Planetary and Space Science 97 (2014) 65–84

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Differentiability and retrievability of CO_2 and H_2O clouds on Mars from MRO/MCS measurements: A radiative-transfer study

J. Hurley [a,b,*], N.A. Teanby [c], P.G.J. Irwin [b], S.B. Calcutt [b], E. Sefton-Nash [d]

[a] STFC Rutherford Appleton Laboratory, Harwell Science and Innovation Campus, Didcot OX11 0QX, UK
[b] Atmospheric, Oceanic & Planetary Physics, Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, UK
[c] School of Earth Sciences, University of Bristol, Queen's Road BS8 1RJ, UK
[d] School of Earth and Space Sciences, University of California, Los Angeles, 595 Charles Young Drive East, CA 90095-1567, USA

ARTICLE INFO

Article history:
Received 14 January 2014
Received in revised form
5 March 2014
Accepted 14 March 2014
Available online 31 March 2014

Keywords:
Mars
Atmospheres
Clouds
Infrared
MRO/MCS
CO_2

ABSTRACT

Since the 1970s, it has been predicted that both CO_2 and H_2O clouds can form in the Martian atmosphere, and many remote-sounding instruments have directly observed layers of extinction asserted to be clouds composed of either CO_2 or H_2O ice on Mars. The Mars Climate Sounder, onboard the Mars Reconnaissance Orbiter (MRO/MCS), entered orbit around Mars in 2006, and has been providing near-continuous coverage of the full planet since, at wavelengths from visible through to the mid-infrared, primarily in limb-viewing geometry, making it a suitable candidate to study the parameters of these clouds.

In this work, the multiple scattering radiative-transfer tool `NemesisMCS` has been used to create a large dataset of simulations of CO_2 and H_2O clouds on Mars as would be measured by MRO/MCS, using a range of atmospheric conditions as well as cloud parameters derived from literature suitable for upper atmospheric clouds, and building specifically on the work of Sefton-Nash et al. (2013). This ensemble of simulations has been used to characterise the spectral signature of plausible CO_2 and H_2O clouds, as well as to assess the suitability of MRO/MCS to observe, to differentiate between, and to derive properties of such clouds.

It has been found, given the noise levels expected for MRO/MCS and the range of atmospheric and cloud parameters sampled in this study, that radiance signals introduced by upper atmospheric clouds having nadir optical depths greater than about 10^{-5} should be distinguishable, with $S/N \geq 1$. This corresponds to specific concentrations greater than about 10^5 particles/g, particle radii greater than around 0.5 μm, and cloud depths greater than about 2 km.

MRO/MCS measurements should be able to be used with confidence to differentiate between upper atmospheric cloud and dust in the lower atmosphere, and clear conditions, with high success ($\approx 100\%$). Lower reliability classification is accomplished for CO_2 clouds, with only 60% being correctly identified as CO_2, and the remainder classified instead as H_2O cloud, in the case of optical depths in the expected range for upper atmospheric cloudswhich are detectable by MRO/MCS, although this result is highly dependent upon the sampled selection of optically thin and thick clouds and the atmospheric model employed. Although almost all the H_2O clouds are correctly identified, the fact that such a large proportion of CO_2 clouds are misclassified as H_2O clouds shows that the spectral information alone from MRO/MCS is insufficient to differentiate between CO_2 and H_2O clouds when optically thin—but detectable—clouds are included in the analysis.

Using a simple look-up table (LUT) scheme and simulated data, retrieval of properties of upper atmospheric clouds of sufficient opacity is possible, with preliminary estimates indicating that H_2O cloud and dust parameters can be correctly reproduced between 48% and 100% of the time, and between 18% and 92% of the time for CO_2 cloud test cases, although it must be noted that these values must be taken as a qualitative measure which does not capture the full range of atmospheric and cloud conditions on Mars which would be present in real MRO/MCS data. Furthermore, because of the optical properties of

---

[*] Corresponding author at: STFC Rutherford Appleton Laboratory, Harwell Science and Innovation Campus, Didcot OX11 0QX, UK. Tel.: +44 1865 272895; fax: +44 1865 272923.
E-mail address: jane.hurley@stfc.ac.uk (J. Hurley).

http://dx.doi.org/10.1016/j.pss.2014.03.015

H_2O and CO_2, on a like-with-like selection, the H_2O clouds always produce greater perturbations in radiance, thus biasing results to a higher success rate for H_2O cloud retrievals. Application of the method to MRO/MCS data with a full-optimal estimation retrieval tool such as `NemesisMCS` will be the topic of a future study.

1. Introduction

1.1. Observation of clouds on Mars

As early as the 1970s and 1980s, Mariner 6 and 7 (Herr and Pimentel, 1970) and Viking (Seiff and Kirk, 1977) missions, as well as laser emission (Deming et al., 1983; Johnson et al., 1976) and stellar occultation ground-based observations indicated that the Martian mesosphere experienced sufficiently cold temperatures to warrant condensation of atmospheric CO_2, and spur the formation of CO_2 ice clouds. Mars Pathfinder (Schofield et al., 1997) as well as ground-based microwave observations (Clancy and Sandor, 1998) concluded that the equatorial mesosphere was commonly colder than the condensation point of CO_2.

