THE EFFECTS OF CO2 CLOUDS ON THE THERMAL STRUCTURE OF THE EARLY MARS ATMOSPHERE

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Introduction:

Constraining the influence of clouds on the ancient Martian climate is critically important to understanding what may have warmed the planet during the Noachian. Climate modeling studies demonstrate that both CO_2 clouds and H_2O clouds are capable of influencing the thermal structure of the early Martian atmosphere [1,2,3,4,5,6,7,8]. However, there is variation in the predicted degree of that influence over various parameter spaces (e.g., surface pressure, [3]) and among different models (e.g., Wordsworth et al. [4] vs. Kite et al. [7]). This is a reflection of the sensitivity of simulated atmospheres to the multiple effects of clouds and is part of the difficulty of accounting for cloud physics in models. Some early Mars climate modeling studies have omitted CO_2 clouds altogether. Here we conduct a physical processes study to characterize the behavior of CO_2 clouds in the 3-D NASA Ames early Mars Global Climate Model (eMGCM) and describe the physics involved. We explore the effects of CO_2 clouds on the early Martian atmosphere at different CO_2 surface pressures (500 mbar, 1 bar, and 2 bar) and isolate their influence on the thermal structure and radiative budget of the atmosphere.

Basic Physics:

CO_2 clouds affect the thermal structure of the atmosphere in two ways (see the Figure 1 cartoon): 1) CO_2 cloud condensation fixes temperatures aloft to warmer values, resulting in cooler temperatures in the lower atmosphere and at the surface [1] and 2), infrared scattering from CO_2 clouds warms the lower atmosphere and increases surface temperatures [2,3]. These two effects are discussed further below.

Kasting [1] explores the effect of CO_2 cloud condensation on the atmospheric thermal structure. Kasting [1] shows with a 1-D radiative convective model that CO_2 condensation reduces the convective lapse rate, leading to cooler surface temperatures and limiting greenhouse warming in dense CO_2 atmospheres. In the absence of CO_2 cloud condensation, temperatures aloft can become quite cool, falling below the condensation temperature (black solid curve in the Figure 1 cartoon). When CO_2 cloud formation is allowed, this fixes temperatures at these altitudes to the condensation temperature, and thus the atmosphere is warmer at these attitudes (black dashed curve in the Figure 1 cartoon). This leads to lower temperatures near the surface; Kasting [1] explains why this happens in terms of the energy balance at the top of the atmosphere. When temperatures at altitude are fixed to warmer values, in order for the outgoing long wave radiation to remain the same (because the planetary albedo is fixed), the lower atmosphere must radiate away less energy, leading to cooler temperatures there. In other words, a warmer atmosphere aloft will emit more energy, and so the lower atmosphere must emit less by cooling in order to maintain overall energy balance.

The second way that CO_2 clouds influence the thermal structure of the atmosphere is through their radiative effects, which were not explored in Kasting [1] but were in later studies [2,3]. CO_2 clouds are perfect scatters in the visible and also scatter in the infrared around 15 microns and above 90 microns [2]. This scattering in the visible and the infrared regimes leads to competing effects (Figure 1). Scattering in the visible can cause the planetary albedo to increase and can result in surface cooling. Meanwhile, scattering in the infrared can lead to more trapped infrared energy in the lower atmosphere, which can produce a greenhouse effect. Forget and Pierrehumbert [2] show with a 1-D model that the infrared scattering from CO_2 clouds can warm the surface (e.g., red solid curve in the Figure 1 cartoon).

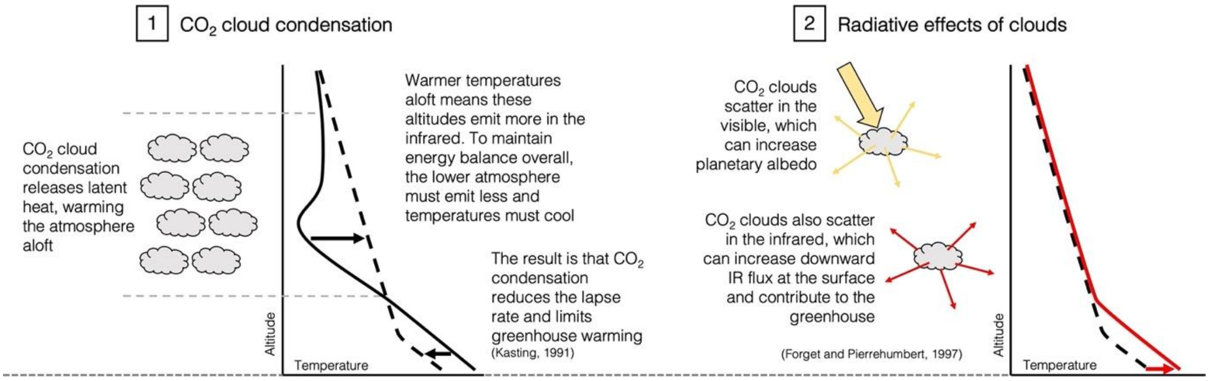

Figure 1: Diagram showing how CO_2 clouds influence the thermal structure of early Mars' atmosphere.

