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A climatic thermostat making Earth habitable

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Abstract: The mean surface temperature on Earth and other planets with atmospheres is determined by the radiative balance between the non-reflected incoming solar radiation and the outgoing long-wave black-body radiation from the atmosphere. The surface temperature is higher than the black-body temperature due to the greenhouse warming. Balancing the ice-albedo cooling and the greenhouse warming gives rise to two stable climate states. A cold climate state with a completely ice-covered planet, called Snowball Earth, and a warm state similar to our present climate where greenhouse warming prevents the total glaciation. The warm state has dominated Earth in most of its geological history despite a 30% fainter young Sun. The warming could have been controlled by a greenhouse thermostat operating by the temperature control of the weathering process depleting CO_2 from the atmosphere. This temperature control has permitted life to evolve as early as the end of the heavy bombardment 4 billion years ago.

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Introduction

Primitive life has existed on Earth since early in its geological history. Stromatolites, which are thought to be fossils of photosynthesizing cyanobacteria, have been found to be as old as 3.5 Ga (giga-anni = billion years) (Schopf 1993). Isotope fractionation in carbon found in 3.8 Ga old rocks from Isua, Greenland indicates a biological origin (Rosing 1999). Within a few hundred million years, this is perhaps the earliest time of stable planetary climate possible for life. In the prior heavy-bombardment period, impacts releasing high enough energies to evaporate the entire ocean would probably have sterilized the Earth if life existed at that time (Kasting & Catling 2003).

At some time around the Archaean–Proterozoic border, 2.5 Ga before present (BP), the atmospheric content of oxygen began rising to its present level, making way for the dominance of aerobic life forms. For a very long period after this there is no evidence of biological evolution. The eukaryotic (cells with a nucleus) and multicellular life seems to have evolved as late as 0.6 Ga BP at the Cambrian explosion, or perhaps in the late Precambrian where the soft body Ediacara fauna originates. This could indicate that the oxygen level rose slowly, reaching levels needed for effective oxygen transport and metabolism in multicellular organisms at the Cambrian explosion.

The habitable zone (HZ) around a Sun-like star is defined by the requirement of liquid water at the surface of planets or moons in the zone. This zone is primarily determined by the radiative output from the star. The dependence of the radiative flux, which is proportional to the inverse distance squared, makes the HZ relatively narrow. At present, our Solar System only contains Earth within the HZ (Kasting & Catling 2003).

The long existence of life indicates that the surface temperature on Earth has indeed kept within the narrow range permitting liquid water for a surprisingly long time, despite a 30% lower solar flux at the beginning of Earth's history. This apparent paradox is dubbed: 'The Faint Young Sun Problem' (Kasting 1988). The solution to the problem could be a self-regulatory mechanism, either through a biotic feedback (Lovelock & Margulis 1982) or a geochemical regulation (Owen *et al*. 1979; Walker *et al*. 1981). The former can only be at play after the evolution and expansion of life to the planetary scale and, therefore, cannot explain the stable climate conditions necessary for the initiation of life.

In addition to extending the time for the habitability of a planet, a geochemical regulation could potentially widen the HZ. There is now mounting evidence that Mars had liquid water on the surface in its early history and, thus, was within the HZ then despite the lower solar luminosity.

