. Such a long-term climate regulation is thought to be given by the global carbon cycle and its effect on atmospheric CO_2 content and biological productivity. This method is briefly presented below.

2. Model description

Our model (Franck et al., 1999, 2000) couples the increasing solar luminosity, $S_\odot$, the silicate-rock weathering rate, F_{wr}, and the global energy balance to estimate the partial pressure of atmospheric carbon dioxide, P_{atm}, the mean global surface temperature, T_{s}, and the biological productivity, Π, as a function of time, t, in the geological past and future.

The global energy balance of the planet's climate is usually expressed with the help of the Arrhenius equation (Arrhenius, 1896):

$$(1-a)S_\odot = 4\sigma T_{\mathrm{bbr}}^4, \qquad (1)$$

where a is the planetary albedo, σ is the Stefan–Boltzmann constant, and T_{bbr} is the effective black-body radiation temperature. The surface temperature of the planet T_{s} is related to T_{bbr} by the greenhouse warming factor ΔT:

$$T_{\mathrm{s}} = T_{\mathrm{bbr}} + \Delta T. \qquad (2)$$

Usually, ΔT is parameterized as a function of T_{s} and P_{atm} (Caldeira and Kasting, 1992; Franck et al., 1999). The main drawback of this parameterization is the limited range of applicability to high atmospheric CO_2 partial pressures, P_{atm}, above 10^5 ppm. In our model the upper limit of P_{atm} can be as high as the total amount of 10^7 ppm carbon dioxide in the Earth system (Kasting and Ackerman, 1986; Tajika and Matsui, 1992). Therefore, we apply the global energy balance given by Williams (1998) valid also for P_{atm} higher than 10^5 ppm and implicitly including the greenhouse effect:

$$S_\odot(1-a(T_{\mathrm{s}},P_{\mathrm{atm}})) = 4I(T_{\mathrm{s}},P_{\mathrm{atm}}), \qquad (3)$$

where I is the outgoing infrared flux. For I and a polynomial approximations of a radiative–convective climate model were used.

The total process of weathering embraces first the reaction of silicate minerals with carbon dioxide, second the transport of weathering products, and third the deposition of carbonate minerals in sediments. The basic assumptions and limitations of this approach are given in Franck et al. (1999). Combining the direct temperature effect on the weathering reaction, the weak temperature influence on river runoff, and the dependence of weathering on soil CO_2 concentration, the global mean silicate-rock weathering rate can be formulated via the following implicit equation (Walker et al., 1981; Caldeira and Kasting, 1992):

$$\frac{F_{\mathrm{wr}}}{F_{\mathrm{wr},0}} = \left(\frac{a_{\mathrm{H}^+}}{a_{\mathrm{H}^+,0}}\right)^{0.5} \exp\left(\frac{T_{\mathrm{s}}-T_{\mathrm{s},0}}{13.7\ \mathrm{K}}\right). \qquad (4)$$

Here the pre-factor outlines the role of the CO_2 concentration in the soil, P_{soil}; a_{H^+} is the activity of H^+ in fresh soil-water and depends on P_{soil} and the global mean surface temperature, T_{s}. The quantities $F_{\mathrm{wr},0}$, $a_{\mathrm{H}^+,0}$, and $T_{\mathrm{s},0}$ are the present-day values for the weathering rate, the H^+ activity, and the surface temperature, respectively. The activity a_{H^+} is itself a function of the temperature and the CO_2 concentration in the soil. The equilibrium constants for the chemical activities of the carbon and sulfur systems involved have been taken from Stumm and Morgan (1981). Note that the sulfur content in the soil also contributes to the global weathering rate, but its influence does not depend on temperature. It can be regarded as an overall weathering bias, which has to be taken into account for the estimation of the present-day value.

Eq. (4) is the key relation for our models. For any given weathering rate, the surface temperature and the CO_2 concentration in the soil can be calculated self-consistently, as will be shown below. P_{soil} can be assumed to be linearly related to the terrestrial biological productivity, Π (see Volk, 1987), and the atmospheric CO_2 concentration, P_{atm}. Thus, we have

$$\frac{P_{\mathrm{soil}}}{P_{\mathrm{soil},0}} = \frac{\Pi}{\Pi_0}\left(1-\frac{P_{\mathrm{atm},0}}{P_{\mathrm{soil},0}}\right) + \frac{P_{\mathrm{atm}}}{P_{\mathrm{soil},0}}, \qquad (5)$$

where $P_{\mathrm{soil},0}$, Π_0, and $P_{\mathrm{atm},0}$ are again present-day values.

