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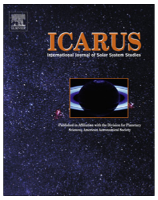

Mass balance of Mars' residual south polar cap from CTX images and other data

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ABSTRACT

Erosion of pits in the residual south polar cap (RSPC) of Mars concurrent with deposition and fluctuating cap boundaries raises questions about the mass balance and long term stability of the cap. Determining a mass balance by measurement of a net gain or loss of atmospheric CO_2 by direct pressure measurements (Haberle, R.M. et al. [2014]. Secular climate change on Mars: An update using one Mars year of MSL pressure data. American Geophysical Union (Fall). Abstract 3947), although perhaps the most direct method, has so far given ambiguous results. Estimating volume changes from imaging data faces challenges, and has previously been attempted only in isolated areas of the cap. In this study we use 6 m/pixel Context Imager (CTX) data from Mars year 31 to map all the morphologic units of the RSPC, expand the measurement record of pit erosion rates, and use high resolution images to place limits on vertical changes in the surface of the residual cap. We find the mass balance in Mars years 9–31 to be −6 to +4 km^3/♂y, or roughly −0.039% to +0.026% of the mean atmospheric CO_2 mass/♂y. The indeterminate sign results chiefly from uncertainty in the amounts of deposition or erosion on the upper surfaces of deposits (as opposed to scarp retreat). Erosion and net deposition in this period appear to be controlled by summertime planetary scale dust events, the largest occurring in MY 9, another, smaller one in MY 28. The rates of erosion and the deposition observed since MY 9 appear to be consistent with the types of deposits and erosional behavior found in most of the residual cap. However, small areas (<10%) of the cap are distinguished by their greater thickness, polygonal troughs, and embayed contacts with thinner units. These deposits may require extended periods (>100 ♂y) of depositional and/or erosional conditions different from those occurring in the period since MY 9, although these environmental differences could be subtle.

1. Introduction

The residual south polar cap of Mars is expected to be a sensitive recorder of martian climate, as it is usually viewed as being in approximate equilibrium with the atmosphere (Leighton and Murray, 1966; Byrne, 2009). Yet reading the history of climate in this expanse of dry ice has been difficult. The margins of the cap at the end of southern summer fluctuate, but the changes in area of ice over the period of spacecraft observation have been small (Piqueux and Christensen, 2008). Pit erosion (Malin et al., 2001) has continued at approximately the same rates during the period of spacecraft observation (Thomas et al., 2013). This consistent erosion has suggested the possibility of a secular loss of material from the cap (Malin et al., 2001; Haberle et al., 2009; Haberle and Kahre, 2010; Kahre and Haberle, 2010). Timescales for significant loss of ice cover due to pit erosion are calculated to be on the order of Mars decades to over 100 ♂y (Byrne and Ingersoll, 2003; Thomas et al., 2013).

Determining a mass balance of the residual cap could be done by tracking volume changes in the ice deposit or by detecting loss or gain of CO_2 in the atmosphere. Either approach, even in the most ideal of measurement scenarios, involves assumptions such as the density of the deposits for the first method, and possible regolith sinks or sources for CO_2 in the second. Measuring the atmospheric pressure with sufficient accuracy to detect the likely magnitude of changes is a challenging task (Haberle et al., 2009; Haberle and Kahre, 2010; Kahre and Haberle, 2010). Volume changes might ideally be measured by repeat laser altimetry, but the available record from MOLA is not of sufficient resolution to go beyond full seasonal

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cycle changes (Smith et al., 2001a,b). Imaging is very good for comparing areas of ice cover, and for tracking scarp retreat, but faces problems in measuring vertical changes. Even with those difficulties, it is worthwhile to see how well we can estimate the recent mass balance of the RSPC with images, at the very least to define limits on the mass balance that other methods might face.

In this study we first attempt an estimation of the current mass balance of the RSPC by mapping the different morphologic units and estimating the recent erosional and depositional rates for each unit. To investigate the mass balance of earlier periods, we then make a comprehensive census of all equidimensional and linear pits resulting in a map of the apparent erosional ages of the cap. We then combine data on recent deposition rates with unit thicknesses to map accumulation periods likely required to form different parts of the cap. These results are finally combined with the morphologic characteristics and embayment relationships to test if the current conditions can explain the morphologic history.

2. Data and methods

This study is based primarily on Context Imager data (CTX, Malin et al., 2007) in the form of map projected mosaics. These cover the entire RSPC in Mars years 28, 30, and 31, and part of the cap in MY 29 during southern summer (Generally L_s 310–350°). Other useful image data include those from Mariner 9 (Masursky et al., 1972; Levinthal et al., 1973), Viking (Klaasen et al., 1977), Mars Observer Camera (MOC) on Mars Global Surveyor (Malin et al., 1992), Mars Reconnaissance Orbiter (MRO) HiRISE (High Resolution Imaging Science Experiment, McEwen et al., 2007). The CTX maps are projected in polar stereographic projections at 6 m/pixel. Brightness values used are the approximate Lambert albedos. Mars year 32 data became available late in the preparation of this work; for consistency we base all quantitative work on the data through MY 31. Inspection of MY 32 data suggests that scarp retreat rates remain close to those of previous years. We do not attempt quantitative photometry, but rely on some comparisons of relative brightnesses to distinguish boundaries and make temporal comparisons. Other CTX data are similarly projected, but at larger pixel scales (typically projected to 50 m/pixel).

