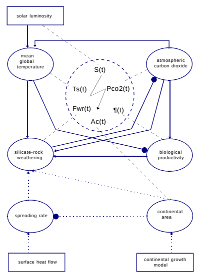
Self-regulation in the Earth system and the determination of a habitable zone

Introduction

A qualitative geosphere-biosphere model consisting of the components solid Earth, hydrosphere, atmosphere, and biosphere is considered. The model is based on a quasi-equilibrium of the large-scale global carbon balance between the main sources and sinks modified by the biosphere. To calculate the weathering rate we take into account the growth of continental area over geological time scales and extrapolate the present continental growth rate to the future. We determine the "life corridor" for the existence of a photosynthesis-based biosphere dependent on the state parameters of the Earth system. Furthermore, the habitable zone around the Sun in the past, present and the planetary future under certain boundary conditions of the existence of photosynthesis-based life is calculated.

Model description



The model is based on the Caldeira Kasting model (Caldeira and Kasting, 1993), which is extended by a geodynamic model of the geosphere.

It consists of the following compartments: geosphere, atmosphere, and biosphere, which are linked through nonlinear feedbacks. An external forcing is given by the increasing solar luminosity.

Climate

The climate of the planet is described by the energy balance equation for the surface temperature T_s :

$$4\sigma T_{eff}^{4} = S(t)(1-a), \quad T_s = T_{eff} + \Delta T \tag{1}$$

where ΔT is the greenhouse warming which is a monotonous increasing function of the CO_2 content in the atmosphere P_{atm} , i.e. $\Delta T = \Delta T(P_{atm})$.

Insolation S(t) increases in time:

$$S(t) = S_0(1-0.38t/4.55)^{-1} . \tag{2}$$

For constant P_{atm} we get from (1) temperatures below 0^oC in the past in contradiction to geologic records (Faint Young Sun paradoxon). A solution of this paradox can be found if the intrinsic feedback mechanism of the carbonate-silicate cycle is taken into account.

Carbon cycle

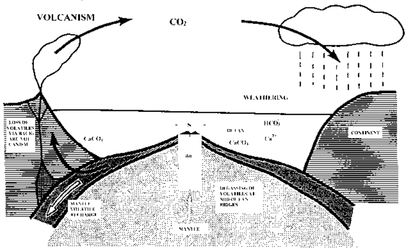


Fig. 1: Global carbon cycle

Balance equation between sources and sinks of the carbon in the atmosphere for geologic times (see Fig. 1) yields

$$f_{wr} \cdot f_A = f_{sr} , \tag{3}$$

where $f_{wr} = F_{wr}/F_{wr,0}$ is the weathering rate (per area) normalized to the present day value $F_{wr,0}$ (sink of carbon), $f_A = F_A/F_{A,0}$ the normalized continental area and $f_{sr} = F_{sr}/F_{sr,0}$ the normalized spreading rate (source of carbon). The equation can be written as

$$f_{wr} = \frac{f_{sr}}{f_A} = GFR , \tag{4}$$

where GFR is the geophysical forcing ratio. The total amount of carbon in the Earth system can be roughly approximated to 10^7 ppm.

Weathering rate

Carbonate-silicate rock weathering depends on the temperature and the carbon in the soil P_{soil} :

$$f_{wr} \propto (a_{H^+}(P_{soil}))^{0.5} \exp\left(\frac{T_s - T_0}{13.7}\right) , \tag{5}$$

where a_{H^+} is the activity of H^+ in the soil. P_{soil} is a function in the following linear form:

$$P_{soil} = P_{atm} + \alpha\Pi . \tag{6}$$

Π denotes the biologic productivity. Therefore, the biosphere *increases* the weathering rate of carbon.

Biologic productivity

Π is a function of the surface temperature and atmospheric CO_2:

$$\Pi(T_s,P_{atm}) = \Pi_{max} \cdot \Pi_T(T_s) \cdot \Pi_P(P_{atm}) . \tag{7}$$

For Π_T we have a parabolic form, for Π_P a Michaelis-Menten hyperbola (see Fig. 2).

