Scattering greenhouse effect in early Martian climate: an investigation of CO_2 ice clouds stability against radiative heating by line-by-line calculation

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It has been proposed that warm and wet climate was induced on early Mars by the scattering greenhouse effect of CO_2 ice clouds. However, such clouds receive strong infrared heating in warm atmosphere and might evaporate before causing sufficient greenhouse effect. In this study, we calculate the net heating rate of cloud layer in a warm CO_2-H_2O atmosphere by the line-by-line integration and band model, and compare respective results. When the atmospheric pressure is as low as 1 atm, significant difference exists among those results. The former method predicts a narrower range of atmospheric pressures and surface temperatures for the net heating rate of cloud layer to be negative. This range strongly depends on the radius of cloud particles and the optical thickness of cloud layer. If the particle radius is fixed at 10 μm, the optical depth for visible light is smaller than 3, and the atmospheric pressure is higher than 1 atm, the cloud layer can stably exist without evaporation under the surface temperatures higher than the freezing point of water.

1 Introductioin

Geomorphological evidence suggests that the early (3.8 Gyr ago) Martian climate was warm enough for liquid water to exist stably on the surface [1]. Because of the photochemical stability, CO_2 may be the main constituent of the past atmosphere like the present. Even if Mars has a thick CO_2 atmosphere, however, the high temperature of upper troposphere due to the latent heat of CO_2 condensation weakens the greenhouse effect. Therefore the warm climate cannot be sustained by CO_2-H_2O atmosphere under the faint young sun when the radiation processes of clouds are neglected [2]. Recently, the scattering greenhouse effect of CO_2 ice clouds has been proposed to explain the warm atmosphere of early Mars [3]. If the backward scattering of the planetary radiation is larger than that of solar radiation by the clouds, we can expect climate warming.

However, if such clouds cause the greenhouse effect, they might eventually evaporate by the strong infrared heating from the surface and troposphere before sufficient warming occurs. In order to clarify the stability of clouds against the radiative heating, it is necessary to calculate the net heating rate of cloud layer, especially the atmospheric infrared radiative transfer.

The previous studies have used band models for calculating the radiative transfer of model Martian atmospheres bearing CO_2 clouds [3,4]. However, the approaches by these band models contain potential problems to treat this issue exactly. First, the band parameters are generally tuned up for the Earth's atmosphere. It is not clear whether these parameters are adaptable for atmosphere with completely different atmospheric pressure and composition from those of the Earth's atmosphere. Second, the resolutions in wavenumber of band models are too coarse to resolve the wavenumber dependence of optical constants of CO_2 ice.

Line-by-line (LBL) integration is the most exact method calculating the radiative transfer in which we can take the wavenumber resolution arbitrarily using line parameters collected for various gases. This provides a reference to confirm the result of band models.

In this study, therefore, we investigate the scattering greenhouse effect of CO_2 ice clouds and their stability against radiative heating by detailed calculations of the atmospheric infrared radiative transfer using the line-by-line integration and compare them to result of the band model.

2 Model

We use a one-dimensional, radiative-convective model for a CO_2 atmosphere with H_2O vapour saturated at each altitude. The assumed vertical temperature profile is illustrated in figure 1. We take radii of cloud particles 10 μm, (estimated as causing the strongest greenhouse effect [4]). Optical coefficients of the cloud particles are derived from the refractive complex indices of CO_2 ice [6] by the Mie theory with assuming spherical particles. We solve the radiative transfer in the cloud layer using the δ-Eddington approximation. We assume that the surface albedo is 0.2 for the solar radiation and 0 for the infrared radiation. Incident solar radiation is given by the latitudinal and annual average value under the solar luminosity of 0.75 times the present value. We calculate the radiative transfer of cloud free layer by neglecting the absorptions of the solar radiation but taking into account those by CO_2 and H_2O for infrared radiation. The transmissivity is calculated by the line-by line integration and the random model which is a familiar type of band models.

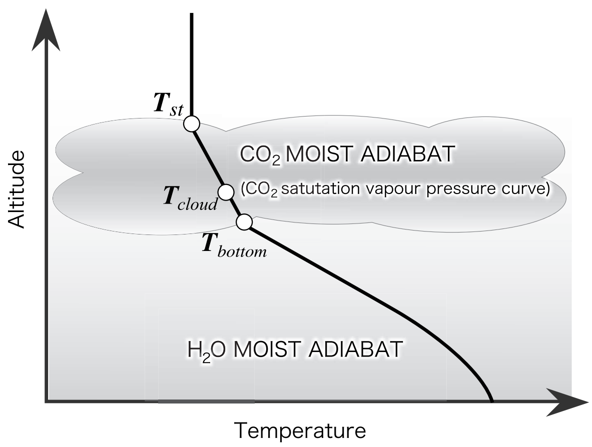

Fig. 1: Assumed vertial temperature profile. The atmospheric temperature lapse rate is H_2O moist adiabat below the cloud layer and CO_2 moist adiabat (CO_2 saturation vapour pressure curve) in the cloud layer. The cloud exists in a layer with temperature below the CO_2 condensation temperature. The stratospheric temperature T_{st} is approximately given by $\sigma T_{st}^4 = F_s(1-A)/2$, where F_s is the solar radiation incident flux at top of atmosphere and A is the planetary albedo. The cloud temperature T_{cloud} is chosen as follows; $T_{cloud} = (T_{st} + 3T_{bottom})/4$, where T_{bottom} is the temperature at bottom of the cloud.