The main role of the biosphere in the context of our model is to increase P_{soil} in relation to the atmospheric CO_2 partial pressure and proportional to the biological productivity Π. Π is considered to be a function of temperature and CO_2 partial pressure in the atmosphere only.

$$\frac{\Pi}{\Pi_{\mathrm{max}}} = \left(1-\left(\frac{T_{\mathrm{s}}-T_{\mathrm{opt}}}{T_{\mathrm{opt}}}\right)^2\right)\left(\frac{P_{\mathrm{atm}}-P_{\mathrm{min}}}{P_{1/2}+(P_{\mathrm{atm}}-P_{\mathrm{min}})}\right). \qquad (6)$$

Π_{max} is the maximum productivity and is assumed to be twice the present value Π_0 (Volk, 1987). $P_{1/2}+P_{\mathrm{min}}$ is the value at which the pressure-dependent factor is equal to 1/2 and $P_{\mathrm{min}} = 10$ ppm the minimum value for photosynthesis. For fixed P_{atm}, Eq. (6) produces maximum productivity at the optimum temperature ($T_{\mathrm{s}} = T_{\mathrm{opt}}$) and zero productivity outside the temperature tolerance interval $[0^\circ\mathrm{C}\ldots 2T_{\mathrm{opt}}]$.

The present biosphere can be described with $T_{\mathrm{opt}} = 25^{\circ}\mathrm{C}$. For the description of a thermophilic or hyperthermophilic biosphere we have also investigated models with maximum biological productivity at $T_{\mathrm{s}} = 50^{\circ}\mathrm{C}$ and zero productivity for $T_{\mathrm{s}} \leqslant 0^{\circ}\mathrm{C},\ T_{\mathrm{s}} \geqslant 100^{\circ}\mathrm{C}$.

First, we have solved the system of Eqs. (1–6) under the assumption that the weathering rate F_{wr} is always equal to the present value $F_{\mathrm{wr},0}$. This is clearly a rather rough approximation. We call this approach the geostatic model (GSM).

Franck et al. (1999) have introduced the geodynamic model (GDM). In this case, a balance between the $\mathrm{CO_2}$ sink in the atmosphere–ocean system and the metamorphic (plate-tectonic) sources is expressed with the help of dimensionless quantities (Kasting, 1984):

$$f_{\mathrm{wr}} \cdot f_{\mathrm{A}} = f_{\mathrm{sr}}, \tag{7}$$

where $f_{\mathrm{wr}} \equiv F_{\mathrm{wr}}/F_{\mathrm{wr},0}$ is the weathering rate normalized by the present value, $f_{\mathrm{A}} \equiv A_{\mathrm{c}}/A_{\mathrm{c},0}$ is the continental area normalized by the present value, and $f_{\mathrm{sr}} \equiv S/S_0$ is the spreading rate normalized by the present value.

With the help of Eq. (7) we can calculate the weathering rate from geodynamical theory. The main idea consists in the coupling of the thermal and degassing history of the Earth. To formalize this coupling we need a relation between the mantle heat flow, expressing the thermal history, and the sea-floor spreading rate, expressing the degassing history. The spreading rate is given as a function of the mantle heat flow calculated by the cooling process of an oceanic plate which is approximated by the cooling of a semi-infinite half-space. The derivation of this formula is given in the well-known textbook on geodynamics by Turcotte and Schubert (1982):

$$S(t) = \frac{q_{\mathrm{m}}(t)^2 \pi \kappa A_{\mathrm{o}}(t)}{[2k(T_{\mathrm{m}}(t) - T_{\mathrm{s},0})]^2}. \tag{8}$$

Here q_{m} is the mean heat flow from the mantle, S is again the sea-floor spreading rate, k is the thermal conductivity, T_{m} is the average mantle temperature, κ is the thermal diffusivity, and $A_{\mathrm{o}}(t)$ is the area of ocean basins at time t. $T_{\mathrm{s},0}$ is taken as the constant outer temperature of the upper boundary layer in the parameterized convection approximation (Franck, 1998). The evolution of the global average mantle heat flow is a result of the parameterized convection model. The area of the planet's surface A_{e} is obviously the sum of $A_{\mathrm{o}}(t)$ and the area of continents $A_{\mathrm{c}}(t)$, i.e.,

$$A_{\mathrm{e}} = A_{\mathrm{o}}(t) + A_{\mathrm{c}}(t). \tag{9}$$

Eqs. (8) and (9) can be used to introduce continental growth models into the equations for the volatile cycle. For the present study, i.e. the investigation of an Earth-like planet under the external forcing of the Sun, we used a continental growth model that is based on geological investigations (Condie, 1990). Nevertheless, it turns out as a result of sensitivity tests for various continental growth models (Franck et al., 2000) that the corresponding HZs do not differ in their qualitative behavior and that the life span of the biosphere is always of the same order of magnitude.

