ICY SATELLITE SUBSURFACE OCEANS: TIDAL DYNAMICS, DISSIPATION, AND THE SOLID SHELL
Hamish C. F. C. Hay[1] and Isamu Matsuyama[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, United States (hhay@lpl.arizona.edu).

Introduction: The interiors of icy satellites with subsurface oceans are puzzling environments. How to produce enough thermal energy to prevent these oceans from freezing is one of the many unanswered questions revolving around worlds like Enceladus, Titan, and Europa.

It is well established that the action of tidal forces due to a satellite's obliquity or eccentricity can provide non-negligible to significant amounts of heat to the thermal energy budget of icy moons [e.g., 1]. These tides act to deform the entire satellite on a diurnal timescale, causing energy to be dissipated in the interior as heat through mechanical friction. Such dissipation occurs in the solid [eg., 2] and liquid regions of the satellite [e.g., 3-6].

In this work, we investigate fluid dissipation in Enceladus due to the action of tides. The presence of a rigid ice layer overlying the ocean is modelled using the membrane approximation of [7]. Dissipation is modelled through either linear or quadratic drag. The former is applied to verify the numerical code against existing literature, and the latter is used to provide what is thought to be a more realistic approach to drag in turbulent fluids. It should be stressed, however, that the dissipation mechanism in icy satellite oceans is an unknown. Quadratic drag can only be applied using a numerical method.

Numerical model: We numerically solve the Laplace Tidal Equations (LTEs) describing depth-integrated momentum and mass conservation in a thin, rotating fluid shell [7];

$$\partial_t \eta + \nabla \cdot (h\boldsymbol{u}) = 0 \tag{1}$$

$$\partial_t \boldsymbol{u} + 2\boldsymbol{\Omega}\times\boldsymbol{u} + \alpha\boldsymbol{u} + \frac{c_D}{h}|\boldsymbol{u}|\boldsymbol{u} + \frac{1}{\rho_o}\nabla P = (1 + k_2 - h_2)\nabla U_2 \tag{2}$$

Here, η is the ocean surface displacement about the equilibrium tide, h is the ocean thickness, $\boldsymbol{u}$ is the horizontal velocity vector, and $\boldsymbol{\Omega}$ is the angular velocity of the satellite. Linear and quadratic drag coefficients are denoted as α and c_D respectively. The ocean density is ρ_o and the ocean pressure is P. g is the satellite's surface gravity and k_2 and h_2 are the degree-2 tidal Love numbers. The gradient of the tidal potential, U_2, is an applied force which is enhanced by Love's reduction factor, $1 + k_2 - h_2$ [7].

The ocean we model is global, has constant thickness and is incompressible. For Enceladus the incompressibility constraint is well justified given the small size of the satellite. [9] have shown that there are extreme variations in the thickness of Enceladus' ice shell (and ocean), casting doubt on the assumption of a constant thickness ocean. Relaxing this assumption complicates the problem significantly and can only be solved numerically. We shall investigate this in future work.

To model the effect of an overlying ice shell on the ocean, we have incorporated the massless membrane approximation from [7]. We verify our model against [7] using linear drag, before exploring ocean dissipation with the more realistic quadratic drag model.

A finite-difference model on a regular latitude-longitude grid was developed in [6] to solve the LTEs while neglecting the ice shell. For this work we employ a far more powerful and robust model that applies a finite-volume solver over an unstructured geodesic grid (figure 1). The benefits of such a model will not be detailed here, but the new model has undergone the same testing as applied in [6] and has performed excellently.

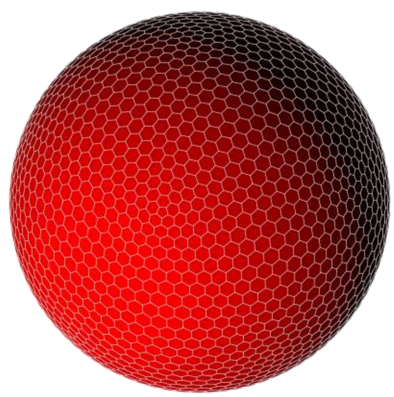

Figure 1. The icosahedral-geodesic grid.

Simulations: A variety of simulations have been run for Enceladus, varying the thickness of the ocean from 1km to 50km. For each ocean thickness explored, we use an ice shell thickness of 1km, 10km, and 25km. These values cover a range of shell thickness from that expected at the south pole, to the mean global thickness [9]. Firstly, we run simulations exploring only linear drag and compare to the results from [7], shown in Figure 2.

