Susceptibility of the early Earth to irreversible glaciation caused by carbon dioxide clouds

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SIMPLE energy-balance climate models of the Budyko/Sellers type[1,2] predict that a small (2–5%) decrease in solar output could result in runaway glaciation on the Earth. But solar fluxes 25–30% lower early in the Earth's history[3,4] apparently did not lead to this result. One currently favoured explanation is that high partial pressures of carbon dioxide, caused by higher volcanic outgassing rates and/or slower rates of silicate weathering, created a large enough greenhouse effect to keep the planet warm[5–7]. This does not resolve the problem of climate stability, however, because as we argue here, the oceans can freeze much more quickly than CO_2 can accumulate in the atmosphere. Had such a transient global glaciation occurred in the distant past when solar luminosity was low, it might have been irreversible because of the formation of highly reflective CO_2 clouds, similar to those encountered in climate simulations of early Mars[8]. Our simulations of the early Earth, incorporating the possible formation of such clouds, suggest that the Earth might not be habitable today had it not been warm during the first part of its history.

In the models of Budyko[1] and Sellers[2], a small reduction in solar luminosity results in the advance of ice and snow cover towards the Equator. This additional ice and snow reflects more solar radiation back to space and further cools the planet. If solar luminosity is reduced beyond some critical value in these models, this ice-albedo feedback leads to catastrophic freezing of Earth's entire surface.

Simple models like these cannot explain why the Earth was warm early in its history. The presence of sedimentary deposits in early Archaean rock sequences from Isua, West Greenland, shows that liquid water was present as early as 3.8 Gyr ago[9], when solar luminosity was as much as 25% less, according to standard solar evolution models[3]. High concentrations of greenhouse gases, such as ammonia[4] or carbon dioxide[5] can explain the warm climate; the problem then is to explain why the greenhouse gases were abundant. Walker *et al.*[6] proposed that

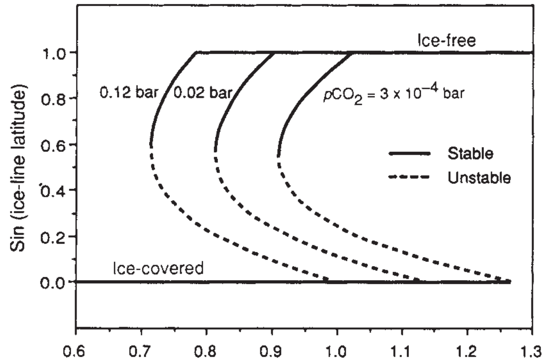

FIG. 1 Steady-state ice lines (x_s) as a function of effective solar luminosity, S_{eff}, for three values of atmospheric pCO_2. If a perturbation were to shift the Earth from its present state ($S_{eff}=1$, $pCO_2=3\times10^{-4}$ bar, $x_s=0.95$) to an ice-covered state today ($S_{eff}=1$, $pCO_2=3\times10^{-4}$ bar, $x_s=0$), then sufficient CO_2 (~0.12 bar) would accumulate in the atmosphere within 30 Myr to make the ice-covered state unstable. The model would then shift to the ice-free state ($S_{eff}=1$, $pCO_2=0.12$ bar, $x_s=1$) and silicate-rock weathering would begin to remove the excess CO_2 from the atmosphere.

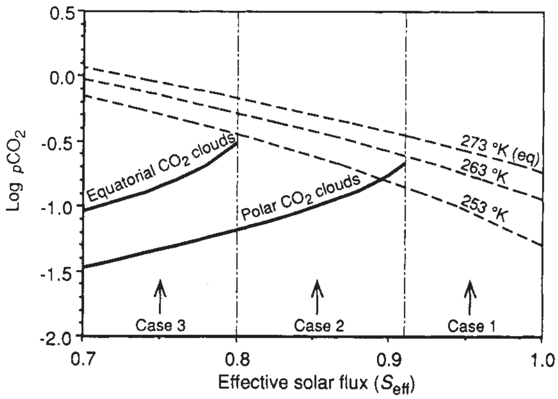

FIG. 2 Solid curves indicate the onset of polar and global CO_2-cloud cover, dashed curves show equatorial surface temperature as a function of effective solar luminosity and atmospheric pCO_2. Case 1: starting from an ice-covered state with low atmospheric pCO_2, volcanic CO_2 would accumulate in the atmosphere and initiate ice-melting before the formation of CO_2 clouds. Case 2: polar CO_2 clouds would form before the onset of equatorial ice-melting. Case 3: CO_2 clouds would form globally before the onset of ice-melting, in which case CO_2-global warming would probably be incapable of melting off the ice.

