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On the Climatic Impact of CO_2 Ice Particles in Atmospheres of Terrestrial Exoplanets

D. Kitzmann[1], A. B. C. Patzer[1] and H. Rauer[1,2]

[1]Zentrum für Astronomie und Astrophysik, Technische Universität Berlin
[2]Institut für Planetenforschung, Deutsches Zentrum für Luft- und Raumfahrt (DLR)

Abstract. Clouds play a significant role for the energy budget in planetary atmospheres. They can scatter incident stellar radiation back to space, effectively cooling the surface of terrestrial planets. On the other hand, they may contribute to the atmospheric greenhouse effect by trapping outgoing thermal radiation. For exoplanets near the outer boundary of the habitable zone, condensation of CO_2 can occur due to the low atmospheric temperatures. These CO_2 ice clouds may play an important role for the surface temperature and, therefore, for the question of habitability of those planets. However, the optical properties of CO_2 ice crystals differ significantly from those of water droplets or water ice particles. Except for a small number of strong absorption bands, they are almost transparent with respect to absorption. Instead, they are highly effective scatterers at long and short wavelengths. Therefore, the climatic effect of a CO_2 ice cloud will depend on how much incident stellar radiation is scattered to space in comparison to the amount of thermal radiation scattered back towards the planetary surface. This contribution aims at the potential greenhouse effect of CO_2 ice particles. Their scattering and absorption properties are calculated for assumed particle size distributions with different effective radii and particle densities. An accurate radiative transfer model is used to determine the atmospheric radiation field affected by such CO_2 particles. These results are compared to less detailed radiative transfer schemes employed in previous studies.

Keywords. planets and satellites: atmospheres, scattering, radiative transfer

1. Introduction

Clouds can have an important impact on the climate of terrestrial planetary atmospheres by either scattering the incident stellar radiation back to space (albedo effect) or by trapping the infrared radiation in the atmosphere (greenhouse effect). They can therefore play an essential role for the determination of the extension of the habitable zone around different types of stars (see e.g. Kasting, Whitmire, & Reynolds 1993; Selsis *et al.* 2007).

While the inner boundary of the habitable zone is determined by the albedo effect of water droplet clouds (Kasting 1988), the outer boundary, on the other hand, is thought to be influenced by the potential greenhouse effect of CO_2 ice clouds (e.g. Kasting *et al.* 1993). However, due to the quite different refractive index, the effects of CO_2 ice clouds differ from those of water droplet or ice clouds. In particular, their warming effect results from back-scattered thermal radiation in contrast to the absorption and re-emission processes by water ice and droplet clouds. Apart from the wavelength-dependent optical depths, the crystal size is the most important quantity which determines the climatic impact of CO_2 particles (Forget & Pierrehumbert 1997).

Clouds composed of CO_2 ice crystals have also been discussed to play a major role for warming the atmosphere of early Mars. For a dense early Martian atmosphere, Forget & Pierrehumbert (1997) and Pierrehumbert & Erlick (1998) have shown that CO_2 ice clouds can yield a greenhouse effect by scattering of infrared radiation provided that the effective particle radii are larger than $\sim 6\ \mu$m. Smaller particle radii, on the other hand, yield a dominating albedo effect. A similar approach for early Mars was used by Mischna *et al.* (2000). Their results indicate that the altitude of CO_2 clouds influence the efficiency of the scattering greenhouse effect.

However, the previous studies of the greenhouse effect of CO_2 clouds relied on simplified radiative transfer schemes such as two-stream approximations, for example. In this contribution, we study the accuracy of such schemes in comparison to a more elaborate high-order discrete ordinate radiative transfer method and discuss the implications for the resulting scattering greenhouse effect of CO_2 ice clouds.

2. Model description

2.1. *CO_2 cloud properties*

Following the approach of Forget & Pierrehumbert (1997) we describe the size distribution of the CO_2 ice cloud particles by a modified gamma distribution with an effective variance of 0.1. The effective radii are varied between 0.1 μm and 200 μm. From observations in Earth's atmosphere, it is well known that water ice crystals are rarely spherical but show a broad distribution of different particle shapes. In contrast to H_2O, CO_2 crystals can have cubic or octahedral shapes as found in laboratory measurements by e.g. Wergin *et al.* (1997). Additionally, combinations of both (cuboctahedra) or more complicated shapes, such as rhombic-dodecahedral crystals, can also occur. However, in-situ measurements of the real shapes of CO_2 ice cloud particles are not yet available. In accordance with all previous studies on the climatic impact of CO_2 ice clouds, we therefore use here the approximation of spherical particles. The optical properties are calculated for a distinct single particle size using Mie theory and subsequently averaged over the assumed size distribution functions. The refractive index of CO_2 ice was taken from Hansen (2005, 1997).

