Vertical structure and greenhouse effect of radiatively controlled CO_2 cloud layer in a Martian paleoatmosphere

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Abstract: The scattering greenhouse effect of a CO_2 ice cloud layer has been proposed as a potential mechanism for keeping the Martian climate warm enough to support flowing water under a faint young Sun. Previous studies have shown that such warm climate is possibly achieved if a cloud layer with optimal ranges of particle size and optical depth is placed in the atmosphere. However, it has not been examined whether or not such an optimal cloud layer could be formed. In this study, we construct a one dimensional, radiative-convective equilibrium model including cloud formation processes due to radiative cooling and estimate the parameters of cloud layer and the cloud-induced greenhouse effect. Our numerical analysis suggests that a CO_2 ice cloud layer which can cause strong greenhouse effect is formed with achieving both radiative and vapor pressure equilibria, and the global mean surface temperature rises above the melting point of H_2O when the surface pressure is larger than 3 bar and the mixing ratio of cloud condensation nuclei is kept within the range 10^5 –10^7 kg^{-1}.

1 Introduction

Geomorphological evidence suggests that the Martian climate was intermittently warm enough to support flowing water on the surface about 3.8 Gyr ago (e.g. Jakosky and Phillips 2001). Because of photochemical stability, CO_2 was likely the major component of the past atmosphere as well on the present Mars. However, it remains an open question whether or not a dense CO_2 atmosphere caused sufficient greenhouse effect under a faint young sun. Indeed, a 1D radiative-convective equilibrium model shows that increase in temperature at upper troposphere due to CO_2 condensation would significantly weaken the greenhouse effect when the cloud optical effects are neglected (Kasting 1991).

Recently, the scattering greenhouse effect of CO_2 ice cloud layer is accepted as a candidate for warming mechanism (Pierrehumbert and Erlick 1998). CO_2 ice has very low infrared absorbance except the 15-micron band. However, a CO_2 ice cloud layer can cause greenhouse effect because such a layer possibly reflects infrared radiation more effectively than solar radiation.

The magnitude of this greenhouse effect strongly depends on the cloud particle size and ice path which dominantly control the cloud optical properties (Pierrehumbert and Erlick 1998; Yokohata *et al.* 2000). The cloud having particle size smaller than 2 micron cannot extinct infrared radiation. When the particle size is larger than 50 micron, the cloud cannot reflect infrared radiation selectively because the cloud optical properties for infrared radiation approach ones for solar radiation. In addition, when the CO_2 ice path is too large, the cloud strongly reflects not only infrared radiation but also solar radiation because the cloud layer becomes opaque for both types of radiation. Therefore, the conditions for strong greenhouse effect enough to explain warm and wet climate are limited (Forget and Pierrehumbert 1997; Mischna *et al.* 2000).

On the other hand, the estimation of cloud parameters have been considered as a difficult problem so far because it is implicitly supposed that the cloud formation is mainly driven by the moist convection like that in the Earth's troposphere. However, it is not clear whether or not moist convection is actively driven in the ancient Martian atmosphere in which the major atmospheric component CO_2 is condensable. According to a recent numerical study of moist convection in such a system, convective motion is dramatically suppressed within condensable layer because a rising thermal loses buoyancy there (Odaka *et al.* 2006). In this study, therefore, we suppose that the radiative cooling rather than moist convection dominantly controls cloud formation processes. The cloud parameters derived from this assumption are numerically estimated as well as the resultant scattering greenhouse effect of the cloud.

2 Model

We construct a one dimensional, radiative-convective equilibrium model taking into account the cloud formation. The model atmosphere consists of CO_2 and H_2O, the latter of which fully saturates within the troposphere. We calculate radiative transfer by using two-stream approximation codes allowing multiple scattering processes (Toon *et al.* 1989). The delta-Eddington approximation code and the hemispheric mean approximation, source function code are adopted for solar and infrared radiation, respectively. The optical coefficients of cloud particles are derived from the refractive complex indices of CO_2 ice (Warren 1986) by using the Mie scattering theory. Gaseous absorption of CO_2 and H_2O is calculated by the correlated k-distribution method (See Appendix).

In an atmospheric layer in which temperature falls to the CO_2 condensation temperature, CO_2 condenses (vaporizes) with balancing the latent heat for CO_2 condensation (vaporization) with the radiative cooling (heating) energy. In each layer, uniform particle size is assumed and calculated from the particle mass estimated by dividing the mass density of cloud by the number density of cloud condensation nuclei (CCN). The CCN mixing ratio is assumed to be constant in a model run. Terminal state of the atmosphere, if available, is obtained when the radiative-convective and vapor pressure equilibria are simultaneously satisfied.

The other parameters used this study are shown in Table 1.

