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Does Titan's long-wavelength topography contain information about subsurface ocean dynamics?

Jakub Kvorka[a], Ondřej Čadek[a,*], Gabriel Tobie[b], Gaël Choblet[b]

[a] Department of Geophysics, Charles University, Faculty of Mathematics and Physics, V Holešovičkách 2, Praha 8 180 00, Czech Republic
[b] Université de Nantes, Laboratoire de Planétologie et Géodynamique, UMR 6112, 2 rue de la Houssinière, Nantes F-44322, France

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ABSTRACT

The long-wavelength topography of Titan is characterized by relatively small amplitudes (about 1 km peak to peak), an anomalous equatorial bulge (the poles are about 300 m lower than the equator), and small gravity anomalies, indicating a high degree of compensation. In the past years, the nature of Titan's non-hydrostatic topography has been addressed in several studies. The topography has been interpreted in terms of isostatic or viscous models and discussed in connection with tidal heating in the ice shell and surface erosion. Here, we present a model of the shape evolution of Titan's ice shell driven by tidal heating in the shell and spatial variations of the heat flux from a subsurface ocean. The model is obtained by solving a general set of equations coupling the viscoelastic flow of ice with the thermal evolution of the ice shell and phase transitions at the ice/water interface. The equations are solved in a domain with radially varying material properties and moving boundaries. The motion of the boundaries is a consequence of ice flow within the shell, melting and crystallization at the bottom boundary and erosion and deposition at the surface. Our model suggests that Titan's anomalous topographic bulge can be explained by lateral variations of ocean heat flux of the order of 0.1–1 mW m^{-2}, provided that the heat flux is stable over a period of at least 10 Myr and the ice shell has a sufficiently high viscosity, exceeding 10^{16} Pa s at the base of the shell. Such a high value of viscosity implies that either the ice grains are coarse ($\gtrsim$ 10 mm) or the temperature of the ocean is significantly (by more than 40 K) lower than the melting temperature of pure water ice. The heat flux pattern predicted on top of the ocean is consistent with a flow characterized by upwelling of warm water in polar regions and downwelling of cold water at low latitudes. The negative correlation between the topography and geoid at degree 3 reported in a previous study (but not confirmed at higher degrees yet) is shown to be compatible with erosion and deposition occurring at a rate of 0.01–0.1 mm yr^{-1} . Our results underline the importance of gravity and topography measurements for understanding Titan's surface and deep interior processes.

1. Introduction

Saturns largest moon Titan, with its dense atmosphere rich in organics (e.g. Bézard et al., 2014) and a subsurface ocean (e.g. Tobie et al., 2005a; Lorenz et al., 2008; Nimmo and Bills, 2010; Baland et al., 2011; 2014; Béghin et al., 2012; Iess et al., 2012; Hemingway et al., 2013), was one of the primary targets of the Cassini–Huygens mission. Comparison of Titan's gravity field (Iess et al., 2010) with the radar-based topography observations (Zebker et al., 2009; Stiles et al., 2009; Lorenz et al., 2013; Mitri et al., 2014) suggests that the ice crust of the moon is not in hydrostatic equilibrium. Although the observed shape of Titan differs from the hydrostatic reference ellipsoid by several hundred meters, the variations of the gravity field, determined up to degree 3, are small, indicating a high degree of compensation.

Using the approach of Ojakangas and Stevenson (1989), originally developed for modeling ice shell thickness variations on Europa, Nimmo and Bills (2010) explored the concept of Airy isostasy in which spatial changes of ice thickness are caused by lateral variations in tidal heating. They found that the observed topography can be reproduced using a model with average ice crust thickness of about 100 km, in agreement with a heat flux of 4–5 mW m^{-2} corresponding to a chondritic composition, and concluded that Titan's ice shell is in a conductive, rather than convective regime.

An alternative compensation mechanism was suggested by Choukroun and Sotin (2012) who proposed that the observed shape of Titan, characterized by large-scale polar depressions, is

* Corresponding author.
E-mail addresses: kvorka@karel.troja.mff.cuni.cz (J. Kvorka), oc@karel.troja.mff.cuni.cz (O. Čadek), gabriel.tobie@univ-nantes.fr (G. Tobie), gael.choblet@univ-nantes.fr (G. Choblet).

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associated with enhanced ethane precipitation at high latitudes, leading to the accumulation of dense hydrocarbon clathrates in these regions. They showed that the 300 m topographic lows around the poles can be explained by 3-km thick deposits of ethane-rich clathrates, accumulated during the last 300–1200 Myr.

Hemingway et al. (2013) noticed a strong inverse correlation between gravity and topography at long wavelengths that are not affected by tides and rotation. This means that the gravity signal generated by mass anomalies inside the ice crust, or at the ice/water interface, mechanically compensating the topographic load at the surface, must be stronger than the gravity signal generated by the topography itself. The authors interpreted this situation as a consequence of intense surface erosion and deposition and argued for a substantially rigid ice shell with an elastic thickness exceeding 40 km. It should be noted, however, that the gravity field of Titan is known only up to harmonic degree 3 and a further analysis of Cassini data is needed to confirm the negative correlation between gravity and topography at higher degrees.

Lefèvre et al. (2014) investigated the long-term mechanical stability of internal mass anomalies on Titan by using a viscous relaxation model. They showed that deflections at the base of the ice crust are stable only for a conductive, highly viscous ice layer above a relatively cold ($<$ 250 K) ocean, while models with crustal density variations also admit a moderate convection.

In this paper we investigate the relationship between the ice thickness variations on Titan and the thermal evolution of the ice shell driven by spatial variations in the tidal heating generated inside the crust and the basal heat flux associated with thermal convection currents in the ocean. Understanding this relationship is potentially important also for other icy moons with a subsurface ocean because it would allow the topography and gravity data acquired by spacecraft to be interpreted in terms of processes in the deep interior that are inaccessible to direct observation.

