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Climatic Consequences of Very High Carbon Dioxide Levels in the Earth's Early Atmosphere

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The possible consequences of very high carbon dioxide concentrations in the earth's early atmosphere have been investigated with a radiative-convective climate model. The early atmosphere would apparently have been stable against the onset of a runaway greenhouse (that is, the complete evaporation of the oceans) for carbon dioxide pressures up to at least 100 bars. A 10- to 20-bar carbon dioxide atmosphere, such as may have existed during the first several hundred million years of the earth's history, would have had a surface temperature of approximately 85° to 110°C. The early stratosphere should have been dry, thereby precluding the possibility of an oxygenic prebiotic atmosphere caused by photodissociation of water vapor followed by escape of hydrogen to space. Earth's present atmosphere also appears to be stable against a carbon dioxide-induced runaway greenhouse.

EARTH HAS APPROXIMATELY 60 BARS of carbon dioxide tied up in carbonate rocks, roughly two-thirds the amount present in the atmosphere of Venus (1, 2). This carbon, along with other volatile elements, was presumably brought to the earth during accretion as a component of infalling planetesimals. A substantial fraction of these volatile compounds should have been released upon impact (3-5). Carbon may have been degassed as CO₂ or as some more reduced gas (CO or CH₄), depending on the oxidation state of the infalling material and of the upper mantle. Once in the atmosphere, however, any reduced carbon species should have been oxidized to CO₂ by OH radicals produced from water vapor photolysis (6). Consequently, the earliest atmosphere may have contained large amounts of CO₂—up to one-third of the earth's total inventory, or 20 bars, according to Holland's estimate (3). If the fraction of the earth's surface occupied by continents was initially small, carbonate formation would have been inhibited and sea-floor carbonate sediments would have been rapidly recycled; thus, a dense (approximately 10 bar) CO₂ atmosphere could conceivably have persisted for several hundred million years (7).

To explore the possible climatic consequences of high CO₂ concentrations in the early atmosphere, we made a series of calcu-

lations using a one-dimensional radiative-convective climate model. The primary goal of these calculations was to determine whether a runaway greenhouse could have occurred on the early earth. A runaway greenhouse is here defined as an atmosphere in which water is present entirely as steam or clouds; no oceans or lakes are present at the surface. We concern ourselves only with times subsequent to the accretion period, when the earth was heated solely by absorption of solar radiation. The possibility of a runaway greenhouse during accretion will be considered elsewhere. A second purpose of this study was to determine the stability of a high CO₂ primitive atmosphere against water loss through photodissociation of water vapor followed by escape of hydrogen to space. An understanding of this latter question is needed in order to estimate the earth's initial water inventory and to predict the oxidation state of the early atmosphere. An interesting by-product of our calculation is an estimate of the stability of the earth's current atmosphere to large CO₂ increases.

The radiative-convective model employed here is based on one used in previous studies of the earth's climate system (8, 9). It has, however, been updated to include new absorption coefficients for H₂O and CO₂ (10) along with a self-consistent calculation of solar energy deposition (11). The band model coefficients used to define gaseous

absorption were derived for pressures of 0.1 and 1 bar; calculated transmission functions are not expected to be accurate at higher pressures. This should have little effect on our results, since the dominant mode of energy transport at these higher pressures is convection.

The most important physical assumptions made in the model are related to our treatment of tropospheric lapse rate, relative humidity, and clouds. The lapse rate was set equal to its moist adiabatic value, following Ingersoll's formulation (12), which is valid for large water vapor amounts. The use of the moist adiabatic lapse rate causes the surface temperature T_s to increase much more slowly with increasing CO₂ than it would in a fixed lapse-rate model (8, 13, 14) because the temperature of the upper troposphere increases more rapidly than does T_s .

Relative humidity cannot be calculated self-consistently with a one-dimensional model because it is determined by three-dimensional dynamical processes. Since our primary goal is to calculate upper limits on surface temperature, we wish to ensure that the troposphere is nearly saturated with water vapor at high CO₂ concentrations. At low CO₂ concentrations, however, we want the troposphere to revert to its present unsaturated state. To effect such a transition the tropospheric relative humidity was assumed to increase as the fractional amount of water vapor at the surface increased (15). This assumption is consistent with the idea that the behavior of atmospheric water vapor is related to its mixing ratio (12). Our parameterization has no rigorous theoretical justification, however, and may be regarded simply as an artifice for connecting unsaturated low T_s solutions to nearly saturated high T_s solutions.

