Reports

Cloud Feedback: A Stabilizing Effect for the Early Earth?

Abstract. *The effect of variations in cloud cover, optical properties, and fractional distribution with altitude on the mean surface temperature of a model of the early earth has been investigated. In all cases examined, cloud-climate feedbacks result in temperatures greater than those in models with no cloud feedbacks. If the model of hydrospheric feedback effects is correct, then cloud feedbacks are as important to the climate as changes in solar luminosity and atmospheric composition during the earth's atmospheric evolution. In particular, the early earth need not become completely ice-covered if strong negative cloud feedbacks occur. However, until a proper understanding of cloud feedbacks is available, conclusions regarding conditions in the early atmosphere must remain in doubt.*

Early studies of ice albedo feedback in energy balance climate models indicated a large sensitivity of the (model) climate to decreases in the solar constant (*1*), although more realistic treatments using planetary albedo changes rather than surface albedo changes reduced model sensitivity by about one-half (*2, 3*). Sagan and Mullen (*4*) argued that these large sensitivities imply a completely ice-covered primitive earth at a time when the solar luminosity of the young sun was 20 to 30 percent lower than today; yet there is considerable evidence for a substantial amount of liquid water throughout the geologic record (*5–8*). Sagan and Mullen (*4*), Owen *et al.* (*9*), and others have reconciled this contradiction by postulating large differences in early atmospheric composition that cause very strong greenhouse effects which offset the lower solar constant. Owen *et al.* (*9*) discuss a thousandfold increase in CO_2, but in their model only a hundredfold increase is needed to maintain a global mean surface temperature of 273 K (*10*).

We draw a different conclusion from this contradiction—namely, that these climate models may not have properly accounted for all of the key feedback processes that occur in the earth's atmosphere (*11*). In particular, whereas previous investigations of cloud feedback deduced small increases or little change in model sensitivity (*2, 3*), we report here on a model, with cloud feedback, that is much less sensitive to solar luminosity changes than most other models. However, determining the correct cloud-climate feedback, even for today's climate, is a critical and still open question. These and other model results are contradictory [see (*11*) for a discussion], and the available data are inadequate for choosing a correct cloud parameterization. The large differences in our model with and without cloud feedbacks may indicate the range of uncertainty in predicting current climate changes (*12*) or reconstructing past climates. Thus, our understanding of cloud feedbacks does not allow us to choose between different parameterizations. Nevertheless, the model results presented here suggest a plausible alternative to drastic compositional changes for explaining warmer temperatures on the primitive earth.

Our consideration of possible cloud feedbacks concerns those associated with three possible changes in the primitive atmosphere from the present one (*8*): (i) reduced solar luminosity, (ii) absence of oxygen and ozone, and (iii) combined reduction of the solar constant and increase of carbon dioxide abundance. The changes in surface temperature produced by specified changes in these parameters have often been studied (*13*); however, effects of cloudiness have either been neglected because they were assumed to provide no important feedbacks on climate (*9*) or parameterized with too much emphasis on the solar or thermal effect (*14*).

The model we used [developed primarily by Lacis *et al.* (*15*)] is the one-dimensional radiative convective model used by Wang *et al.* (*12*). In this model the effective cloud cover fraction at each altitude is a function of the convective heating and precipitation rates, where the fraction of convective heating caused by condensation is a function of surface temperature. As with all such models, the convective effects actually represent the effects of all atmospheric motions on the atmospheric thermal structure and, in our model, on the global cloud vertical distribution. Hence, the clouds in our model represent a parameterization of all cloud types, not just the cumulus clouds produced by actual convection. For these calculations, we used a constant, 6.5 K km^{-1}, lapse rate in the convective adjustment and a fixed relative humidity profile (*16*). The cloud feedback is thus tied to the change of the surface energy budget and the vertical distribution of convective (dynamic) heating because the optical thickness of the clouds is a specified function of altitude (*12*). The increase of low, optically thick cloud cover generally acts as a negative feedback on temperature changes, while the increase of high, optically thin cloud cover acts as a positive feedback (*12*). This difference in feedbacks is crucial to the interesting behavior exhibited by the model.