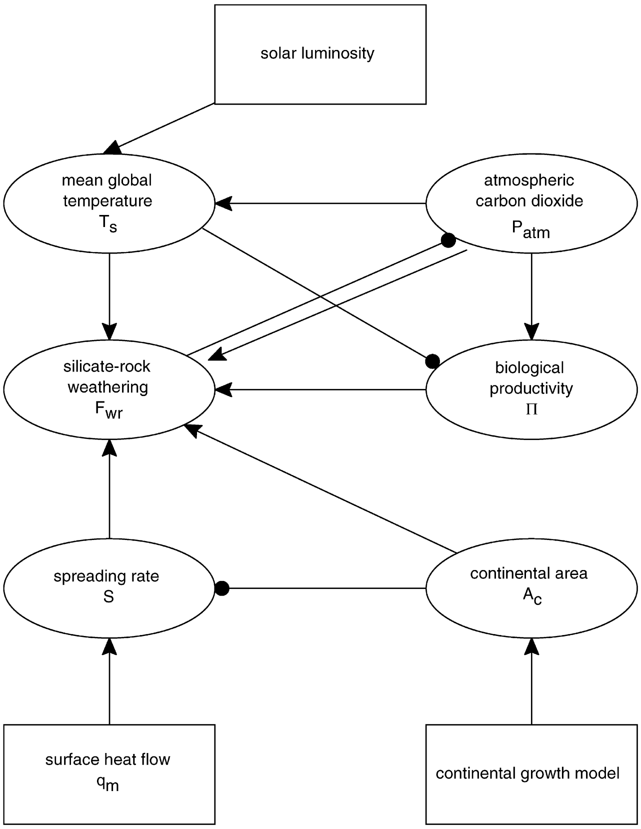

Fig. 1. Positive and negative feedbacks in our Earth system model.

Now, we have the means to calculate the weathering rate for every time step of the evolution of an Earth-like planet with the help of Eqs. (7)–(9) and to determine self-consistently the climatic parameters and the biological productivity from the system of Eqs. (1)–(6). Our Earth system model is sketched in Fig. 1.

The aim of all these calculations is the determination of the HZ. In our approach, the HZ for an Earth-like planet is the region around the Sun within which the surface temperature of the planet stays between $0^{\circ}\mathrm{C}$ and $2T_{\mathrm{opt}}$ and the atmospheric $\mathrm{CO_2}$ content is higher than 10 ppm suitable for photosynthesis-based life (i.e. biological productivity $\Pi > 0$):

$$\mathrm{HZ} := \{R \mid \Pi(P_{\mathrm{atm}}(R,t), T_{\mathrm{s}}(R,t)) > 0\}. \tag{10}$$

The upper limit of $\mathrm{CO_2}$ content is the total amount of $\mathrm{CO_2}$ in an Earth-like planet's atmosphere which is taken as 5 bar or 10 bar, respectively. The term "Earth-like" explicitly implies the occurrence of plate tectonics as a necessary condition for the operation of the carbonate-silicate cycle as the mechanism to compensate the gradual brightening of the Sun during its "life" on the main sequence. In our model, the geodynamical evolution of the considered Earth-like planet provides an even stronger constraint. In the geological past the volcanic input of $\mathrm{CO_2}$ to the atmosphere was much

