CO_2 Clouds, CAPE and Convection on Mars: Observations and General Circulation Modeling A. Colaprete[1], Jeffrey R. Barnes[2], R. M. Haberle[1], and F. Montmessin[3], [1]NASA Ames Research Center (NASA Ames Research Center, Moffett Field, MS 245-3, Mountain View,CA 94035),[2]College of Oceanic and Atmospheric Sciences, Oregon State University, [3]Laboratoire de Meteorologie Dynamique, Institut Pierre Simon Laplace, Paris, France.

Introduction: The Thermal Emission Spectrometer and the Radio Science experiment flying on board the Mars Global Surveyor (MGS) spacecraft have made observations of atmospheric temperatures below the saturation temperature of CO_2. This supersaturated air provides a source of convective available potential energy (CAPE), which, when realized may result in vigorous convective mixing. To this point, most Mars atmospheric models have assumed vertical mixing only when the dry adiabatic lapse rate is exceeded. Mixing associated with the formation of CO_2 clouds could have a profound effect on the vertical structure of the polar night, altering the distribution of temperature, aerosols, and gasses.

Presented in this work are estimates of the total planetary inventory of CAPE and the potential convective energy flux (PCEF) derived from radio science (RS) and Thermal Emission Spectrometer (TES) temperature profiles. A new Mars Global Circulation Model (MGCM) CO_2 cloud model is developed to better understand the distribution of observed CAPE and its potential effect on Martian polar dynamics and heat exchange, as well as effects on the climate as a whole. The new CO_2 cloud model takes into account the necessary cloud microphysics that allow for supersaturation to occur and includes a parameterization for CO2 cloud convection. Its is found that when CO_2 cloud convective mixing is included, model results are in much better agreement with the observations of the total integrated CAPE as well as total column non-condensable gas concentrations presented by Sprague et al. (2005). When the radiative effects of water ice clouds are included the agreement is further improved.

CAPE and PCEF: The convective available potential energy is a commonly used concept in terrestrial meteorology. CAPE is the measure of the potential air parcel buoyancy associated with warming which results from condensation and latent heat release. Water vapor is a minor component of the terrestrial and martian atmospheres and, thus, condensation is typically limited by the rate of vapor diffusion or the total availability of the condensing vapor itself. However, for the case of martian CO_2, the dominant atmospheric species is condensing and growth is not limited by diffusion or the availability of vapor, but rather limited by the rate at which latent heat can be removed from the system. This difference is important when considering the potential for latent heat driven convection.

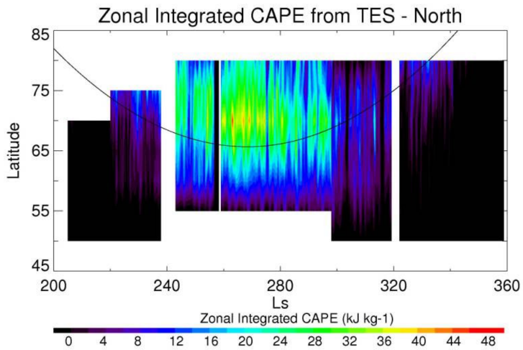
Colaprete et al. (2003) introduced the concept of CAPE as it pertains to CO_2 condensation and the possibility of CO_2 convection on Mars. Within the polar night, because of latent heating from condensing atmospheric CO_2, lapse rates generally follow the saturation temperature of CO_2. Under these conditions the atmosphere is absolutely stable. However, in some instances it is possible for temperatures to cool below the saturation temperature of CO_2. Under these conditions the atmosphere becomes unstable; a supersaturated air parcel has the potential of condensing, releasing latent heat, becoming warmer than its surroundings, and thus becoming buoyant. This potential instability is different from any terrestrial instability. Terrestrial convection is frequently limited by the availability of condensing water vapor. In contrast, on Mars, CO_2 convection is uninhibited and would be limited only by the detrainment of warm air out of the parcel or by the presence of wind shear.