Parameter	Value
Solar luminosity	$0.75 \times$ current value
Surface albedo	0.2
Surface pressure	0.5, 1.0, 2.0, 3.0, 5.0, 10.0 [bar]
CCN mixing ratio	10^5, 10^6, 10^7, 10^8 [kg^{-1}]
CO_2 ice density	1.565×10^3 [$kg\ m^{-3}$]

Table 1: Parameters used in our calculations

3 Results and Discussion

We first show the terminal temperature and cloud profiles for typical case (Figure 1). Here the surface pressure was set equal to 2 bar and the mixing ratio of CCN is fixed to be 10^7 kg^{-1}. The initial profiles are given by the radiative-convective equilibrium for cloud-free atmosphere. It is important that the terminal state with a cloud layer actually exists due to the negative feedback mechanism between the cloud particle size and its growth rate (Mitsuda *et al.* 2005). In this case, the formed cloud layer thickness is 20 km, the particle size is 4 micron, and the mass density is 10^{-6} kg m^{-3}. This cloud layer produces strong surface warming about 40 K compared to the cloud-free case of 20 K. We confirm that the terminal state always exists for given range of model parameter sets.

The effect of changing the mixing ratio of CCN is illustrated in Figure 2, in which the results for 2-bar atmospheres are shown. When the mixing ratio is smaller than 10^7 kg^{-1}, the cloud produces strong greenhouse effect up to 50 K. On the other hand, when the mixing ratio becomes 10^8 kg^{-1}, the cloud produces less warming. There are two

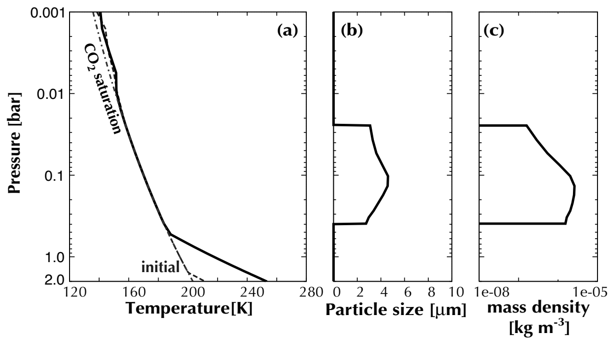

Figure 1: Vertical profiles of temperature (a), cloud particle size (b) and cloud mass density (c). The surface pressure and mixing ratio of CCN are fixed at 2 bar and 10^7 kg^{-1}, respectively. In panel a, the dash curve represents initial profile and dash-dot curve represents the saturation temperature of CO_2.

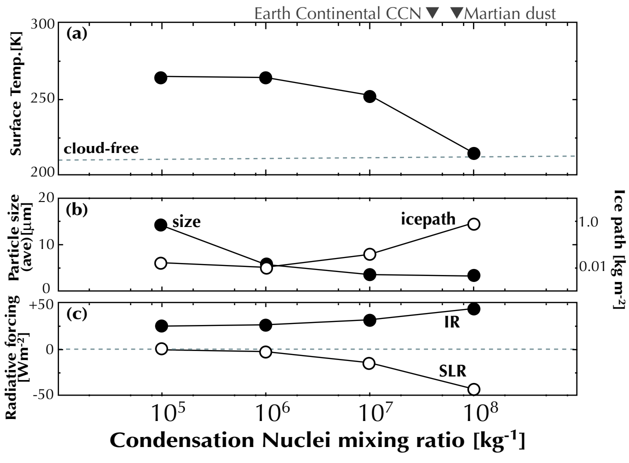

Figure 2: Surface temperature (a), cloud particle size and ice path (b) and radiative forcing (c, IR: < 4000 cm^{-1}, SLR: > 4000 cm^{-1}) as functions of mixing ratio of CCN for 2 bar atmosphere. Typical mixing ratios of continental CCN in the Earth's atmosphere and dust in Martian atmosphere are shown for comparison.

reasons for this behavior: First, the cloud particles cannot grow enough large size to reflect infrared radiation when CCN is too abundant. Second, as the surface temperature decreases, the CO_2 condensation levels expand and make the cloud too optically thick.

Figure 3 shows the effects of surface pressure change under fixed mixing ratio of CCN at 10^7 kg^{-1}. The surface warming is intensified with increasing the surface pressure. This is a result of cloud thickening because the CO_2 condensation level expands with surface pressure. Because the cloud scatters solar radiation primarily forward, the cloud radiative forcing of solar radiation is little changed by the increase in cloud ice path. In contrast, a thicker cloud more strongly backscatters infrared radiation and strengthens greenhouse effect.

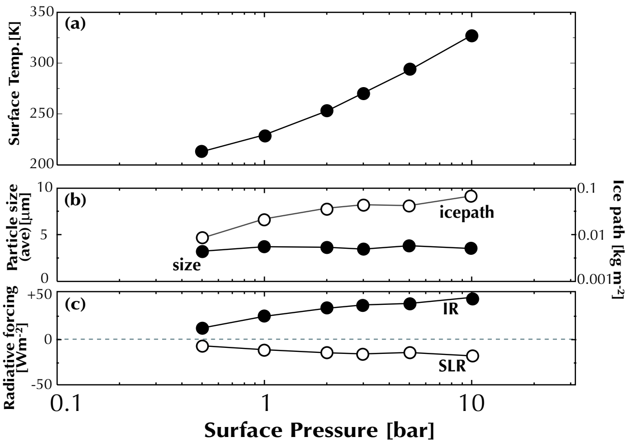

Figure 3: Surface temperature (a), cloud particle size and ice path (b) and radiative forcing (c) as functions of surface pressure under constant CCN mixing ratio of 10^7 kg^{-1}. The format of this figure is same as Figure 2 except the horizontal axis.

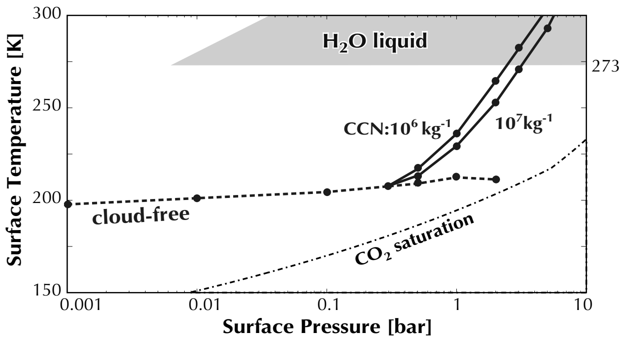

Figure 4: Relationship between the surface pressure and temperature of CO_2-H_2O atmosphere on early Mars. The solid curves include cloud formation owing to radiative cooling and the dash curve neglects it. The dash-dot curve represents the saturation temperature of CO_2. The grey region in the upper-right of figure represents the condition that liquid water exists stably.

Figure 4 illustrates the relationship between the surface pressure and temperature of CO_2-H_2O atmosphere. The solar luminosity was about 25 % less than its current value when most of valley networks were formed (Gough 1986). Under such conditions, the CO_2 condensation in upper tropopause begins to occur at the surface pressure above 0.5 bar and the surface temperature scarcely increases with increasing the surface pressure if cloud formation is neglected (Kasting 1991). However, if cloud formation is included, the surface temperature increases with increasing the surface pressure. Explanation of the warm and wet climate on early Mars requires that the surface pressure is larger than 3 bar and the mixing ratio of cloud condensation nuclei is within the range of 10^5 – 10^7 kg^{-1}.

The low erosion rate estimated for heavily cratered terrain infers that warm and wet climate which allows valley networks to form has occurred intermittently on early Mars. The strong dependency of surface temperature on atmospheric parameters may be consistent with such temporal warm climate. From observations, the mixing ratios of CCN in the Earth's atmosphere and the Martian atmospheric dust which can behave as CCN vary 1 order of magnitude or more (Twomey and Wojciechowski 1969; Pollack *et al.* 1979). Therefore, the temporal warm climate might be induced by the variation of CCN mixing ratio. It is important to clarify the physical processes controlling the CCN mixing ratio for estimating the actual effects of CO_2 ice clouds on early Martian climate.

4 Conclusions

The scattering greenhouse effect of a CO_2 ice cloud layer strongly depends on cloud particle size and ice path. This study attempts to estimate these parameters assuming cloud formation by radiative cooling. We derive the vertical profiles of temperature and cloud that satisfy both the radiative-convective and vapor pressure equilibria in the cloud layers.

Our numerical calculations show that the global mean surface temperature can rise above melting point of H_2O under the faint young Sun when the surface pressure is larger than 3 bar and mixing ratio of cloud condensation nuclei is kept at nearby 10^5 – 10^7 kg^{-1}. The strong dependency of surface temperature on CCN mixing ratio might explain temporal warm climate inferred from geomorphology.

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Appendix

We construct a transmittance code by using the correlated k-distribution method for both CO_2 and H_2O for applying to dense CO_2 atmosphere. The correlated k-distribution parameters are tabulated over 8 pressures (10^{-6} – 10 bar, by decade) and 6 temperatures (100 – 350 K, by 50 K) based on line-by-line calculations with HITEMP and HITRAN2004 (Rothman *et al.* 2005). For the Voigt line profile, 25 cm^{-1} cutoff is adopted with neglecting χ factor (Sekiguchi 2004). However, in the 300 – 600 cm^{-1} region, we include χ factor by Winters *et al.* (1964) and 500 cm^{-1} cutoff is adopted for including far wing effect of 15-micron absorption band. Because correlated k-distribution terms neglect the effects of CO_2 pressure-induced absorption (0 – 350 and 1150 – 1800 cm^{-1}) and H_2O continuum absorption, these effects are calculated by methods given by Kasting *et al.* (1984) and Roberts *et al.* (1976), respectively.

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