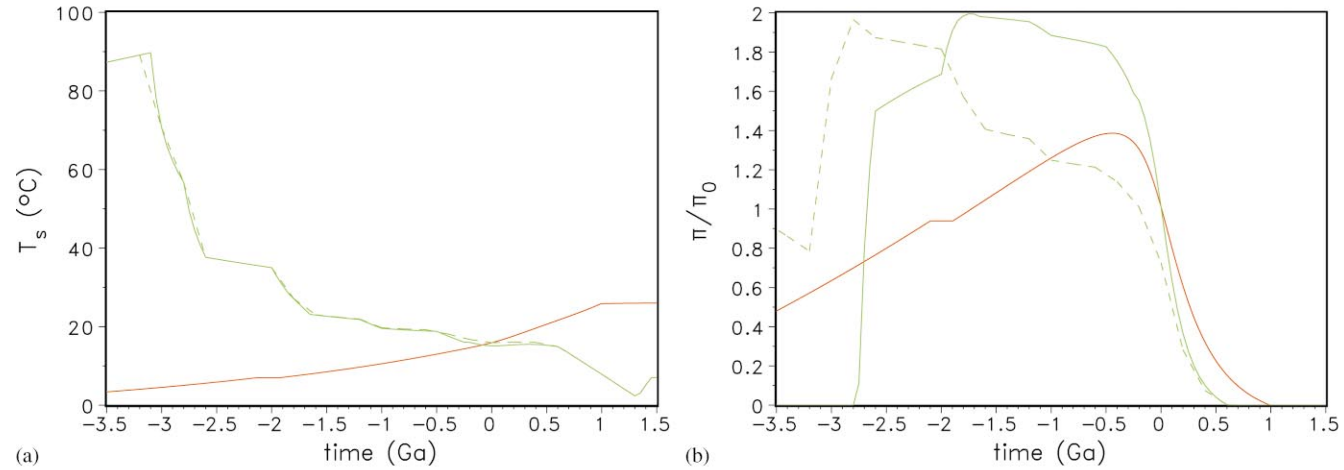

Fig. 2. Past and future evolution of the surface temperature (a) and normalized biological productivity (b) for the GSM (red) and the GDM (green). The full green line corresponds to $T_{\text{opt}} = 25^\circ$C and the dashed green line to $T_{\text{opt}} = 50^\circ$C.

higher than today and the continental area (available for weathering) was much smaller than today.

3. Results and discussion

In our computer model, we started with the parameters for the present state of the Earth system ($f_{\text{wr}} = F_{\text{wr}}/F_{\text{wr},0} = 1$). From the ratio of the dimensionless mid-ocean seafloor spreading rate and the dimensionless continental area from Franck and Bounama (1995; 1997) we calculated f_{wr} via Eq. (7) for time steps of one million years back to Earth's history. With a numerical root-finding method, we solved the system of Eqs. (1–9) self-consistently back to the Hadean. At this geological era, life changed from anaerobic to aerobic forms, and for the biological productivity Eq. (6) may be applied. Starting from the present state again, we ran our model 1.5 Ga into the future. Furthermore, we performed the procedure at varying distances of our model planet Earth from the Sun between 0.6 and 2.0 AU.

The results for the surface temperature, T_s, and biological productivity, Π, as the key parameter for the determination of the HZ are shown in Figs. 2 a and b. We have plotted both, the geostatic and the geodynamic models for optimum temperatures $T_{\text{opt}} = 25$ and 50°C, respectively. The temperature curves (Fig. 2a) for the geological past are always in the temperature window $[0\ldots100^\circ\text{C}]$, which is in qualitative agreement with the general temperature record but of course does not hint to such effects like snowball states (see, e.g., Hoffmann et al., 1998).

We find a strong change in biological productivity (Fig. 2b) in the GDM for the past period resulting from higher temperatures. For $T_{\text{opt}} = 25^\circ$C, corresponding to a temperature tolerance interval $[0\ldots50^\circ\text{C}]$, the biological productivity has a maximum in the Proterozoic but is zero in the early Archaean. For $T_{\text{opt}} = 50^\circ$C, corresponding to a temperature tolerance interval $[0\ldots100^\circ\text{C}]$, the maximum of Π is in the late Archaean and is always greater than zero. This is a hint to the preferred conditions for thermophiles and hyperthermophiles in early Earth's history (Schwartzman et al., 1993). In the future, biological productivity of the GDM decreases to zero some hundred million years earlier than for the GSM, reducing the life span of the biosphere for the same amount. The effect results both from the further continental growth and from the further decrease in spreading rate forcing lower atmospheric CO_2 content (Franck et al., 2000).