Forget et al. [3] explore this with the 3-D Laboratoire de Météorologie Dynamique (LMD) Global Climate Model (GCM) and show that CO_2 clouds can lead to surface cooling or surface warming depending on the atmospheric mass. They find that including CO_2 cloud radiative effects in the model results in warmer surface temperatures for surface pressures ≤ 3.5 bar (with maximum warming in the 2 bar case), but cooler surface temperatures for surface pressures ≥ 4 bar. However, they also find that atmospheric collapse occurs for cases with surface pressures > 2.5 bar.

These prior studies of CO_2 clouds on early Mars have explored either their radiative influences [2,3] or the effect of cloud condensation on atmospheric thermal structure [1], but not both in 3-D. Here we present simple 3-D simulations with a self-consistent cloud treatment to establish the behavior of CO_2 clouds in our global climate model and document the ways in which CO_2 clouds affect the thermal structure of the atmosphere.

Methods:

We perform simulations for this work using the NASA Ames early Mars Global Climate Model (eMGCM; [9]) which includes appropriate physical treatments for CO_2 clouds [8]. A bulk CO_2 cloud condensation scheme is included in which CO_2 condenses onto a fixed number of seed nuclei (10^5 #/kg of gaseous CO_2). Cloud particles are subject to advection and gravitational sedimentation. The radiative effects of clouds are accounted for; tables of the appropriate optical coefficients were generated with a Mie code using the indices of refraction from Warren [10]. For all simulations presented here, the atmosphere is completely dry; there are no water sources on the surface, no water vapor in the atmosphere, and no water clouds. This version of the model uses the "legacy" latitude-longitude dynamical core [11,12]. We are in the process of transitioning the model to the NOAA/GFDL cubed-sphere finite volume (FV3) dynamical core, and plan to use that version for early Mars studies in future work (see *Kahre et al., this meeting [13]*).

Case	Surface Pressure	CO_2 cloud formation / radiative treatment
a	500 mbar	No clouds
b	500 mbar	Inert clouds
c	500 mbar	Active clouds
d	1 bar	No clouds
e	1 bar	Inert clouds
f	1 bar	Active clouds
g	2 bar	No clouds
h	2 bar	Inert clouds
i	2 bar	Active clouds

Table 1. Nine simulations performed here and their CO_2 surface pressures (middle column) and the treatment of CO_2 clouds (right column).

To examine the influence of CO_2 clouds on the atmosphere, we perform simulations with three different cloud treatments for three different surface pressure scenarios (500 mbar, 1 bar, 2 bar of CO_2). These cases a-i are listed in Table 1. Simulations either have no CO_2 cloud formation at all in which atmospheric temperatures are allowed to fall below the CO_2 condensation temperature ("no clouds" cases), have clouds forming that are radiatively inert ("inert clouds" cases), or have clouds forming that are radiatively active ("active clouds" cases).

Results and Discussion:

We find that CO_2 clouds in our model affect the thermal structure of the atmosphere in the two ways described in the "Basic Physics" section, consistent with the findings of Kasting [1], Forget and Pierrehumbert [2], and Forget et al. [3]. When CO_2 clouds are allowed to condense in the model atmosphere (as in cases b, e, and h), this results in warmer atmospheric temperatures between ~15 and 60 km in altitude and cooler temperatures below that compared to cases in which no condensation is allowed

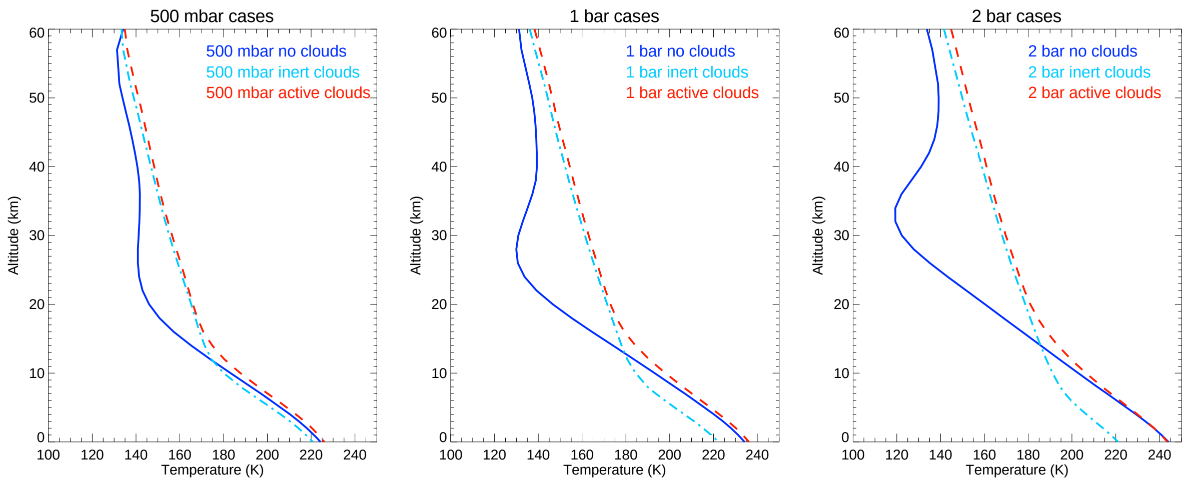

Figure 2: Mean annual temperature profiles between 30° S and 30° N for 500 mbar cases (left), 1 bar cases (middle), and 2 bar cases (right). Blue solid lines are "no cloud" cases, cyan dot-dashed lines are "inert cloud" cases, and red dashed lines are "active cloud" cases.