MOC and HiRISE comparisons have been made at 1.5 m/pixel; some HiRISE-only comparisons are at 0.25–0.50 m/pixel. Comparisons of MOC and HiRISE with CTX are generally at 6 m/pixel projections. In all these images the Sun is <30° above the horizon, and usually under 20°. Views are mostly within a degree of nadir, but areas poleward of 87°S require off-nadir pointing, generally <20°. Map projections use the MOLA 128 pix/deg binned data (Smith et al., 2001a,b), which are interpolated poleward of 87°S. Thus elevations poleward of 87°S are not used in quantitative comparisons. Features in different CTX images generally project within 100 m of each other, but in the more poleward areas these offsets can be larger, as the data are taken off-nadir on areas having only approximate topographic data. These mismatches in projection have no practical effects on mapping unit boundaries, pit statistics, or topographic comparisons.

Shadow measurements are used to find or to limit heights of scarps, ridges, and depths of troughs. These are made from MOC and HiRISE images with incidence angles generally between 70° and 80° and pixel scales of 0.25–1.5 m. While very high incidence angles can sometimes provide better measures of shadows of small features, atmospheric scattering often makes these shadows difficult to definitively measure. The season of observation also affects the ability to measure shadows because albedo contrasts can confuse shadow patterns; periods with some remaining seasonal frost often are the most useful even if shadows are somewhat shorter.

Throughout this paper we use the solar longitude of Mars (L_s) to designate the season: 0° is the start of northern spring; 270° is the start of southern summer. Our map coordinates are Aerographic; these use West longitudes (Archinal et al., 2011). We use MY to denote a particular Mars year and ♂y to denote intervals of Mars years. MY 1 started in April 1955 (Clancy et al., 2000; Piqueux et al., 2015). Some further methods specific to particular problems are elaborated below.

3. Unit map of the RSPC

Morphologic units have been previously mapped in Thomas et al. (2009). This earlier approach used only four units, two being thick (~10 m) materials with large pits, one being intermediate thickness with linear depressions (fingerprint terrain), and an undifferentiated "B" unit generally less than 3 m thick and encompassing a wide variety of pit sizes, densities, and shapes.

We have remapped the morphologic units, primarily from inspection of a 6 m/pixel MY 31 mosaic covering L_s 327–341°, applying largely qualitative divisions. In some instances MOC or HiRISE data were used in conjunction with the CTX data to arrive at a unit designation. Many of the divisions are subject to interpretation, and a noticeable fraction of the area has been left as an undifferentiated mix of other morphologies. Uncertainties in the morphologic classification probably have little effect on the mapping of estimated ages (see Section 7) or on the estimated volumes because of the modest area fractions involved and because of the similarities of thicknesses and erosion rates among the possibly confused units. Table 1 lists unit descriptions. Fig. 1 shows the map, Fig. 2 shows example images of each unit.

With two exceptions, these are morphologic units based on pit sizes, shapes, density, and other details of the surface such as presence of polygonal troughs and ridges. The mapping scheme here is an extension from the classifications in Thomas et al. (2005, 2009). The exceptions are units B1 and B2. B1 is composed of smooth bright areas that were in place at the time of Mariner 9 observations, clearly defined in B-frame (narrow angle camera) coverage. B2 includes smooth areas that were deposited after the MY 9 observations. These are areas with distinctive outlines that changed brightness relative to surroundings (darker in MY 9, relatively brighter later) sometime after MY 9 and that show distinct smooth areas abutting older, rougher materials in MOC, CTX, and HiRISE data (Thomas et al., 2009, Figs. 14 and 15). Many of the other units were present in MY 9 and many have been modified since then. Some reclassification during the mapping has resulted in elimination of what was unit B3.

Table 2 lists the areas, estimated thicknesses, and other measured and calculated properties of each unit. The first result from this new, higher resolution mapping is a total RSPC area that is ~8% less than previous reported measures (Malin et al., 2001; Thomas et al., 2005, 2009). Much of the difference is due to the better exclusion of trough areas: troughs total ~3000 km length within the cap. Previous mapping may have included areas as much as 6 km wide along some of the troughs not covered by ice.

The thickness estimates use new shadow measurements of pit and scarp depths in addition to previous measurements (Thomas et al., 2009). The values in Table 2 are the estimated average thicknesses. For instance, unit B9 has only partial covering, and its maximum thickness is only on the order of 1 m. The resulting total volume estimate of the RSPC is roughly half that reported by Thomas et al. (2009), where the estimates were based on maximum thicknesses. A significant part of the difference comes from units A2 (previous 7 m thickness; now 2 m average) and the B units (4 m maximum vs. ~2 m average now). The thickness estimates are of the heights above significant discontinuities: the flat floors of pits or of troughs. In some areas these flat areas are known to have water ice and thus are clearly part of the underlying PLD