The magnitude of a possible "cirrus greenhouse" effect on surface temperature has been discussed (*12, 15*). Our results also exhibit this sensitivity to cirrus cloud amount. At temperatures

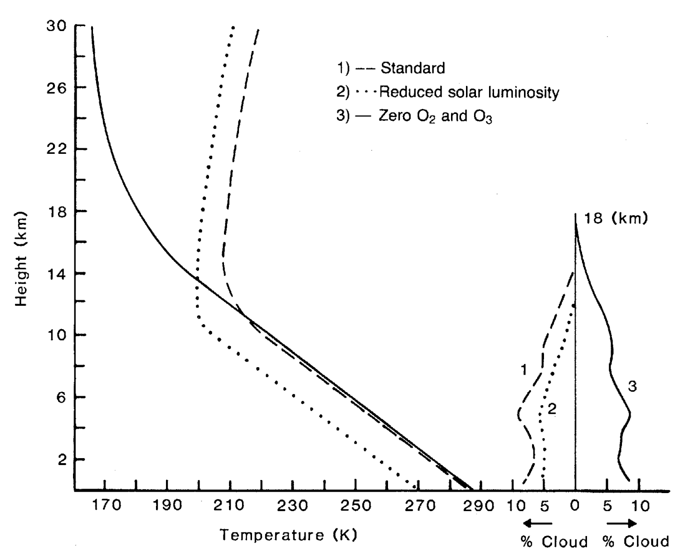

Fig. 1. Calculated temperature profiles and percentage cloud distributions for the three cases: (1) standard; (2) reduced solar luminosity; and (3) zero oxygen and ozone.

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much lower than today, total water vapor abundance and cloud mass density would be reduced; that is, low-optical-thickness "cirrus" cloud would prevail at lower altitudes. Therefore, we also study models with the optical thickness changed to represent cirrus at altitudes where the temperature is below 246 K. Below we compare model results with and without this modification. The temperature profiles and cloud cover distribution that result for the cases discussed are shown in Fig. 1 and the cloud properties, surface temperature, and planetary albedoes are listed in Table 1.

Because the interaction of cloud cover and surface ice cover to determine planetary albedo cannot be studied in a vertical-structure model, we do not include ice albedo feedback in these calculations. In any case, the effect of ice albedo feedback may have been secondary to cloud feedback in the early atmosphere. Although the presence of liquid water is now established for more than 80 percent of the earth's history (*17*), the existence of continental areas is much more difficult to demonstrate. Goodwin (*18*) suggests that only 5 to 8 percent of the present continental crust was established between 3 billion and 4 billion years ago, suggesting an early earth dominated by a near-global ocean. This reconstruction of the primitive geologic data argues against ice growth and decay processes resembling those in the present-day climate (*19*). Nevertheless, we estimate the ice albedo effect on this model's sensitivity from the results of (*3*) based on the same model without cloud feedback. Both feedbacks would probably produce a sensitivity intermediate between those obtained with only one feedback. We suggest that this intermediate-sensitivity model gives a lower limit on the surface temperature of the early earth.