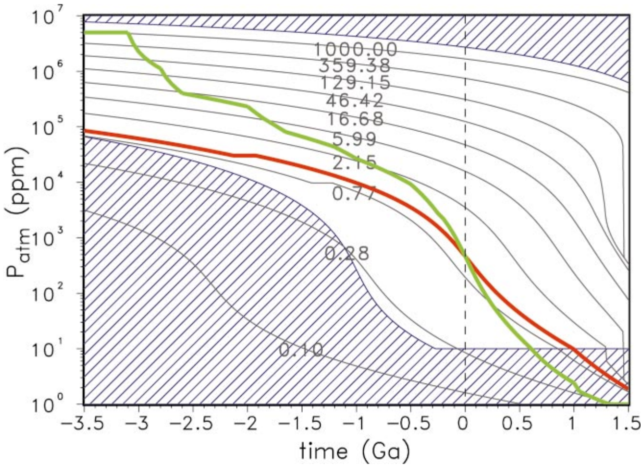

Fig. 3. Evolution of the atmospheric carbon content for GSM (red) and GDM with $T_{\text{opt}} = 50^\circ$C (green). The terrestrial life corridor is the non-dashed region. The plotted isolines are the solutions of GSM for the indicated fixed values of the normalized weathering rate f_{wr}.

Fig. 3 shows the atmospheric carbon content over the time from the Hadean to the planetary future for the two models. In the dashed region of Fig. 3 no photosynthesis is possible because of inappropriate temperature or atmospheric carbon content. In the non-dashed region, photosynthesis-based life is possible. This region is called the "terrestrial life corridor". The reference model GSM

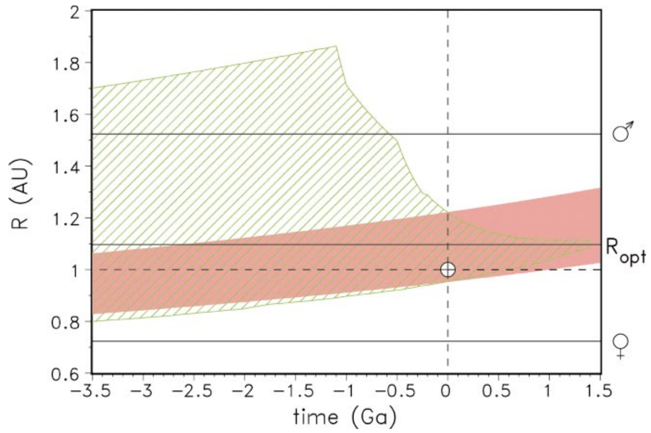

Fig. 4. Evolution of the HZ for GSM (red) and GDM (green). The optimum position of an Earth-like planet is at $R_{\mathrm{opt}} = 1.08$ AU. In this case the life span of the biosphere is at maximum. The total amount of carbon P_{CO_2}(total) is 10 bar and the optimum temperature for the biosphere T_{opt} is 50°C.

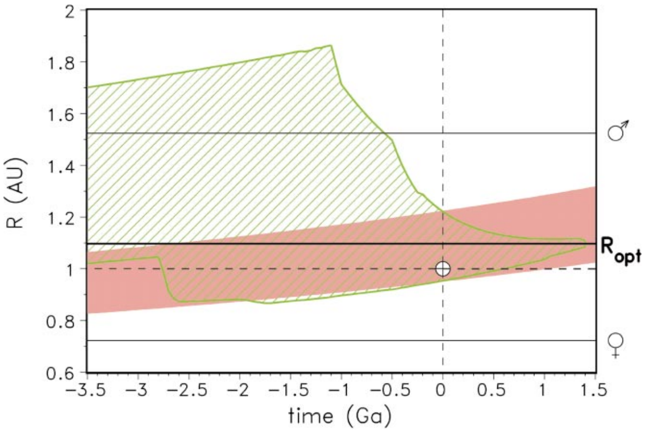

Fig. 5. Evolution of the HZ for GSM (red) and GDM (green). The optimum position of an Earth-like planet is at $R_{\mathrm{opt}} = 1.08$ AU. In this case the life span of the biosphere is at maximum. The total amount of carbon, P_{CO_2}(total), is 10 bar and the optimum temperature for the biosphere, T_{opt}, is 25°C.

