MARTIAN GLOBAL SCALE CO_2 EXCHANGE FROM ORBITAL TRACKING DATA.

O. Karatekin, T. Van Hoolst, V. Dehant, *Royal Observatory of Belgium, Brussels, Belgium***.**

Introduction

CO_2 in the Martian atmosphere condensates and sublimates on seasonal time scales, resulting in large mass exchanges between the atmosphere and the surface. As the mass redistribution is on global-scale, it mainly affects the long wavelength components of the gravity field. Chao and Rubincam(1990) showed that the time-variations of the gravity field could be large enough to have a measurable effect on the orbit of a spacecraft. There are several other possibilities to estimate the global scale mass exchanges over Mars (see, Zuber (2003). Detection of temporal changes in the long wavelength of Martian gravitational field provide one of the most direct methods as it does not need physical models related to the surface/atmosphere interactions or to the subsurface modelling. It also offers the advantage of continuous data for many years as tracking data will be available for any Mars orbiter.

The low-degree zonal coefficients of the Martian time-variable gravity were derived from the tracking data of Mars Global Surveyor (MGS) spacecraft by Smith et al. (2001), Yoder et. al (2003) and most recently by Balmino et al. (2005). The perturbation of the MGS orbit due to the time-variable gravity field is at the edge of detectibility and the reported coefficients contain the influence of higher degree zonals since they were obtained from the tracking data of a single spacecraft. Nevertheless, Smith et al. (2001) calculated successfully the seasonal mass variations of polar caps by combining the ΔC_{20} solution with Mars Orbiter Laser Altimetry (MOLA). Orbital analysis of MGS allowed Yoder et. al (2003) to estimate the solid Love number k_2 of Mars as well as to test the compatibility of several ice-cap models with the deduced time-variable gravity solution. Aharonson et al. (2004) calculated the density of seasonal polar deposits by combining Gamma Ray Spectroscopy (GRS) data of Mars Odyssey with the MOLA data as well as with the time-variable gravity data of MGS. Karatekin et al. (2005) investigated the influence of higher degree zonals on the reported time-variable gravity coefficients and compared ΔC_{20} and ΔC_{30} observations with those calculated from the mass redistributions given by GCM and the CO_2 thickness measurements of High Energy Neutron Detector (HEND) onboard Mars Odyssey (Litvak et al. 2004).

The use the tracking observations alone to obtain direct measure of the global scale mass redistribution has been challenging, mainly due to the low signal-to-noise ratio of the time-variable gravity signal (Smith and Zuber 2003, Karatekin et al. 2003). The objective of the present study is to determine the seasonal mass exchanges between the polar caps and atmosphere, as well as the global atmospheric pressure variations directly from the reported time-variable gravity field coefficients, ΔC_{20} and ΔC_{30}.

Theory

The changes in the zonal Stokes coefficient ΔC_{n0} of degree n and order 0 of the gravity field due to the mass exchange between the surface and atmosphere can be expressed as an integral over the seasonal surface mass density variations, $\Delta\sigma$ as (Chao and Rubincam 1990):

$$\Delta C_{n0}(t) = \frac{R^2}{M}\int \Delta\sigma(\Omega, t) P_n(\cos\theta) d\Omega. \qquad (1)$$

where M and R are the radius and mass of the planet, $d\Omega$ the infinitesimal surface element ($d\Omega = \sin\theta d\theta d\lambda$), θ co-latitude, λ longitude, and P_n is the Legendre's polynomial of degree n. The atmosphere is assumed to be locally in hydrostatic equilibrium and elastic yielding of the planet under the surface loading and any seasonal mass variation inside the planet are neglected. The effect of elastic yielding is less than 1% (see, Van Hoolst et al. 2003, Chao and Rubincam 1990).

