Title: The greenhouse effect of CO$_2$ ice cloud and climate stability on early Mars

Abstract: The scattering greenhouse effect of CO$_2$ ice clouds is accepted as a mechanism to make the Martian climate warm enough to support flowing water under a faint young Sun (e.g.\ Pierrehumbert and Erlick (1998) {\it JAS}, {\bf 55}, 1897). 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 given (e.g.\ Mischna {\it et al}.\ (2000) {\it Icarus}, {\bf 145}, 546). However, it has not been examined whether or not such an optimal cloud layer could exist stably in the early Martian atmosphere.

In this study, we construct a 1-D radiative model for the CO$_2$-H$_2$O atmosphere and analyze cloud stability on the basis of the numerical estimation of the ice condensation or evaporation rate in a cloud layer. We assume that the latent heat release of CO$_2$ condensation is balanced with the radiative cooling in 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$_2$O when the atmospheric pressure is larger than 1 bar and the number column density of cloud condensation nuclei is fixed at $\sim$ 10^{10} m^{-2}. If the column number density of nuclei is unchanged, the cooling rate decreases as the particle size increases. When the particle size is too small, the particle growth occurs by CO$_2$ condensation due to positive radiative cooling, and when the particle size is too large, ice particles begin to evaporate owing to negative radiative cooling. Therefore the particle size approaches to an equilibrium value at which the latent heat release becomes zero. This negative feedback mechanism between the particle size change and the radiative cooling rate may stabilize warm climate on early Mars.
Owing to this negative feedback mechanism between the particle size change and the radiative cooling rate, warm climate may stably exist on early Mars.