The stratospheric water vapor content was estimated by allowing relative humidity to increase to unity above the convective region, provided that the H₂O volume mixing ratio, $f(\text{H}_2\text{O})$, did not increase with altitude. This approximate cold-trapping mechanism tends to overestimate the H₂O content of the stratosphere because it ignores latitudinal variations in tropopause temperature. This is acceptable for our purposes because we wish to derive upper limits on surface temperature and hydrogen escape rate.

Clouds were not included explicitly in our model because we do not know how they would vary as a function of CO₂ concentration. Their effect on climate was included implicitly by adopting a high surface albedo ($A_s = 0.22$). This value of A_s was chosen because it allows the model to reproduce the

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observed mean value of T_s (288 K) for the present earth, given the present solar insolation. By holding A_s fixed, we assume zero cloud feedback at higher CO_2 levels. This parameterization ignores the effects of clouds on the infrared radiation budget. In reality, clouds do absorb infrared radiation; they also reflect more sunlight back to space than assumed in our model. Under certain (pathological) conditions—the development of a widespread optically thin cirrus layer, for instance—cloud feedbacks could cause surface temperatures at elevated CO_2 and O_3 concentrations to be considerably higher than calculated here. For other possible changes, such as an increase in areal coverage by optically thick, low-altitude clouds, the increase in planetary albedo would probably more than offset any increase in the greenhouse effect, and a net cooling would result. If, on the other hand, fractional cloud cover remained constant and the cloud tops remained at roughly a constant temperature,

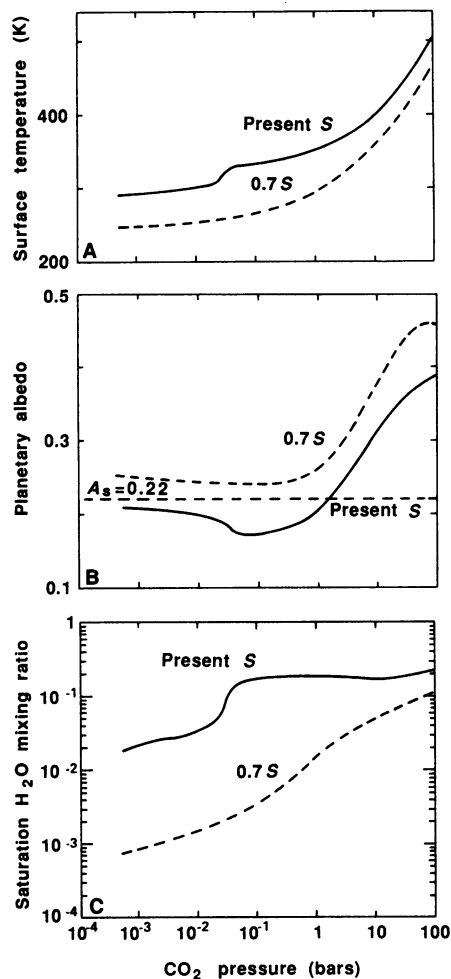


Fig. 1. Effect of increased CO_2 pressure on (A) surface temperature, (B) planetary albedo, and (C) saturation H_2O volume mixing ratio at the surface. Solid curves are for present solar luminosity S and atmospheric composition; dashed curves represent 30% reduced luminosity and no O_2 or O_3 .

T_s should be virtually unaffected. Without a physical model for predicting which of these effects is most plausible, it seems fruitless to speculate as to what the actual effect of clouds would be.

Calculations were performed for both early and present earth. For the early earth model, the solar luminosity S was set at 70% of its present value (16), and a 0.8-bar N_2 background atmosphere was assumed (17). For the present earth model, the modern value of solar luminosity was used and O_2 and O_3 were included in the model atmosphere. The present earth calculations, besides being interesting from an academic standpoint, help to bracket some of the uncertainties in the problem by providing a reasonable upper limit on surface temperatures for the early earth. Even if several of our assumptions (for example, neglect of cloud feedback) turned out to be invalid, it seems unlikely that their effect on surface temperature could be as large as that of a 40% solar flux increase.

