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The effect of the internal structure of Mars on its seasonal loading deformations

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Abstract

Mars is continuously subjected to surface loading induced by seasonal mass changes in the atmosphere and ice caps due to the CO_2 sublimation and condensation process. It results in surface deformations and in time variations of gravity. Large wavelength annual and semi-annual variations of gravity (particularly zonal coefficients ΔJ_n) have been determined using present day geodetic satellite measurements. However loading deformations have been poorly studied for a planet like Mars. In this paper, we compute these deformations and their effect on spacecraft orbiting around Mars. Loading deformations of terrestrial planet are typically investigated assuming a spherical planet, radially symmetric. The mean radial structure of Mars is not well known. In particular the radius of the liquid or solid core remains not precisely determined. One may then wonder what is the effect of these uncertainties on loading deformations. Moreover, Mars presents a strong topography and probably large lateral variations of crustal thickness (relative to the Earth). The paper answer the questions of what is the effect of such lateral heterogeneities on surface deformations, and is the classical way to calculate loading deformation well adapted for a planet like Mars. In order to answer these questions we have investigated theoretically loading deformations of Mars-like planets. We first investigated classical load Love numbers. We show that for degrees inferior to 10, the load Love numbers mainly depend on the radius of the core and on its state, and that for degree greater than 10, they depend on the mean radius of mantle–crust interface. Using a General Circulation Model (GCM) of atmosphere and ice caps dynamics we show that loading vertical displacements have a 4–5 cm magnitude and present a North–South pattern with periodic transitions. Finally we investigated the effect of lateral variations of the crustal thickness on these loading deformations. We show that thickness heterogeneities perturb the deformations and the time variation of gravity at about 0.5%. However this perturbation on ΔJ_n is only about 1‰ due to main direct attraction of surface fluid layers. We conclude that lateral variations of crustal thickness are today negligible. However, observation of load Love numbers would bring information on the radial internal structure of the planet, particularly on the core radius. ΔJ_n study would permit to infer the load Love number k'_n, particularly for degree 2 and 3, knowing surface fluid layer dynamics. However k'_n load Love numbers are quite small (about 0.05), and despite the present good agreement between GCM and ΔJ_n observations, will only be estimated in the near future when a slightly better precision in observation and modeling will make it possible to infer these numbers. The investigation of load Love number h'_n, which are larger than k'_n numbers, would be particularly interesting. It would permit to study degree 1 contribution of atmosphere and ice caps dynamics, which is the most important component of surface fluid dynamics on Mars. Surface displacement measurements would be necessary on a few places near the pole regions, which may be possible in the future, with a project involving precise positioning of a lander on the surface of Mars.

Keywords: Mars, interior; Atmosphere, dynamics

1. Introduction

Mars is continuously subjected to surface loading induced by its surface fluid layers. Mass distribution in polar ice caps and in the atmosphere varies on a seasonal timescale due to condensation and sublimation of CO_2 (Folkner et al., 1997). It results in surface deformations and in time variations of

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gravity which can be determined using geodetic satellite measurements. Chao and Rubincam (1990) first showed that time variations of coefficients J_2 and J_3 could be expected due to seasonal CO_2 cycle and computed these variations. Smith et al. (1999), also Sanchez et al. (2006), investigated time variations of gravity using estimations of atmospheric pressure and polar frost provided by the NASA/Ames General Circulation Model (GCM). Karatekin et al. (2005, 2006) calculated and compared the seasonal variations of the low degree coefficients of the gravitational potential field based on both the NASA/Ames GCM and the LMD (Laboratoire de Météorologie Dynamique in Paris VI) GCM (Forget et al., 1999; Angelats i Coll et al., 2004, 2005). Finally, martian degree 2 and 3 time-variable gravity coefficients have been estimated by different authors (e.g., Lemoine et al., 2006; Konopliv et al., 2006), using MGS and Mars Odyssey tracking data. One can see that the coefficients have a magnitude of about 10^{-9} and that the present formal errors in the determination is about 10% to 100% for the degree 2 coefficients, and about 1% for the degree 3. These seasonal time variations of gravity are expected to be mostly induced by surface fluid dynamics. Indeed Karatekin et al. (2005) showed that ΔJ_n observations and GCM estimations are quite well correlated.

Time variations of gravity are not only due to mass variations in surface fluid layers but also to surface loading deformations of the solid component of the planet induced by them. The deformations of the planet depend on its internal structure, particularly on its density and elastic parameters. However, the mean internal structure of the planet is not precisely known (Sohl and Spohn, 1997) as there has never been usable seismic measurements on Mars. The models for the interior of Mars are then constructed from extrapolation of what we know for the Earth, from laboratory measurements, from meteorite constraints, and from measurements of the global properties of Mars such as the mass and moment of inertia. Uncertainties are at the level of a few percent and one may wonder what is the effect of these uncertainties in the radial structure on the computation of Mars' loading deformations.

Surface gravity and displacement variations can be expressed with the help of nondimensional Love numbers, which depend on the internal structure of the planet (density and rheology). The tidal Love number of degree 2, k_2, is especially very sensitive to core properties such as its state and dimension. A difference of about 30% can be found between models with liquid and solid outer cores (Van Hoolst et al., 2003). Yoder et al. (2003) investigated the Sun tides and calculated the core radius, assuming a fluid core. The k_2 Love number has been obtained from spacecraft tracking. Radioscience measurements have been used to determine the gravitational forces acting on the spacecraft and therewith to determine the effects of the tidal mass redistribution, i.e. to determine the k_2 Love number. These recent results from geodesy experiments favor models with a large core and a hot mantle (Yoder et al., 2003; Konopliv et al., 2006). However this determination is not easy as the effects are at the limit of the uncertainties of the measurements. A confirmation of this comes from the large spectrum of values one finds in the literature. Consequently, while most recent results tend to show that the core is liquid and large, the radius of the core and the rheological properties of the outer core remain presently in debate. In the absence of useful seismic information, additional information provided by the study of the k'_n loading Love numbers could be particularly useful to conclude on the size and the mechanical properties of Mars' core. The knowledge of core radius is important to understand Mars' evolution and its present-day mantle dynamics. A smaller core would be favored by thermal evolution models that sustain large plumes that are possibly responsible for Tharsis' rise (Breuer et al., 1997; Spohn et al., 2001; Van Thienen et al., 2006). Lateral temperature variations, which are generated by the variations of the low conducting crust thickness, may also explain recent Tharsis volcanism (Schumacher and Breuer, 2006).

