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Anni Määttä et al.

Previous CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ condensation parameterization. The simulations are compared to the published CO₂ ice cloud observations.

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 new CO₂ 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 lognormal form for the distribution and its evolution is described through the integral properties (moments) of the distribution.

We have performed three simulations, one with the previous, simple parametrization of CO₂ condensation, one with the new CO₂ 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+H₂O/CN. 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 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.

The model produces CO₂ ice clouds in the polar regions in the troposphere during the winter and in the mesosphere at equatorial altitudes. Figure 1 shows the CO₂ ice column density as a function of latitude and solar longitude for the two simulations: MPCO₂ and MPCO₂+H₂O/CN with observations from several instruments [Clancy et al., 2007, Montmessin et al., 2006, Määttä 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 CO₂ 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 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. 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.

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Discussion

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