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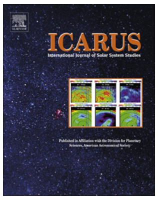

Variability of the martian seasonal CO_2 cap extent over eight Mars Years

Sylvain Piqueux [*], Armin Kleinböhl, Paul O. Hayne, David M. Kass, John T. Schofield, Daniel J. McCleese

Jet Propulsion Laboratory, California Institute of Technology, M/S 183-601, 4800 Oak Grove Drive, Pasadena, CA 91109, USA

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ABSTRACT

We present eight Mars Years of nearly continuous tracking of the CO_2 seasonal cap edges from Mars Year (MY) 24 to 31 using Mars Global Surveyor (MGS) Thermal Emission Spectrometer (TES) and Mars Reconnaissance Orbiter (MRO) Mars Climate Sounder (MCS) thermal infrared data. Spatial and temporal resolutions are 1 pixel per degree and $10°L_s$ (aerocentric longitude of the Sun). The seasonal caps are defined as the regions where the diurnal radiometric temperature variations at ~32 μm wavelength do not exceed 5 K. With this definition, terrains with small areal fraction of defrosted regolith able to experience measurable diurnal temperature cycles are not mapped as part of the cap. This technique is adequate to distinguish CO_2 from H_2O ices, and effective during the polar night or under low illumination conditions. The present analysis answers outstanding questions stemming from fragmented observations at visible wavelengths: (1) the previously sparsely documented growth of the North seasonal caps ($160° < L_s < 270°$) is shown to be repeatable within 1–2° equivalent latitude, and monotonic over the MY 24–31 time period; high repeatability is observed during the retreat of the caps in non-dusty years (~1° or less equivalent latitude); (2) the MY 25 storm does not seem to have impacted the growth rate, maximal extents, or recession rate of the North seasonal caps, whereas the MY 28 dust storm clearly sped up the recession of the cap (~2° smaller on average after the storm, during the recession, compared to other years); (3) during non-dusty years, the growth of the South seasonal cap ($350° < L_s < 100°$) presents noticeable variability (up to ~4° equivalent latitude near $L_s = 20°$) with a maximum extent reached near $L_s = 90°$; (4) the retreat of the Southern seasonal cap ($100° < L_s < 310°$) exhibits large inter-annual variability, especially near $190° < L_s < 220°$; (5) the recession of the MY 25 South seasonal cap is significantly accelerated during the equinox global dust storm, with surface temperatures suggesting increased patchiness or enhanced dust mantling on the CO_2 ice. These results suggest that atmospheric temperatures and dust loading are the primary source of variability in an otherwise remarkably repeatable cycle of seasonal cap growth and recession.

1. Introduction

The waxing and waning of the seasonal caps is one of the global processes associated with the CO_2 cycle on Mars. The seasonal caps condense from atmospheric CO_2 during fall and winter in response to the decrease of the solar heating, and gradually shrink during Spring and Summer. Since Leighton and Murray (1966) demonstrated that CO_2 ice should accumulate in the polar regions and was the main likely constituent of the seasonal caps, a large body of telescopic and robotic observations has been produced to confirm and refine our understanding of the relationship between the surface and atmospheric CO_2 reservoirs (see the review of observations and results by Benson and James (2005)). In addition, General Circulation Models (GCM) and regional thermal models have demonstrated that the polar energy budget – and therefore the global climate – is controlled by the optical properties (i.e. albedo and emissivity) of solid carbon dioxide (Toon et al., 1980; Pollack et al., 1990; Paige and Wood, 1992; Wood and Paige, 1992; Haberle et al., 2008; Schmidt et al., 2009), which in turn are determined by a number of environmental parameters (e.g. dust and water ice contamination [Kieffer, 1970; Warren and Wiscombe, 1980; Hansen, 1999; Langevin et al., 2007; Bonev et al., 2008], CO_2 crystal size [Hansen, 1997; Kieffer et al., 2000; Titus et al., 2001; Hayne et al., 2012], solar phase [Paige and Ingersoll, 1985; Wood and Paige, 1992; Cantor et al., 1998; James and Cantor, 2001], and regional atmospheric circulation [Colaprete and Toon, 2002; Colaprete et al., 2003, 2008; Schmidt et al., 2009]).