In this work, we investigate the theoretical elasto-gravitational deformation of Mars induced by surface loadings with respect to the internal structure of the planet. We first investigate the impact of the radial internal structure of Mars on its load Love numbers, using classical computation of Love numbers, assuming radial symmetry in stratified Mars models. Yet, considering the strong variations of Mars' topography, particularly the North–South dichotomy, the Tharsis region, or the Hellas basin (...), lateral variations of crustal thickness are believed to be particularly strong (Smith et al., 1999). One can wonder if such large crustal heterogeneities could affect significantly the loading deformations and if the classical way to calculate the load Love numbers with a mean homogeneous crust is well adapted for Mars. To answer these questions we investigated the impact of crustal thickness variations on the loading deformations. We used a numerical model of elasto-gravitational deformation of terrestrial planets, recently developed by Métivier et al. (2005, 2006), which is able to take into account the lateral heterogeneous structure of the planet (and the topography) within the calculation.

In the first part of the paper, we present the calculation of the classical load Love numbers, assuming the planet as a sphere with internal layers of constant thicknesses. We present also the annual evolution of the surface vertical displacement. In the second part, we present the effects of lateral variations in crustal thickness on these deformations.

2. Loading deformations of a spherical Mars

2.1. Load Love numbers

Loading deformations of terrestrial planets are classically calculated assuming a planet with a spherical symmetry and a hydrostatic equilibrium state. It is well known since the work of Love (1911) that in such model surface displacements and surface gravity variations can be expressed in terms of nondimensional coefficients, the Love numbers, which depend only on the spherical harmonics degree of the forcing. Let us define $\mathbf{u}$ the surface displacement, ϕ the surface gravitational potential and g the normal gravity variation on the deformed surface, induced by a surface load potential V. Load Love numbers h'_n for the radial displacement, l'_n for the tangential displacement and k'_n for the mass redistribution potential, and the tidal gravimetric factor delta number δ'_n for the surface gravity change are defined such as:

$$\mathbf{u}(\theta,\varphi)=\sum_{n=0}^{\infty}\sum_{m=-n}^{n}\frac{V_{nm}}{g_o}\big(h'_n Y_{nm}(\theta,\varphi)\,\mathbf{e}_r+l'_n\,\nabla_1 Y_{nm}(\theta,\varphi)\big), \tag{1}$$

$$\phi(\theta,\varphi)=\sum_{n=0}^{\infty}\sum_{m=-n}^{n}V_{nm}k'_n Y_{nm}(\theta,\varphi), \tag{2}$$

$$g(\theta,\varphi)=\sum_{n=0}^{\infty}\sum_{m=-n}^{n}\frac{n}{a}V_{nm}\delta'_n Y_{nm}(\theta,\varphi), \tag{3}$$

where V_{nm} are the load potential spherical harmonic coefficients, g_o—the mean surface gravity, a—Mars' mean surface radius, Y_{nm}—the spherical harmonic function of degree n and order m, and ∇_1—the surface unit gradient ($\nabla_1=\mathbf{e}_\theta\,\partial_\theta+\mathbf{e}_\varphi\sin\theta^{-1}\partial_\varphi$).

Alterman et al. (1959) established the system of equations, the so-called y_i-system, which permits to solve the elasto-gravitational deformation of such a planet. This approach has been previously applied to Mars by Banerdt et al. (1982) to investigate long-wavelength loading by the Tharsis plateau. One can then extract the load Love numbers from the solution. We solved the "y_i" system of equations using a Runge–Kutta method assuming the classical boundary conditions (e.g., Alterman et al., 1959; Farrell, 1972; Dahlen and Tromp, 1998), i.e.

- continuity of displacement through solid–solid interfaces,
- continuity of radial displacement through solid–fluid interfaces,
- continuity of traction through the internal interfaces,
- free surface condition on surface traction,
- continuity of gravitational potential and of gravity through the internal interfaces,
- continuity of the surface gravity and the surface potential assuming the harmonic properties of the gravity field outside the planet.

One particular attention has to be made for the degree 1. It is well known that degree 1 deformations on a terrestrial planet is directly linked to the frame of the calculation and that the two surface boundary conditions on potential and gravity are degenerated. In order to conserve the mass center position we choose to change the surface condition on gravity with a new surface condition on the potential (following, e.g., Greff-Lefftz and Legros, 1997):

$$(\phi+V)_{n=1}=0, \tag{4}$$

which means that $k'_1=-1$.

2.2. Variations of the mean Mars model

In order to investigate the sensitivity of Mars' loading Love numbers to the radial internal structure of the planet, we tested different models. The internal structure of Mars is deduced from Sohl and Spohn (1997) (see Table 1). The planet contains a solid inner core, a liquid outer core, a lower mantle, an upper mantle and a crust (assumed to be similar to the elastic lithosphere). Other models with different radial constitution are also possible. Folkner et al. (1997), for example, estimated the core radius to be between 1300 and 1700 km.

Table 1
Characteristics of the mean Mars model that we used in our calculation

Radius (km)	Density ($\mathrm{g\,cm^3}$)	V_p ($\mathrm{km\,s^{-3}}$)	V_s ($\mathrm{km\,s^{-3}}$)
0–500	7.266	6.520	3.470
500–1468	7.036	6.243	0.000
1468–2033	4.220	9.987	5.674
2033–2360	4.007	9.402	5.263
2360–3280	3.599	8.663	4.369
3280–3390	2.850	7.718	3.926

Note. This model has been inferred from the work of Sohl and Spohn (1997).

