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Orbital monitoring of martian surface changes

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ABSTRACT

A history of martian surface changes is documented by a sequence of global mosaics made up of Mars Global Surveyor Mars Orbiter Camera daily color images from 1999 to 2006, together with a single mosaic from the Mars Reconnaissance Orbiter Mars Color Imager in 2009. These observations show that changes in the global albedo patterns of Mars take place by a combination of dust storms and strong winds. Many of the observed surface changes took place along the tracks of seasonally repeating winter dust storms cataloged by Wang and Richardson (2015). These storms tend to sweep dust towards the equator, progressively shifting albedo boundaries and continuing surface changes that began before the arrival of MGS. The largest and most conspicuous changes took place during the global dust storm of 2001 (MY 25), which blanketed Syrtis Major, stripped dust from the Tharsis region, and injected dust into Solis Planum. High wind speeds but low wind stresses are predicted in Syrtis, Tharsis and Solis by the NASA Ames GCM. Frequent changes in these regions show that dust accumulations are quickly removed by stronger winds that are not predicted by the GCM, but may result from smaller-scale influences such as unresolved topography.

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1. Introduction

Changes in the appearance of Mars' surface have fascinated humans for centuries. Once thought to be due to vegetation, modern spacecraft have shown that the changes are caused by relentless redistribution of sand and dust by the martian winds. Major surface albedo changes took place during the decades between the Viking Orbiter mission and the arrival of Mars Global Surveyor (MGS) in 1998 (Geissler, 2005). The long interval between the observations made these changes difficult to interpret, because it was not known whether the surface changes took place abruptly or gradually. Beginning with MGS, Mars has been continuously monitored by a succession of orbiting spacecraft since 1999. The Mars Orbiter Camera (MOC) (Malin et al., 1991) on MGS produced a daily photographic record of the entire planet's surface until late 2006, documenting almost 4 complete martian years (Malin et al., 2010). MGS maintained a steady orbit over this period that provided consistent illumination and viewing conditions ideal for detecting surface changes. The frequent MOC observations allow us to examine the sequence of events that led to surface changes and better infer how the winds act upon the martian surface.

MOC was followed by the Mars Color Imager (MARCI) (Malin et al., 2001; Bell et al., 2009) on Mars Reconnaissance Orbiter (MRO), which began daily imaging in March 2006 and continues to operate at this writing. This report focuses on the MGS MOC observations and describes the construction and interpretation of a Mars "movie", a time series of global mosaics of Wide-Angle MOC images. A MARCI mosaic made after the 2007 global dust storm is also included in the analysis, but the history of martian surface changes detailed here is derived from the MOC observations. Many significant changes can be seen in these data. In the sections below, we point out specific examples grouped for discussion by the timescales of the changes. Progressive changes include moving albedo boundaries that advanced incrementally over a succession of martian years, continuing changes that began before MGS arrived. Episodic changes typically took place during dust storms that occurred in the perihelion season (within 65° Ls of Ls 251°). Quasi-continuous changes were observed in Tharsis and in the Solis Lacus region south of the Valles Marineris. High resolution images of these targets now available from the HiRISE camera on Mars Reconnaissance Orbiter (MRO) offer more insight into the nature and mechanisms of the surface changes. Here we document the various

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timescales of martian surface changes and suggest hypotheses for the eolian processes responsible.

2. Approach

2.1. Data processing

Over 4000 selected color image pairs from the MOC Wide Angle Camera (WAC) were processed into 43 separate mosaics for this project. These mosaics record snapshots of Mars at intervals of about two months (30° of solar longitude, Ls) from June 1999 to October 2006. Uneven coverage meant that the time steps were not always equal, but nearly so. Each mosaic is the average of approximately 100 individual red and blue filter image pairs spanning many days of observations (typically 10º of Ls, more if incomplete coverage), so that meteorological phenomena such as clouds and dust storms are blurred but surface features are emphasized.

The data were downloaded from the Planetary Data System and processed with the USGS ISIS 2 software using the approach described in Geissler (2005). The images were radiometrically calibrated and geometrically reprojected to a simple cylindrical map projection at a resolution of 10 pixels per degree. A Lunar-Lambert limb-darkening correction was applied with coefficients 0.6 for blue images and 0.75 for red. The images were cropped to show only regions viewed at incidence and emission angles less than 70° and phase angles greater than 15°. The images were averaged together and a procedure was applied to remove seams between images by adding a low-pass filtered version of the mosaic together with a mosaic of high-pass filtered versions of the individual frames (Soderblom et al., 1978). For display purposes, a green channel was synthesized by interpolating between the WAC red and blue images.