Of these parameters, atmospheric dust loading experiences the largest documented inter-annual variability (Smith, 2004, 2009) producing variations in cap albedo (Bonev et al., 2002) and modifying the regional distribution of energy. Atmospheric dust reduces direct solar energy flux to the ground (Hanel et al., 1972; Martin

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[*] Corresponding author. Fax: +1 818 354 2494.
E-mail address: Sylvain.Piqueux@jpl.nasa.gov (S. Piqueux).

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et al., 1979), but increases the temperature of the atmosphere and its thermal infrared flux toward the surface (Davies, 1979; Smith, 2004). For this reason, it has long been postulated that the general seasonal cap properties (i.e. growth and recession rates, maximum extent, general timing) should present some degree of inter-annual variability that a series of studies have attempted to characterize (Benson and James, 2005). Determining seasonal cap growth/recession rates is important because they are sensitive indicators of the regional and global environment, and strongly influences the global energy budget.

Outstanding questions stemming from prior studies of seasonal caps include:

- What is the extent of inter-annual variability during the cap growth? Earth-based telescopic observations of both the North and South waxing seasonal caps are virtually impossible because the Fall/Winter hemispheres are always tilted away from Earth during opposition, and cannot adequately be imaged. As a result, systematic observations of the Fall/Winter caps have only started with the Mars Global Surveyor (MGS) era, but are limited by poor illumination conditions.
- What are the effects of major dust storms on the dynamics of the North seasonal caps? Global dust storms occur most frequently during the period of growth/maximum extent of the North cap, when the historical records and visible orbital observations are sparse (Benson and James, 2005). As a result, the effect of global dust storms on the dynamics of the North seasonal cap is poorly documented.
- What are the effects of major dust storms on the dynamics of the South seasonal caps? Seemingly contradictory observations have been reported, at least at the regional scale, with accelerated recessions following major dust storms (Bonev et al., 2002; James et al., 2010) contrasting with reports of decreased recession rates (James et al., 1979, 1987; Titus and Kieffer, 2002). In addition, GCM results provide contradictory theoretical answers, with models predicting either a localized acceleration of sublimation (Bonev et al., 2002), no regional or global change (Hourdin et al., 1993; Kahre and Haberle, 2010), or cap-scale accelerated sublimation (Bonev et al., 2008), fueling a need for additional observations and data analysis.
- What is the cap variability during non-dusty years? Observations suggest the existence of seasons of great repeatability in the North, and periods of more frequent inter-annual variations (Iwasaki et al., 1979, 1982, 1999; James, 1979, 1982; Cantor et al., 1998; James and Cantor, 2001; Benson and James, 2005; Cantor et al., 2010; Appere et al., 2011), especially regarding an elusive pause in the North cap recession near $L_s = 20°$ (Iwasaki et al., 1979, 1982; James, 1979; James and Cantor, 2001). In the South, cap edge variability at spatial scale of 10s of km has been reported (James et al., 1979, 1996b, 2001, 2010; James and Lumme, 1982; Giuranna et al., 2007; Schmidt et al., 2009).