2.2. *Radiative transfer calculations*

Radiative transfer calculations are performed in plane-parallel geometry for each considered size distribution to determine the radiative effects of the CO_2 ice particles using a single cloud layer. For the solution of the radiative transfer equation, different discrete ordinate methods are employed. In particular, we use the atmospheric radiative transfer code DISORT (Stamnes *et al.* 1988). Additionally, we also employ two-stream approximations, namely a δ-Eddington quadrature method for the incident stellar radiation and a hemispheric mean two-stream method in the IR (see Toon *et al.* 1989) for comparison with previous studies (Mischna *et al.* 2000; Colaprete & Toon 2003). For the discrete ordinate solver we use 24 streams in all calculations. This allows for a much better description of the scattering phase function than in the case of the two-stream approaches. Such a more detailed method usually accounts much better for problems dominated by anisotropic scattering.

As a result of the radiative transfer calculations, we obtain the fraction of the incident stellar light transmitted and forward-scattered through the cloud layer (spectral transmittance), as well as the fraction of back-scattered thermal radiation (spectral reflectance). The downward radiation flux from the central star which is incident at the cloud top can be decomposed as

$$F_{\mathrm{s},\lambda} = f_{\mathrm{s},\lambda} F_{\mathrm{s}} \tag{2.1}$$

where $f_{\mathrm{s},\lambda}$ is the normalised spectral distribution and F_{s} the total (wavelength-integrated) flux. For simplicity, we describe $f_{\mathrm{s},\lambda}$ by black-body radiation. Thus, for a given stellar effective temperature, we obtain the total percentage of transmitted and forward scattered stellar radiation $\epsilon_{s,t}$ by a convolution of $f_{\mathrm{s},\lambda}$ with the spectral transmittance and performing a subsequent wavelengths integration.

Similarly, the upward thermal radiation incident at the cloud base (F_{a}) can be decomposed analogous to Eq. (2.1). In this study, we consider the atmosphere below the cloud to be opaque such that only thermal radiation directly from below reaches the cloud base. Therefore, we adopt a temperature 160 K which roughly corresponds to the temperature where CO_2 would condense [cf. model calculations of Mischna *et al.* (2000) or Colaprete & Toon (2003))]. As pointed out by Forget & Pierrehumbert (1997), the thermal emission by the cloud itself would have only a minor contribution and is therefore neglected in our study. The total percentage of back-scattered thermal radiation $\epsilon_{\mathrm{a,r}}$ is analogously calculated by a convolution of $f_{\mathrm{a},\lambda}$ with the spectral reflectance and performing a subsequent wavelengths integration.

The net radiative effect can then be described as a function of the total transmittance and reflectance by the fraction

$$\frac{F_{\mathrm{a}}}{F_{\mathrm{s}}} = \frac{\epsilon_{\mathrm{s,t}}}{(1-\epsilon_{\mathrm{a,r}})} \quad \begin{cases} >1 & \text{net heating effect} \\ =1 & \text{radiatively neutral} \\ <1 & \text{net cooling effect} \end{cases} \tag{2.2}$$

For a ratio larger than one, the cloud has a net heating effect on the atmosphere below the cloud, while for values smaller than one, a net cooling effect occurs. A ratio of exactly one represents a radiatively neutral cloud. A more detailed model description can be found in Kitzmann, Patzer, & Rauer (2012).

Note that this approach neglects the contribution of Rayleigh scattering by the CO_2 gas below the cloud. Incident stellar radiation is partly scattered upwards by the gas molecules. A part of this upward scattered radiation can subsequently be scattered back down by the CO_2 cloud. A strong molecular Rayleigh scattering thus enhances the net warming effect of the CO_2 cloud. However, focussing on the differences between the employed radiative transfer schemes, the relative differences in the ratio of Eq. (2.2) are not affected by neglecting the gas because the contribution of Rayleigh scattering would be the same for all of these schemes.

Cool M-type dwarf stars are of particular importance in view of the detectability of (potentially) habitable exoplanets. By using such cool stars, the importance of Rayleigh scattering is also limited. For an effective stellar temperature of 3000 K, Rayleigh scattering would influence the atmospheric energy budget by less than $\sim 5\ \mathrm{Wm}^{-2}$, even for an atmosphere composed of several bar of CO_2 (von Paris *et al.* 2010).

3. Results

As a result of the radiative transfer calculations we obtain the spectral transmittance and reflectance as a function of the cloud optical depth† and the effective particle radius of the gamma distribution (see Fig. 1). Note that these results are independent of the wavelength distributions of the incident stellar and atmospheric thermal radiation.

The smallest particles ($a_{\mathrm{eff}} = 0.1\ \mu$m) yield an almost 100% transmittance for wavelengths larger than 1 μm (even for high optical depths up to 10). This implies that their effects on the incident stellar radiation will be small if the maximum of the stellar radiation is located in this wavelength region. On the other hand, they also have a reflectance

† Unless otherwise stated τ refers to the particular wavelength of $\lambda = 0.1\ \mu$m.