The radiative energy balance

The surface temperature of a planet is determined from the balance between incoming solar radiation R_i and outgoing black-body radiation R_o. This energy balance depends on, among other factors, the planetary albedo. The albedo of an object is the fraction of the sunlight hitting an object that is reflected. The planetary albedo is not a constant factor: it depends on the state of the climate itself, through the amount of clouds and ice. The feedback of clouds on temperature is very complicated. It depends on the height of the clouds in the atmosphere and the state of the atmosphere surrounding the clouds. The clouds cool by reflecting the incoming radiation and they heat by trapping the outgoing radiation. Ice and snow on the surface unambiguously cool by reflecting the incoming short-wave radiation, so the amount of ice and snow influences the planetary albedo. This effect can be described in a model of the climate represented by just one parameter, the mean surface temperature T (Crafoord & Källén 1978; Ghil *et al.* 1985). This temperature determines the long-wave radiation and the reflection of the short-wave radiation through the albedo. The amount of ice and snow is larger when the temperature is lower, so the lower the temperature the higher albedo. If the temperature is below some low temperature T_1, the planet will be completely ice covered and a further decrease in temperature cannot increase the albedo above the value α_1 for a fully ice-covered planet. If the temperature is above some other high temperature T_2, the ice is completely melted and a further increase in temperature will not lead to a decrease in albedo below the value α_2 for an ice-free planet. The simplest functional form is a linear dependence of the albedo on temperature between these two temperatures. This is a reasonable choice when no other information is available *a priori*. We then have the relation

$$\alpha(T)=\alpha_1\mathcal{I}_{[0,T_1]}+\frac{(T_2-T)\alpha_1+(T-T_1)\alpha_2}{T_2-T_1}\mathcal{I}_{(T_1,T_2]}+\alpha_2\mathcal{I}_{(T_2,\infty)}, \tag{1}$$

where $\mathcal{I}_{(a,b]}$ is the indicator function for the interval $(a, b]$. The change of temperature T is determined by the difference $R_\mathrm{i}-R_\mathrm{o}$ in incoming and outgoing radiation according to the equation

$$c\frac{dT}{dt}=R_\mathrm{i}-R_\mathrm{o}=[1-\alpha(T)]S-\sigma g(T)T^4, \tag{2}$$

where c is the heat capacity, σ is the Stefan–Boltzmann constant and $S=\tilde{S}/4$ is a quarter of the solar constant. (The quarter comes from the ratio of the cross-sectional area to the surface area of the sphere.) The factor $g(T)$ expresses the atmospheric greenhouse effect. The black-body temperature T_bb of the planet is the temperature at the level in the atmosphere from where the long-wave radiation is emitted. This level is the height of the optical thickness at the long-wave band seen from space. Depending on greenhouse gasses and clouds the level of outgoing radiation is approximately 3 km above the surface. The difference between the black-body temperature and the surface temperature is the greenhouse warming (or cooling). On Earth the atmosphere is transparent to the sunlight, which thus heats the surface, which, in turn, heats the atmosphere from below. The lower atmosphere (the troposphere) thus experiences a positive lapse rate (negative temperature change with height). The lapse rate depends in a complicated way on the static stability

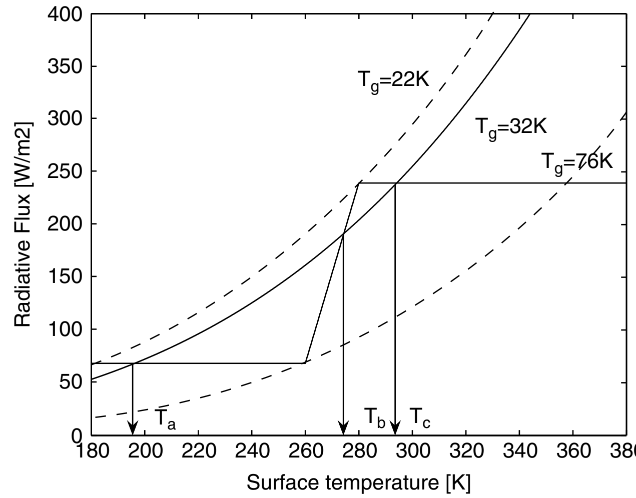

Fig. 1. The incoming and outgoing fluxes as a function of global temperature. When the greenhouse warming is below 22 K the warm stable climate state at T_c disappears through a saddle-node bifurcation and the 'deep freeze' state at T_a is the only stable climate state.

and atmospheric dynamics. In the present climatic conditions the lapse rate is of the order of 10 K km^{-1}, thus the greenhouse effect on Earth is approximately 3 km × 10 K km^{-1}= 30 K. Without the greenhouse effect there would be no liquid water at the surface of Earth. The atmospheric greenhouse effect, the change in cloudiness and other factors must all be expressed through the 'transfer function' $g(T)$, where T represents a mean surface temperature, from which the black-body temperature is derived: $\sigma g(T)T^4=\sigma T_\mathrm{bb}^4$. The simple model (2) is relevant because the behaviour does not depend critically on the specific choice of the parameters (Budyko 1969; Sellers 1969; Crafoord & Källén 1978).

