Scattering greenhouse effect of CO_2 ice cloud and climate stability on early Mars

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The scattering greenhouse effect of CO_2 ice cloud has been proposed as a mechanism to make the Martian climate warm enough to support flowing water under a faint young Sun. We construct a one-dimensional radiative model for the CO_2-H_2O atmosphere and analyze cloud stability on the basis of the numerical estimation of the ice condensation or evaporation rate in a cloud layer. Our numerical analysis suggests that a CO_2 ice cloud layer is stabilized and the global mean surface temperature rises above melting point of H_2O when the atmospheric pressure is larger than 1 bar and the column number density of cloud condensation nuclei is kept at nearby 10^{10} m^{-2}. A negative feedback mechanism between the particle size change and the radiative cooling may stabilize warm climate on early Mars.

1 Introduction

Geomorphological evidence suggests that Martian climate was warm enough for liquid water to exist stably on the surface about 3.8 Gyr ago [e.g. 1]. Because of the photochemical stability, CO_2 may be the main constituent of the past atmosphere as well on the present Mars. Even if Mars had a thick CO_2 atmosphere, however, increase in temperature at upper troposphere due to CO_2 condensation would weaken the greenhouse effect under a faint young Sun. The warm climate, therefore, cannot be sustained when radiation processes of clouds are neglected [2].

Recently, the scattering greenhouse effect of CO_2 ice cloud has been proposed to explain such warm climate [3]. If cloud layer causes the backward scattering of the planetary radiation more effectively than that of solar radiation, climate may become warm. The previous studies have shown that the magnitude of greenhouse effect strongly depends on the cloud parameters particularly the particle size and optical depth. Warm climate on ancient Mars is possibly achieved when the cloud column mass density and cloud particle size are 10^{-1} - 1 kg m^{-2} and 7.5 - 20 μm, respectively [4, 5]. However, it has not been examined whether or not such a values of cloud parameters could realize stably in the early Martian atmosphere.

The cloud particle size and optical depth could be changed by several processes: collisional coalescence of cloud particles, evaporation due to settling of cloud particles, evaporation (condensation) by radiative heating (cooling) and so on. However, the thermal velocity of cloud particles is too large to coalesce because CO_2 ice particles can coalesce at collisional velocity of less than $\simeq 0.1$ m s^{-1} according to an analytical model [6] with material properties of CO_2 ice [7]. In addition, the effect of particle settling is also negligible because the particle removal rate due to settling is smaller than the condensation (or evaporation) rate by radiative processes [8]. Therefore, we focus on the influence of radiative effects to the particle size and optical depth in a thick CO_2 atmosphere on early Mars.

2 Model

We use a one-dimensional radiative model for the CO_2-H_2O atmosphere. We calculate radiative transfer by using the two-stream approximation. We treat clouds as a single and homogeneous layer and the delta-Eddington approximation is adopted there. The vertical temperature profile is given as illustrated in figure 1. The optical coefficients of cloud particles are derived from the refractive complex indices of CO_2 ice [9] by using the Mie scattering theory. Uniform particle size and column number density of condensation nuclei are given as free parameters. The solar luminosity is

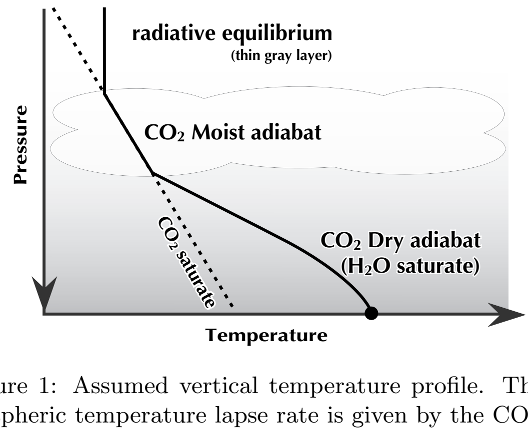

Figure 1: Assumed vertical temperature profile. The atmospheric temperature lapse rate is given by the CO_2 dry adiabat below the cloud layer and the CO_2 moist adiabat (CO_2 saturation vapour pressure curve) in the cloud layer. The stratosphere is isothermal and its temperature is given by the radiation equilibrium with the thin and gray atmosphere approximation. We give surface pressure and temperature as parameters. Cloud temperature is given by $(T_t + 3T_b)/4$, where T_t and T_b are the temperature at top and bottom of the cloud, respectively.