Based on the data available and previously analyzed, the small apparent inter-annual variability of CO_2 cap recession rates have lead investigators to explore various feedbacks with the atmosphere and the subsurface (Bonev et al., 2002, 2008; Haberle et al., 2008; Kahre and Haberle, 2010). However, quality data acquisition and interpretation has usually been impeded by the poor viewing conditions of the polar caps at visible wavelengths, due to (1) the unfavorable relative positions of the Earth, Mars and the Sun at opposition for telescopic observations during cap growth (Benson and James, 2005), (2) the poor illumination conditions during the polar Fall and Winter (James et al., 1979), (3) the limited contrast between the surface and clouds (Soderblom et al., 1973; James, 1979; James et al., 1979), (4) the difficulty in distinguishing seasonal CO_2 ice from a retreating annulus of H_2O ice (Kieffer and Titus, 2001; Bibring et al., 2005; Titus, 2005b; Wagstaff et al., 2008; Brown et al., 2010, 2012), and (5) the impossibility to observe surface features during extreme dust storms (Hartmann and Price, 1974).

To overcome these limitations, several studies have used radiometric surface temperature, determined at thermal infrared wavelengths, to map the edges of the caps (Kieffer, 1979; Christensen et al., 1998; Kieffer et al., 2000; Giuranna et al., 2007; McCleese et al., 2008), also dubbed CROCUS dates/lines in the literature (CROCUS stands for "Cap Recession Observations indicate CO_2 has Ultimately Sublimated", [Kieffer et al., 2000]). Thermal infrared observations present several advantages over visible/near infrared data: (1) thermal emission can be measured under all illumination conditions, allowing year round surveys of the polar regions, even during the polar night (Kieffer, 1979); (2) brightness temperatures are indicative of the dominating surface/subsurface material, and can therefore discriminate seasonal CO_2 ice from H_2O ice covering the warmer regolith, especially following the recession phase of the caps (Kieffer and Titus, 2001); and (3) spectral windows can be selected to observe the surface with minimal atmospheric interference and avoid confusion with clouds and surface obscuration by hazes and dust (Kieffer, 1979). Limitations associated with thermal infrared observations of the surface include: (1) lower spatial resolution (i.e., kilometers to many tens of meters, InfraRed Thermal Mapper (IRTM, [Kieffer, 1979]), Termoskan [Selivanov et al., 1989], Thermal Emission Spectrometer (TES, [Christensen et al., 2001]), Thermal Emission Imaging System (THEMIS, [Christensen et al., 2004])) than frequently achieved with visible wavelength instruments (i.e., 10s of meters to 10s of cm, Viking Orbiter Cameras [Carr et al., 1972], Mars Orbiter Camera (MOC, [Malin et al., 1992]), THEMIS [Christensen et al., 2004], High Resolution Science Experiment (HiRISE, [McEwen et al., 2007])), and (2) lower instantaneous spatial coverage, resulting in the need to bin many observations acquired over several sols to generate a regional map. These limitations have been shown to be unimportant given the spatial and temporal scales (i.e. regional and seasonal, respectively) of seasonal cap dynamics. However, in previous thermal infrared studies, only a fraction of the North and South seasonal cap growth and recession cycles were examined, and little to no inter-annual comparisons were discussed. The intention of this work is to fill this gap and produce an analysis of the long-term regional variability of the seasonal cap growth and retreat cycles using the wealth of thermal infrared observations of the polar surfaces acquired nearly continuously since 1999 ($L_s = 110°$) by TES and the Mars Climate Sounder (MCS).

For this study, the denomination of each Mars Year (MY) is chosen following the definition proposed by Clancy et al. (2000) and clarified by Piqueux et al. (submitted for publication), with each new MY starting at $L_s = 0°$, and MY 1 chosen to start on April 11th 1955. With this definition, the current work focuses on the cap edge dynamics from MY 24 to MY 31. Local times in hours are defined as the 1/24th fraction of a martian sol.

In the next section, we review the different definitions of cap edges found in the literature and further describe the one chosen for this work. We then present the datasets used and discuss the methods applied to facilitate the comparison between instruments and observations. Finally, we present and discuss the seasonal and inter-annual variability of the cap edges.

2. Methods

2.1. Cap edge definition

Several definitions of thermal cap edges have been proposed in the literature. Christensen et al. (1998) use cut-off TES brightness