Decreased solar luminosity. Lowered insolation leads to reduced temperatures throughout the atmosphere, and the resulting decrease of convective heating leads to a decrease in cloud cover. The cloud cover reduction is roughly uniform with altitude (Fig. 1, case 2), but the effect of the decrease of low-level cloud predominates, producing a decrease in planetary albedo and a negative feedback on surface temperature in this model (*12*). The incident solar radiation at the earth is taken to be 1100 W m^{-2}. A 25 percent increase in solar luminosity from this stage of early evolution is required to reach the present luminosity (*9, 20*). For this decrease in the solar constant, the surface temperature falls from 286.5 to 267 K; thus $\beta \equiv S_0\, dT/dS$ is roughly 96 (β is a measure of the sensitivity of model global mean surface temperature, T, to changes in solar luminosity, S; S_0 is the present-day solar luminosity). The cloud cover feedback has reduced the sensitivity of this model from $\beta = 110$ [similar to the basic model of Owen *et al.* (*9*)] to below that of most other energy balance models [see (*3*)]. This reduction in sensitivity is especially marked because, at these lower temperatures, the water vapor greenhouse effect is sharply reduced. Further, the decrease in water vapor with temperature probably decreases water cloud mass as well. Consequently, when we change optical thickness to represent cirrus cloud above about 4 km, this changes the relative solar and thermal effects of the clouds and causes a warming of the surface to 270 K, giving $\beta = 82$. This mean temperature is above that at which sea ice forms, so that the earth represented by this model is not completely ice-covered.

Table 1. Surface temperatures and hydrospheric characteristics calculated for two possible atmospheric compositions of the early earth.

Characteristic	Reduced solar luminosity	Zero O_2 and O_3
Surface temperature (K)	270.2	287.8
Cloud (percent)	31.3	55.6
Mean cloud height (km)	3.99	5.03
Average optical depth	3.06	6.00
Planetary albedo	0.23	0.32

No oxygen or ozone. Without cloud feedback, removing O_2 and O_3 causes strong cooling of the stratosphere, which results in a decrease in surface temperature because the downward thermal flux from the stratosphere decreases (*21*). The decrease in static stability of the stratosphere leads to somewhat higher penetration of convection, which, in our interactive cloud model, produces a few percent cloud cover in the lower stratosphere. Since we assign cirrus optical thicknesses to these clouds, the surface is warmed by the clouds more than it is cooled by the removal of O_2 and O_3.

Table 2. Magnitude and direction of surface temperature changes and sign of interactive feedback effect for constant cloud cover at fixed altitude and for this model with cloud feedback.

Perturbation	Without cloud feedback	With cloud feedback	Direction of feedback
Solar luminosity			
Reduced 20 percent	−20.8	−18.1	−
Increased 2 percent	+2.17	+1.95	−
Carbon dioxide			
× 2	+1.90	+2.68	+
× 5	+5.00	+6.30	+

Reduction of solar luminosity and increase of CO_2. The interactive cloud feedback parameterization produces feedbacks of opposite sign for a solar contant increase and a CO_2 increase. As discussed in (*12*), increased CO_2 raises the "radiation-to-space" level to a higher altitude, requiring an increase in the total depth of the convective heating layer. In our model this change causes an upward shift of cloud cover (Fig. 1, case 3), in effect exchanging optically thick clouds for optically thin clouds. Hence the albedo decreases and the cloud greenhouse effect increases, leading to a positive temperature feedback. Changes in solar luminosity change cloud cover at all levels (see above and Fig. 1, case 2), primarily changing the albedo. Thus if the early earth was subjected to both an increase of CO_2 and a decrease of solar constant, the resulting cloud feedbacks should reinforce each other. In Table 2, we compare the surface temperature changes produced in our model, with and without cloud feedback, by changes in solar constant and CO_2 abundance. When both are changed (down 20 percent and up 500 percent, respectively), the model surface temperature is 272 K, a change of −14 K. In addition, if the colder upper-level clouds are changed to cirrus optical thicknesses, the surface temperature is another 2 K warmer. These model results for changing atmospheric composition illustrate the importance of understanding cloud feedbacks, since they may modify the importance of most other climate perturbations.

Comparing the sensitivity of this model with and without ice albedo and cloud feedbacks, we estimate a combined sensitivity $\beta \lesssim 100$; if we include the effect of thinning clouds, then $\beta < 100$. For a 20 percent decrease in solar luminosity, alone, this sensitivity would give a surface temperature $\gtrsim 265$ K and, using the formulation of (*3*), an ice-line latitude $> 40°$. Thus, even without compositional changes this model does not predict a completely ice-covered primitive earth. If, in addition, we consider a modest increase of CO_2 and the absence of O_2 and O_3 [for instance, see (*8*)], then the surface temperature could be > 274 K.