For the purpose of the present study, two further approximations are introduced. Firstly, $\Delta\sigma$ is assumed to be a function of co-latitude only. This is a very reasonable assumption since, during the cap retreats and advances, the shape of the seasonal polar caps remains mostly axi-symmetric, except when the surfaces of seasonal deposits are close to minimum (James et al. 2001). Secondly, atmospheric pressure contributions to $\Delta\sigma$ are neglected. Based on GCM simulations of the Martian atmosphere, Karatekin et al. (2005) showed this would introduce errors less than 6% and 2% for ΔC_{20} and ΔC_{30}, respectively. Accordingly, the integral in equation 1 vanishes everywhere except in the regions where CO_2 condensation/sublimation occurs:

$$\Delta C_{n0} = \frac{2\pi R^2}{M}\int_{\mu_{e_N}}^{1} \Delta\sigma P_n(\mu) d\mu + \qquad (2)$$
$$(-1)^n \frac{2\pi R^2}{M}\int_{\mu_{e_S}}^{1} \Delta\sigma P_n(\mu) d\mu.$$

The integrals on the right hand side are over the North and South seasonal caps, respectively. We also introduced $\mu(t) = \cos\theta(t)$, and the North and South polar edges have $\mu = \mu_{e_N}$ and $\mu = \mu_{e_S}$, respectively.

The distribution of the surface mass density, $\Delta\sigma$, over the polar regions is poorly constraint. For a given $\Delta\sigma$ distribution, the mass variations of the polar caps $\Delta M_{N,S}$ are a linear function of the variations of the zonal gravitational coefficients (see Karatekin et al. 2006). For a linear $\Delta\sigma$ distribution ($\Delta\sigma(\mu) = a + b\mu$), the mass variation over the pole is $\Delta M_{N,S}(t) = \pi b R^2 [1 - \mu_{e_{N,S}}(t)]^2$, assuming zero ice cap thickness at the boundaries of the seasonal polar caps. If $\Delta\sigma$ is assumed to be constant over the North and South poles, the mass variations are given as $\Delta M_{N,S}(t) = 2\pi R^2 [1 - \mu_{e_{N,S}}(t)]\Delta\sigma$. The simplest assumption is to consider point masses in the geometric center of the polar-ice caps, for which it can be shown that the variations of the odd (even) zonal harmonics are linearly proportional to the sum (difference) of the relative mass variations in the two hemispheres (Zuber and Smith 2003). In the point mass model, all CO_2 cap mass is assumed to be on the geographical center of the pole. For a given polar mass, the effect on the zonal gravity coefficient is then maximal among all possible polar cap models. Therefore, the mass estimates in the point mass model are lower bounds.

Results

The mass variations ΔM for constant and linear $\Delta\sigma$ distributions as well as for the point mass approximation are shown in Figure 1. The plots refer to the arithmetic mean of the solutions resulting from the 4 combinations of the reported ΔC_{20} and ΔC_{30} from Smith et al. (2001) and Yoder et al. (2003). On the same graph we plot also ΔM from HEND, and GCM models . The LMD (Forget et al. 1999) and the NASA Ames (Haberle et al. 1999) GCMs were run on a surface grid of $7.5^0 \times 9^0$ using a dust scenario, consistent with a moderately dusty planet. The LMD run consistent with the Martian Climate Data Base v3.0 (Lewis et al. 1999) provides the largest ΔM estimates. The differences between the two GCM solutions are largely due to differences in physical modelling. Neutron flux measurements of HEND scale with the amount of hydrogen on the surface or subsurface of Mars. The summer measurements, when no CO_2 deposit is present on the surface, were used to determine the amount of hydrogen in the subsurface, and the changes in the neutron flux with seasons were interpreted in terms of CO_2 deposits given in kg/m^2 (Litvak et al. 2004).

The constant σ approximation likely overestimates the mass variations for realistic μ_{e_N} and μ_{e_S} since it assumes unrealistically high $\Delta\sigma$ concentration at the polar cap boundaries. As other models will likely yield mass variations in between the constant $\Delta\sigma$ and the point mass models, which present the upper and lower bounds, we do not consider more complicated models than the linear $\Delta\sigma$ model. Moreover, the differences between the ΔM solutions are within the uncertainties of the tracking data solutions.

The global scale atmospheric pressure, P_s, is directly related to the mass variations of the polar caps. Assuming the atmosphere to be in hydrostatic equilibrium, we have:

$$\Delta P_s = -\frac{g}{4\pi R^2}(\Delta M_S + \Delta M_N). \qquad (3)$$

The variation of ΔP_s over a Martian year is shown in Figure 2. The current solution is in line with the 3 data sets, but shows better agreement with the HEND results.

Discussion and Conclusions

Global-scale mass exchange between the atmosphere and polar caps has been estimated from the temporal variations of ΔC_{20} and ΔC_{30} derived from the orbital analysis of MGS. The mass and pressure variations obtained from the present analysis show good agreement with numerical models of NASA Ames and HEND observations despite some artifacts from the low signal-to noise ratio of the time-variable gravity signal and its representation by a limited number of harmonics.