We tested different Mars model with various core and crust mean thicknesses. We constrained our models with the well known mean surface gravity of the planet (about 3.69 $\mathrm{m\,s^{-2}}$). A change of layer thicknesses (from Table 1 model) induces change in the total mass of the planet and consequently modify the mean surface gravity. In order to conserve the mean mass of the planet, we additionally shifted the local density with a constant, which depends on change of interface radius. We denote by r the original mean radius of the interface. The surface gravity of the planet (assuming here a three-layers model of the planet) is

$$g_o=-\frac{4\pi G}{3a^2}\big(\rho_o^{\mathrm{core}}b^3+\rho_o^{\mathrm{mantle}}\big(r^3-b^3\big)+\rho_o^{\mathrm{crust}}\big(a^3-r^3\big)\big), \tag{5}$$

where b is the mean radius of the core–mantle boundary, r the radius of the mantle–crust boundary, a the surface radius, and G is the universal gravitational constant. Let us change, for example, the radius of the mantle–crust boundary by an amount h, then the surface gravity is now equal to:

$$g_o=-\frac{4\pi G}{3a^2}\Big(\big(\rho_o^{\mathrm{core}}+\delta\rho\big)b^3+\big(\rho_o^{\mathrm{mantle}}+\delta\rho\big)\big((r+h)^3-b^3\big)+\big(\rho_o^{\mathrm{crust}}+\delta\rho\big)\big(a^3-(r+h)^3\big)\Big). \tag{6}$$

$\delta\rho$ is a mean change of global density in the model. In order to conserve the value of g_o, knowing Eq. (5), one can calculate the density perturbation $\delta\rho$ that we will have to add everywhere in the planet:

$$\delta\rho=\big(\rho_o^{\mathrm{crust}}-\rho_o^{\mathrm{mantle}}\big)\left(\frac{r}{a}\right)^3\left(3\frac{h}{r}+3\left(\frac{h}{r}\right)^2+\left(\frac{h}{r}\right)^3\right). \tag{7}$$

Typical values of $\delta\rho$, for $h=100$ km, are about 2–3% of the local density, which is far beyond the precision on present estimations of martian density. However, without this $\delta\rho$, the total mass involved would be sufficient to change significantly the surface gravity, and consequently to affect the Love numbers determination [see Eq. (1)].

Solutions for different core and mantle–crust boundary radius are presented in Figs. 1–3. Fig. 1 presents load Love numbers depending on the core radius, assuming a liquid outer core

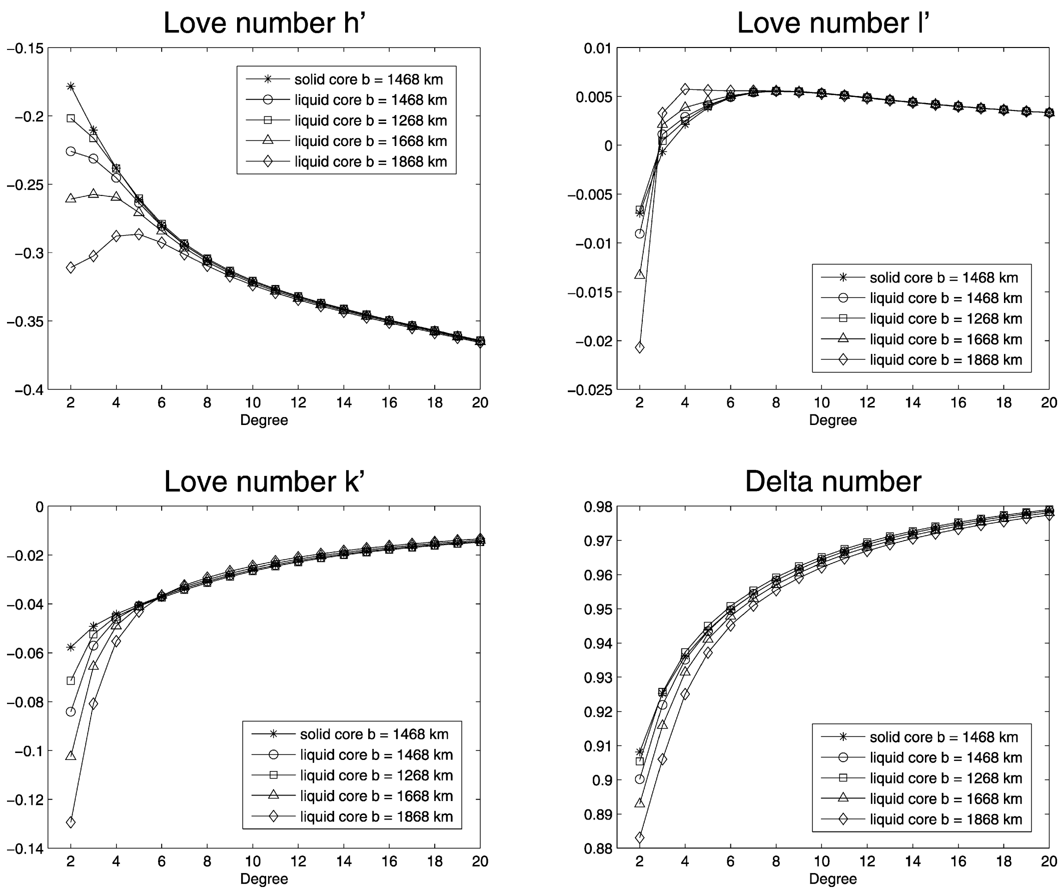

Fig. 1. Load Love numbers depending on the core radius, assuming a liquid core. One example for a solid core is also presented as a reference.

(one example for a solid core is also presented as reference). Fig. 2 presents load Love numbers depending on the core radius, assuming a solid outer core (one example for a liquid core is also presented as reference). Finally, Fig. 3 presents load Love numbers depending on the mantle–crust interface radius. One can see that low degree load Love numbers are essentially sensitive to the radius of the core, particularly for degree 2 and 3. The crust mean thickness only affects the larger degree load Love numbers ($n > 10$). One can see also that the load Love numbers dependency on core radius is completely different if we assume a solid or a liquid outer core. For a solid outer core, load Love numbers do not vary very much ($-0.17 < h'_2 < -0.19$ and $-0.055 < k'_2 < -0.065$). However, for a liquid core, load Love numbers are clearly more dependent on core radius ($-0.2 < h'_2 < -0.31$ and $-0.07 < k'_2 < -0.13$). Moreover, sets of possible load Love number values for a solid core and a liquid core are different. The knowledge of low degree load Love numbers would consequently permit to infer the mean core radius and the rheology of the outer core. Presently we can barely infer more than degree 2 and 3 seasonal time-variable gravity, with a particularly good accuracy for degree 3 (e.g., Lemoine et al., 2006). We believe that determination of the corresponding load Love numbers would be of great interest to distinguish between the current Mars models.