The results of increasing the CO_2 pressure up to 100 bars are shown in Fig. 1. The solid curves represent the present earth and the dashed curves represent the early earth. Both cases are apparently stable against the development of a runaway greenhouse. Surface temperature for the present earth model with 100 bars of CO_2 is 506 K, or 233°C (Fig. 1A). The saturation H_2O vapor pressure is 29 bars, so that the total surface pressure is 130 bars. At this pressure the oceans would boil only if T_s were about 100° hotter. Thus, the bulk of the earth's water (1.4×10^{24} g, or 270 bars) would reside in the ocean. For an early earth with 10 to 20 bars of CO_2 , the oceans should have been even more stable; T_s would have been 85° to 110°C, with a vapor pressure of 0.6 to 1.5 bars.

An important factor in stabilizing the climate at high CO_2 concentrations is the increase in planetary albedo (A_p) caused by Rayleigh scattering. For the early earth model A_p remains near 0.25 at low CO_2 pressures, but rises to about 0.4 at CO_2 pressures of 10 to 20 bars (Fig. 1B). For the present earth model, A_p is lower because of increased absorption of solar energy by H_2O and O_3 .

In addition to being stable against a runaway greenhouse, our early earth atmosphere is also stable against loss of water through photodissociation followed by escape of hydrogen to space. The maximum (diffusion-limited) escape rate is proportional to the total hydrogen mixing ratio in the stratosphere in all of its chemical forms (18). The stratospheric H_2O content remains low as long as water is a minor atmospheric constituent (12). For the early earth model,

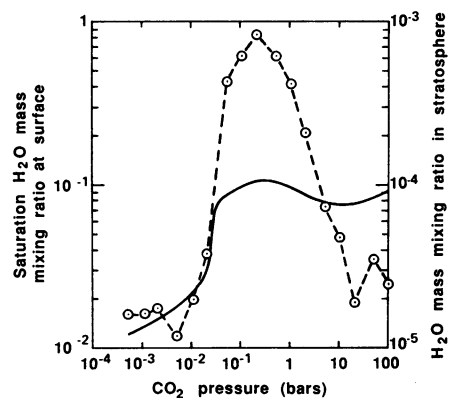


Fig. 2. Saturation mass mixing ratio of H_2O at the ground [solid curve, $c_{\text{sat}}(\text{H}_2\text{O})$] and in the stratosphere [dashed curve, $c_0(\text{H}_2\text{O})$] for the present earth model.

H_2O makes up less than 10% of the atmosphere (Fig. 1C), and the stratospheric H_2O mixing ratio is less than 10^{-7} at all CO_2 pressures. The associated hydrogen escape rate is $< 5 \times 10^6$ H atoms per square centimeter per second. This rate is too small to affect the amount of water in the ocean and has a negligible impact on the atmospheric hydrogen budget. Thus, our results would appear to rule out the possibility of an oxygenic prebiotic atmosphere, which has been suggested by some workers (19, 20).

The sharp increase in T_s and $f_{\text{sat}}(\text{H}_2\text{O})$ at CO_2 pressures near 0.03 bar in the present earth model is a consequence of our relative humidity parameterization (15). Above this CO_2 pressure, water vapor constitutes about 20% of the lower atmosphere, so that the troposphere is 80% saturated. This abrupt increase probably has little physical significance; a different choice of parameterizations could either shift the increase to a different CO_2 pressure or eliminate it entirely. Models that assume a constant relative humidity (9) do not exhibit such a feature. Neither, however, are they useful for determining upper limits on surface temperature or stratospheric water vapor abundances. The surface H_2O mixing ratio in the present earth model actually decreases slightly at CO_2 pressures between 1 and 10 bars. The reason is that CO_2 is not that efficient as a greenhouse gas; thus, the increase in surface pressure caused by the addition of CO_2 outstrips the increase in H_2O vapor pressure caused by higher T_s .