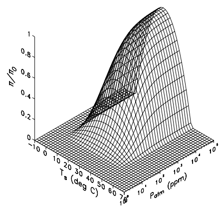


Fig. 2: Biologic productivity as a function of T and P_{atm} .

Geodynamics

A basic assumption of the Caldeira-Kasting model is a static geosphere, i.e.

$$GFR(t) \equiv GFR(0) = \text{const.} . \tag{8}$$

This so-called geostatic model (GSM) is a rather rough approximation. A geodynamic model (GDM) with spreading and continental growth give us a significant improvement.

Continental growth. For continental growth a data-based model (see Fig. 3) was used (Condie, 1990).

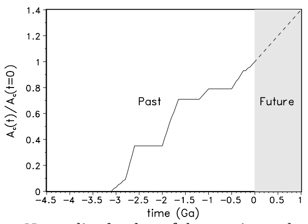


Fig. 3: Normalized value of the continental area.

Spreading rate. According to the boundary layer theory the spreading rate is given as a function of the heat flow calculated by the cooling process of an oceanic plate (Franck et al., 1998):

$$F_{sr}(t) = \frac{q_m(t)\pi\kappa A_o(t)}{[2k(T_m(t)-T_{s,0})]^2} . \tag{9}$$

The mantle heat flow $q_m(t)$ and temperature $T_m(t)$ are determined by a parameterized convection model.

Using Eq. 4 as the initial equation and using Eqs. 1,2 and 5-7 the coevolution of the geosphere-biosphere system can be described by solving

$$f_{wr}(P_{atm},t) = GFR(t) . \tag{10}$$

The corresponding temperature is calculated using Eq. 1.

Results and discussion

Eq. 10 was solved for the GSM and the GDM scheme. Fig. 4 shows the evolution of the global temperature under increasing insolation (Eq. 2). Up to 1 Ga into the future, the temperature varies only within an interval of 10^oC to 40^oC. This stabilization of the surface temperature is a result of the carbonate-silicate self-regulation within the Earth system. In contrast to the GSM approach, the GDM scheme shows a temperature stabilization at a higher level in the past and a lower one in the future.

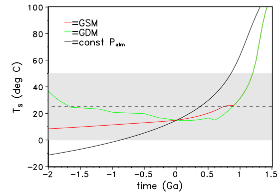


Fig. 4: Surface temperature for the GSM and GDM scheme.

The terrestrial life corridor TLC can be defined in the following way:

$$TLC = \{(T_s,P_{atm}) | \Pi(T_s,P_{atm}) > 0\} . \tag{11}$$

Then we get the following picture of the Earth system evolution:

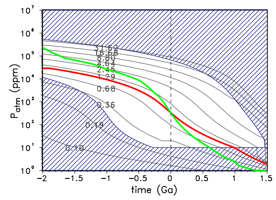


Fig. 5: Terrestrial life corridor for GSM and GDM.

Besides calculating the TLC, i.e., the evolution of atmospheric carbon regimes supporting photosynthesis-based life in time, we calculated the behaviour of our virtual Earth system at various distances from the Sun, using different insolations.

If R denotes the distance from the Sun insolation S is rescaled to

$$S'(R,t) = S(t)\left(\frac{R_{Earth}}{R}\right)^2 . \tag{12}$$

The habitable zone (HZ) can be defined by the interval $[R_{inner},R_{outer}]$, where the biologic productivity is greater than zero, i.e., the planet is within the TLC. Fig. 6 shows the HZ for the GDM and the GSM model.

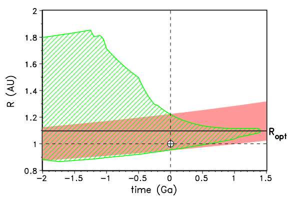


Fig. 6: Habitable zones for GSM and GDM.

For the geostatic case (GSM) the width of the HZ slightly increases and shifts outward over time. In about 1 Ga the inner boundary reaches the Earth distance from the Sun (*R* = 1 AU) and the biosphere ceases to exist. The GDM shows both a shift and a narrowing of the HZ: the inner boundary reaches the Earth distance in about 600 Ma from now, while the outer boundary decreases in a strong nonlinear way. An optimum distance from the Sun can be identified (*R*=1.09 AU), where the life span would be extended to 1.4 Ga.

References

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