To compare with other energy sources within the atmosphere, available CAPE can be recast as a potential convective energy flux (PCEF). The PCEF of a parcel, which has units of W m^{-2}, is the vertical energy flux released if all available CAPE is realized:

$$PCEF = \frac{1}{\tau_{conv}} \int_{z_1}^{z_2} g \frac{(T_p - T_e)}{T_e} m_{sat} dz \qquad (1)$$

In Eq. 1, m_{sat} is the mass of saturated air in the interval dz and tconv is the characteristic time of CAPE release. On earth, a typical thunderstorm will release 1000 J kg^{-1} in less than an hour. Thus a terrestrial thunderstorm, 25 km in diameter with a typical total condensed water vapor mass equal to 5 x 10^8 kg, can have a PCEF as large as 10 kW m^{-2}.

Observation of Martian CAPE: The RS and TES experiments provide two distinct measurements of Martian temperatures. For the purpose of locating and measuring regions of CAPE, each measurement has its strengths and weaknesses. On the strong side, RS measurements have higher vertical resolutions than TES and are not limited by surface-atmosphere temperature contrasts. On the weak side, RS spatial and seasonal coverage is extremely limited. TES observations have the strength of excellent seasonal and spatial coverage, but have signal-to-noise limitations when observing the cold, nearly isothermal temperatures of the polar night. Furthermore, IR scattering by water and CO_2 clouds may affect TES temperature retrievals.



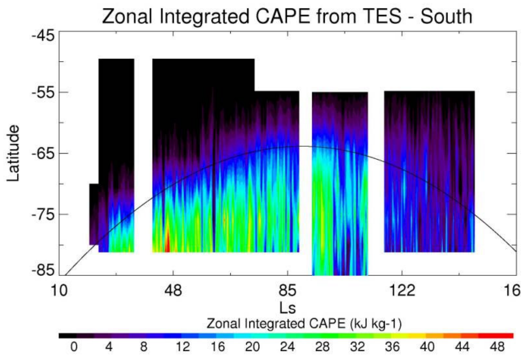


Figure 1. The Northern (left) and Southern (right) hemisphere zonal integrated CAPE in temperature profiles retrieved from TES observations.

The zonally averaged, integrated column TES CAPE for the North and South winter seasons is shown in Figure 1. CAPE in the TES profiles is present at all times during the polar winter season and at latitudes as much as 10 degrees equatorward of the polar night terminator. In the North the greatest amount of CAPE appears to follow along the polar night terminator and the CO_2 cap boundary. There are significant differences in the structure and amount of saturation between the Northern and Southern polar winters. In the South the presence of strong traveling waves is not as apparent as in the North and the saturation is much more confined to lower altitudes and longer lasting when compared to the north.

A Carbon Dioxide Cloud Model for the GCM: Carbon dioxide cloud schemes in MGCMs, if present at all, tend to be very simple. The reason for this is in part due to the limited number of observations, the lack of laboratory measurements and the computational expense associated with doing complex microphysics. However, another reason for the use of overly simple CO_2 cloud schemes is the prevailing view that condensation processes within the polar night are easily represented with bulk thermo-dynamical considerations. The previous CO_2 cloud scheme in the NASA Ames MGCM assumed that when temperatures fell below the saturation temperature of CO_2 the necessary amount of atmospheric mass needed to return to the saturation temperature, through the release of latent heat, condenses and is instantly precipitated to the surface. Simulations using this approach estimated that anywhere between 10% and 90% of the annual CO_2 condensation might occur in the atmosphere, depending on the amount of atmospheric dust present (Pollack et al., 1990).