(cases a, d, g, Figure 2). These atmospheric temperature differences are greater for the more massive atmosphere cases (Figure 2). Global mean surface temperatures are cooler in the "inert cloud" cases than they are in the "no cloud cases," with the largest temperature differences occurring for the 2 bar cases, while the 500 mbar cases have only minor surface temperature differences. This surface temperature cooling with CO_2 condensation occurs because of the warming at higher altitudes (see "Basic Physics" section), consistent with the finding of Kasting [1].

Here, our simulations are also consistent with the findings of Forget and Pierrehumbert [2] and Forget et al. [3] as cases with active clouds (c, f, i) have warmer surface temperatures than cases with inert clouds (b, e, h; Figure 2). The impact of the radiative effects of clouds on the vertical atmospheric temperature profile is minimal at 500 mbar but substantial at 2 bar (Figure 2). Cases with "active clouds" (c, f, i) have warmer global mean annual surface temperatures than cases with "inert clouds (b, e, h) by ~ 5 K, 12 K, and 21 K for the 500 mbar, 1 bar, and 2 bar cases respectively. This is a greater amount of warming by the radiative effects of CO_2 clouds in this model compared to Forget et al. [3].

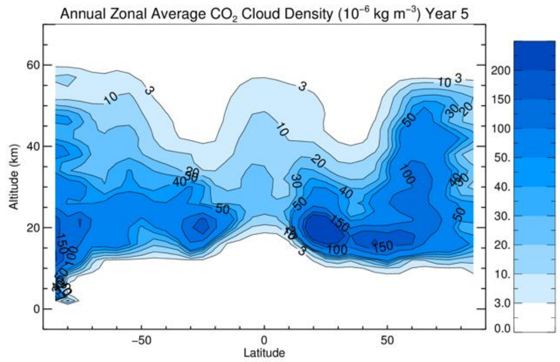

Figure 3: Annual zonal mean CO_2 cloud density in units of 10^{-6} kg m^{-3} for case "i" (2 bar CO_2 surface pressure with radiatively active clouds).

This may be because the model used here appears to be cloudier than that of Forget et al. [3]. Zonal mean CO_2 cloud densities in the 2 bar "active cloud" case (Figure 3) have a similar overall distribution to that of the corresponding case shown in Figure 10 of Forget et al. [3]. In both models, the cloud deck rests at ~10 km in altitude and there are local cloud density maxima over the tropics and poles as well as local minima over the equator at ~15 - 20 km in altitude. However, maximum cloud densities in this work are ~2-3 times those of Forget et al. [3]. We are continuing to explore why CO_2 cloud densities are higher here, but this may explain why the radiative effects of CO_2 clouds appear to provide more surface warming here than in Forget et al. [3].

Another factor that might influence the radiative effects of the clouds in our model is the value used for the number of available cloud condensation nuclei (CCN). Results shown here use a value of 10^5 #/kg of gaseous CO_2 (the same value used in Forget et al. [3]) and we are currently testing the sensitivity of our model results to this parameter. Because condensed cloud mass is evenly distributed on the particles within a model grid box, this parameter effectively controls the size of cloud particle radii in the model. A larger CCN value will result in more particles that are smaller while a lower CCN value will have fewer but larger particles. The IR scattering effect of the clouds works best for large particles that can efficiently interact with IR radiation (~15 microns).

Conclusion:
In conclusion, we argue that it is important for CO_2 clouds to be included in global climate models used for early Mars studies. Here, we perform simplified, idealized simulations with and without CO_2 clouds to examine and document the influences of these clouds on the thermal structure of the atmosphere. The vertical temperature structure of the atmosphere differs substantially between simulations with no clouds and those with radiatively active CO_2 clouds. These differences will affect the dynamics, which could impact other processes not explored here including the water cycle; this is important for early Mars studies which predict precipitation rates. In the simulations presented here, while atmospheric temperatures differ between cases, surface temperatures by coincidence are similar between the "no cloud" and "active cloud" cases. While this is the result for our model, others may be different, as evidenced by the results of Forget et al. [3] who do not find as much warming due to the radiative effects of their CO_2 clouds. For these reasons, we argue that CO_2 clouds should not be ignored in early Mars climate modeling with massive atmospheres. In future work, we aim to explore the effects of these clouds in conjunction with other warming mechanisms including H_2O clouds and H_2 collision induced absorption to improve our understanding of how these warming mechanisms affect the atmosphere and each other.

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