If our model of cloud feedbacks is correct, then changing the cloud cover and optical thickness distributions with altitude would affect the primitive atmosphere almost as much as small changes in solar luminosity and large changes in atmospheric composition. The large changes of composition suggested in (*4*, *14*) and used in (*9*) to prevent an ice-covered early earth may be unnecessary. More modest increases of CO_2 in the early atmosphere than discussed in (*9*) might be sufficient to produce surface temperatures higher than today.

However, we do not know which parameterization of cloud feedback is correct. Our results, when compared with those of other models with and without cloud feedbacks, indicate the very large uncertainties that remain in reconstructing the history of the early earth. They also illustrate the importance of incorporating correct cloud feedbacks in climate models. Until more study of hydrospheric processes, including clouds, can improve the parameterizations used in simple climate models, reconstructions of past climates remain so uncertain that conclusions about the early atmosphere based on such models must remain tentative.

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References and Notes

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11. Warren and Schneider [see (*2*)] illustrate a similar conclusion with regard to parameterized ice albedo feedback and feedbacks on infrared cooling rates at a given surface temperature. Their results illustrate that simple models of the early earth, which are not ice-covered, may be within the range of uncertainty in parameterizing these processes. We show here that the same may be said for cloud feedbacks.
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Numbers of Receptor Sites from Scatchard Graphs: Facts and Fantasies

Abstract. *Data for ligand and receptor binding presented in the format of a Scatchard graph are compared with the same data shown as bound ligand plotted against the logarithm of free ligand. From this comparison it is apparent that extrapolations in the Scatchard graph to yield total number of receptor sites are generally not correct.*

For the validity of their conceptual and experimental methods, most scientists depend on assurances from reputable predecessors in their field. The latter individuals in turn have usually adopted the procedures from some comparable persons who preceded them. If the forerunners in the use of a technique have not recognized its limitations or have obscured them, a tradition of analysis may develop that generates pervasive misinformation in the scientific literature.

Ligand binding by biological receptors is widely summarized and analyzed in a Scatchard graph in which the ordinate shows the moles of effector bound per total moles of receptor divided by the concentration of free ligand (*B*/*F* in the endocrine literature) and the abscissa shows the moles of bound effector (*B*). For the simplest possible situation, one in which it has been established unequivocally by means other than binding measurements that there is only one receptor site, a Scatchard graph is a reliable device for measuring the binding constant.

In biological systems there are usually many receptor sites on a single binding entity, be it a pure protein, cellular constituent or organelle, membrane, or cell. The simplest possible molecular situation is one in which every binding site is identical in nature and has the same affinity for the ligand. In such a case, the Scatchard graph in principle will be linear and the intercept on the abscissa will be the total number of receptor sites, *n*. In this case also, a graph showing the moles bound, *B*, plotted against the concentration of free ligand, *F*, on a logarithmic scale (Fig. 1a) has some characteristic features: (i) an inflection point (+) appears at half-maximum binding, that is, at $n_{1/2}$; (ii) the S-shaped curve is symmetric about the inflection point; and (iii) a plateau at *n* is reached asymptotically as the concentration of free ligand approaches very large (infinite) values.

In practice, when binding data are plotted on a Scatchard graph there is an enormous temptation to fit them to a straight line, either by eye or by least-squares methods, so that the number of receptor sites and the binding constant can be extracted. In most cases it can be shown readily, by plotting the same data on a semilogarithmic graph (Fig. 1a), that the conclusions derived from the Scatchard graph are completely untenable.

Let me illustrate with an example from the neurobiological literature. The binding of an effector drug by benzodiazepine receptors from preparations of cerebral cortex, under a specified set of conditions, has been presented in a published Scatchard graph (*1*), a portion of which is reproduced in Fig. 1b. Individual points have been fitted by a straight line with a very good correlation coefficient, and the total number of receptor sites (830) computed from the intercept on the ab-

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