A climatic thermostat making Earth habitable

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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 temperature control of the weathering process depleting the atmosphere from $CO_2$. This temperature control has permitted
life to evolve as early as the end of the heavy bombardment 4 billion years ago.

Introduction

Primitive life has existed on Earth since early in its geological history. Stromatolites, which are thought to be fossils of photosynthesizing cyanobacteria are found as old as 3.5 Ga (giga-anni = billion years) \cite{Schopf1993}. Isotope fractionation in carbon found in 3.8 Ga old rocks form Isua, Greenland indicates a biological origin \cite{Rosing1999}. This is perhaps within a few hundred million years the earliest time of stable planetary climate possible for life. In the prior heavy-bombardment period impacts releasing energies enough to evaporate the entire ocean would probably have sterilized the Earth if life existed at that time \cite{KastingCatling2003}.

At some time around the Archaean-Proterozoic border, 2.5 Ga BP, the atmospheric content of oxygen began rising to its present level, making way for dominance of aerobic life forms. For a very long period after then 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 Precambrium where the soft body Ediacara fauna originates. This could indicate that the oxygen level rose slowly, reaching levels needed for effective oxygen transports and metabolisms 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 goes as inverse distance squared makes the HZ relatively narrow. At the present time our solar system contains only 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 surprisingly long, despite a 30% lower solar flux at the beginning of Earth’s history. This apparent paradox is dooted "The Faint Young Sun Problem" (Kasting, 1988). The solution to the problem could be a selfregulatory 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 can therefore not explain the stable climate conditions necessary for the initiation of life.

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

**The radiative energy balance**

The surface temperature of the planet is determined from the balance between incoming solar radiation $R_i$ and outgoing black-body radiation $R_o$. This energy balance depends, among other factors, on the planetary albedo. The albedo of an object is the fraction of the sunlight hitting the object which is reflected.
The planetary albedo is not a constant factor; it depends, through the amount of clouds and ice, on the state of the climate itself. The feedback of clouds on temperature is very complicated. It depends on the height in the atmosphere where the clouds are 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 $\alpha_1$ for the 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 $\alpha_2$ for the ice free planet. The simplest functional form is a linear dependence of the albedo on temperature in between these two temperatures. This is a reasonable choice when no other information is available a priory. We then have the relation

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

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

\[ c \frac{dT}{dt} = R_i - R_o = [1 - \alpha(T)]S - \sigma g(T)T^4 \]  

(2)

where \( c \) is the heat capacity, \( \sigma \) 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 \( T_{\text{b-b}} \) 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 gases and clouds the level of outgoing radiation is approximately 3 kilometers 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, this, in turn, heats the atmosphere from below. The lower atmosphere (the troposphere) thus experiences a negative lapse rate (temperature change with height). The lapse rate depends in a complicated way on the static stability and atmospheric dynamics. In the present climatic conditions the lapse rate is of the order -10K/km, thus the greenhouse effect on Earth is approximately 3km×10K/km=30K. Without the greenhouse effect there would be no liquid water at the surface of the 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; \( \sigma g(T)T^4 = \sigma T_{\text{b-b}}^4 \). The simple model (2) is relevant because the behavior does not depend critically on the specific choice of the
parameters (Budyko, 1969; Sellers, 1969; Crafoord & Källén, 1978).

The behavior 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 $R_i > R_o$ implying that $c dT/dt > 0$ and the temperature will rise to $T_a$ (see figure 1). If, on the other hand, the perturbation is positive and the temperature is a small amount larger than $T_a$ we have $R_i < R_o$ implying that $c dT/dt < 0$ 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 gasses and clouds. Expressing the greenhouse effect in terms of the difference between the the surface temperature and the black-body temperature $T_g = (T - T_{b-b})$ 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 the paranthesis is an empirical factor expressing the increase in greenhouse effect with temperature due to increase of atmospheric water vapor 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 blue curve in figure 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 $T_a$ which is still present. A saddle-node bifurcation has occurred resulting in a large change of 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 $T_g$ (figure 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 like 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 in 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
80 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 $-40^\circ C$ to some $+50^\circ C$ within a few years. This
kind of dramatic climatic changes 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:

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

(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 figure 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
$\alpha$, the larger $\alpha$ the smaller is 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 long timescale
stability is not ensured if the parameters governing the value of $T_c$ itself is
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 figure 4. At times prior to approximately 2 Ga before present the solar flux was lower and not permitting liquid water at the surface of the Earth, contrary 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 $CO_2$ in geological timescales depends on the balance between outgassing through volcanos and burrial through weathering of silicate rocks. The rates 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 depending 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;

\[
\frac{d[CO_2]}{dt} = F_o - F_w \theta(T - T_0)
\] (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 \(T_0 = 285K\) 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 which is independent of time while the \(CO_2\) greenhouse effect must be described as an additional factor. The energy balance (2) then becomes:

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

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

\[
T_c^x = [\{1 - \alpha_2\}S + f/\sigma]^{1/4} + T_g - 51]/0.8
\] (6)

If \(T_c^x > T_0\) we have

\[
T_c^y = [\{1 - \alpha_2\}S/\sigma]^{1/4} + T_g - 51]/0.8
\] (7)

But \(T_c^y < T_c^x \Rightarrow T_c^x < T_0\) contrary 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 from \(CO_2\) and the
temperature drops again. This mechanism is a greenhouse thermostat. The weaker heating from the faint young sun is thus automatically compensated by a stronger early $CO_2$ greenhouse. The resulting constant surface temperature is indicated as the fat blue curve in figure 4. In the future the thermostat will not be functional since the atmosphere will be depleted from $CO_2$ 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 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 is keeping 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 ge-
ological time determined by geochemical thermostats could be important for
initiation of biological life and potentially widen the habitable zone around a
sun-like star. When bacterial type life or the like 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 Verlag, N.Y.

Ghil, M., Benzi, R., & Parisi, G. (eds). 1985. *Turbulence and Predictability in Geophysical Fluid Dynamics and Climate Dynamics*. Amsterdam/New York/Oxford/Tokyo: North-Holland Publ. Co.

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. *Annu. 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 ë3700-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. *Journ. Applied Meteorology*, 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.
*Journ. Geophys. Res.*, 86, 9776–9782.
FIGURE CAPTIONS

Fig. 1 The incoming (red) and outgoing (blue and green) 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.

Fig. 2 The bifurcation diagram for the energy balance. If the greenhouse warming fall 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 dodded 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 $-\alpha$.

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 Earths geological history since the heavy bombardment epoch. The surface temperature has been governed by the greenhouse thermostat. The thermostat was operational until the solar luminosity became strong enough perhaps 1.5-1 Ga BP. The present atmospheric content of $CO_2$ and other gasses is regulated by biology itself, not included in the graph.
Figure 1:

Figure 2:
Figure 3:

Figure 4: