The greenhouse effect of CO_2 ice cloud and intermittency of warm Martian paleoclimate

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Geomorphological evidences suggest that Martian paleoclimate was often warm enough for liquid water to exist stably on the surface. The scattering greenhouse effect of CO_2 ice cloud is the most popular candidate for warming mechanism. Previous studies have shown that the cloud with particle size of 10-20 micron has strong effect. However, the intermittency of ice cloud greenhouse remains an open question. So far, we have suggested that cloud vertical structure which satisfies radiative equilibrium is kept by a feedback adjustment mechanism. Here we show the dependency of the equilibrium cloud structure on the number density of cloud condensation nuclei (CCN). We propose that the cloud-induced warm climate automatically changes into the cold one by the lost of CCN due to gravitational settling.

Our 1D radiative-convective model includes a CO_2 condensation scheme which adjusts atmospheric temperature and cloud mass mixing ratio with satisfying CO_2 gas-solid equilibrium. We assumed that the supersaturation of CO_2 is compensated by condensation instead of convection. Condensed CO_2 is left at each altitude with forming cloud. The cloud particle size assumed to be uniform in each layer is calculated from the cloud mass density divided by the CCN number density which is given constant for all altitudes as a parameter. We calculate radiative transfer by using two-stream approximation codes allowing multiple scattering processes. The optical coefficients of CO_2 ice particle are derived from the Mie theory. Gaseous absorption consists of CO_2 and H_2O line absorption and continuum absorption and CO_2 pressure-induced absorption. Assuming an ancient Mars, 75% of the present solar flux, 2 bars of atmosphere and 10^3-10^9 kg^{-1} of the CCN number density are given. The numerical calculations start from the cloud-free and radiative-convective equilibrium state.

When the CCN number densities are 10^3-10^8 kg^{-1}, the atmosphere evolves toward radiative-convective-condensation equilibrium states. The condensation layer rapidly changes into radiative equilibrium after about 1 day, which corresponds to cloud growth time. The surface temperature strongly depends on the CCN number density and it rises up near the H_2O melting point at 10^5-10^6 kg^{-1} of CCN number density. The larger the CCN number density, the smaller the cloud particle size. The cloud optical depth for each unit atmospheric colum mass is controlled by radiative cooling rate of gases, and almost independent of CCN number density. The cloud optical depth is approximately proportional to the CCN number density and geometrical cross section of the cloud particle. When the CCN number density is kept at 10^5-10^6 kg^{-1}, the particle size is adjusted within 15-7 micron which is suitable size for the selective backscattering of IR radiaiton. If the CCN number density comes off this range, the greenhouse effect weakens.

The cloud fall time is defined the time for a cloud particle to settle across from the top to the bottom of cloud layer. Here the settling velocity is given by the Stokes velocity for the cluod particle with average size at equilibrium state. The smaller the CCN number density, the shorter the fall time because cloud particle becomes larger. When the CCN number density is 10^4 kg^{-1} or less, the fall time is less than 0.1 day, which is shorter than the cloud growth time, and the cloud greenhouse effect cannot realize. On the other hand, the fall time is as long as about 100 day when the CCN number density is kept among 10^5-10^6 kg^{-1}. In this case, a warm climate is possibly realized while the subsequent cooling will occur due to the loss of cloud unless CCN is supplied.

Martian paleoclimate might repeat warming by CCN supply due to the mechanisms such as volcanic eruption, meteoroid impact and so on and subsequent cooling by the loss of cloud particles due to gravitational settling.