Degree 1 load Love numbers are not presented in Figs. 1 and 3, because they do not follow the same pattern than larger degree load Love numbers (like on the Earth, e.g., Greff-Lefftz and Legros, 1997). Moreover, we find that martian degree 1 load Love numbers poorly depend on the internal properties. The values that we obtain for the different models are all contained in the intervals mentioned in the following values:

$$h'_1 = -1.059 \pm 0.002, \qquad l'_1 = -0.968 \pm 0.007,$$
$$k'_1 = -1, \qquad \delta_1 = 0.882 \pm 0.005. \tag{8}$$

2.3. *Magnitude of deformations and seasonal variations*

Knowing a given distribution of pressure induced by the atmosphere or ice caps, one can determine the loading deformations occurring on the solid Mars surface. We used information provided by the LMD GCM to infer pressure and the external potential induced by the mass of the atmosphere and ice caps (up to degree 8). We present in Fig. 4 surface displacements induced by the loading over one year (669 martian days). The origin of time corresponds to northern hemisphere spring equinox. The load Love numbers used assume a 1468 km liquid outer core and a 3280 km mantle–crust interface radius. We see that surface displacements are in the centimeter level, with largest values about 5 cm. Surface displacements present most of the time a rather North–South stable pattern, which corresponds to a degree one zonal harmonic. It means that loads are dominated by mass on the ice caps. At two given times during the year the pattern does completely change. During these

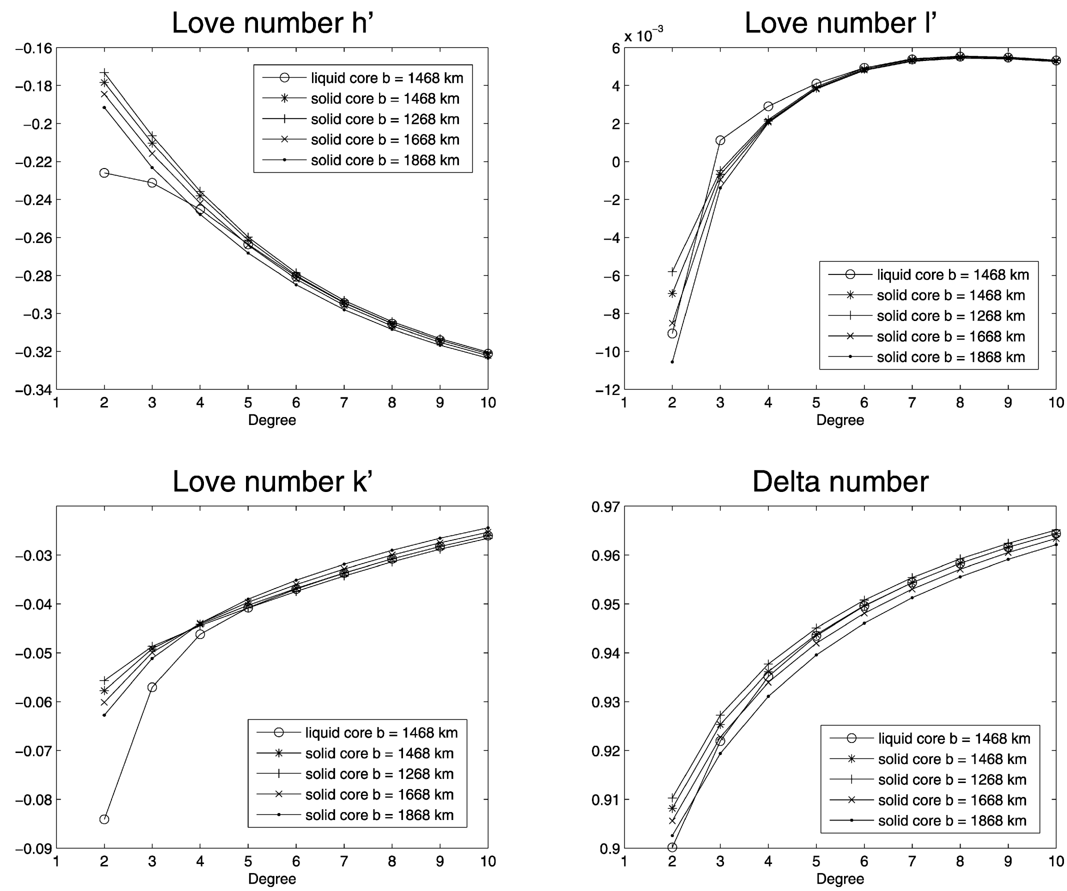

Fig. 2. Load Love numbers depending on the core radius, assuming a solid core. One example for a liquid core is also presented as a reference.

periods, displacements are small and present a transition pattern where they are negative on Tharsis region and positive on other regions (null on the polar regions). This transition phase is due to a CO_2 sublimation–condensation period, where mass is exchanged between polar ice caps, and transported by the atmosphere.

Investigating surface displacements would be particularly interesting to infer degree 1 loading deformation. This degree 1 cannot be inferred by gravity satellite measurement. It is well known that loading deformations can be directly related to time variation of mass of the atmosphere and ice caps. Since the dynamics of these fluid layers seems to be dominated by the degree 1, a few measurement station located close to the polar regions would permit to constrain the mass involved by annual surface fluid dynamics. This kind of investigation would be possible in the future with the development of surface network measurements. One step in this direction is provided by the X-band radioscience coherent transponder LaRa (which stands for Radioscience transponder) proposed within the ExoMars ESA mission. The experiment consists in sending radio signal from the Earth to the transponder; the transponder sends the signal back to Earth coherently. The Earth ground station measurements consist then in two-way Doppler measurements from the radio link between the ExoMars lander and the Earth over at least one martian year (Dehant et al., in preparation).