(1) Line-by-line integration

In the line-by-line integration, the wavenumber resolution is taken 0.5 cm^{-1}. HITRAN [7] is referred for the absorption line parameters. 25 cm^{-1} cutoff for CO_2 and 50 cm^{-1} cutoff for H_2O are adopted for the Voigt line profile. The Voigt function is approximated by the Humlicek's algorithm [8,9]

(2) Random model

We use the random model with the wavenumber resolution of 25 cm^{-1} and the Lorentzian absorption line profile neglecting Doppler broadening. The strong absorption approximation is adopted for the band parameters from Houghton (2002) [10].

3 Results and Discussion

(1) The infrared radiation incident flux

Figure 2 compares the results of the infrared radiation incident flux to the cloud layer obtained by LBL and random model calculation. There are $\sim$ 10 % differences between results by the LBL integration and by the random model when the atmospheric pressure is 5 atm and the surface pressure is higher than $\sim$ 270 K. The LBL integration estimates smaller absorption for each atmospheric pressure when the surface temperature is lower than $\sim$ 260 K. On the other hand, random

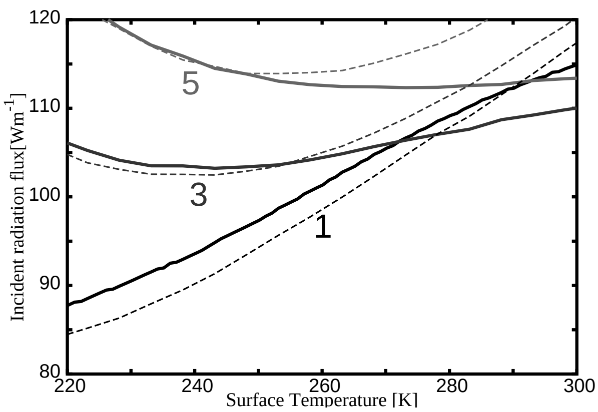

Fig. 2: The infrared radiative incident flux to the cloud as a function of the surface temperature and the atmospheric pressure (in 10^5 Pa displayed with the curves). The solid curves are the results of LBL integration and the dashed ones are in those of the band model.

model estimates smaller absorption when the surface temperature is higher than $\sim$ 260 K. The reasons of those differences are explained below.

a. Case for the lower surface temperature

The ramdom model underestimates the infrared radiation incident flux owing to the strong absorption approximation. Because this approximation assumes zero transmissivity near the center of absorption line, it overestimates the absorption when the absorption is weak. The error by this approximation increases as the atmospheric pressure decreases.

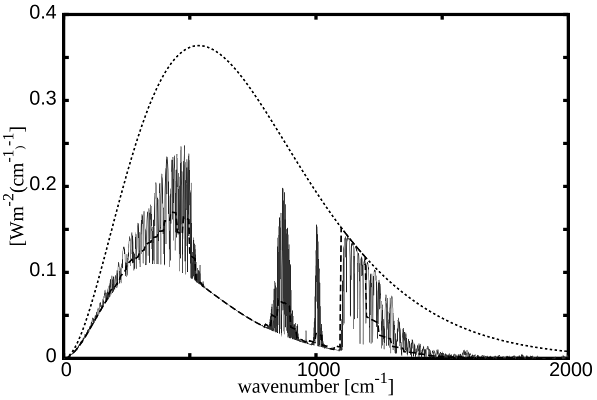

Fig. 3: The incident infrared radiation spectra. The result by the LBL integration (solid curve) and the that by the random model (dashed curve) are shown with the surface radiation spectrum (dotted curve). Here the atmosperic pressure is 1 atm and surface temperature is 273 K.

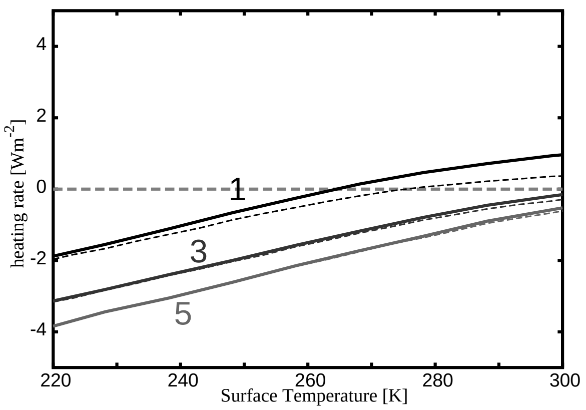

Fig. 4: The net heating rate of the cloud layer when the optical depth is 3 for the visible light (0.7 μm in wavelength). The style and the numeral of each curve correspond to those in figure 3.

b. Case for the higher surface temperature

The random model overestimates the infrared radiation incident flux due to underestimation of the absorption by H_2O . It is to be noted that the absorption by H_2O near 1200 cm^{-1} is neglected in the random model parameters (cf. figure 3). The difference between the results from both calculation method increases as the atmospheric pressure and the surface temperature increase (figure 2). This tendency is explained by increased absorption at the bands neglected in the random model.