taken to be 75 % of the present values [10] and the surface albedo to be 0.216 [11]. We assume that the atmospheric gases are transparent for solar radiation. Line-by-line integration is carried out to calculate the gaseous absorption for infrared radiation by using the absorption line parameters tabulated in HITRAN2000 [12]. The wavenumber interval is taken 0.5 cm^{-1}. For the Voigt line profile of CO_2, 25 cm^{-1} cutoff is adopted [13]. However, 50 cm^{-1} cutoff for H_2O is adopted in order to express the effect of continuum absorption in the 8- to 12-μm region [Y. Abe, personal communication]. The Voigt function is approximated by the Humlicek's algorithm [14, 15]. For cloud layer the gaseous absorption is described by the random model with band parameter from Houghton 2002 [16] and the wavenumber interval of 25 cm^{-1}.

We assume that the release of latent heat for CO_2 condensation rate is balanced with the radiative cooling in cloud layer. We analyze cloud stability on the basis of the numerical estimation of interdependency between cloud particle size and the CO_2 condensation or evaporation rate in cloud layer.

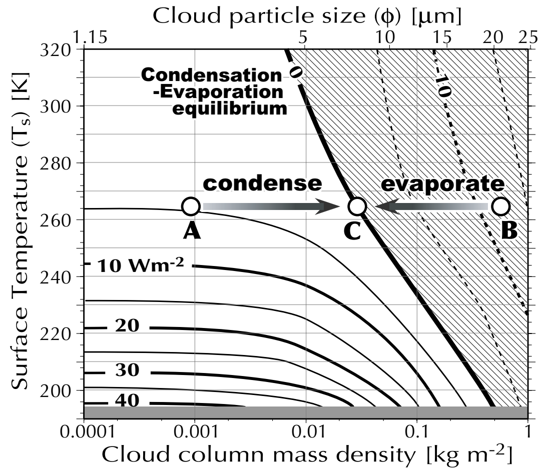

Figure 2: The CO_2 condensation rate (unit in equivalent cooling rate Wm^{-2}) at various surface temperature and cloud particle size. The surface pressure is 1 bar and column number density of condensation nuclei is 10^{10} m^{-2}. The specification of two factors, the cloud particle size and column number density of the nuclei, uniquely determines cloud column mass density because cloud particles have uniform size. If cloud particles are small (ex. point A), CO_2 condenses because of radiative cooling. If cloud particles are large (ex. point B), cloud particles evaporate because of radiative heating. Therefore, cloud particle size would converge on the point C, at which the CE equilibrium is achieved.

3 Results

3.1 CO_2 condensation rate

Figure 2 shows CO_2 condensation rate as a function of the cloud particle size when the column number density of condensation nuclei and surface pressure are fixed. When the condensation rate is negative, evaporation of CO_2 ice occurs. It is observed that an inverse correlation exists between the particle growth and the condensation rate. This correlation is important because a negative feedback mechanism between the particle size and the condensation rate is expected. The particle size may approach an equilibrium value with which condensation rate becomes zero, that is, the condensation-evaporation (CE) equilibrium is achieved when the effect of surface temperature change is negligible.

The condensation rate decreases with increasing surface temperature and becomes negative under the surface temperature above a critical temperature. This is because (1) the infrared heating from lower atmosphere becomes strong and (2) the emission from cloud layer becomes weak as cloud temperature drops with increasing surface temperature.

3.2 Estimation of equilibrium surface temperature

The equilibrium surface temperature is estimated assuming that the CE equilibrium and ra-