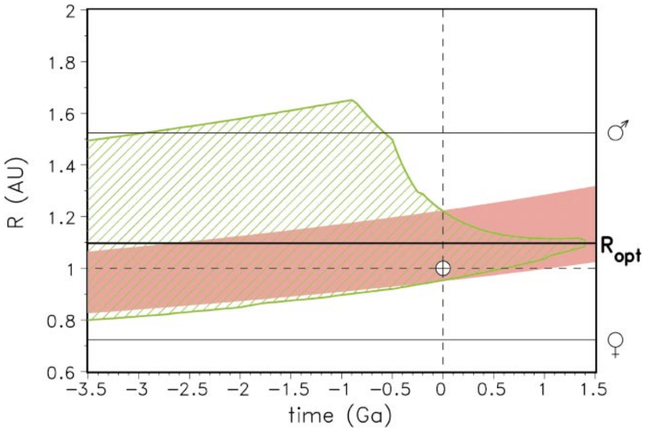

Fig. 6. Evolution of the HZ for GSM (red) and GDM (green). The optimum position of an Earth-like planet is at $R_{\mathrm{opt}} = 1.08$ AU. In this case the life span of the biosphere is at maximum. The total amount of carbon P_{CO_2}(total) is 5 bar and the optimum temperature for the biosphere T_{opt} is 50°C.

is based on a weathering rate that is always equal to the present-day rate $F_{\mathrm{wr}}/F_{\mathrm{wr},0} = 1$. The GDM takes into account the influence of an enlarging continental area and the changing spreading rate on weathering. It has higher weathering rates for the past (i.e. $F_{\mathrm{wr}}/F_{\mathrm{wr},0} > 1$). This can be explained easily with the help of Eq. (7), because in the geological past we have higher spreading rates, f_{sr}, and a smaller continental area, f_{A}. In the planetary future we find the reverse situation: lower spreading rates and higher continental area. This is the reason why the biosphere's life span is shorter, because photosynthesis can persist only up to the critical level of 10 ppm atmospheric CO_2 concentration. Compared to the smooth curve of the GSM model, our favorite model GDM provides a curve with a certain structure that is directly related to the step-like continental growth (Franck et al., 2000).

Besides calculating the terrestrial life corridor, i.e., the evolution of atmospheric carbon regimes with possibilities for photosynthesis-based life in time, we also calculated the behavior of our virtual Earth system at various distances, R, from the Sun, which gives different insolations. This determines the HZ as the region around the Sun within which an Earth-like planet might enjoy conditions needed for advanced life forms. The results for the estimation of the HZ are shown in Figs. 4–6 where we have plotted the width and position of the HZ for geostatic and geodynamic models over time.

In Fig. 4, we show the HZ for the GSM and the GDM with a total carbon content of 10 bar and $T_{\mathrm{opt}} = 50$°C, i.e. 100°C as the upper bound for the biological productivity. First, we find that the width and the position of the HZ are completely different for the models GSM and GDM. For the geostatic case (GSM), the width of the HZ is nearly constant and shifts only slightly outward with time, which is the result of increasing insolation. In about 1000 Ma the inner boundary of the HZ reaches the Earth distance ($R = 1$ AU) and the biosphere ceases to exist, as already found in the results for the biological productivity (Fig. 2b) and the terrestrial life corridor (Fig. 3). Our favorite GDM shows both a shift and a narrowing of the HZ. The inner boundary reaches the Earth distance in about 600 Ma in correspondence with the shortening of the life span of the biosphere by about 400 Ma compared to GSM. In the GDM, the outer boundary shows the following behavior: the nearly linear increase of the outer edge of HZ from 1.7 AU at −3.5 Ga to the maximum greenhouse limit of 1.8 AU at −1.1 Ga results only from the increase in solar luminosity. After −1.1 Ga ago geodynamics comes directly into play via two processes: first, more effective weathering because of growing continental area and, second, decreasing CO_2 input because of decreasing volcanic activity caused by decreasing spreading rate. The effect of these two processes provokes a lowering of the outer edge of HZ down to 1.08 AU in about 1.4 Ga. At this point, the outer and the inner boundary of the HZ coincides and the HZ of our favored GDM vanishes. Therefore, the negative feedback mechanism of Walker et al. (1981) cannot be applied directly to our model.

At present, for our models GSM and GDM the outer edge of the HZ is about 1.2 AU. That is noticeably smaller than the 1st CO_2 condensation limit of Kasting et al. (1993) at 1.37 AU. The reason for this is the weaker greenhouse effect in the model of Williams (1998) compared to other greenhouse models. For example, the application of a different greenhouse model based on a radiative–convective climate model (Caldeira and Kasting, 1992) gives 1.39 AU for the present outer boundary of HZ (Franck et al., 2000). But this greenhouse model works only for CO_2 contents lower than 10^5 ppm and is therefore not suitable to determine the HZ in the early stages of Earth's evolution.

