A Comparison of Mars GCM Carbon Dioxide Cloud Simulations with Observations

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Introduction:

During the polar night in both hemispheres of Mars, regions of low thermal emission, frequently referred to as "cold spots", have been observed by Mariner 9, Viking and Mars Global Surveyor (MGS) spacecraft. These cold spots vary in time and appear to be associated with topographic features suggesting that they are the result of a spectral-emission effect due to surface accumulation of fine-grained frost or snow. Presented here are simulations of the Martian polar night using the NASA Ames General Circulation Cloud Model. This cloud model incorporates all the microphysical processes of carbon dioxide cloud formation, including nucleation, condensation and sedimentation and is coupled to a surface frost scheme that includes both direct surface condensation and precipitation.

Using this cloud model we simulate the Mars polar nights and compare model results to observations from the Thermal Emission Spectrometer (TES) and the Mars Orbiter Laser Altimeter (MOLA). Model predictions of "cold spots" compare well with TES observations of low emissivity regions, both spatially and as a function of season. The model predicted frequency of CO_2 cloud formation also agrees well with MOLA observations of polar night cloud echoes. Together the simulations and observations in the North indicate a distinct shift in atmospheric state centered about Ls 270 which we believe may be associated with the strength of the polar vortex.

Model Description:

In this work we introduce a new microphysical cloud model that has been coupled to the Ames Mars general circulation model (GCM). This cloud model, based on the Community Aerosol and Radiation Model for Atmospheres (CARMA), includes all the processes of cloud microphysics including nucleation, condensation and sedimentation. Both dust and carbon dioxide cloud particles are transported within the GCM forming a coupled cloud climate model that can be used to more accurately simulate the formation of CO_2 clouds within the Martian atmosphere. This GCM cloud model provides a platform from which to address many of the existing question regarding carbon dioxide clouds formation and their role in the Martian climate.

The NASA Ames General Circulation Model is described in Haberle et al. (1999) and the references contained therein. The model is based on finite difference solutions to the primitive equations cast in spherical-sigma coordinates. A significant difference between the model used here and that described in Haberle et al. (1999) is a new dynamical core that allows the inclusion of atmospheric tracers. This version of the model has 17 vertical layers that monotonically increase in width from the surface to approximately 0.067 mbar (~ 45 km). The horizontal resolution is 4^o latitude and 5^o longitude.

Within the model radiative heating from CO_2 gas and suspended dust are accounted for in both solar and infrared wavelengths. The full diurnal cycle is modeled with a 10-layer soil conduction scheme and a modified "level-2" boundary layer scheme. Surface properties including albedo and thermal inertia are based on the Consortium data set.

Two additions are included in this version of the Ames GCM. The first is an active atmospheric dust scheme that varies spatially and temporally. The second is a carbon dioxide microphysical cloud model. Each model addition is described below.

Carbon Dioxide Clouds:

The microphysical processes of nucleation, condensation and sedimentation dictate the nature and location of the cloud particles. These processes can depend strongly on microphysical properties, such as the contact parameter and critical supersaturation. Each microphysical process is briefly described below as it pertains to CO_2 cloud formation in the current Martian atmosphere.

Nucleation The process of nucleation describes the initial formation of a crystal from clusters of molecules (homogenous nucleation) or on a dust grain or similar substrate (heterogeneous nucleation). The homogenous nucleation of most vapors requires very high levels of saturation (> 400 %). Therefore, only heterogeneous nucleation is considered in these simulations. Heterogeneous nucleation is highly selective for particles size and depends strongly on the contact parameter m and the supersaturation $S = s-1$, where the saturation, s, is the ratio of the partial pressure of CO_2 vapor to the vapor pressure of CO_2 ice. The contact parameter is a measure of the variance in interfacial energies between a molecule and substrate and may be calculated from the ratio of the surface free energies. In a physical sense the contact parameter may be thought of as the amount of contact between the dust grain and the vapor. In general, for a given radius and contact angle, as the supersaturation increases, the free energy of germ formation decreases and the nucleation rate increases quickly. The supersaturation at which the nucleation rate is equal to 1 s^{-1} is defined as the "critical supersaturation" and has been measured by Glandorf et al. (2002) to be approximately 0.35 for nucleation of CO_2 ice onto water coated silicon. Glandorf et al. (2002) also measured the contact parameter for CO_2 ice nucleation and estimated it to be $m = 0.95$. These values are used throughout this work. Because of its strong dependence on the supersaturation and nuclei size, nucleation ultimately limits the number of particles and the size of the particles that can form within a carbon dioxide cloud.

Condensation Once a particle is nucleated condensation can occur. The rate of mass and heat transfer between the particle and its environment determines the rate of growth of the cloud particle. The maximum rate of growth can be limited by the rate of mass transfer to the particle, the rate of heat conduction away from the particle, or surface kinetic effects. Since for CO_2 clouds the condensing species is the primary atmospheric constituent, diffusion to the particle of the condensing gas through an inert gas does not limit the rate of mass transfer. At high growth rates the rate at which heat is conducted away from the particle is less than the rate at which the particle or its immediate environment is warmed by released latent heat. Immediately after nucleation, when supersaturations are greatest (~ 35%), the limited conduction of heat can greatly reduce the growth rate of the cloud particle. The limitation of growth due to surface kinetics does not appear to be significant under current Martian conditions (Colaprete et al., 2002, Glandorf et al., 2002). Due to the availability of mass, CO_2 cloud particles grow to large sizes with average particle radii greater than 100 ?m and maximum sizes greater than 500 ?m.