The behaviour of (2) is easily understood from a graphic representation. Figure 1 shows the incoming and outgoing radiations as a function of temperature. There are three temperatures T_a, T_b, T_c for which the curves cross such that the incoming and outgoing radiations are in balance. These points, the fixed points, are the stationary solutions to (2). Consider the climate to be at point T_a. If some small perturbation makes the temperature become lower than T_a we will have $R_\mathrm{i}>R_\mathrm{o}$ implying that $cdT/dt>0$ and the temperature will rise to T_a (see Fig. 1). If, on the other hand, the perturbation is positive and the temperature is a small amount larger than T_a we have $R_\mathrm{i}<R_\mathrm{o}$ implying that $cdT/dt<0$ and the temperature will decrease to T_a again. Thus, T_a is a stable fixed point. A similar analysis shows that T_b is an unstable fixed point and T_c is a stable fixed point. If the temperature at some initial time is lower than T_b it will eventually reach the temperature T_a and if it is higher than T_b it will reach the temperature T_c. The present climate is the climate state T_c where the ice albedo does not play a significant role in cooling the Earth.

The outgoing radiation depends on the surface temperature T through the atmospheric concentration of greenhouse

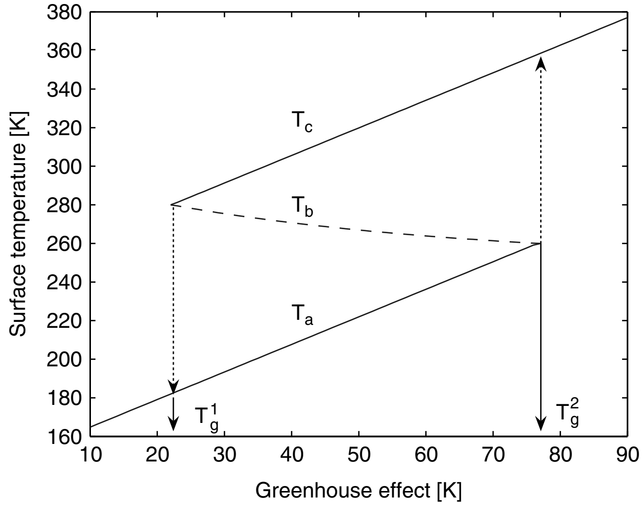

Fig. 2. The bifurcation diagram for the energy balance. If the greenhouse warming falls below $T_g^{(1)}$ the climate will fall into the Snowball Earth climate. The greenhouse warming has to exceed $T_g^{(2)}$ for the planet to leave the Snowball Earth climate. The dotted arrows indicate a hysteresis loop.

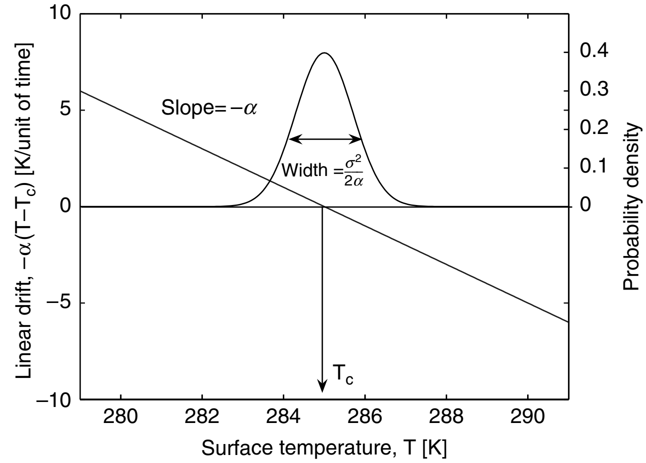

Fig. 3. The stability of the warm climate state against random fluctuations is determined by the radiative cooling feedback represented by the parameter $-\alpha$.