The Pathfinder camera observed ‘blue wave’ clouds at altitudes above 70 km (Smith et al., 1997) which were suggested to be composed of CO_2 ice (Clancy and Sandor, 1998). Mars Global Surveyor's Mars Orbital Camera imaged mesospheric clouds at visible frequencies from the limb whilst its Thermal Emission Spectrometer and Mars Orbiter Laser Altimeter onboard confirmed these detections, using infrared nadir measurements and laser altimetry respectively, between 1997 and 2006 (Mars Years 24 through 28, with Mars Year 1 starting at 11 April 1955)—these were asserted to occur between 60 and 80 km, with constituent particles of either H_2O- or CO_2-ice (Clancy et al., 2004, 2007), and with opacities varying between diffuse at the north pole to those having extinction of up to 300 km^{-1} at the south pole (Colaprete et al., 2003). Instruments on Mars Express, which entered orbit in 2003, corroborated these detections: the High Resolution Stereo Camera and the OMEGA Visible and Infrared Mineralogical Mapping Spectrometer imager (Maattanen et al., 2010; Montmessin et al., 2007; Scholten et al., 2010) both seeing mesospheric clouds in the 60–80 km range mainly during two periods before and after aphelion (L_s=330–60° and 90–135°), with 1–2 μm constituent particles of either H_2O or CO_2 ice. Mars Express' SPICAM Ultraviolet and Infrared Atmospheric Spectrometer made the first observations of CO_2 ice clouds: sub-visible (very optically thin in the visible wavelength range, but observable at nearby altitudes in the infrared) between 80 and 100 km altitude (Montmessin et al., 2006). It pointed to super-saturation of CO_2 in the southern winter sub-tropical latitudes, and further estimated the CO_2-ice cloud particle radius at 0.1 μm.

It is now widely accepted that the atmospheric CO_2 on Mars condenses in winter polar regions to form CO_2 ice polar caps, as well as above approximately 50 km in the mesosphere in the low- and mid-latitudes, as temperatures near the polar surface and lower latitudinal mesosphere can drop below the CO_2 frost point. Due to the condensation, especially in the presence of cloud condensation nuclei such as dust aerosols, CO_2 ice clouds likely form there. More recently, Mars Odyssey's Thermal Emission Imaging System observed CO_2 clouds in the northern mid-latitudes during Martian northern autumn and winter (McConnochie et al., 2010). There has been concerted effort put into the development of global circulation models such as the Laboratoire de Meteorologie Dynamique du CNRS global circulation model (LMD-GCM, Lewis et al., 1999), and modelling studies conducted, such as Gonzalez-Galindo et al. (2011). These act to compare observational results with the distribution of modelled sub-CO_2-condensation temperatures. Generally, current literature acknowledges that there are three distinct CO_2 cloud regimes: northern-summer equatorial clouds, northern-winter-solstice mid-latitudinal clouds, and intense snow storms over the winter poles, although there is wide debate upon the formation mechanisms thereof. However, the total geographic and temporal distribution of clouds remains unconstrained due to limitations in data coverage.

Sefton-Nash et al. (2013) studied a comprehensive ensemble of MRO/MCS limb spectra, and detected frequent and widely spatially distributed mesospheric clouds. They used a simple line-of-sight scattering approach to model synthetic spectra, which was suggestive of cloud composition, but which was not conclusive when taken in isolation. Using this simple scattering model, they concluded that most of the detected mesospheric clouds were composed of H_2O ice, with some CO_2 ice clouds possible—but the evidence was indirect, and based on nearby temperatures, as well as the spectra themselves. Modelling the spectra of such optically thin clouds in a fully comprehensive manner is challenging, and requires consideration of the scattered radiation from the lower atmosphere and surface, in addition to the consideration of the MCS field-of-view responses. In this paper, the work of Sefton-Nash et al. (2013) is built upon, with a full radiative-transfer approach to modelling mesospheric cloud spectra, to determine if MCS data alone can be used to spectrally identify cloud composition, as well as to derive the physical properties of these clouds such as optical thickness, particle radius, and cloud top height. In the upper atmosphere, cloud particles are significantly smaller than those in the lower atmosphere, and the differentiability between H_2O and CO_2 clouds becomes more difficult as the particle radii decreases. Thus, in this paper, small cloud particles representative of upper atmospheric clouds are assessed.

1.2. MRO/MCS

Mars Climate Sounder (MCS) is a filter radiometer onboard NASA's Mars Reconnaissance Orbiter (MRO) which has been providing near-continuous coverage of Mars since it entered orbit in 2006. MRO is in a sun-fixed polar 255–320 km orbit, which allows for full pole-to-pole coverage of Mars, with an inclination of

Table 1
MCS' spectral channels, with noise (as Noise Equivalent Spectral Radiance NESR and Noise Equivalent delta Temperature NEdT) values assuming a 2 s integration time (Kleinbohl et al., 2009).

Focal plane	Channel #	Bandpass (cm^{-1})	NESR (nW cm^{-2} sr^{-1} cm)	NEdT at 120 K (K)
A	A1	595–615	5.57	0.49
	A2	615–645	3.99	0.40
	A3	635–665	4.19	0.47
	A4	820–870	2.87	1.14
	A5	400–500	2.78	0.12
	A6	3333–33 333	–	–
B	B1	290–340	4.53	0.16
	B2	220–260	5.68	0.23
	B3	231–243	17.4	0.70