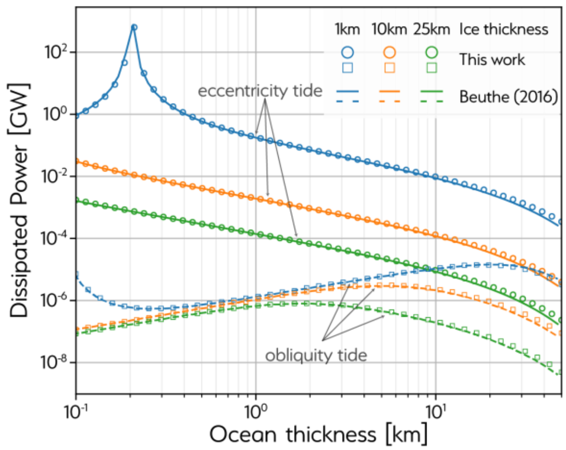

Figure 2. Dissipated energy in Enceladus' ocean as a function of the ocean and ice shell thickness for both the eccentricity and obliquity tides using $\alpha = 10^{-6}$ s^{-1}. Solid and dashed lines are semi-analytical solutions from [7], and circles and squares are numerical results from this work. The different colours represent different ice shell thicknesses.

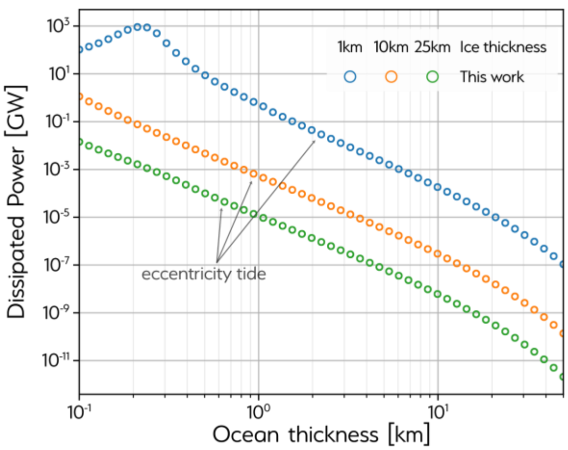

Figure 3. Same as figure 2, but for quadratic drag and without the obliquity tide.

Clearly, our numerical method accurately recreates the solutions of [7] using linear drag. The maximum error in our solution is below 5%, with the worst errors occurring for the thickest oceans. There is no ocean thickness where obliquity tide dissipation exceeds that of the eccentricity tide.

Results for the eccentricity tide using quadratic drag are shown in Figure 3. As quadratic drag depends more sensitively on ocean velocity, there is a much larger variation in ocean dissipation, and for the thickest oceans tidal dissipation from quadratic drag is negligible.

Conclusions: We investigate tidal dissipation in Enceladus' subsurface ocean using a finite-volume method. Using the thin shell membrane theory of [7] and linear drag, our numerical model is shown to have excellent agreement with semi-analytical solutions [7].

Ocean dissipation using quadratic drag is also investigated using our model, as such a drag regime can only be applied numerically. As anticipated, in the quadratic drag regime we find that there is a much more extreme variation in ocean dissipation between thin and thick oceans than compared to the linear drag regime. For a nominal ocean thickness of 38km on Enceladus, ocean dissipation via quadratic drag is negligible. In the future, other modes of fluid dissipation must be considered to fully understand tidal heating in icy satellites oceans [8].

Part of our future work will focus on a purely numerical scheme to couple the physics between fluid ocean and overlying solid ice shell. Approaching this numerically will allow us to investigate the interesting scenario of a variable thickness ocean and ice shell of arbitrary thickness.

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References: [1] Peale, S.J., et al. (1979) *Science*, *203*, 892-894. [2] Tobie, G., et al. (2005) *Icarus*, *177*, 534-549. [3] Tyler, R. (2011) *Icarus*, *211*, 770-779. [4] Matsuyama, I. (2014) *Icarus*, *242*, 11–18. [5] Chen, E. M. A. et al. (2014) *Icarus*, *299*, 11-30. [6] Hay, H. C., & Matsuyama, I. (2017) *Icarus*, *281*, 342-356. [7] Beuthe, M. (2016) *Icarus*, *280*, 278-299. [8] Egbert, G. D., & Ray, R. D. (2000) *Nature*, *405*, 775-778. [9] Beuthe, M., et al. (2016) *Geophysical Research Letters*, *43*.