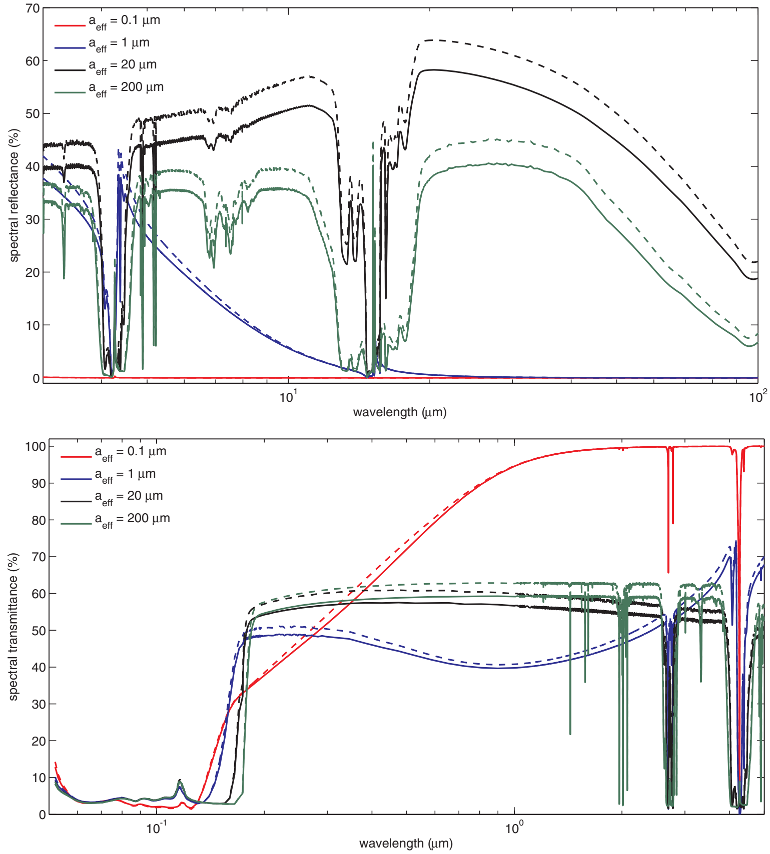

Figure 1. Spectral transmittance (*upper panel*) and reflectance (*lower panel*) for an optical depth of $\tau = 4$. Results are shown for four different cloud particle size distributions. Calculations using DISORT (two-stream methods) are denoted by solid lines (dashed lines).

of almost zero which means that these small particles won't yield a scattering greenhouse effect.

The transmittance of larger particles is always less than 100% and decreases at higher optical depth. The strongest negative impact on the transmittance is obtained for particles with $a_{\text{eff}} = 1\ \mu$m. The transmittance of the largest particles approaches the large particle limit of Mie theory which results in the same optical properties (optical depth, asymmetry parameter, and single scattering albedo) for all big particles at short wavelengths. The spectral reflectance for these $a_{\text{eff}} = 1\ \mu$m particles, on the other hand, is very low, especially in the wavelength region where most of the atmospheric thermal radiation is transported ($\lambda > 8\ \mu$m). This fact and their large negative impacts on the transmittance suggest that these particles will rather cool the lower atmosphere than yielding a net scattering greenhouse effect.

However, large particles can yield high reflectance values in the IR. The reflectance for $a_{\text{eff}} = 20\ \mu$m is overall almost 20% higher than that of the largest particles ($a_{\text{eff}} = 200\ \mu$m). This indicates that the scattering greenhouse effect will be most efficient for particles with sizes comparable to the wavelength of the thermal radiation.

Figure 1 shows the results of both radiative transfer approaches. Our findings indicate that the two-stream methods overestimate the amount of both, the transmitted stellar and the back-scattered thermal radiation. For the δ-Eddington two-stream method, the

