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Introduction

Previous CO_2 ice cloud modeling studies [Colaprete et al., 2003, Tobie et al., 2003, Forget et al., 1998, Kuroda et al., 2013, Colaprete et al., 2008] allowed to develop and test ideas on CO_2 ice cloud formation; however, the studies were often made in idealized settings and included simplified physics and/or limited model boundaries such as a low model top. Listowski et al. [2014] developed refined CO_2 cloud microphysics adapted for the Martian conditions of a near-pure vapor condensing in highly supersaturated conditions [Listowski et al., 2013]. They showed with a one-dimensional model and a temperature structure including tidal and gravity wave effects that an additional source of condensation nuclei (CN) was required in the mesosphere for the formation of observed-like clouds.

The model of Listowski et al. [2014] has now been coupled with the LMD Mars GCM (MGCM), jointly developed by several laboratories, including LATMOS, LMD, and IAA. The MGCM is now able to simulate the formation of CO_2 ice clouds in the Martian atmosphere taking into account mineral dust particles and water ice crystals as potential condensation nuclei (CN). The first simulations are used for testing the new microphysics and comparing its results to the previous simplified CO_2 condensation parameterization. The simulations are compared to the published CO_2 ice cloud observations.

Model description

We are using the most recent version of the MGCM and most of the included processes have been described in Navarro et al. [2014], including water ice cloud microphysics and their radiative effect. The microphysics use a subtimestep: CO_2 cloud processes are calculated 50 times within a physics timestep (the microphysical timestep is 18 s).

The new CO_2 ice cloud microphysics follow closely the implementation of water ice cloud microphysics in the MGCM, performed via the so-called modal approach, frequently used in GCMs. This means that the particle size distribution is described assuming a log-normal form for the distribution and its evolution is described through the integral properties (moments) of the distribution. Our model uses two variables for describing each particle type: the total number concentration of the particles and the total mass.

We do however discretize the CN size distribution for calculating the heterogeneous nucleation rate and probability. This is necessary for ensuring that a realistic fraction of the available CN is activated for nucleation, since nucleation is very dependent on the CN size. We use the Classical Nucleation Theory applied to Mars [Määttänen and Douspis, 2014] and a contact parameter of 0.952 [Glandorf et al., 2002]. Nucleation is calculated separately for the three potential CN types (water ice crystals, dust particles and meteoric particles).

The growth rate of the CO_2 ice crystals is calculated as in Listowski et al. [2014], but the iterative solution they proposed has been replaced by an analytical solution that is much faster and more efficient especially for use in a GCM.

Sedimentation of CO_2 ice crystals is calculated within the microphysics timestep as well and the code sediments all CN that have been captured by the CO_2 ice crystals. This means that the CN are scavenged by the CO_2 crystals. During snowfall to the ground, the ices and dust are incorporated into the surface reservoirs. The fall speed is calculated with the classical Stokes-Cunningham relation with the correction taking into account the flow regime.

We have performed three simulations, one with the previous, simple parametrization of CO_2 condensation, one with the new CO_2 cloud microphysics but only including dust particles as CN, and one using both dust and water ice as CN, respectively called PARAM, MPCO2, and MPCO2+H2OCN. The simulations have been run for three Martian years and we take the results from the last simulation year to insure convergence. We use the climatological dust scenario that describes well an average Martian Year without a global dust storm. We do not include photochemistry in these simulations due to its computational cost. This may induce an overestimation of the water vapour concentration in the middle atmosphere, which may in turn lead to and overestimation of the water ice formation and influence CO_2 ice cloud formation in the mesosphere. We use a spatial resolution of 5.6258° longitude x 3.758° latitude, corresponding to a 64 longitude x 48 latitude horizontal grid, and 32 vertical levels. The model top is defined at the pressure level 3×10^{-3} Pa that corresponds approximately to an altitude of 120 km (for a surface pressure of 610 Pa and an atmospheric scale height of 10 km).

