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Numerical simulation of tides and oceanic angular momentum of Titan's hydrocarbon seas

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ABSTRACT

Tides and tidal currents in Titan's hydrocarbon seas are numerically simulated by a 3-dimensional ocean circulation model using a bathymetry map constrained by Cassini. These predictions are used to calculate the tidally induced variations of the oceanic angular momentum of the seas. The tides behave as a quasi-standing wave with anti-nodes at the northern and southern shores. The tidal currents in Kraken Mare are mainly oriented along the major axis of the sea and are dominated by fast hydraulic currents through a narrow strait. The axial oceanic angular momentum primarily changes due to redistribution of liquids in Kraken Mare and maximizes when there is ebb at the northern shore and flood at the southern shore. On the other hand, variations of the equatorial oceanic angular momentum are contributed by both tides and tidal currents. The oceanic torque between sea and sea bottom is minor compared to its atmospheric counterpart, i.e. the mountain torque between atmosphere and mountains.

1. Introduction

Liquid hydrocarbon seas on Titan's surface detected by Cassini (Stofan et al., 2007; Brown et al., 2008; Stephan et al., 2010; Sotin et al., 2012; Mastrogiuseppe et al., 2014) represent one of the three major geophysical fluids on Titan, along with the dense atmosphere and putative deep subsurface water ocean. A major mechanism of fluid motions in Titan seas is the tide raised by Saturn. Tides in seas on Titan's surface have been investigated for a number of motivations: (1) dissipation of Titan's orbital eccentricity by sea bottom friction associated with tidal currents (Sagan and Dermott, 1982; Dermott and Sagan, 1995; Sears, 1995; Sohl et al., 1995; Lorenz et al., 2014), (2) erosive deformation of crater lakes by tidal currents (Lorenz, 1994), (3) oceanographic characterization of tides and tidal currents (Sears, 1995; Tokano, 2010a; Lorenz et al., 2012, 2014), (4) ocean mixing (Lorenz et al., 2014), (5) engineering study for future missions (Lorenz et al., 2012).

An aspect related to Titan's ocean tides that has not been discussed so far is the angular momentum budget. Earth's oceans possess a huge angular momentum, which can be exchanged with the sea bottom and atmosphere and thereby contributes to Earth's rotation variations (Ray et al., 1994). Tides caused by the Moon and Sun are the major cause of the oceanic angular momentum (OAM) variations on Earth on diurnal time scales (Seiler, 1991). While the angular momentum exchange between Titan's atmosphere and surface or deep interior have been addressed in a number of studies (Tokano and Neubauer, 2005; Karatekin et al., 2008; Lorenz et al., 2008; Van Hoolst et al., 2009; Mitchell, 2009; Goldreich and Mitchell, 2010; Tokano et al., 2011; Tokano, 2012; Van Hoolst et al., 2013; Richard et al., 2014), an analogous angular momentum exchange between sea and sea bottom on Titan has not been investigated for want of bathymetry data necessary for the calculation of the OAM. A separate calculation of this quantity is necessary for a comprehensive assessment of Titan's angular momentum variations.

Meanwhile, the geographical distribution of Titan seas has been mapped to a large extent (Lorenz et al., 2014) and the bathymetry is known at least for portions of Ligeia Mare (Mastrogiuseppe et al., 2014), so that a preliminary bathymetry map of all major seas and lakes can be constructed (Lorenz et al., 2014). This makes it possible to calculate the OAM using the predicted tides and tidal currents analogously to the terrestrial OAM (Seiler, 1991; Ponte and Rosen, 1994; Ray et al., 1997). There have already been numerical ocean tide models for Titan in the past, but they assumed a global ocean of uniform depth (Sears, 1995) or were based on simplified, incomplete sea maps (Tokano, 2010a), which are no longer suitable for a realistic OAM calculation.

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The purpose of the present study is to quantify the OAM and oceanic torque on Titan's surface with the output from a numerical tide simulations using a new bathymetry map constrained by the Cassini spacecraft (Lorenz et al., 2014). A numerical approach is necessary for two reasons: (1) there are no observations of tides and tidal currents in Titan seas, (2) the geometry of Titan seas is too complex to estimate the spatial and temporal variations of tides and tidal currents analytically. In Section 2 a model description of the ocean model is given with emphasis on changes made since the model version of Tokano (2010a). Section 3 quantitatively describes the predicted tides and tidal currents in some detail since the calculation of the OAM relies on these predictions and the predictions themselves may be useful for various purposes not discussed in this paper. In Section 4 the OAM of Titan's seas is calculated and characterized. Section 5 discusses the uncertainties of the OAM calculations as well as the prospects of observations of tides in Titan's seas during the remainder of the Cassini mission and by future missions.

2. Model description

2.1. Ocean tide model

Tides and tidal currents are numerically predicted by a 3-dimensional baroclinic ocean circulation model for Titan's seas developed by Tokano (2010a). The dynamical core of the ocean model is based on the Bergen Ocean Model (BOM) (Berntsen et al., 1996; Berntsen, 2004) and details of the model structure and numerical scheme can be found in Tokano (2010a).