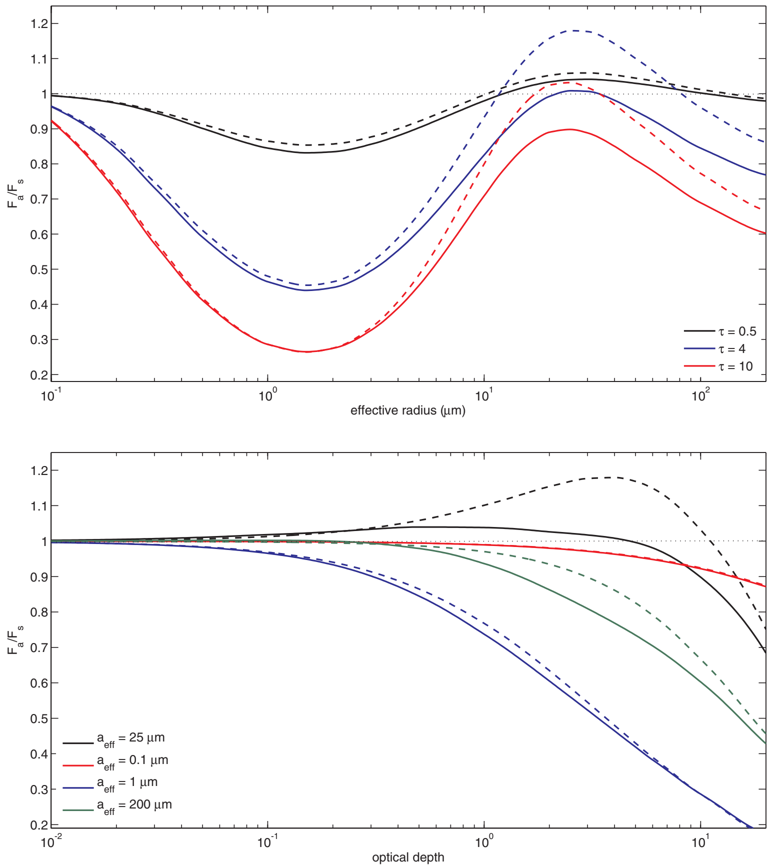

Figure 2. Ratios $F_\mathrm{a}/F_\mathrm{s}$ as a function of effective radius and three optical depth values (*upper panel*). The *lower panel* shows the ratios $F_\mathrm{a}/F_\mathrm{s}$ as a function of the optical depth and for four different effective radii. Calculations using DISORT (two-stream methods) are denoted by solid lines (dashed lines).

differences are about 5% while the hemispheric mean two-stream yields deviations larger than 10%. Thus, two-stream methods will, in general, overrate the positive net scattering greenhouse effect of CO_2 clouds by allowing more stellar radiation to be transmitted through the cloud layer and more thermal radiation back-scattered to the planetary surface. However, the exact climatic impact will depend on the spectral distributions of the radiation incident on the cloud.

Our results are applied to a central star with an effective temperature of 3000 K, roughly corresponding to a cool M5 main sequence dwarf star. The obtained ratios $F_\mathrm{a}/F_\mathrm{s}$ are shown in Fig. 2 for both radiative transfer approaches as a function of the optical depth τ and effective particle radius a_eff.

The results depicted in Fig. 2 suggest that the CO_2 particles have a negative or neutral impact over a large range of the considered parameter space. Only particles with sizes comparable to the wavelength of the thermal radiation contribute to a net greenhouse effect as expected, but only if the optical depth is not too large. For higher optical depths, again a cooling effect is found. This kind of behaviour as a function of the optical depth is consistent with the studies of Mischna *et al.* (2000) or Colaprete & Toon (2003).

Larger or smaller particle sizes show a cooling effect which is very large for particles with effective radii near 1 μm. This is caused by the large optical depth of these particles at small wavelengths where the maximum of the incident stellar radiation is located. Very small particles (0.1 μm) on the other hand, are almost radiatively neutral for all considered optical depths. Even at $\tau = 20$ they show only a small cooling effect. For these particles the main contribution to the optical depth occurs at very small wavelengths. Since the maximum of the incident stellar radiation for the chosen low effective temperature is located near $\lambda = 1$ μm the impact of these small particles is very small. This effect is similar to the low efficiency of Rayleigh scattering by the gas molecules for cool M-type stars.

A comparison of the different radiative transfer methods shows that the efficiency of warming by CO_2 ice clouds differs quite noticeably for different approximations in the numerical treatment of the radiative transfer equation. Consistent with previous reports of e.g. Forget & Pierrehumbert (1997) or Mischna *et al.* (2000), two-stream methods predict a strong scattering greenhouse effect at medium optical depths near $\tau = 4$. In contrast to this, the application of DISORT results in an almost radiatively neutral cloud. Obviously the largest deviations occur for particle sizes which roughly correspond to the wavelength of the thermal radiation because this is the regime where Mie scattering is important. The hemispheric mean two-stream method in particular seems to yield quite inaccurate results compared to a more elaborate discrete ordinate radiative transfer. The deviations are also clearly a function of the optical depth. For lower optical depths, the differences are small, while they are the largest in the imporant region of the most efficient greenhouse effect.

Therefore, previous studies on the impact of CO_2 ice clouds on the outer boundary of the habitable zone using two-stream approximations overestimated the positive scattering greenhouse effect. It is evident that more accurate radiative transfer methods are necessary to describe the anisotropic radiative effects of CO_2 clouds. However, a quantitative analysis of the scattering greenhouse effect of CO_2 clouds and their impact on the position of the outer boundary of the habitable zone would require an atmospheric model with more detailed calculations, including also the gas component.

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