The ΔM given by different models of $\Delta\sigma$ remain small compared to the discrepancies of the GCM and the HEND solutions. The uncertainties associated with the time-variable gravity solution do not allow to estimate a surface mass density model. The simple models employed in the present study can be further developed as the data quality will be improved.

Theoretically, Martian time-variable gravity can be estimated with any spacecraft provided that the tracking is sufficient. Possible improvements of time-varying gravity solutions (such as by simultaneous tracking of more than one orbiter), could be used to better constrain the physical models of GCM which have been trying to reproduce local surface pressures much smaller than than their surface resolution. Such solutions will also be likely used to determine the year-to-year variations of polar masses variations.

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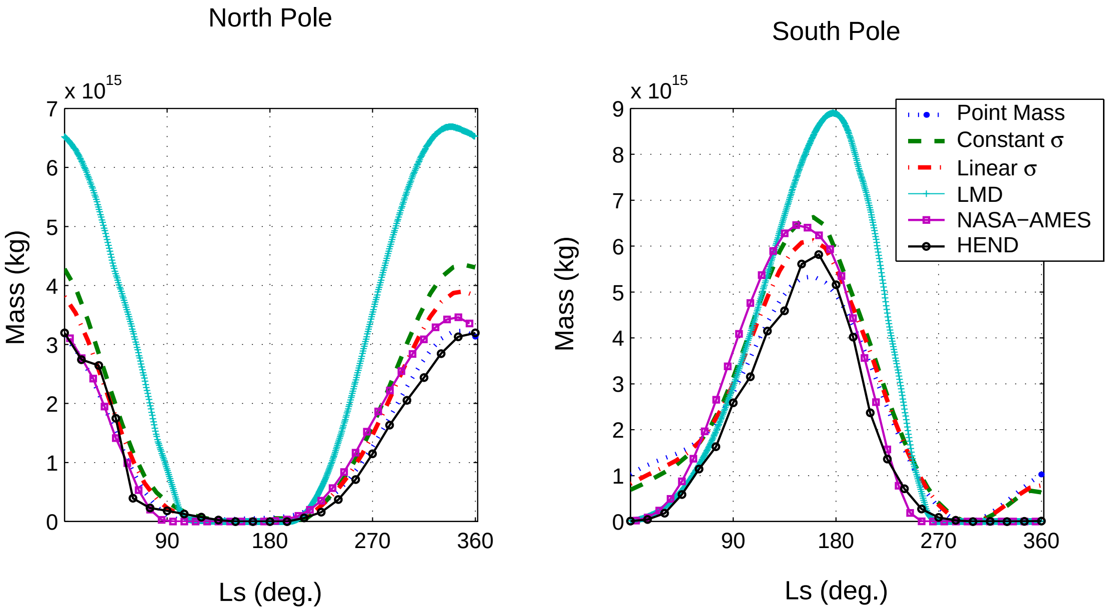

Figure 1: Comparison of relative mass variations in polar caps. The solutions from the averaged ΔC_{20} and ΔC_{30} time-series for different surface mass density σ distributions are compared with those from the two GCM and the HEND.

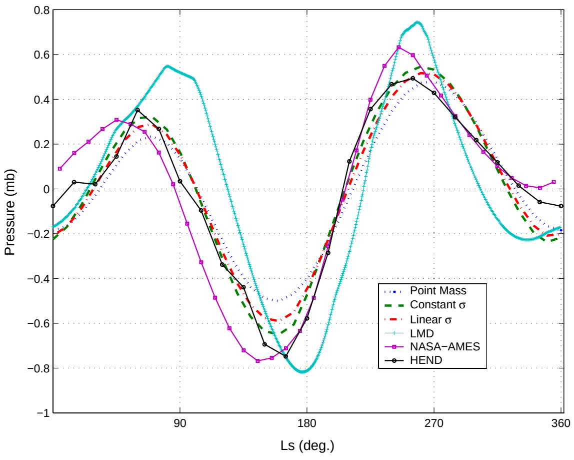

Figure 2: Variations of mean pressure. The solutions from the averaged ΔC_{20} and ΔC_{30} time-series for different surface mass density σ distributions are compared with those from the two GCM and the HEND.

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