gasses and clouds. Expressing the greenhouse effect in terms of the difference between the surface temperature and the black-body temperature $T_g = (T - T_{bb})$ the outgoing radiation may be written $g(T)\sigma T^4 = \sigma\ (T - T_g - 0.3*[T-270])^4 = R_o(T, T_g)$. The last factor in parenthesis is an empirical factor expressing the increase in greenhouse effect with temperature due to the increase in atmospheric water vapour with temperature.

Consider the climate state represented by T_c in the situation $T_g < T_g$[Present day]. Then for T_g not too small, corresponding to the upper dashed curve in Fig. 1, the equilibrium temperature is lowered a little, as we would expect when the greenhouse warming decreases. However, if T_g becomes smaller than some value $T_g^{(1)}$ the two curves do not cross in more that one point and there is no stable fixed point near T_c. The climate will then run into the only stable fixed point T_a that is still present. A saddle-node bifurcation has occurred resulting in a large change in climate. If T_g grows again the climate state T_c will not recover until T_g exceeds some other value $T_g^{(2)} > T_g$[Present day] and the system returns through a hysteresis loop. For each value of T_g we have either one or three fixed points and we can plot the fixed points in a bifurcation diagram as functions of T_g (Fig. 2). The two full curves represent the stable fixed points and the middle dashed curve represents the unstable fixed point. The unstable and one of the stable points coincide at the bifurcation points $T_g^{(1)}$ and $T_g^{(2)}$.

The stable climate state T_a corresponds to a totally ice-covered planet. The totally ice-covered planet has been termed ‘Snowball Earth’ (Hoffman *et al.* 1998). There is geological evidence of such an extreme ‘deep freeze’ climate several times in the late Neoproterozoic period around 0.7 Ga BP. This is based on findings of glacial deposits such as moraine in many places which at those times were near the equator. The speculated way out of the deep freeze is the following: the balance on geological timescales between silicate weathering, binding atmospheric CO_2 into rocks and volcanic out-gassing of CO_2 was changed during the deep freeze. Due to the cold conditions the atmosphere dried out and weathering effectively stopped. Unchanged volcanic out-gassing resulted in an ever increasing amount of CO_2 in the atmosphere. At some point, after about 10–30 million years, this would result in a greenhouse warming strong enough to melt the ice. The warming would then be almost explosive with global mean temperature going from some -40 °C to some $+50$ °C within a few years. This kind of dramatic climatic change will strongly stress the planetary biota.

Stability of the climatic state

The planetary climate is influenced by internal and external factors which can push the climate state away from the equilibrium position. If the perturbations are small the equilibrium state will be restored within a typical timescale, depending on the size of the perturbation and the strength of the restoring force. The fluctuations can be represented as an independent white noise $\eta(t)$ with intensity $\tilde{\sigma}$. Linearizing (2) around the equilibrium state T_c we get

$$c\frac{dT}{dt} = -\alpha(T - T_c) + \tilde{\sigma}\eta. \qquad (3)$$

The parameter $-\alpha$ is the expansion coefficient for the right-hand side of (2). Equation (3) is the Ohrnstein–Uhlenbeck process (Gardiner 1985), where the variance is $\langle (T-T_c)^2 \rangle = \tilde{\sigma}^2/2\alpha$ (see Fig. 3) and the timescale for restoring the equilibrium temperature can be defined as the autocorrelation time $\tau = \alpha^{-1}$. The stability against the random perturbations is thus measured by α: the larger α is, the smaller the response to the ‘noise’ and the faster the perturbation is forgotten. The stability of the climate state represented by the temperature T_c governs the conditions for biota. However, a