Forget et al. (1997) incorporated a parameterized "snowfall" routine into a MGCM to explore the effects of large-scale topography on CO_2 cloud formation. Here the amount of mass condensed was still calculated from the difference in atmospheric and saturation temperature and occurred "instantaneously" within a single time step. However, rather than all of the condensed cloud mass being instantaneously precipitated to the surface, cloud mass was allowed to sublime (or condense) as it fell through warmer (or colder) levels of atmosphere on its way to the surface. No horizon-tal advection was allowed, however, and the sedimentation to the surface occurred entirely over a single model time step.

Neither of these MGCM CO_2 cloud schemes allows for supersaturation and the presence of CAPE. If the supersaturation observed is the result of microphysical barriers then a new atmospheric condensation scheme that more accurately represents CO_2 cloud microphysical processes may be required. A new CO_2 cloud model that incorporates CO_2 microphysical cloud processes, the effects of non-condensable gasses (e.g. Argon and N_2), and a CO_2 cloud convection parameterization has been incorporated into the NASA Ames MGCM. The NASA Ames MGCM, described in Haberle et al. (1999) and the references contained therein, is based on finite difference solutions to the primi-tive equations cast in spherical-sigma coordinates. This version of the model has 24 vertical layers that monotoni-cally increase in width from the surface to approximately 0.0025 mbar (~80km). The horizontal resolution is 5o lati-tude and 6o longitude. Within the model, radiative heating from CO_2 gas and suspended dust are accounted for in both solar and infrared wavelengths. The radiative effect of CO_2 clouds is not accounted for. The full diurnal and seasonal thermal cycles are modeled with a 20-layer soil conduction scheme and a modified "level-2" Mellor-Yamada boundary layer parameterization.

Model Performance: Figures 2 shows the total PCEF derived from TES observations versus two MGCM simulations: no CO_2 convection (Fig. 2, top) and with CO2 convection (Fig. 2, bottom). The atmospheric dust distribution derived from TES observations has, in general, low levels of dust within the polar nights (Pearl et al., 2001). The low concentration of dust has a strong effect on the total atmospheric cooling (Pollack et al., 1990) and, hence, the formation of supersaturation and CO2 clouds. It was found that in

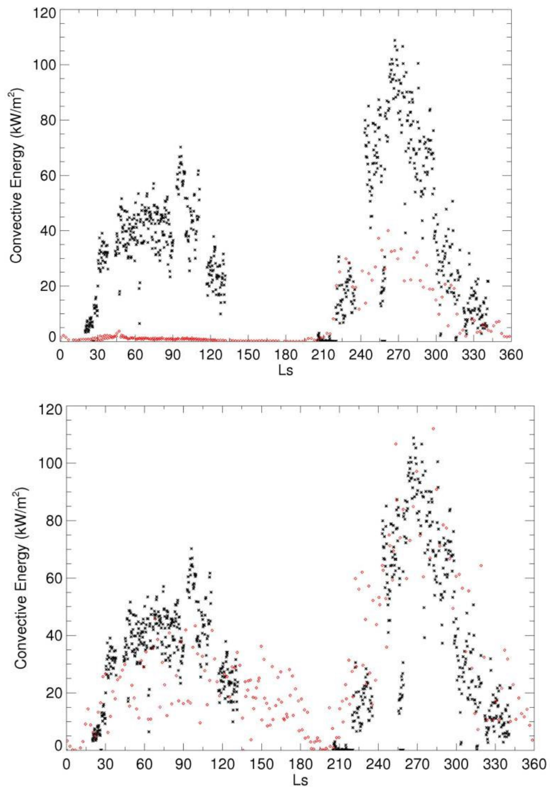


Figure 2. The total Potential Convective Energy Flux in temperature profiles retrieved from TES observations (black stars) and predicted from the MGCM when CO_2 cloud convection is not included (red diamonds) (top) and when CO_2 convection is included (bottom).

simulations in which the effects of convection associated with non-condensable enrichment and CO_2 clouds were neglected, atmospheric temperatures during southern winter were on average warmer than the saturation temperature of CO_2. In these simulations very small amounts of CAPE were achieved and few CO_2 clouds formed (Fig. 2, top), inconsistent with the observations of temperature presented here and with the observation of MOLA cloud echoes which have attributed to CO_2 clouds (Nuemann et al., 2003; Colaprete et al., 2003). If atmospheric convection associated with CO_2 clouds is allowed, a much better agreement is achieved between the observed and simulated total PCEF (Fig. 2, bottom). However, even with CO_2 convection, simulated PCEF in the south is still about 20% lower than the observations. One possible additional source of atmospheric cooling is the IR cooling from water ice clouds.