This behavior is seen more clearly if one plots the H_2O mass mixing ratio at the surface [$c_{\text{sat}}(\text{H}_2\text{O})$] as a function of CO_2 pressure (Fig. 2). The maximum value of $c_{\text{sat}}(\text{H}_2\text{O})$ occurs at a CO_2 pressure of 0.2 bar, at which point the greenhouse effect of CO_2 is large but the surface pressure is still relatively low. Corresponding to this maximum in $c_{\text{sat}}(\text{H}_2\text{O})$ is a pronounced peak in

stratospheric H₂O mass mixing ratio [$c_0(\text{H}_2\text{O})$] (Fig. 2). This peak is a consequence of the decreased efficiency of the cold trap at high H₂O levels (8, 12). At the high point of this curve the oceans could be depleted of water in about 9 billion years if the diffusion-limited hydrogen escape flux was achieved. A 30° increase in T_s, which could result from a mere 10% increase in solar flux according to our model, would cause $c_0(\text{H}_2\text{O})$ to rise to about 0.1 at this CO₂ pressure. The oceans would then disappear in only a few hundred million years, as may have happened on Venus (8). The present atmosphere might therefore be said to be marginally stable against water loss at CO₂ pressures of 0.1 to 1 bar. At still higher CO₂ pressures, the stratosphere should once again be dry and the oceans should be more stable.

Our calculations do not prove that the early atmosphere must have been hot. The question of how CO₂ was originally partitioned between the atmosphere, ocean, and solid planet is complex, and it is possible that the early atmosphere was much less massive than we have assumed. We have shown, however, that a dense CO₂ atmosphere could have existed on the early earth without violating any known constraints on the planet's subsequent evolution.

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10. Infrared absorption by H₂O and CO₂ was calculated in 55 spectral intervals by fitting synthetic spectra computed from the Air Force Geophysical Laboratories (AFGL) tape [R. A. McClatchey et al., *Air Force Geophys. Lab. Tech. Rep. AFCRL-71-0279* (Bedford, MA, 1971)]. The calculations were performed at pressures of 1 and 0.1 bar and at temperatures of 200, 300, and 600 K. H₂O was assumed to obey the Fels-Goody model [S. B. Fels, *Appl. Opt.* 18, 2634 (1979)] and CO₂ was assumed to follow the Malkmus model. Self-broadening efficiencies for H₂O and CO₂ were enhanced by factors of 5 and 1.3, respectively, and broadening of H₂O lines by CO₂ was enhanced by a factor of 2 [J. R. Izatt et al., *J. Opt. Soc. Am.* 59, 19 (1969); P. Varanasi, *J. Quant. Spectrosc. Radiat. Transfer* 11, 223 (1971)]. The fitting method used here avoids errors that would otherwise be incurred by applying such band models over relatively broad (50 to 100 cm⁻¹) spectral intervals [J. T. Kiehl and V. Ramanathan, *J. Geophys. Res.* 88, 5191 (1983)]. H₂O continuum absorption and pressure-induced CO₂ absorption were treated as described by Ingersoll (12). Absorption in the visible and near infrared was computed in each of 38 spectral intervals ranging from 0.2 to 4.4 μm. At wavelengths longer than 0.67 μm, exponential sum coefficients for H₂O and CO₂ were derived from the AFGL tape. The coefficients were computed for pressures of 10⁻³ to 10 bars and a temperature of 300 K. At wavelengths between 0.54 and 0.67 μm, H₂O absorption was estimated from tabulated lines in the solar spectrum [C. E. Moore et al., *Natl. Bur. Stand.* 61 (Washington, DC, 1966)]. CO₂ absorption between 1.04 and 0.71 μm was estimated from laboratory spectra [G. Herzberg and L. Herzberg, *J. Opt. Soc. Am.* 43, 1037 (1953)].

11. Rayleigh scattering by CO₂ is particularly important because its scattering cross section is about 2.5 times as high as that of air [(H. C. Van de Hulst, in *The Atmospheres of the Earth and Planets*, G. P. Kuiper, Ed. (Univ. of Chicago Press, Chicago, 1957), p. 49]. Our cross sections are the same as those used in another recent model of the climatic effects of large CO₂ increases [I. M. Vardavas and J. H. Carver, *Planet. Space Sci.* 32, 1307 (1984)].
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15. Tropospheric relative humidity was assumed to obey the relation