Sedimentation Cloud particle fall velocities are calculated from the Stokes-Cunningham equation for terminal velocity modified for particle shape. In the simulation presented here dust grains are assumed to be flat plates and cloud particles are assumed to be spherical. As cloud particles fall they are able to evaporate or grow. Cloud particles that precipitate to the surface are removed from the atmosphere and added to the surface inventory of CO_2 ice. Dust nuclei within any cloud particles that precipitate to the surface are also removed from the atmosphere and added to the surface dust budget.

In general particle concentrations are small ($C_{dust} < 50$ cm^3 and $C_{cloud} < 10$ cm^3), therefore, coagulation of dust and cloud particles is are neglected in the simulations presented here.

Surface CO_2 Ice:

Two sources of surface carbon dioxide ice are treated in the model. The first source is the direct condensation to the surface. The second source of surface ice is from precipitation of cloud particles to the surface. Direct condensation is calculated by assuming the surface temperature is in equilibrium with the net all-wave radiation, subsurface heat flux and latent heat release from CO_2 condensation. When surface temperatures cool below the saturation temperature of CO_2, the appropriate amount of CO_2 vapor is condensed to the surface to return the surface temperature to the saturation temperature. The net radiative balance of the surface depends on the surface albedo and emissivity. The emissivity of surface ice that has condensed directly to the surface can be very different from that which resulted from cloud precipitation. The relatively small particles (< 0.1 mm) associated with clouds can efficiently scatter infrared wavelengths leading to lower emissivities than for a surface ice composed of larger grain sizes (~ 1 mm). The effect CO_2 clouds have on surface ice emissivity is included in the model much the same was as in Forget (1996), with some differences with regards to the effect of precipitation.

Ice that condenses directly to the surface is assumed to have an emissivity of ? = 0.95. This "slab ice" emissivity can be reduced by either the presence of clouds or precipitation to the surface. The two are separated in this model because of instances when a cloud may be present but no precipitation to the surface is occurring. Surface precipitation can create a lasting decrease in the surface emissivity by depositing small grains. Decrease associated with cloud cover is only effective while the cloud is present. Once the cloud has dissipated and any surface precipitation has ended the fine grain precipitates either grow or are blown away and the emissivity returns to the initial "slab ice". The exact mechanism that returns the emissivity back to slab ice values is not modeled, but rather this transition is fixed to occur over a fixed length of time.

The linear approximation used here for the effective emissivity of a CO_2 cloud is

$$\varepsilon = (1 + \alpha\tau)^{-1/3}$$

where α is a constant with a value between 0.15 and 1.5 and τ is the cloud infrared optical depth (Forget et al., 1997). The constant ? is chosen to fit radiative transfer results for a given particle size and cloud optical depth. The CO_2 clouds that form in the simulations presented here have particles sizes that range from 50 to 500 ?m and typical optical depths of $\tau = 5$ in the infrared. Based on these characteristics a value of $\alpha = 0.3$ has been chosen and used throughout. Surface precipitation results in a decrease in the surface emissivity that depends on grain size and shape and quantity of precipitate. In the simulations presented here all surface grains are assumed to be spherical. The change in emissivity resulting from the accumulation of snow can be related to the snow depth with the linear relation

$$\delta\varepsilon/\delta t = P/(\rho C)$$

where P is the surface precipitation rate, ? is the snow density and C is the ratio of fine to coarse grain CO_2 emissivity in the infrared. The emissivity for 100 ?m spherical CO_2 grains is approximately a factor of 3 lower than that for 2 mm spherical grains (Titus et al., 2001).

Atmospheric Dust:

The formation of clouds is very sensitive to the availability of nucleation sites, assumed in these simulations to be water coated dust grains (Glandorf et al., 2002). Therefore, a time and spatial dependent treatment of the atmospheric dust distribution is required. This dust scheme solves for the concentration of atmospheric dust from considerations of dynamical, microphysical and surface lifting processes.

Dust is lifted from the surface when the surface winds exceed a critical threshold friction velocity. This threshold friction velocity depends on the surface roughness and atmospheric surface density. Since the Martian atmospheric surface density can change by nearly an order of magnitude it is desirable to express the lifting in terms of surface stress. This insures that equal lifting rates are calculated for a given surface stress regardless of topography (Murphy, 1999).

The lifting flux associated with surface stresses only considers the large-scale circulation and neglects smaller effects such as dust lifted by dust devils and sub-grid convection. To account for sub-grid effects a small constant dust flux is assumed to occur everywhere at all times. By varying this background flux the overall atmospheric dust loading can be changed. In the standard run presented here this background flux is 1.5 x 10^{-8} kg m^{-2} s^{-1}. In both cases the lifted dust is distributed by mass over a log-normal distribution of dust particle sizes with a modal radius of r_o = 0.8 ?m and standard deviation of ?= 1.8. When surface water or CO_2 ice is present it is assumed that no dust is lifted from the surface regardless of surface stress.