The long-term shape evolution of icy moon shells has been studied using different approaches, mostly based on approximations of underlying physical processes (e.g. Ojakangas and Stevenson, 1989; Nimmo et al., 2007; Shoji et al., 2014; Kamata and Nimmo, 2017; Čadek et al., 2017). Here we formulate the problem in terms of general partial differential equations for slow viscoelastic flow of thermally conductive ice, supplemented by an equation describing the phase transition at the ice/water boundary. The equations are solved in a spherical geometry using a spectral method and integrated in the time domain. To avoid the difficulties associated with the physical description of a multiphase system we assume that the system under study consists of pure water, and we neglect the effect of other compounds potentially present in the ice shell and the ocean (Tobie et al., 2014).

The deformation of the ice shell and its thermal history depends on the thermal processes in the ocean which occur on a much shorter time scale than those in ice. The motion of subsurface water is controlled by convection flow driven by the transfer of heat from Titan's silicate core to the surface. This flow is geometrically organized by the Coriolis force and is possibly modulated by tidally-driven flow due to the gravitational pull of Saturn. Tyler (2008) suggested that the dissipation due to the tidal flow in subsurface oceans of some icy moons could lead to significant internal heating. However, as shown by Chen et al. (2014), the amount of the heat produced by ocean tidal heating on Titan is likely to be negligible compared to other heat sources.

Numerical models of thermal convection in subsurface oceans of icy moons are still rare. Soderlund et al. (2014) have studied the ocean flow on Europa for a homogeneous basal heat flux and demonstrated that the heat flux on top of the ocean shows chaotic behavior and is small-scale in nature. However, when averaged in time, the heat flux pattern simplifies and can be represented by large-scale heat flux variations. Furthermore, models of heat transfer within the high-pressure mantle of large icy moons (Choblet et al., 2017a; Kalousová et al., 2017) indicate that the heat flux at the ocean floor is expected to present a strong degree of heterogeneity which is likely superposed on the zonal pattern obtained for a homogeneous basal heat flux (e.g. Goodman et al., 2004; Vance and Goodman, 2009; Goodman and Lenferink, 2012).

In the present study, we do not model the heat transfer and possible heat production in the ocean. Our main objective is to constrain the typical heat flux pattern at the ocean surface by modeling the melting/crystallization process at the ice/water interface and the mechanical response of the ice shell to this forcing. We leave the interpretation in terms of ocean dynamics to future studies.

Titan is the only moon in the outer Solar System the surface of which is extensively modified by erosion and surface-atmosphere exchange (e.g. Neish et al., 2013; Birch et al., 2017). As indicated in the study by Hemingway et al. (2013), erosion and deposition may play an important role in the evolution of Titan's topography, primarily driven by thermal-mechanical processes in the deep interior. In the present study, we use a simple topography-dependent model of erosion to examine how much the predicted topography is affected by transport processes at Titan's surface.

The structure of the paper is as follows: In Section 2, we introduce the equations governing the thermal-mechanical evolution of an ice shell underlain by liquid water and we discuss the boundary conditions at the ice/water phase boundary. We also discuss the simplifications that are necessary for the numerical treatment of the problem. In Section 3, we present the topographic maps obtained for models in which the deformation is only driven by tidal heating in the ice shell. An alternative driving mechanism, the variations in basal heating, is investigated in Section 4 where we also examine the role of erosion and deposition in the evolution of Titan's long-wavelength topography. Both driving mechanisms are considered in Section 5 where we determine the heat flux variations on the top of Titan's ocean that are compatible with the observed long-wavelength topography and we hypothesize about the geometry of ocean circulation. The main results of the paper are summarized and discussed in Section 6.

2. Method description

2.1. Governing equations

We consider an icy moon with an internal ocean of density $\rho_{\rm w}$ and an outer shell made of water ice of density $\rho_{\rm i}$. We assume that the ice is incompressible ($\mathrm{d}\rho_{\rm i}/\mathrm{d}t \approx 0$) and the deformation is very slow so that the inertial forces can be neglected. The conservation laws of mass, momentum and energy governing the evolution of the ice shell can then be expressed as

$$\nabla \cdot \boldsymbol{v}_{\rm i} = 0, \tag{1}$$

$$\nabla \cdot \boldsymbol{\sigma}_{\rm i} - \rho_{\rm i} \nabla V = 0, \tag{2}$$

$$\rho_{\rm i} c_{\rm p} \frac{\partial T_{\rm i}}{\partial t} = \nabla \cdot k \nabla T_{\rm i} - \rho_{\rm i} c_{\rm p} \boldsymbol{v}_{\rm i} \cdot \nabla T_{\rm i} + H, \tag{3}$$

where $\boldsymbol{v}_{\rm i}$ is the velocity of ice flow, $\boldsymbol{\sigma}_{\rm i}$ is the Cauchy stress tensor, V is the potential of external forces, $T_{\rm i}$ is the temperature in the ice shell, t is the time, $c_{\rm p}$ is the heat capacity of ice at constant pressure, k is the thermal conductivity of ice, and H is the volumetric heating rate. We assume that the material of the ice shell behaves as a Maxwell viscoelastic fluid on a long time scale (Joseph, 1990),

$$\boldsymbol{\sigma}_{\rm i} = -p_{\rm i} \boldsymbol{I} + \eta \left[\nabla \boldsymbol{v}_{\rm i} + (\nabla \boldsymbol{v}_{\rm i})^{\tau} \right] - \frac{\eta}{\mu} \frac{\delta \boldsymbol{\sigma}_{\rm i}^{\rm d}}{\delta t}, \tag{4}$$

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