Water ice clouds are excellent emitters in the IR and can result in substantial local cooling. Furthermore, both observations (e.g., Bell et al., 1996) and simulations (e.g., Richardson et al., 2002) suggest that large portions of the polar hoods are composed of water ice and occur in the same locations and seasons as the regions of supersaturations described here. To assess the relative importance of water ice clouds on the total inventory of CAPE, a simulation was conducted with the radiative effects of water ice clouds included. An approximate IR emissivity of the water ice clouds was calculated assuming a fixed effective (area weighted) particle size of 5 microns and the model predicted total cloud mass. This emissivity was added to the atmospheric IR emissivity. For simplicity, and since the area and time of interest is primarily in the polar night, no solar effects were included. While this method is simple, it is sufficient to test the effects of the water ice clouds in or near the polar night on the total production of PCEF. The water ice clouds increase the total production of CAPE and result in a better match to the observations of total PCEF. Furthermore, including the radiative effect of water ice clouds provided better agreement in terms of the latitudinal distribution of CAPE.

Modeled CO_2 Cloud Properties: There are a variety of properties or effects of interest that can be explored with the CO_2 cloud model presented here. Some properties relate directly to the clouds, including particle number and size, and spatial and temporal distribution. Others relate to climate processes, including surface precipitation, cloud optical depth, and modification of the thermal state of the atmosphere.

In general there is approximately twice as much cloud mass in the North compared to the south. The higher cloud mass in the North is primarily due to the higher surface pressures (atmospheric mass) in the North. The majority of CO_2 clouds form within or near the polar night. However, there are a number of tropical CO_2 clouds that form in the simulations. These tropical CO_2 clouds have their highest concentrations centered about equinox.

The height at which clouds form within the polar nights varies with season. During the Fall and Spring, polar clouds tend to form nearer to the surface, within the first scale height of the atmosphere. In the middle of the winter the altitude at which polar clouds form increases gradually until it reaches a maximum height shortly after winter solstice. Most tropical CO_2 clouds form at altitudes greater than 65 km.

The CO_2 cloud particle size varies greatly with location and season (Figure 3). In the polar night mean cloud particle sizes are typically around 100 mm in radius, however, there is considerable variability in both time and space. Locations or periods of larger particle sizes are usually associated with increased baroclynic activity along the boundary of the ice cap. In general the North polar cloud particles are about 25% larger than south polar clouds. This difference is in part due to the extra atmospheric mass found in the north; however, greater temperature variance associated with stronger baroclinic activity in the north also plays a role. In the north the largest particles occur during the growth and recession of