3. The effect of topography and lateral variations of crust thickness on loading deformations

Loading deformations on a terrestrial planet are classically calculated assuming a spherical (or ellipsoidal) planet with a radially symmetric internal structure. However terrestrial planets present complex topographies and probable internal lateral variations in density and elastic parameters, generally due to past and/or present mantle dynamics. The structure of the Earth's mantle is known to be quite heterogeneous due to a mantle thermo-chemical convection. This heterogeneous internal structure has been imaged by various authors using seismic tomography inversion (e.g., Gu et al., 2001). Métivier et al. (2007) showed that superplumes within the Earth's mantle could have a significant effect on Earth's body tides, regarding to present gravity measurement accuracy. For loading deformations, the effect of lateral heterogeneities are still unknown, even on the Earth. Surface loads induce deformation mostly located on the solid upper part of the planet. This means that surface loading deformations (and associated time variations of gravity) are probably more likely perturbed by heterogeneities located near the planet surface, within the crust for example. Mars presents a very strong topography variations with large wavelength features, like the North–South dichotomy and Tharsis region (Smith et al., 1999; Zuber et al., 2000). One can wonder if the lateral variations in crustal thickness cannot affect the loading deformation of Mars, and if it cannot be seen in the present

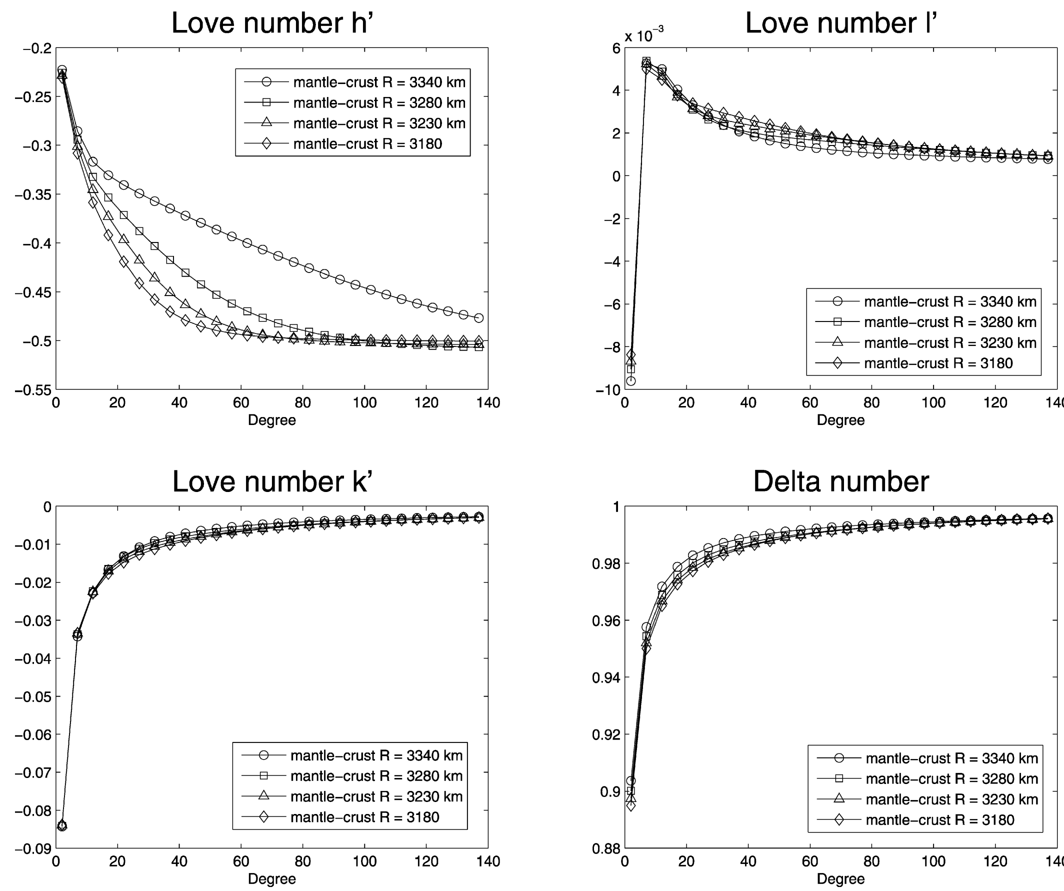

Fig. 3. The load Love numbers depending on the crust mean thickness.

measurement of time-variable gravity (Konopliv et al., 2006; Lemoine et al., 2006). In order to answer this question we investigated the effect of crustal thickness on surface loading deformations of Mars. We assumed lateral variations in crustal thickness following Airy compensation theory (Turcotte and Schubert, 2002). It is more likely that martian topography, in Tharsis region for example, is controlled by a combination of elastic and buoyant support rather than a hydrostatic equilibrium (e.g., Banerdt and Golombek, 2000). However, we believe that modeling the crust following Airy compensation theory is sufficiently realistic for our purpose and will provide orders of magnitude of the effects. Our first goal is to determine if lateral heterogeneities in the crust can simply affect significantly deformations.

Let us now denote h_t the surface topography expressed in the reference frame of Mars areoid. Following the classic hydrostatic compensation principle, one can deduce the topography on the mantle–crust boundary H, for given mantle and crust densities ρ_m and ρ_c:

$$H(\theta,\varphi) = -h_t(\theta,\varphi)\frac{\rho_c}{\rho_m - \rho_c}. \tag{9}$$

Fig. 5 presents the large wavelength surface and mantle–crust topographies that we used in our calculation.

We used the elastogravitational deformation model developed by Métivier et al. (2005, 2006) to compute the loading deformations of Mars. It is a spectral element code, which has been developed to solve the elasto-gravity theory for an aspherical, heterogeneous and non-hydrostatically equilibrated planet. The method is based on the perturbation theory and has been validated on various well known Earth's geodynamical problems (Métivier et al., 2005, 2006).

3.1. Instantaneous perturbation of a loading deformation pattern

We investigated the effect of lateral variations of crustal thickness on different surface load deformations. We used the seasonal variations of the surface pressure and the ice cap masses provided by the LMD GCM in order to deduce surface loading potential. In Fig. 6, we present one example at time $t = 30.6$ days. In a spherical, radially symmetric Mars model, the surface displacement and gravity variations would present the same general pattern (and spectrum) than the surface pressure induced by surface fluid layers. In our experiment, we have lateral variations of crustal thickness, and consequently lateral variations of density and elastic parameters near the crust boundaries. The loading deformation is consequently more complex. Each degree and order component of the loading induces deformations that depend on all spherical harmonics degrees and orders.