$$r = r_0 \left[\frac{p/p_s - 0.02}{1 - 0.02} \right]^n \quad (1)$$

where p is pressure, p_s is surface pressure, and r_0 (= 0.8) is the surface relative humidity. The parameter n allows the relative humidity of the upper troposphere to vary. When $n = 1$, Eq. 1 reduces to the empirical formula of Manabe and Wetherald [*J. Atmos. Sci.* 24, 241 (1967)], which is used in many one-dimensional climate models. When $n = 0$, the troposphere is 80% saturated throughout. This for-

mulation follows a suggestion by R. D. Cess [*ibid.* 33, 1831 (1976)] which he made on the basis of observed latitudinal gradients in T_s and r . He proposed that $\Omega = 1 - 0.03(T_s - 288 \text{ K})$. We have replaced this formula with

$$\Omega = 1 - \frac{f_{\text{sat}}(\text{H}_2\text{O}) - f_p}{0.1 - f_p}$$

with $0 \leq \Omega \leq 1$ and where $f_{\text{sat}}(\text{H}_2\text{O})$ [= $p_{\text{sat}}(\text{H}_2\text{O})/p_s$] is the saturation H₂O mixing ratio at the surface and f_p (= 0.0166) is the value of $f_{\text{sat}}(\text{H}_2\text{O})$ for the present atmosphere ($T_s = 288 \text{ K}$). Ω is assumed to be unity for $f_{\text{sat}}(\text{H}_2\text{O}) < f_p$ and 0 for $f_{\text{sat}}(\text{H}_2\text{O}) > 0.1$. We used this equation instead of Cess's formula because we feel that the behavior of water vapor in an atmosphere is more closely related to its mixing ratio than to surface temperature (12). It gives approximately the same result as Cess's formula for a 1-bar atmosphere, but yields a slower increase in r at higher surface pressures.

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17. The surface pressure of the model atmosphere is given by $p_s = p_n + p_{\text{CO}_2} + p_{\text{sat}}(\text{H}_2\text{O})$, where p_n is the pressure of gases other than CO₂ and H₂O. The CO₂ pressure so defined is the pressure that would be exerted by a pure CO₂ atmosphere containing a given amount of gas. It differs from the actual CO₂ partial pressure at the surface by a factor of 44/ M , where M is the mean molecular weight of the atmosphere. The CO₂ pressure used here is linearly proportional to CO₂ column content, whereas the actual CO₂ partial pressure is not.
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Ultraviolet Irradiation Transforms C3H10T1/2 Cells to a Unique, Suppressible Phenotype

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Transformation of C3H10T1/2 cells by exposure to ultraviolet (UV) irradiation followed by tetradecanoyl phorbol acetate (TPA) has been used as a model of two-stage carcinogenesis. However, cells cloned from UV-TPA-induced foci (UV-TDTx cells) had a unique phenotype. Cloned UV-TDTx cells appeared transformed in pure culture but were unable to form foci when cocultured with C3H10T1/2 cells. However, in the presence of TPA, UV-TDTx cells form foci in mixed culture with C3H10T1/2 cells. This phenotype was the only one observed for UV-TPA transformants. These data suggest that (i) communal suppression of cell division is a discrete phenomenon that must be overcome as one step in the multistage process of transformation, and (ii) this protocol permits the routine isolation of transformed cells responsive to density-dependent growth suppression.

C3H10T1/2 CELLS (1) ARE A MAJOR cell culture model for the study of transformation by chemical carcinogens (2, 3) and ionizing radiation (4, 5). The presence of dominant transforming oncogenes from high-dose methylcholanthrene (MCA) C3H10T1/2 transformants has been demonstrated (6) and the genes identified as altered *K-ras* (7). A two-step C3H10T1/2 transformation protocol was developed that reflects in vivo initiation and promotion (8). After low doses of carcinogens or radiation, C3H10T1/2 cells require subsequent exposure to a tumor promoter for transformation. Although numerous studies have utilized C3H10T1/2 cells to define and characterize

initiators and promoters, the molecular changes required for two-stage transformation are unknown. We planned to isolate two-stage C3H10T1/2 transformants and search by DNA-mediated transfection (6, 7) for dominant transforming oncogenes. However, two-stage C3H10T1/2 transformants had properties not shared with most single-step transformants isolated in response to chemical carcinogens or ionizing irradiation (2-5).

Plates with 2000 C3H10T1/2 cells were

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