The model solves the primitive equations using the hydrostatic and Boussinesq approximation. In the Boussinesq approximation, which is commonly made in terrestrial ocean models, the density is regarded as constant except in terms multiplied by the gravity. This approximation eliminates sound waves, whose phase speed is five orders of magnitude faster than the tidal current in Titan's seas and which would require an extraordinarily small time step interval. The Boussinesq approximation is satisfied as long as the density perturbation is much smaller than the mean density. Density perturbations in oceans can be caused by a variety of mechanisms but in the case of Titan seas it is most essential to make sure that pressure compressibility is negligible. Pressure compressibility is negligible if $gh/c_s^2 \ll 1$, where g is the gravitational acceleration, h is the sea depth and c_s is the speed of sound (Vallis, 2006). In Titan's seas $g = 1.354\ \mathrm{m\,s^{-2}}$, $h < 200\ \mathrm{m}$ and $c_s \sim 1500\ \mathrm{m\,s^{-1}}$, so that $gh/c_s^2 < 1.2 \times 10^{-4}$ and pressure compressibility is negligible in Titan's surface seas, in contrast to the subsurface water ocean, which may be several hundred kilometers deep.

The bottom stress is specified as $\tau = \rho C_D |u_b| u_b$, where C_D is the drag coefficient ($C_D = \max[0.0025, \kappa^2/\ln^2(z_b/z_0)]$), u_b is the sea bottom current, $\kappa = 0.4$ is the von Kármán constant, z_b is the vertical distance of the nearest grid point to the sea bottom and $z_0 = 0.01$ m.

We do not necessarily expect temperature and composition variations to be absent in Titan seas, but simulating these effects requires detailed considerations of light penetration in the sea, evaporation/precipitation of methane and surface wind, which are beyond the scope of the present study. Thus we neglect any density variations in the present study for simplicity. In this case a baroclinic model such as this would not be necessary. However, baroclinic effects such as thermohaline circulation are going to be investigated in a future study, so for practical reasons we use a baroclinic ocean model for this study as well.

The density of the liquid has to be specified in the model, even though the exact chemical composition of Titan seas is unknown. Cassini radar altimetry data from Ligeia Mare, the second largest sea on Titan, are most consistent with liquids that are composed of a mixture of methane and ethane and possibly some nitrogen but without substantial dissolved polar species and suspended materials (Mastrogiuseppe et al., 2014). Considering this observation we arbitrarily assume that the seas are well mixed and consist of 40% CH_4, 40% C_2H_6 and 20% N_2, yielding a density of $\rho = 600\ \mathrm{kg\,m^{-3}}$ at a sea temperature of 91 K.

2.2. Tide-raising force

The tidal forcing is represented by the horizontal gradient of the tide-raising potential in the momentum equations. The tide-raising potential on Titan's surface is calculated after Dermott and Sagan (1995) and Tyler (2008) as a function of time, colatitude and longitude. It consists of radial and librational tides of Saturn as a result of Titan's eccentric orbit and of Titan's obliquity tides (with an obliquity of 0.3°). The tide-raising potential varies with a period of one Titan day (15.9454 days). In the case of Titan the maximum obliquity tidal potential is 12 times smaller than the maximum radial and librational tidal potential. For simplicity, other mechanisms of ocean circulation (wind, precipitation/evaporation, melting of icebergs etc.) are not taken into account in this study.

In the calculation of the effective tide-raising potential in the seas the tidal deformation of the underlying sea bottom, which in the case of Titan is the ice shell, has to be taken into account analogously to terrestrial ocean tide models (e.g. Seiler, 1991). The correction is done by multiplying the tide-raising potential by the Love number reduction factor $\gamma_2 = 1 + k_2 - h_2$, where k_2 is the degree-2 tidal potential Love number and h_2 is the degree-2 radial displacement Love number. γ_2 depends on the interior structure of Titan. It is most sensitive to the thickness of the ice shell above the subsurface ocean of Titan, but also strongly depends on the rigidity of the ice shell. For a shell rigidity of 3.3×10^9 Pa (e.g. Sotin et al., 1998), it varies between almost zero for extremely thin shells to values of about 0.2 for a shell thickness of 200 km (Fig. 1). For a shell rigidity reduced by a factor of ten with respect to the standard value, γ_2 remains below 0.1. The factor γ_2 decreases with decreasing shell thickness and decreasing shell rigidity because the behavior then tends more to that of the liquid case for which $\gamma_2 = 0$. We here choose $\gamma_2 = 0.1$ as a baseline case, yet one simulation is also done with $\gamma_2 = 0.2$, which is representative of Titan with a 200 km thick ice shell above the subsurface ocean.

For comparison the Titan ocean model of Sears (1995) used $\gamma_2 = 0.853$ (with $k_2 = 0.22$ and $h_2 = 0.367$) assuming no subsurface ocean.

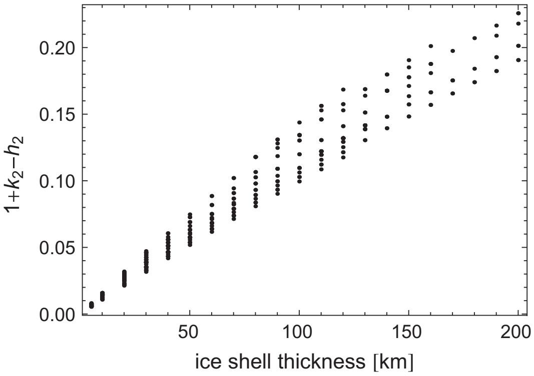

Fig. 1. The Love number reduction factor $\gamma_2 = 1 + k_2 - h_2$ as a function of ice shell thickness for a set of interior structure models of Titan (see Baland et al. (2011)) with shell rigidity equal to 3.3×10^9 Pa. The Love numbers are calculated in the static and incompressible approximation as e.g. in Wahr et al. (2006). We solve for the Love numbers by using standard methods described e.g. in Section 3.1 of Sabadini and Vermeersen (2004). Only those interior structure models are retained that satisfy the observed moment of inertia of $C/MR^2 = 0.3431 \pm 0.0004$ and Love number $k_2 = 0.589 \pm 0.159$ (Iess et al., 2012).