On the left, Fig. 6 presents (from the top to the bottom) the surface vertical displacements, the surface gravitational potential, and the surface variations of gravity (on the deformed surface) for a spherical model of Mars (same model than in

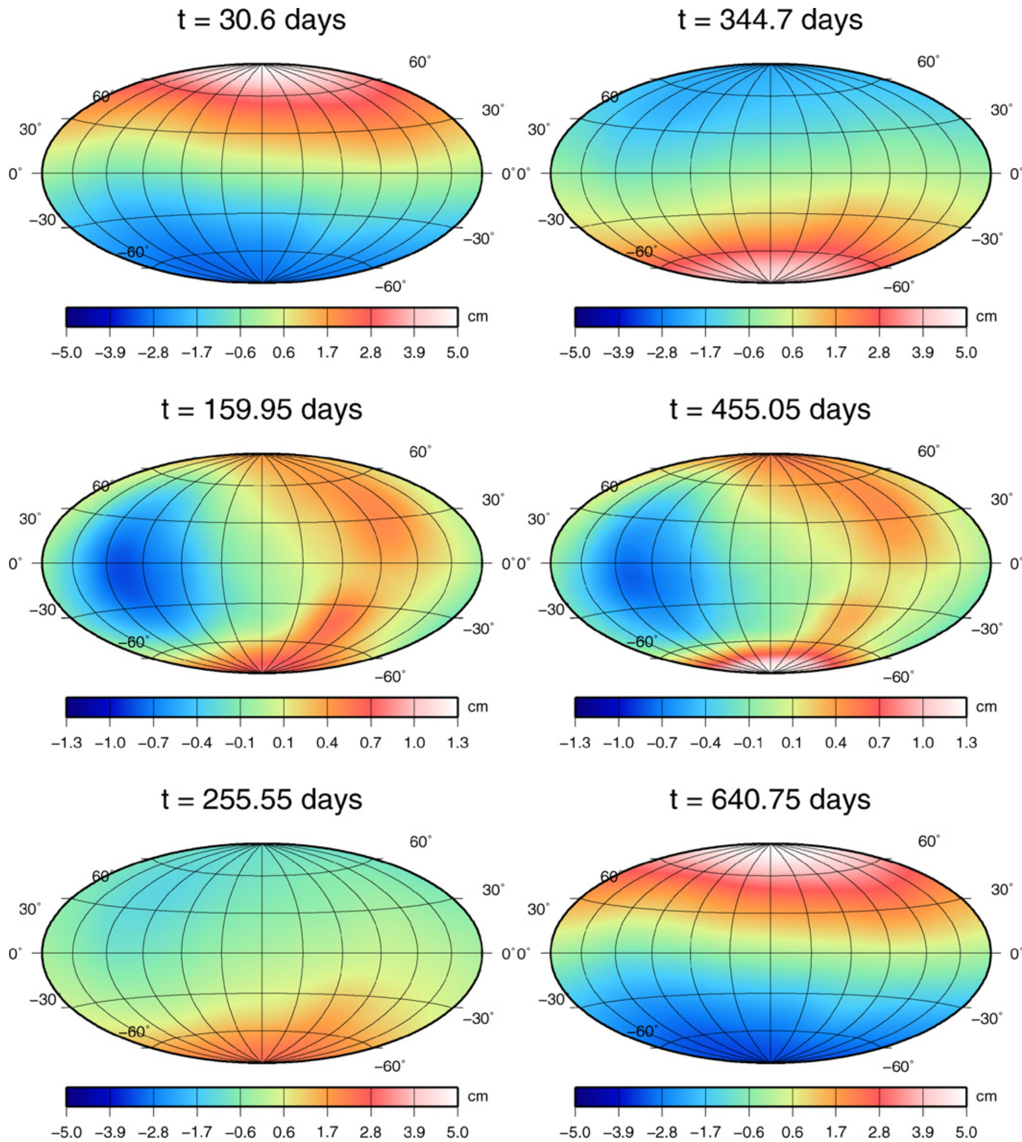

Fig. 4. Surface vertical displacements induced by loading of the atmosphere and ice caps over one year (669 martian days). The origin of time corresponds to northern hemisphere spring equinox.

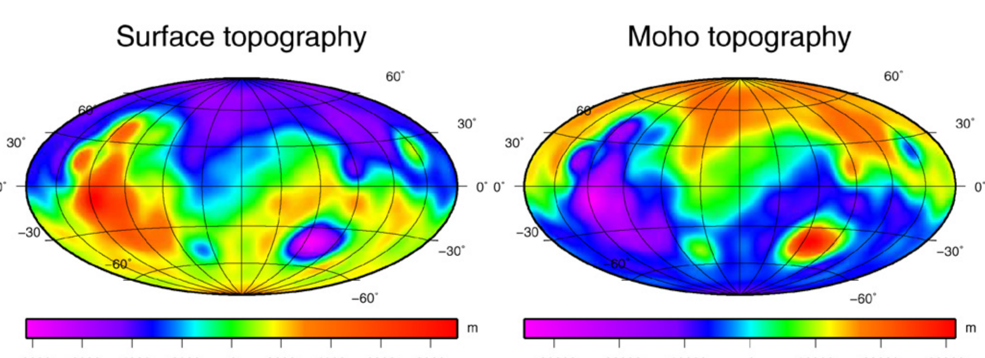

Fig. 5. Large wavelength surface and mantle–crust interface topography of Mars, calculated using Airy compensation theory.

Section 2.3). On the right-hand side, Fig. 6 presents the additional perturbations due to lateral variations of crustal thickness, for the respective surface functions. These perturbations present clearly a signature from topographic features like Tharsis rise, the volcanoes and Hellas Basin. However, one can see that these perturbations due to crustal thickness heterogeneities are only about 0.5% on deformations and gravitational components of Mars' surface response.