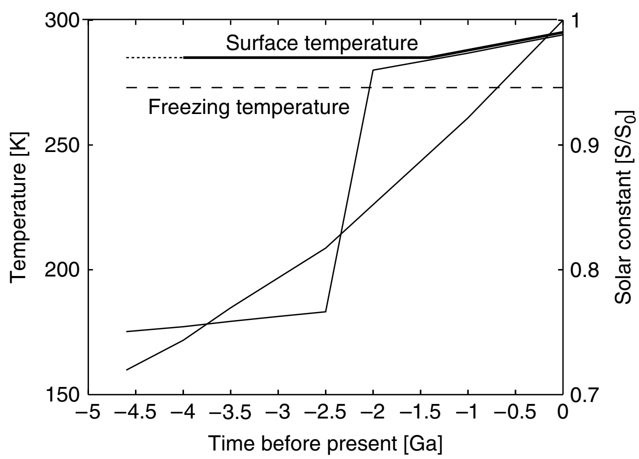

Fig. 4. The surface temperature has, except for a few Snowball Earth episodes in the late Neoproterozoic, been above the freezing point of water for most of Earth's geological history since the heavy bombardment epoch. The surface temperature may have been governed by the greenhouse thermostat. The thermostat was operational until the solar luminosity became strong enough, perhaps 1–1.5 Ga BP. The present atmospheric content of CO_2 and other gasses is regulated by biology itself and are not included in the graph.

long timescale stability is not ensured if the parameters governing the value of T_c itself are changing. The early Sun was about 30 % less luminous than today, which implies that T_c determined by (2) would be lower than today. For a fixed value of the greenhouse gas mixing ratio, the equilibrium temperature can be found from (2) as a function of the solar flux S. This is shown schematically in Fig. 4. At times prior to approximately 2 Ga BP, the solar flux was lower and would not permit liquid water at the surface of the Earth, in contrast to what is observed, except for the spells of Snowball Earth in the late Neoproterozoic period (0.7–0.6 Ga BP). A possible solution to this enigma is that the concentration of greenhouse gasses was much higher in the early atmosphere.

The greenhouse thermostat

The atmospheric concentration of CO_2 on geological timescales depends on the balance between outgassing through volcanoes and burial through weathering of silicate rocks. The rate of change of atmospheric CO_2 concentration governed by these two factors does not depend on the concentration itself. This implies that they will not balance unless they are exactly equal and opposite. The outgassing is independent of the surface temperature while the silicate weathering rate is strongly dependent on temperature. Weathering requires precipitation dissolving atmospheric CO_2 in the form of carbonic acid. The rate of precipitation is strongly temperature dependent. In the present climatic conditions, weathering takes place in the tropics while it is almost absent in the dry and cold polar regions. The simplest way to describe the effect of temperature on silicate weathering is by a step function:

$$\frac{d[CO_2]}{dt} = F_o - F_w \theta(T - T_0), \tag{4}$$

where F_o is the rate of outgassing, F_w is the rate of weathering, $\theta(T-T_0)$ is the Heaviside step function and $T_0 = 285$ K is the temperature below which there is no weathering (Walker *et al.* 1981). If $F_w > F_o$ the CO_2 will be depleted from the atmosphere. This will, however, cool the planet by diminishing the greenhouse effect. When the temperature falls to T_0 weathering stops and the atmospheric CO_2 rises again by outgassing. In terms of the energy balance, the greenhouse factor T_g should represent the part of the greenhouse that is independent of time while the CO_2 greenhouse effect must be described as an additional factor. The energy balance (2) then becomes

$$c\frac{dT}{dt} = [1-\alpha(T)]S - \sigma(T - T_g - 0.3[T-270])^4 + f\theta(T_0 - T), \tag{5}$$

where $f\theta(T_0 - T)$ is the additional CO_2 greenhouse heating. The behaviour is now fundamentally different from the behaviour of (2). For $T_c < T_0$, the warm climate state is given by