These procedures reduced but did not eliminate imperfections in the mosaics. Artifacts including seams and striping are visible along the orbit tracks, from top left to bottom right. However, the mosaics are sufficient for the task of tracking surface albedo changes; the artifacts are easily recognizable and do not interfere with the interpretation of surface features.

MRO MARCI data were processed using USGS ISIS 3 software on a cluster of 50 CPUs. The even and odd channels were calibrated separately and map projected before being mosaicked together. Values of the local incidence, emission, and phase angles for each pixel were calculated and stored by the program phocube. These values were used to apply a Lommel–Seeliger photometric correction to the images, weighted by the cosine of the incidence angle divided by the sum of the cosines of the incidence angle and the emission angle. The images were then cropped to restrict the longitude range to within 40° of the image center longitude, to restrict the emission angles to be less than 60°, and to restrict the difference in incidence and emission angles to be greater than 7.5° to remove opposition effects and specular reflection. The images were then averaged and seam-corrected as for the MOC images. These procedures are still experimental, and produce mosaics with more noticeable striping artifacts than the MOC mosaics.

MOC and MARCI imaged the surface using different filter sets. MOC's wide angle color filters were sensitive to wavelengths from 600 to 630 nm in red and from 420 to 450 nm in blue (Malin et al., 1992). MARCI visible images are acquired in 5 filters, two of which approximate the MOC coverage with sensitivities from 573 to 635 nm in red and from 405 to 469 nm in blue (Malin et al., 2001; Bell et al., 2009).

2.2. Data analysis

The time series of mosaics was then assembled to produce an animated sequence of images in which surface changes are easy to spot. A 1/3 scale gif animation of the MOC Mars movie is presented in the Supplementary materials as Supplementary Fig. 2 (along with the full resolution individual mosaics, named year-month-Ls). The gif animation was produced with the publicly available program gifsicle and has additional artifacts caused by color quantization, but all of the surface changes described below are easily visible in the animation.

To quantify the changes that took place from one martian year to the next, difference images were created by subtracting an earlier mosaic from a later mosaic taken at the same season (Ls 330°, when the southern hemisphere was clear and the equatorial volcanoes were free of clouds). We used the red filter mosaics for this purpose because they show much greater surface contrast than the blue filter mosaics. Areas that darkened during the interval appear darker in the difference images. This approach unfortunately emphasized seams and artifacts but helped minimize the effects of seasonal variations in cloud cover and surface frost. The magnitudes and areal extents of the albedo changes can be easily measured from the difference images. The average speed of advancing albedo boundaries was calculated from the width of the bands in the difference images divided by the time interval between observations.

The USGS ISIS program qview was used to make measurements automatically corrected for latitude. Potential sources of uncertainty include differences in viewing angle or conditions, meteorological impacts, and georeferencing errors. Photometric variations in illumination and viewing geometry were minimized by limiting the incidence, emission, and phase angles considered and by averaging together many images within these ranges. Meteorological changes were minimized by comparing images taken during the same season each year, at a time of year when no major dust storms happened to take place, however they are clearly present in places such as the Hellas Basin, as we discuss later. Georeferencing errors were absorbed by the process of averaging many images together, which resulted in blurry mosaics with little misregistration from one mosaic to the next. The major source of uncertainty in the measurement of the speed of advancing albedo boundaries is the variability of the boundary itself.

Individual surface changes were measured by subtracting the red filter image acquired before each change from the image acquired after the change in equal area cylindrical map projections. In most cases the interval between successive images was 30º Ls, but the timing uncertainty was sometimes longer during the perihelion season when the surface could not clearly be seen. The difference images were thresholded and then edited to remove differences caused by changes in contrast (due to changing atmospheric conditions and lighting) and differences caused by artifacts in the mosaics. The threshold was chosen as the highest value that included all the genuine surface changes, excluding artifacts to the extent possible, and was different for each scene. An example of a thresholded difference image is shown as Fig. 1. These thresholded difference images were then used to mask the difference image and isolate the regions involved in the change. The masked difference images were used to compute the area and mean magnitude of each change. The results of these measurements are listed in Table 1.

2.3. Comparison with simulated winds

The timing and direction of observed dust-removal events were compared to wind patterns expected in each region of interest, as simulated by the NASA Ames Global Climate Model (GCM), which has been used extensively to investigate Mars' climate (Haberle et al., 1999; Kahre et al., 2006). The model numerically represents the atmosphere as a set of points that forms a 3-dimensional grid around the surface of Mars, calculating and outputting atmospheric