the temperature dependence of the silicate weathering rate creates a negative feedback that maintains high enough CO_2 concentrations to stabilize the Earth against the ice-albedo catastrophe. This negative feedback was incorporated into an energy-balance climate model by Marshall *et al.*[7], who showed that it could produce cold global climates if the continents were clustered near the Equator. Exposed silicate rock would then be bathed in a relatively warm and wet environment, conducive to CO_2 consumption by weathering. Both lower solar luminosity and the presence of an equatorial, Late Proterozoic supercontinent may therefore help to explain the widespread low-latitude Late Proterozoic glaciation[7,10–13].

Marshall *et al.*[7] further suggested that the silicate-weathering/CO_2 feedback can stabilize the ice line at low latitudes, but reanalysis of their model indicates that this is incorrect. Because atmospheric CO_2 responds much more slowly ($>10^5$ yr; ref. 14) than does sea ice and snow cover (<1 yr), the silicate-weathering feedback cannot buffer the climate system against rapid fluctuations in the ice line. A perturbation analysis[15] of their model shows that there is no stable ice line nearer to the Equator than ~30° latitude, regardless of the partial pressure of atmospheric CO_2. (The convergence problems mentioned by Marshall *et al.*[7] may have been a symptom of this instability.) In their model, a low-latitude glaciation should therefore run away to the globally ice-covered state. Could this have actually happened during the Late Proterozoic era?

To study this question, and to address the general problem of climate stability throughout geological time, we developed a new zonally averaged energy-balance climate model (see Box 1 for description). A key difference between our model and previous energy-balance models is that we have taken into account the possible formation of CO_2-ice clouds. Such clouds may have formed in the atmosphere of early Mars[8] and could have formed on an ice-covered early Earth as well.

At today's solar flux and CO_2 level, our model shows four possible steady states, where x_s is the sine of the ice-line latitude (Fig. 1): ice-free ($x_s=1$), stable partial ice cover ($x_s=0.95$), unstable partial ice cover ($x_s=0.28$) and ice-covered ($x_s=0$). If the Earth was initially in the stable, partially ice-covered state, and was then subjected to a rapid perturbation (relative to the response time of the silicate weathering feedback) that would either temporarily lower the effective solar flux to about 0.9, or produce transient glaciation equatorward of $x_s=0.28$, the Earth would fall into the ice-covered state ($x_s=0$). Without any change

BOX 1 Energy-balance climate model

Our zonally averaged energy-balance climate model uses albedo and outgoing infrared parameterizations derived from a one-dimensional radiative-convective climate model[8,17,20]. In the energy-balance model, the rate of solar energy input to a latitude belt is locally balanced by the sum of the energy leaving the latitude belt as infrared radiation to space and the net heat transport to other latitude belts. This may be represented mathematically by the relation[21]

$$-\frac{d}{dx}D(1-x^2)\frac{dT(x)}{dx}+I(x)=S(x)(1-a_{toa}(x)) \qquad (1)$$

where D is a meridional heat diffusion coefficient, x is the sine of latitude, $T(x)$ is the zonally averaged temperature in a given latitude band, $I(x)$ is the outgoing infrared radiation to space, $S(x)$ is the annual radiation reaching the top of the atmosphere and $a_{toa}(x)$ is the zonally averaged top-of-atmosphere albedo. Boundary conditions on equation (1) are that meridional heat transport vanishes at both the Equator and the poles. Average mean solar energy incident at a given latitude is represented as $S(x)=Q(1-0.477P_2(x))$ (ref. 22), where Q is the solar luminosity at the Earth's orbital distance ($=S_{eff}\times 1{,}360\ \mathrm{W\,m^{-2}}$), and $P_2(x)=(3x^2-1)/2$ is the second Legendre polynomial.