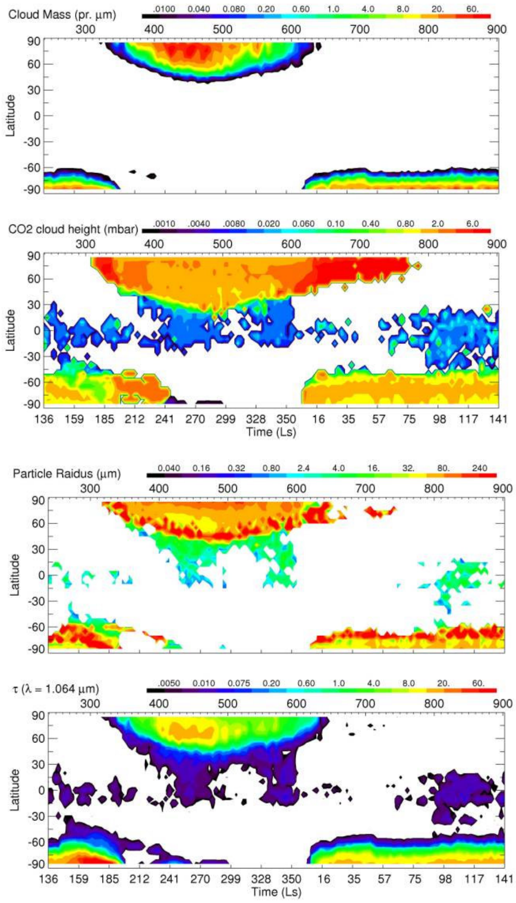


Figure 3. The zonal average CO_2 cloud average (area weighted) particle radius (top panel) and total column optical depth at $\lambda = 1.064$ µm (bottom panel) for the simulation in which CO_2 cloud convection and water ice cloud emissivity is included.

the ice cap. In both hemispheres, a band of CO_2 clouds follows the edge of the receding cap late into spring. In the south, poleward of this band the atmosphere is relatively clear of CO_2 clouds, making it very distinct.

Summary: Traditional Mars GCM's assume total, instantaneous conversion of any CO_2 supersaturation to latent heat. This basic assumption is inconsistent with observations and has several consequences. The first consequence is an over estimate the amount of heating that occurs in the polar night. Supersaturated air does not necessarily result in condensation, and that which does, can do so at rates very different form "instantaneous". While it is estimated from the simulations preformed here that as much as 90% of the supersaturated air does condensed, at any given time the formation of supersaturated air has the potential to increase thermal gradients and, hence, modify the circulation and overall energy balance of the atmosphere.

A second consequence is the potential for convection. The traditional MGCM assumption results in a polar night atmosphere that is never colder than the saturation temperature of CO_2, thus, the atmosphere is always stable with respect to convection. Supersaturation necessarily results in the potential for convection. Thus, the actual polar night may not be stable at all, but rather frequented by convective CO_2 cloud towers. Polar night CO_2 convection has important consequences for the polar energy budget, mixing of gasses, aerosols and temperatures, and hence dynamics and climate.

When low (τ_{vis}<0.1) polar dust optical depths, consistent with TES observations, and no CO_2 convection is included, model polar night atmospheric temperatures are much warmer than those observed by TES and RS. With a CO_2 convection scheme included, the model is able to better reproduce the observed amounts and distribution of CAPE and PCEF. Agreement is further improved when the radiative effects of water ice clouds are included. Adding convection into the polar night also appears to improve the agreement between the simulations and observations of the distribution of non-condensable gases such as argon.

Cloud properties predicted by the model test well against observations. In particular, the high altitude, mesospheric clouds seen in recent TES and SPICAM data are reasonably reproduce by the model. In the tropics, the formation of these mesospheric clouds in the model are clearly tied to the underlying large scale topography and are likely the product of gravity waves. During the spring time recession of the polar caps, the model predicts an abundance of CO_2 clouds forming along the cap boundary. These cap boundary clouds are at relatively low altitudes, are at times and locations optically thick, and can result in significant precipitation. In the simulations, late springtime, low-level clouds were observed. For example, near surface CO_2 fogs were predicted to form during the night at high northerly latitudes (>45°) as late as Ls 90. The presence of these non-seasonal clouds may be testable against MOLA observations.

References: Sprague et al., 36th LPSC abstract #2085, 2005; Colaprete et al., JGR 108, 2003; Pollack et al., 1990; Forget et al., Icarus 131, 1998; Haberle et al., JGR, 104, 1999; Pearl et al., JGR 106, 2001; Nuemann et al., JGR, 108 2003; Bell et al., JGR 101, 1996; Richardson et al., JGR 107, 2002.