According to Kasting et al. (1993), the outer boundary of the HZ is determined by CO_2 clouds that attenuate the incident sunlight via Rayleigh scattering. The critical CO_2 partial pressure for the onset of this effect is about 5–6 bar. Recently, the effect of CO_2 clouds has been challenged by Forget and Pierrehumbert (1997). CO_2 clouds have the additional effect of reflecting the outgoing thermal radiation back to the surface. They may have played a role in warming Earth when the Sun was fainter than today, assuming that enough CO_2 was available on early Earth. In this way, they could have extended the size of the HZ in the past. In the future, however, solar luminosity will be too high and atmospheric CO_2 content will be too low for the formation of CO_2 clouds. As will be discussed below, we felt that we do not have to take into account these effects at least for our models with a maximum atmospheric CO_2 content of about 5 bar.

Furthermore, we can state from Fig. 4 that in the framework of our favorite model GDM the optimal distance of the Earth system would be about 1.08 AU. At such a distance the self-regulation mechanism would work optimally against increasing external forcing arising from increasing solar insolation, and the life span of the biosphere would be extended to 1.4 Ga. But after this time the biosphere would definitely cease to exist. For the model parameters of the GDM in Fig. 4 ($T_{\text{opt}} = 50^\circ$C, $P_{CO_2}(\text{total}) = 10$ bar) an Earth-like planet at the position of Venus is always outside the HZ while such a planet at Martian distance is within the HZ from the Hadean up to about 500 Ma ago.

Fig. 5 shows the HZ for the GSM and the GDM with $T_{\text{opt}} = 25^\circ$C, i.e. 50°C as the upper bound for the biological productivity and again $P_{CO_2}(\text{total}) = 10$ bar. In this case, we find a qualitative change of the inner boundary of the HZ for GDM in the past. First, at about 2 Ga ago, this boundary shifts slightly outward and is more distant from the Sun than for the geostatic case. But at more than about 2.8 Ga ago the Earth is outside the HZ because mean global temperatures are obviously higher than 50°C. So we find that the inner boundary of the HZ up to 2 Ga ago is mainly determined by the upper temperature limit for photosynthesis.

In Fig. 6 we have plotted the HZ for GSM and GDM with $T_{\text{opt}} = 50^\circ$C but a total carbon content of 5 bar. This value of $P_{CO_2}(\text{total}) = 5$ bar was chosen because of the discussions about the role of CO_2 clouds in early Martian climate (Pollack et al., 1987; Kasting 1991, 1997; Squyres and Kasting, 1994; Forget and Pierrehumbert, 1997; Haberle, 1998). First, it was calculated that condensation of CO_2 decreases the lapse rate and reduces the magnitude of the greenhouse effect. This cloud-effect is important at low solar luminosity and CO_2 partial pressure higher than 5 bar. According to this Martian surface temperature cannot be raised to arbitrary levels by increasing atmospheric CO_2 content above 5 bar. Forget and Pierrehumbert (1997) found that the crystals of CO_2 ice should scatter radiation at thermal infrared wavelength more effectively than they scatter visible and near-infrared radiation. Therefore, CO_2 clouds can keep the early Mars warm by shielding infrared backscattering from the Martian surface. In this way, the described phenomenon may imply that the HZ may be wider than the calculated without the help of CO_2 clouds effect. In our climate model we did not consider CO_2 clouds, but as can be seen in Fig. 6, even with $P_{CO_2}(\text{total}) = 5$ bar, an Earth-like planet at Martian position would have been within the HZ from about 3 Ga to about 0.5 Ga ago. So we conclude that the outer boundary of the HZ is mainly determined by the total amount of CO_2 that can be in the atmosphere and the extension of the HZ up to Martian position seems to be realistic for the past.

Concerning the planet Mars itself, we know that because of its smaller size all geological processes caused by the internal cooling of the planet should go off much faster than for the Earth. Nevertheless, we can speculate that our findings about the HZ are an upper bound for the time that Mars was habitable in the past. This is in good agreement with investigations concerning an early warmer and wetter Martian environment (Golombek, 1999) and with recent observations that plate tectonics may have once operated on Mars (Connerney et al., 1999).

In contrast to Mars, we find in our model that the Venusian position was never and will never be within the HZ.

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