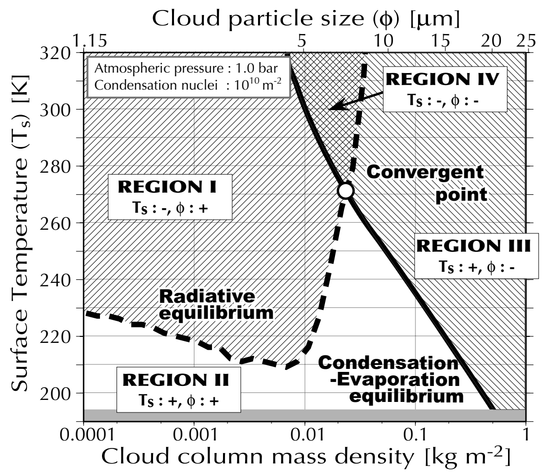

Figure 3: The relationship between cloud particle and surface temperature condition on the CE equilibrium (solid) and radiative one (dashed). The surface pressure and column number density of condensation nuclei are fixed at 1.0 bar and 10^{10} m^{-2}, respectively. We show the directions of change in the cloud particle size (ϕ) and surface temperature (T_s) in this parameter space, which are estimated from CO_2 the condensation rate and radiative balance of whole atmosphere, respectively.

diative balance of whole atmosphere are simultaneously satisfied. We call this state the simultaneous equilibrium state. The surface temperature under the simultaneous equilibrium state is uniquely determined if the column number density of condensation nuclei is kept to be constant. The equilibrium surface temperature is 271 K when the atmospheric pressure is 1 bar and the column number density of condensation nuclei is 10^{10} m^{-2}.

Owing to the negative feedback mechanism between the particle size and condensation rate, the simultaneous equilibrium state is stable against disturbances of the particle size and surface temperature. If the surface temperature and particle size are perturbed from such state, the CE equilibrium is recovered first and the surface temperature slowly evolves toward the simultaneous equilibrium. This is because the relaxation time scale for the former equilibrium is estimated to be about 10 hours from the relationship between condensation rate and cloud column mass density while the radiative relaxation time is a few weeks. Thus, the CO_2 cloud may stabilize the warm climate in early Mars.

3.3 Effect of column number density of condensation nuclei

Figure 4 shows the equilibrium surface temperature as a function of the column number density of condensation nuclei. When the column number density is larger than about 10^{11} m^{-2}, there is no solution which achieves the simultaneous equilibrium state. To induce the greenhouse effect, the cloud particle size and optical depth must be within limited ranges, respectively [4, 5]. When the column number density of condensation nuclei is very large, the cloud particle size satisfying CE equilibrium becomes too small to cause greenhouse effect. In this case, a CO_2 atmosphere condenses onto the surface resulting in the climate collapse (Figure 5). However, when the column number density of condensation nuclei is near 10^{10} m^{-2}, the equilibrium surface temperature can rise nearby H_2O melting point under the atmospheric pressure of 1 bar.

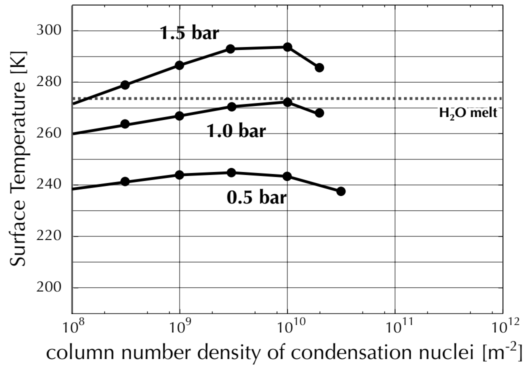

Figure 4: Equilibrium surface temperature as a function column number density of condensation nuclei. The dashed line shows H_2O melting point.

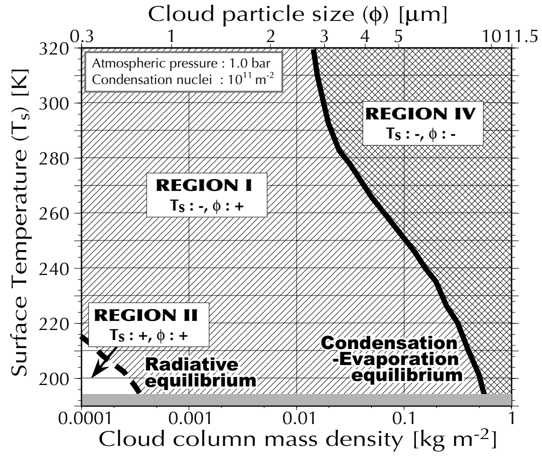

Figure 5: The equilibrium conditions taking column number density of condensation nuclei to be 10^{11} m^{-2}. The line styles are the same in figure 3.