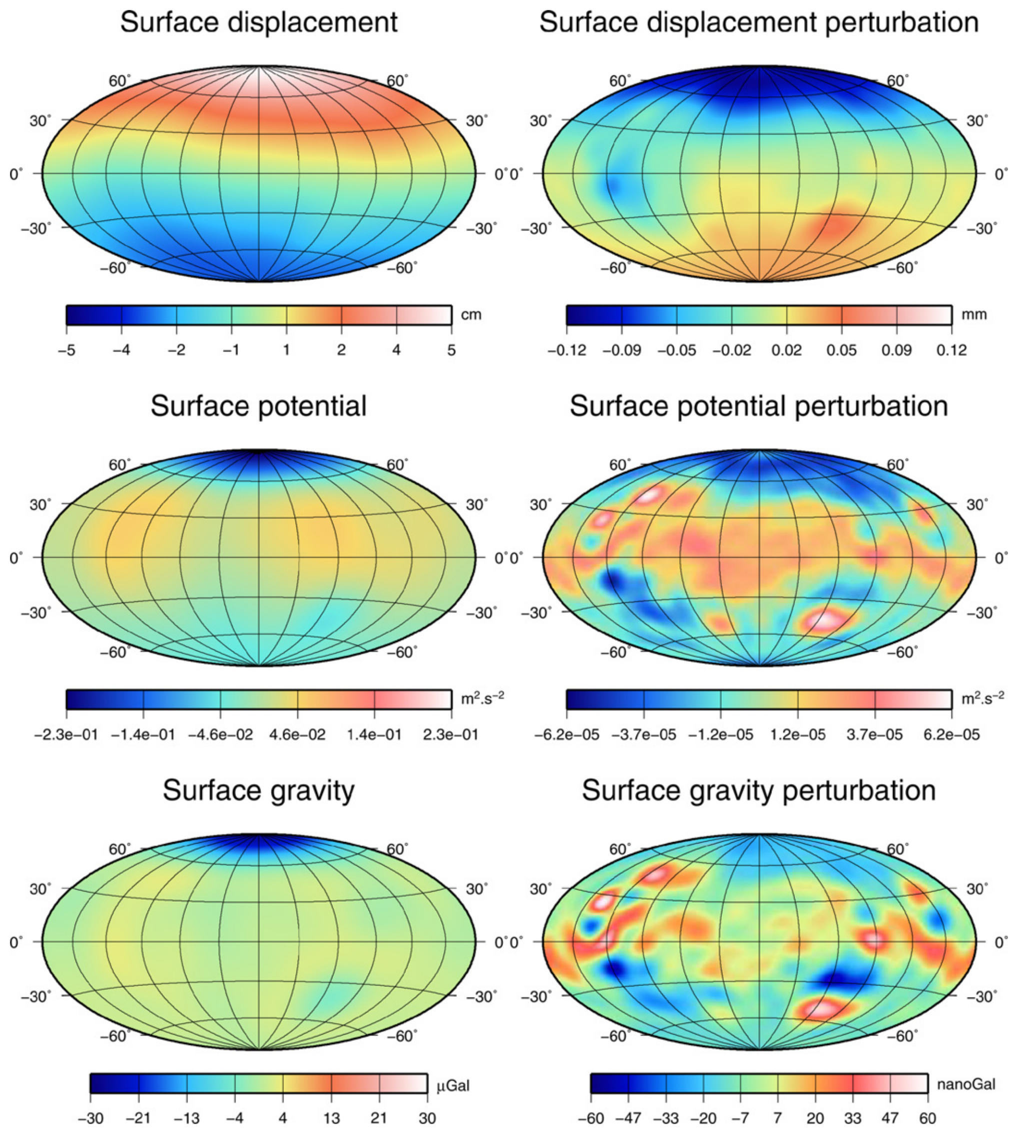

Fig. 6. Loading deformations induced by a surface load determined from the LMD GCM at $t = 30.6$ days. On the left: Response of a mean spherical model of Mars. On the right: Additional response perturbation induced by lateral variations of crustal thickness.

3.2. *Time variations and perturbations of J_n coefficients*

Time variations of Mars' J_n coefficients have been observed recently (Lemoine et al., 2006; Konopliv et al., 2006) from their effects on spacecraft orbits. We calculated the effect of the crust lateral thickness on these coefficients. Let us denote ΔJ_n the time variation of the degree n coefficient J_n for a spherical, radially symmetric, Mars model. We denote by $\Delta\Delta J_n$ the additional perturbation, which is due to lateral variation of the crustal thickness. The global variation of the surface potential is

$$\phi(\theta,\varphi)=\sum_{n=1}^{+\infty}\sum_{m=-n}^{+n}V_{nm}\left((1+k'_n)Y_{nm}(\theta,\varphi)+\sum_{n'=1}^{+\infty}\sum_{m'=-n'}^{+n'}\delta k'^{n'm'}_{nm}Y_{n'm'}(\theta,\varphi)\right),\tag{10}$$

where $\delta k'^{n'm'}_{nm}$ is the degree n' and order m' perturbation of k'_n load Love number due to lateral variations of crustal thickness and induced by a load of degree n and order m. Therefore, if we look only to the zonal component of degree p, one can show that:

$$\Delta J_p=(1+k'_p)\frac{V_{p0}}{g_o a},\tag{11}$$

and

$$\Delta\Delta J_p=\sum_{n=1}^{+\infty}\sum_{m=-n}^{+n}\delta k'^{p0}_{nm}\frac{V_{nm}}{g_o a}.\tag{12}$$

The $\delta k'^{p0}_{nm}$ have been extracted, using Legendre transform, from the global solutions presented in the last subsection. We used the same GCM coefficients of surface load than in the previous sections. We then calculated the ΔJ_n and $\Delta\Delta J_n$ of Mars response over one year (see Fig. 7).