Outgoing infrared radiation, $I(x)$, may be parameterized as a function of surface temperature by an equation of the form[1,2]

$$I(x)=A+BT(x) \qquad (2)$$

The coefficients A and B depend on the atmospheric CO_2 partial pressure[7]. We determined these coefficients by performing least-squares fits, with an r.m.s. error under $5\ \mathrm{W\,m^{-2}}$, to more than 2,000 runs of the radiative-convective climate model[8,17,20], for 10^{-4} bar $< P < 2$ bar, where P is CO_2 partial pressure, and $194\ \mathrm{K} < T < 303\ \mathrm{K}$. The fitting process yielded

$$A(\varphi)=-326.4+9.161\varphi-3.164\varphi^2+0.5468\varphi^3 \qquad (3)$$

and

$$B(\varphi)=1.953-0.04866\varphi+0.01309\varphi^2-0.002577\varphi^3 \qquad (4)$$

where φ is the natural log of atmospheric pCO_2 divided by a reference level of 300 p.p.m. In the radiative-convective model[8,17,20], the troposphere is considered to be fully saturated with H_2O. Assuming a lower relative humidity would make the model even more susceptible to irreversible glaciation. The effect of clouds on the outgoing infrared flux was computed by subtracting a constant amount ($15.56\ \mathrm{W\,m^{-2}}$) from the cloud-free value. This allows the model to reproduce the present mean surface temperature, given the observed solar insolation and planetary albedo. Holding the cloud infrared constant at lower surface temperatures should again produce an upper limit on greenhouse warming, as cloud cover could have been reduced under such circumstances[23].

The top-of-atmosphere albedo (a_{toa}) at a given latitude is a function of surface albedo (a_s), solar zenith angle (θ) and the abundances of CO_2, N_2 and H_2O. We used the radiative-convective model to develop a polynomial representation of a_{toa} as a function of these quantities

$$\begin{aligned}a_{toa}=&-0.6711+1.573a_s-0.01988P+0.005749T+0.03815\mu\\&-0.1003a_sP-0.002478a_sT-0.0006519a_s\mu\\&+0.0001603PT-0.0001957P\mu-0.0001123T\mu\\&-0.1846a_s^2+0.01747P^2-0.00001143T^2+0.009790\mu^2\end{aligned} \qquad (5)$$

Here, $P=pCO_2$ in bars and $\mu=\cos\theta$. The value of μ in a given latitude band is $S(x)/(2Q)$. We calculated the effective surface albedo by finding the value needed to produce the latitudinal distribution of planetary albedo[22], obtaining $a_s(x)=0.2595+0.210P_2(x)$, for ice-free surfaces. This expression includes the effect of (present-day) clouds. For areas with mean annual temperature below −10 °C, the surface was assumed to be ice-covered and to have a surface albedo of 0.663; this gives a planetary albedo of 0.62 under modern polar conditions. Following others[7,21], we set the diffusion coefficient ($D=0.6334\ \mathrm{W\,m^{-2}\,K^{-1}}$) to produce a present-day ice line (x_s) equal to 0.95.

The model forms CO_2 clouds at sine latitude x when

$$T(x)<281+68.2\psi+15.4\psi^2+1.34\psi^3 \qquad (6)$$

where ψ is the common log of surface pCO_2 in bars (Fig. 3). This inequality represents the radiative convective model results to within 2 K when $-5<\psi<1$.

$T(x)$ itself was approximated as $T(x)=T_0+T_2P_2(x)$ (ref. 21). Numerical experiments showed that retaining an additional T_4 term did not significantly alter our results.

in atmospheric pCO_2, an increase in solar flux by ~27% above the present value would be needed to melt the equatorial ice (Fig. 1). At solar fluxes higher than this, a reverse ice-albedo feedback would completely deglaciate the Earth. But this is not what would actually happen were the present Earth to freeze. In the ice-covered state little or no silicate rock would be exposed to weathering, so CO_2 from metamorphic and mantle sources could accumulate in the atmosphere at a rate of $\sim 8\times 10^{12}\ \mathrm{mol\,yr^{-1}}$ (ref. 16). In less than 30 Myr, atmospheric pCO_2 would build up to nearly 0.12 bar, and equatorial ice would become unstable (Fig. 2). This evolution corresponds to case 1 in Fig. 3.