$$T_c^< = [\{1-\alpha_2)S + f/\sigma\}^{1/4} + T_g - 51]/0.8. \tag{6}$$

If $T_c^< > T_0$, we have

$$T_c^> = [\{1-\alpha_2)S/\sigma\}^{1/4} + T_g - 51]/0.8. \tag{7}$$

However, $T_c^> < T_c^< \Rightarrow T_c^< < T_0$, in contrast to the assumption. In this case T_c is not a steady-state solution. The surface temperature will increase until it reaches T_0 where weathering efficiently depletes the atmosphere of CO_2 and the temperature drops again. This mechanism is a greenhouse thermostat. The weaker heating from the faint young Sun is thus automatically compensated for by a stronger early CO_2 greenhouse effect. The resulting constant surface temperature is indicated as the thick curve in Fig. 4. In the future the thermostat will not be functional since the atmosphere will be depleted of CO_2 so the increasing solar flux will result in a steady increase in surface temperature.

Perspective

The surface temperature on Earth has been relatively stable permitting the liquid water necessary for biology as we know it in most of its geological history. This is despite a relatively large change in solar flux and atmospheric content of greenhouse gasses, which suggests a thermostat mechanism controlling the surface temperature. A possible thermostat could be operational through silicate weathering depleting the atmosphere from the constantly outgassed volcanic CO_2. The temperature at which weathering becomes active will determine the surface temperature by adjusting the atmospheric greenhouse CO_2 level for the long-wave outgoing radiation balancing the incoming solar radiation. The thermostat will regulate temperature until the solar flux is so large that it can maintain a surface temperature above the temperature where weathering becomes active without the CO_2 greenhouse warming. From that point in time the surface temperature will increase with the increasing solar flux. The greenhouse thermostat will keep the climate warmer than the stable Snowball Earth situation where the ice albedo keeps the surface globally below the freezing point of water. Relatively constant temperatures over geological time determined by geochemical thermostats could be important for the initiation of biological life and could potentially widen the HZ around a Sun-like star. When bacterial-type (or similar) life is established on a planet it could provide a thermostat by itself, as suggested by the Gaia hypothesis (Lovelock & Margulis 1982). Life on Earth is today a dominant player in controlling the atmospheric levels of O_2, CO_2 and CH_4.

References

Budyko, M.I. (1969). The effect of solar radiation variations on the climate of the Earth. *Tellus* **21**, 611–619.

Crafoord, C. & Källén, E. (1978). A note on the condition for existence of more than one steady state solution in Budyko–Sellers type models. *J. Atmos. Sci.* **35**, 1123–1125.

Gardiner, C.W. (1985). *Handbook of Stochastic Methods*. Springer, New York.

Ghil, M., Benzi, R. & Parisi, G. (eds) (1985). *Turbulence and Predictability in Geophysical Fluid Dynamics and Climate Dynamics*. North-Holland, Amsterdam.

Hoffman, P.F., Kaufman, A.J., Halverson, G.P. & Schrag, D.P. (1998). A Neoproterozoic Snowball Earth. *Science* **281**, 1342–1346.

Kasting, J.F. (1988). Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. *Icarus* **74**, 472–494.

Kasting, J.F. & Catling, D. (2003). Evolution of a habitable planet. *Ann. Rev. Astron. Astrophys.* **43**, 429–463.

Lovelock, J.E. & Margulis, L. (1982). Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis. *Tellus* **26**, 2.

Owen, T., Cess, R.D. & Ramanathan, V. (1979). Enhanced CO_2 greenhouse to compensate for reduced solar luminosity on early Earth. *Nature* **277**, 640–642.

Rosing, M.T. (1999). 13C-depleted carbon microparticles in >3700-Ma sea-floor sedimentary rocks from West Greenland. *Science* **283**, 674–676.

Schopf, J.W. (1993). Microfossils of the early Archean Apex chert: new evidence of the antiquity of life. *Science* **260**, 640–646.

Sellers, W.D. (1969). A global climatic model based on the energy balance of the Earth-atmosphere system. *J. Appl. Meteorol.* **8**, 392–400.

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. *J. Geophys. Res.* **86**, 9776–9782.