(2) Cloud stability

In order to discuss the stability of the cloud layer against radiative heating, we consider the net radiative heating rates. If the net heating is negative, the cloud layer may exist stably without evaporation. Neglecting the convective heat transfer, the net heating rate F_H can be described by the difference between the heating by the solar and infrared radiations and the cooling by the thermal emission of clouds;

$$F_H = \int I_{IR}(\nu)A_{IR}(\nu)\,d\nu + \int I_S(\nu)A_S(\nu)\,d\nu - \int 2\pi B_P(\nu, T_{cloud})A_{IR}(\nu)\,d\nu$$

where $I_{IR,S}$ are the infrared and solar incident radiations to the cloud layer, $A_{IR,S}$ are the infrared and solar absorptance of the cloud layer, B_p is the Planck function and ν is wavenumber.

Figure 4 shows the net heating rate when the cloud optical depth is 3.2 for visible light. There are little difference between the results obtained by LBL integration and random model when the atmospheric pressure is larger than 3 atm. This is because the absorption spectrum of CO_2 ice overlaps that of CO_2 gas, so the errors originated from the underestimation of H_2O absorption and the strong absorption approximation are obscured. The heating rates in the LBL integration are larger than those in the random model for the higher surface temperature when the the atmospheric pressure is 1 atm. This difference increases with the optical depth of cloud layer.

4 Surface temperature under radiative-convective equilibrium

The surface temperature under the radiative balance is estimated assuming the radius of cloud

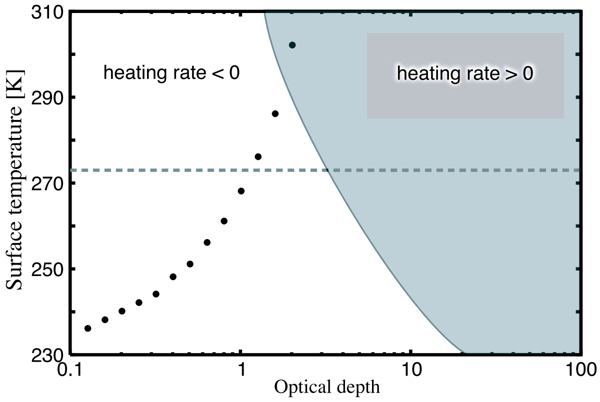

Fig. 5: The surface temperature (closed circles) under radiative balance when the surface pressure and the radius of cloud particles are fixed at 1 atm and 10 μm, respectively. The dashed horizontal line marks the freezing point of water, and the grey region is that the net radiative heating rate of the cloud layer is positive.

particles and the cloud optical depth as parameters. Figure 5 shows results when the atmospheric pressure and the radius of cloud particles are fixed at 1 atm and 10 μm, respectively. The greenhouse effect is enhanced as the cloud optical depth increases. The surface temperatures becomes higher than the freezing point of water when the optical depth for visible light exceeds 1.2. Because the heating rate of the cloud layer increases under thicker cloud and higher surface temperature, the net heating rate becomes positive for more than $\sim$ 1.5 of the optical depth. Therefore, if the thick cloud layer causes strong climate warming, the strong infrared heating would make the cloud layer thinner and thereby the moderately warm and wet climate might be kept stably. However, the greenhouse effect depends on the radius of the cloud particles [3,5]. Further studies are needed to incorporate the mechanisms determing the cloud particle size and thickness cloud layer.

5 Conclusion

We investigate the stability of the CO_2 ice cloud against radiative heating in early Martian climate by using the line-by-line integration and the band model for the calcuration of atmospheric radiative transfer and compare their results. There is little difference between the results of net heating rate of the cloud layer by the LBL integration and those by the band model when the atmospheric pressure is higher than 1 atm. However, the former method predicts a narrower range of surface temperatures under which the cloud can exist stably when the atmospheric pressure is as low as $\sim$ 1 atm. Even under the surface temperature higher than the freezing point of water, the cloud can exist stably when the cloud optical depth is less than 3 for visible light, the atmospheric pressure and the radius of cloud particles are fixed at 1 atm and 10 μm, respectively. Under the radiative balance, warm and wet climate is possibly induced by the stable cloud layer with visible optical depth about 1.5.

Acknowledgments

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