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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 CO_2 or as some more reduced gas (CO or CH_4), 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 CO_2 by OH radicals produced from water vapor photolysis (*6*). Consequently, the earliest atmosphere may have contained large amounts of CO_2—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) CO_2 atmosphere could conceivably have persisted for several hundred million years (*7*).

To explore the possible climatic consequences of high CO_2 concentrations in the early atmosphere, we made a series of calculations 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 CO_2 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 CO_2 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 H_2O and CO_2 (*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 CO_2 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 CO_2 concentrations. At low CO_2 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 H_2O volume mixing ratio, $f(H_2O)$, did not increase with altitude. This approximate cold-trapping mechanism tends to overestimate the H_2O 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 CO_2 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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