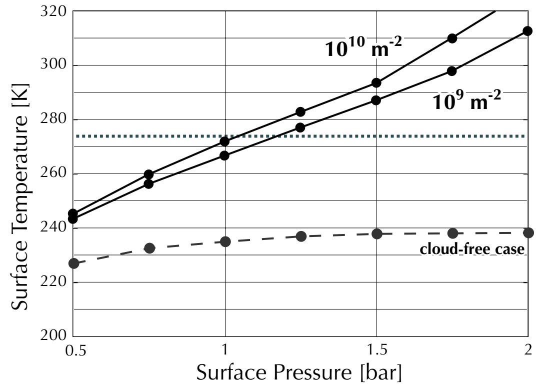

Figure 6: Surface temperature under simultaneous equilibrium state as a function of surface pressure and column number density of condensation nuclei (displayed with the curves). The dashed carve is the surface temperature with neglecting radiative process of the cloud particles.

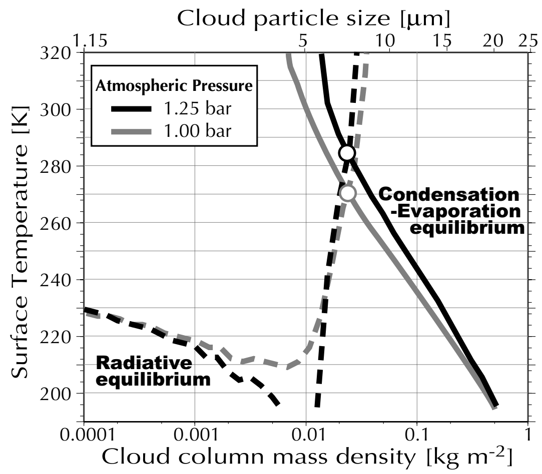

Figure 7: Effect of surface pressure on the equilibrium condition. Column number density of condensation nuclei is fixed at 10^{10} m^{-2}. The line styles are the same in figure 3. Surface temperature at convergent point increases when the surface pressure increases because the curve representing CE equilibrium shifts to upper right, whereas the conditions for radiative equilibrium little change.

3.4 Effect of surface pressure

As shown in figure 6, the greenhouse effect is intensified with increasing the surface pressure from 0.5 to 2 bar. It is to be noted that the increase rate of equilibrium surface temperature is larger than that in cloud-free case. The condensation rate depends on the surface temperature as shown in figure 3. As the surface pressure increases under fixed surface temperature and particle size, the condensation rate tends to increase because the thermal emission from cloud layer increases. Therefore, the conditions for CE equilibrium shift to those with denser cloud, resulting in higher equilibrium surface temperature at simultaneous equilibrium state.

4 Disscussions

4.1 Diurnal variation of clouds

We have neglected diurnal variation of incident solar radiation flux so far. However, the optical depth and particle size of cloud change to some extent depending on solar radiation flux since the relaxation time scale for CE equilibrium is about half of a day.

The diurnal variation of condensation rate is estimated assuming steady vertical temperature profile because of long radiative relaxation time. The cloud particle size varies between 6 and 8 mμ when the atmospheric pressure and the column number density of condensation nuclei are fixed at 1 bar and 10^{10} m^{-2}, respectively.

Cloud thickens owing to radiative cooling during night. However, cloud almost follows the CE equilibrium determined by the balance between the emission from cloud layer and the infrared heating from the lower troposphere and stratosphere. Therefore CO_2 condensation does not significantly proceed. On the other hand, the greenhouse effect of CO_2 ice cloud slightly weakens with increasing incident solar flux according to numerical calculation. Therefore, CO_2 ice cloud would suppress diurnal variation of surface temperature.

4.2 Influence of minor gases

Even in a CO_2-H_2O dominated atmosphere, other minor gases might play an important role in greenhouse effect on early Mars. CH_4 would be the most important among possible minor gases because CH_4 was possibly supplied by volcanic process and from biological source [e.g. 17] and is optically active in both infrared radiation and solar radiation.

CH_4 has been expected to cause climate warming because of strong absorption band in infrared radiation. However, the absorption of solar radiation might also cause cloud evaporation. Therefore it is not clear whether CH_4 causes stronger greenhouse effect or not. We need further quantitative investigation on the influence of CH_4 on the condensation rate.

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