Suppose now that this same perturbation, from stable partial ice cover to global glaciation, occurred earlier in Earth's history when solar luminosity was lower. Our climate model indicates that the results could then be very different. Colder temperatures would permit the formation of CO_2 ice clouds in the upper troposphere. These clouds would further cool the surface by reducing the tropospheric lapse rate (because of the release of latent heat) and by reflecting the additional sunlight back to space. The first of these processes is simulated in our model by assuming that the tropospheric lapse rate follows a moist CO_2 adiabat in the region where CO_2 reaches saturation[8,17]. The second process is not included in our numerical calculations because of uncertainties regarding the horizontal extent and optical depth of these clouds and because doing so would require

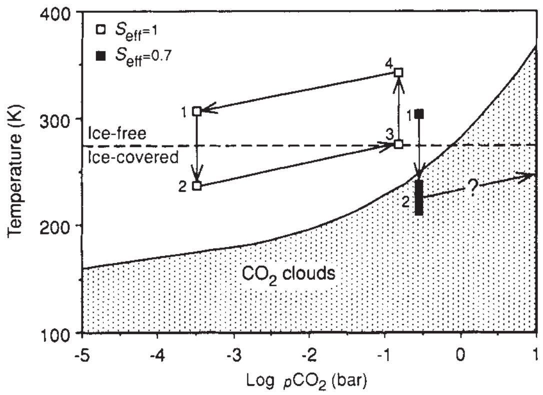

FIG. 3 Evolution of equatorial surface temperature in the event of catastrophic glaciation for two values of effective solar luminosity, S_{eff}. $S_{eff}=1$: if a perturbation were to shift the Earth from its present state (open square 1) to an ice-covered state (open square 2), the Earth's surface would be too warm for CO_2 clouds to form. Carbon dioxide could therefore accumulate in the atmosphere, warming the Earth. The ice-covered state would become unstable (open square 3), and the Earth would shift to the ice-free state (open square 4). Silicate-rock weathering could then remove the excess CO_2 from the atmosphere, returning the system to its present state (open square 1). $S_{eff}=0.7$: if a perturbation were to shift the Earth from an ice-free state at $pCO_2=0.25$ bar (filled rectangle 1) to an ice-covered state (filled rectangle 2), the Earth's surface would be cold enough for CO_2 clouds to form. These clouds would have a cooling effect, and increasing atmospheric pCO_2 may not warm the Earth enough to escape this CO_2-cloud covered state. The upper bound of rectangle 2 represents the calculated equatorial temperature neglecting the cooling effect of the CO_2 clouds. The lower bound represents the equatorial temperature if the CO_2 clouds produced a planetary albedo of 0.8. In this case, the Earth would remain covered with CO_2 clouds and surficial water ice even if solar luminosity were increased to today's value ($S_{eff}=1$).

a radiative model that incorporates scattering in the infrared. (CO_2 ice, unlike water or water ice, is a nearly pure scatterer at most infrared wavelengths[18].) The radiative effect of CO_2 clouds can, however, be estimated qualitatively: because CO_2 clouds are poor absorbers, their contribution to the greenhouse effect should be relatively small, so their primary influence should be to cool the Earth by increasing its albedo.

The points where CO_2 clouds begin to form in our model are indicated by the solid curves in Fig. 2. We have divided the earlier phase of the Earth's history into two parts, labelled 'case 2' and 'case 3'. When S_{eff} is less than ~0.92 (earlier than ~1 Gyr ago[3]) our model predicts that CO_2 clouds would start to form at the poles (case 2). When S_{eff} is less than ~0.8 (earlier than ~3 Gyr ago[3]) CO_2 cloud cover would extend all the way down to the Equator. It is uncertain what the albedo of such a CO_2 cloud-covered planet would be. If it were as high as 0.8, our model predicts that the Earth would not be able to emerge from that state, even at the present solar luminosity. Thus, if the Earth had experienced runaway glaciation before ~3 Gyr ago, the situation might have been effectively irreversible.