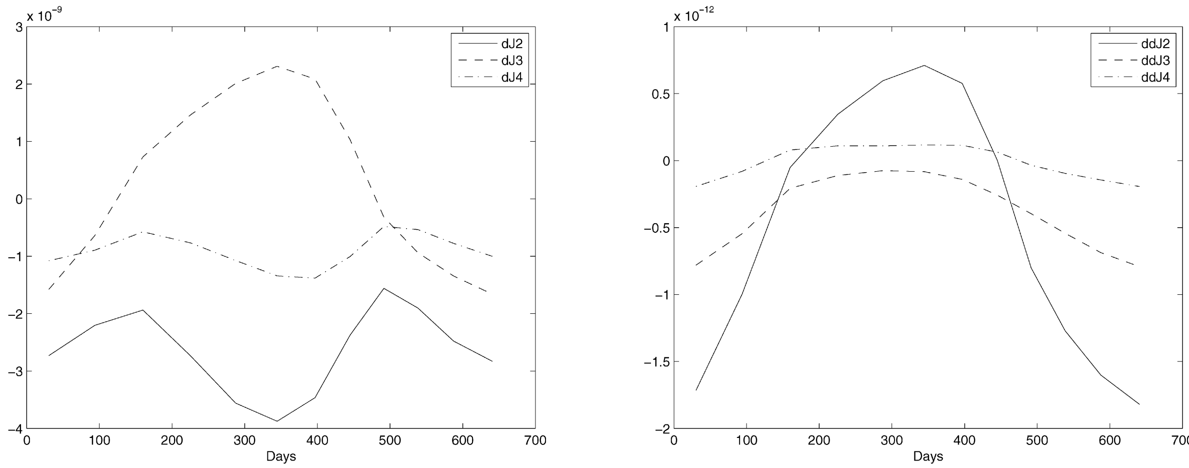

Fig. 7. Time variation (over one year) of the J_n due to loading (direct effect + deformation) and the perturbation induced by lateral variations of crustal thickness (on top: ΔJ_n, and on bottom: $\Delta\Delta J_n$).

The graphics in Fig. 7 show that time variations of J_n are relatively strong, particularly for degree 2 and 3. The effect of lateral variations of crustal thickness are particularly small on J_n coefficients. Actually, the perturbation is at the same order of magnitude as in Section 3.1. However, here we took also into account the direct effect of the surface fluid layer on ΔJ_n, which is larger than the deformation contribution. Consequently the global perturbation is about 1‰. Lemoine et al. (2006) showed that the present determination of time variation of J_n can be achieved with 1% accuracy (only for degree 3). The increase of precision that will be reached with Mars Reconnaissance Orbiter will be even better (Zuber et al., 2007). We conclude here that lateral variations of crustal thickness can be neglected today to interpret time variation of Mars' gravity measurements but that it is important to consider the loading deformations.

4. Discussions and conclusions

In this paper, we studied the effect of the internal structure of Mars on its loading deformation. Mars' load Love numbers depend strongly on the mean radial structure. Low degree load Love numbers (inferior to degree 10) depend essentially on the radius of the core and on its rheological properties. We see particularly that degree 2 and 3 k' Love number (as well as h') can vary by a factor 1.5–2 depending on the core radius and the outer core rheology. Larger degree load Love numbers depend mostly on the radius of the mantle–crust boundary, particularly for the radial load Love number h'. These results are particularly important when considering that spacecrafts orbiting around Mars are sensitive to gravity perturbations (involving k' Love number) which can therefore be evaluated from the orbiter tracking with radioscience. Determination of degree 2 and 3 load Love numbers would bring crucial information on the core properties.

We then investigated the effect of lateral heterogeneities on loading deformations. Considering that surface deformations are affected mostly by the upper part of the planet, we focused on the perturbation induced by lateral variations of crustal thickness. Martian topography show relatively large variations compared to the Earth topography and presents strong lateral features like the North–South dichotomy, the Tharsis region, or the Hellas basin. This topography suggests important lateral variations of crustal thickness. Using a spectral element model of deformation we show that crustal thickness affects the loading deformation by about 0.5% for large wavelength loads. However, we showed that the effect on the time variation of Mars' J_n coefficients is quite small (about 1‰) due to the fact that the direct gravitational effect of atmosphere and ice caps masses is more important than the deformation component. Lemoine et al. (2006) showed that the present determination of time variations of J_n can be achieved with 1% accuracy for degree 3. Advanced radioscience as introduced on Mars Reconnaissance Orbiter will allow most probably to gain one order of magnitude on this number. We conclude here that lateral variations of crustal thickness can be neglected today to interpret time variation of Mars' gravity measurements.

One important interest of loading deformations is that load Love numbers involve many degrees of deformation, not only the degree 2, as it is the case for tidal Love numbers. Combined determinations of different k'_n load Love numbers associated with k_2 tidal Love number would permit to assess definitely the characteristics of the martian core (radius and rheology). In order to investigate potential load Love number k'_n prime, one would need simultaneous measurements of time-variable gravity (ΔJ_n for example) and surface mass redistribution. The latter can be provided from orbit measurements [such as the Gamma Ray spectroscopy or the high-energy neutron detector (HEND) onboard Mars Odyssey (Mitrofanov et al., 2003)] or from a general circulation model provided that the simulations are realistic enough. Comparing gravity and surface mass redistribution would permit to infer k'_n. Unfortunately, the martian k'_n are quite small (k'_2 is about 0.05 for Mars, compared to 0.3 for the Earth). Consequently, despite the present good agreement between GCM and ΔJ_n observation (Karatekin et al., 2005), we would probably need today a better precision in measurements and GCM to be able to infer k_2 and k_3. The higher precision of Mars Reconnaissance Orbiter may provide this opportunity. It must be noted however that this orbiter has also a polar orbit, which is not the most appropriate to obtain the J_2 but suitable for J_3.

Another interesting study, not yet available, would be to look at the surface vertical displacements. Indeed h'_n numbers are larger than k'_n and would be more easily extracted from measurements. Moreover, investigating surface displacements would be particularly interesting to infer degree 1 loading deformations. This degree 1 cannot be determined from gravity satellite measurements. It is well known that loading deformations can be directly related to time variations of the mass in the atmosphere and ice caps. Since the dynamics of these fluid layers seems to be dominated by the degree 1, a few measurement stations located close to the polar regions would permit to constrain the mass involved by annual surface fluid dynamics. This kind of investigation might be possible in the future with the development of surface network measurements. A first step in that direction is provided by the X-band transponder LaRa (Lander Radioscience) that has been proposed for the ExoMars mission of ESA.

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