Scattering greenhouse effect of radiatively adjusted CO_2 ice cloud in a Martian paleoatmosphere

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The scattering greenhouse effect of CO_2 ice cloud has been proposed as a potential mechanism for warming the Martian climate enough to support flowing water under a faint young Sun. Previous studies have shown that the magnitude of greenhouse effect strongly depends on the cloud particle size, optical depth and vertical distribution. On the other hand, physical estimate of these cloud parameters still remain an open issue.

It is often supposed that dynamics of moist convection has to be solved to estimate the cloud parameters directly. However, convection might not be actively driven when the major atmospheric component is condensable. For example, CO_2 gas consumed by condensation is quickly supplied from ambient air. In this case, latent heat release by condensation may be balanced with radiative cooling without vertical advection. Moreover, if cloud becomes to receive net radiative heating as it grows, the cloud particle size would be autonomously adjusted to achieve the radiative equilibrium in each layer. In this case, cloud vertical profile could be determined without CO_2 precipitation.

To confirm the possibility of such radiative adjustment and examine the greenhouse effect of CO_2 cloud, we construct a one-dimensional radiative-convective model equipped with a CO_2 codensation scheme which adjusts atmospheric temperature and cloud mass density with satisfying CO_2 gas-solid equilibrium. We assumed that the supersaturation of CO_2 is fully 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 mixing ratio of cloud condensation nuclei (CCN) 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 by the Mie theory. Gaseous line absorption of CO_2 and H_2O is calculated by the correlated k-distribution method. CO_2 pressure-induced absorption and H_2O and CO_2 continuum one are considered separately. For solar luminosity, 75% of the present value is given.

For CCN mixing ratio smaller than 10^8 kg^{-1}, the CO_2-H_2O atmosphere of 1 bar or more reaches the terminal state satisfying radiative equilibrium in cloud layer independent of initial profile. The terminal state is achieved due to two negative feedbacks between the growth and cooling of cloud layer. One is increase in extinction in the cloud layer, which causes stronger radiative heating. Another is the change of terminal profile of lower atmosphere. The cloud layer induces stronger greenhouse effect with increasing particle size. Then, the cloud layer becomes to heated by stronger infrared radiation from lower atmosphere.

For the mixing ratio larger than 10^9 kg^{-1}, thick atmosphere is not sustained owing to its condensation onto the surface. This is because the anti-greenhouse effect is caused by the small cloud particles in such environment with abundant CCN.

Our numerical calculations show that the surface temperature can exceed H_2O melting point under the faint young Sun when the surface pressure is higher than 3 bar and CCN mixing ratio is kept among 10^5-10^7 kg^{-1}. The dependency of surface temperature on CCN mixing ratio might explain temporal warm climate inferred from geomorphology. 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.