How the early Earth managed to avoid becoming globally glaciated is a question of considerable importance to those interested in the general problem of planetary habitability. One possibility is that the Earth remained in a low-ice state simply because it started out hot following accretion: a dense, CO_2-N_2-H_2O atmosphere that was initially warm would be free of CO_2 clouds even at 70% of present solar luminosity (Fig. 3). Alternatively, the presence of additional greenhouse gases, such as NH_3 (ref. 4) or CH_4 (ref. 19), might have kept the atmosphere warm enough to prevent CO_2 from condensing. In either case, the explanation for why Earth's climate has remained stable is more complex than has been previously assumed. □

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Role of pore fluids in the generation of seismic precursors to shear fracture

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A SYSTEMATIC study of temporal changes in seismic *b*-values (defined as the log-linear slope of the earthquake frequency–magnitude distribution) has shown that large earthquakes are often preceded by an intermediate-term increase in *b*, followed by a decrease in the months to weeks before the earthquake[1]. The onset of the *b*-value increase can precede earthquake occurrence by as much as 7 years. A recently proposed fracture mechanics model of the earthquake source[2] explains these temporal fluctuations in *b* in terms of the underlying physical processes of time-varying applied stress and crack growth. The model predicts two minima in *b*, separated by a short-lived maximum. Here we report the results of controlled laboratory deformation experiments, done in simulated upper-crustal conditions on both air-dried and water-saturated rock specimens. As found in previous experiments[3–5], shear fracture in dry specimens is characterized by a decline in *b* during anelastic deformation to a single minimum reached just before failure. But in water-saturated specimens, when pore-fluid volume is kept constant by servo-control we also observe a second, intermediate-term *b*-value minimum, so reproducing the double *b*-value anomaly predicted by the model[2].

The fracture mechanics model of Main *et al.*[2] is summarized in Fig. 1. In nature, because crustal deformation is accompanied and accomplished by microcracking and small earthquakes[6], sometimes coupled with aseismic deformation, the crust will respond to remotely applied tectonic loading by deforming anelastically; it shows both strain-hardening and strain-softening phases, and a dynamic failure stress lower than peak stress (Fig. 1*a*). Laboratory experiments have shown that a principal flaw under the action of remotely applied stress and stress corrosion processes will extend in a strongly nonlinear fashion[7] (Fig. 1*b*) from an initial length x_0 at time t_0 to effectively infinite length at time t_f. Combining the effects of stress and

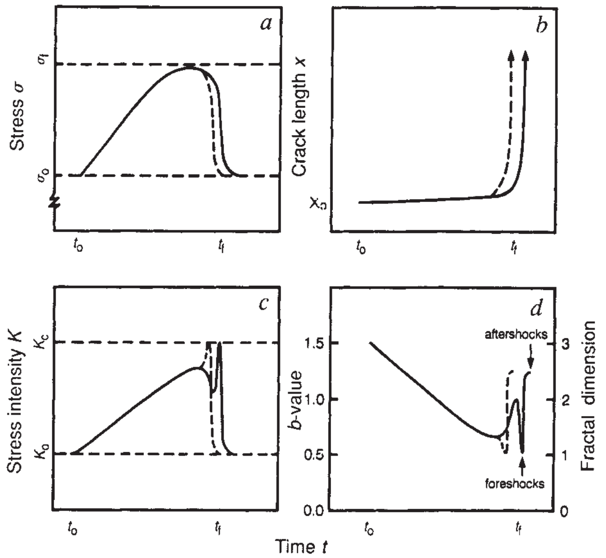

FIG. 1 Fracture mechanics model of the *b*-value anomaly for anelastic failure (precursory strain energy release model)[2]. *a*, Stress–time behaviour for rock deformation; *b*, acceleration of crack tip to critical failure; *c*, combined effects of the stress and crack length of the stress intensity factor, *K*. *d*, Because *b* is negatively correlated and linearly related to *K*, the model predicts both an intermediate-term and a short-term *b*-value minimum. A single minimum will be produced where failure occurs during an earlier part of the cycle (dashed line). σ_0, Initial stress at time t_0; σ_f, nominal failure stress (peak stress); t_0, onset time of loading; t_f, dynamic failure time; x_0, crack length at time t_0; K_c, critical stress intensity (fracture toughness); K_0, stress intensity at time t_0.