Results

The model produces CO_2 ice clouds in the polar regions in the troposphere during the winter and in the mesosphere at equatorial altitudes. Figure 1 shows the CO_2 ice column density as a function of latitude and solar longitude for the two simulations: MPCO2 and MPCO2+H2OCN with observations from several instruments [Clancy et al., 2007, Montmessin et al., 2006, Määttänen et al., 2010, McConnochie et al., 2010, Scholten et al., 2010, Vincendon et al., 2011, Aoki et al., 2018, Clancy et al., 2019, Jiang et al., 2019, Liuzzi et al., 2021]. The polar clouds are formed in a larger altitude range than in the observations, reaching from the surface up to 40 km altitude. The polar atmosphere is cold and supersaturated in a deeper layer than in the observations, causing the thicker cloud formation that forms earlier and lasts longer. The cause of the colder polar winter troposphere may be the prescribed dust column depth coming from observations: as there are very few observations in the polar night, the column depth has been given a minimum value that might still be too high compared to reality. This larger dust content in the polar night causing a too large radiative cooling may be the reason for the cold temperatures. The snowfall from polar clouds contributes about 10% to the formation of the polar ice caps. Substantial mesospheric clouds only form when the model takes into account CO_2 ice nucleation on both water ice crystals and dust grains. The seasonal distribution of the clouds agrees well with observations during most of the mesospheric cloud season, but the pause in cloud formation around the aphelion is more clear-cut than in the observations where cloud formation seems to continue during the whole cloud season, although at a lower frequency during a certain

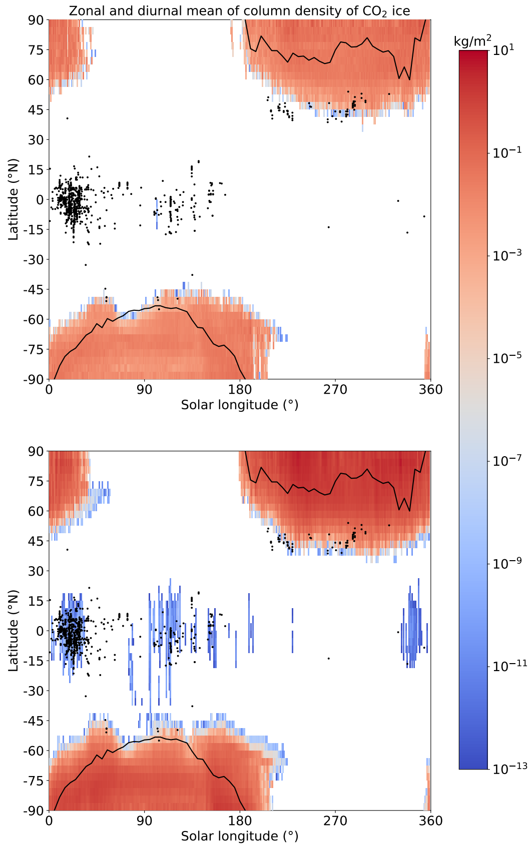

Figure 1: Zonal and diurnal mean of CO_2 ice column density. Top: MPCO2 simulation; bottom: MPCO2+H2OCN simulation. The black solid line limits the area where MCS observed temperatures below CO_2 condensation [Hu et al., 2012]. The black dots show mesospheric CO_2 ice cloud observations (see text).

period around the aphelion. The clear pause in cloud formation in the model is due to the rise in mesospheric temperatures that seems to be related to a change in the circulation regime and winds in the mesosphere. As cloud formation is a very strong function of temperatures, even a small change in temperature can cause large changes in cloudiness. The reasons for the sudden change in the mesospheric state has not been investigated further, but it is planned in a future study dedicated to mesospheric clouds. The optical thickness of the clouds remains two orders of magnitude below observed values, pointing to a need for an exogenous CN source (meteoritic dust: [Listowski et al., 2014, Plane et al., 2018]). Such a source is being added to the model (see the paper by Mathé et al. in this conference).

Conclusion

We present the results of simulations with a new coupled 3D global model - CO_2 ice cloud microphysical model. The cloud model accounts for a condensation theory adapted for the highly supersaturated near-pure vapor conditions of the Martian atmosphere and water ice crystals as condensation nuclei.

The MGCM produces CO_2 ice clouds both in the polar winter troposphere and in the tropical summer mesosphere. The mesospheric only form when water ice crystals are considered as condensation nuclei by the model. This confirms that mineral dust lofted from the surface to the mesosphere is not sufficient as CN. Despite the good agreement of the modeled spatial and seasonal cloud distributions, the modeled CO_2 ice cloud optical depths are orders of magnitude below those observed, confirming the need of an additional CN source in the mesosphere, which could be provided by particles formed after meteor ablation. The polar clouds are formed of crystals ranging from some microns in radius to some tens of microns, agreeing with observed estimates. Snowfall from polar clouds contributes up to 10% of the ice flux to the polar cap ice. This is within the surface ice contribution estimated from observations. The polar clouds extend to higher altitudes and the cloud formation season is longer than the observed ones. Overall, the modeled polar atmosphere is colder than what the observations show, revealed by the very deep supersaturated polar atmosphere in the model, but this might be due to a too high dust optical thickness in the polar regions leading to a large cooling.

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