# Tidal Dissipation in the Subsurface Oceans of Icy Satellites.

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## Introduction

Observations from the Galileo and Cassini missions suggest that several satellites contain subsurface oceans. Magnetic field data from the Galileo mission indicate electromagnetic induction by Europa, Ganymede, and Callisto; suggesting a layer of liquid salty water beneath their surfaces [1, 2, 3, 4]. Assuming that Titan's obliquity has been tidally damped to a Cassini state (a configuration in which the spin and orbit poles coprecess and remain coplanar with the ecliptic pole), the observed obliquity suggests a decoupling of the outer ice shell by a subsurface ocean [5, 6]. This is consistent with coupled thermal and orbital calculations suggesting the presence of a subsurface liquid ammonia-rich layer [7]. Analysis of data from the Cassini mission constrains the composition of particles ejected from fissures across Enceladus south pole. These constraints support models with a subsurface liquid water reservoir [8, 9].

Dissipation of tidal energy is an important mechanism for the evolution of outer solar system satellites. By analogy with Earth, one might expect that oceanic dissipation would dominate the energy loss. However, the majority of studies considering tidal dissipation in outer solar system satellites assume that dissipation occurs only in their solid regions [10, 11, 12, 13, 14, 15]. Sagan and Dermott [16] and Sears [17] consider tidal dissipation in a surface ocean on Titan. However, both of these studies assume a surface, not a subsurface, ocean. Tyler [18, 19, 20] illustrates that tidal flow in a global ocean can be resonantly enhanced, significantly increasing tidal dissipation. However, these studies assume that the presence of an overlying ice shell has a negligible effect, and therefore they are strictly applicable only to surface, not subsurface, oceans.

We extend the work of Tyler [20] by taking into account the effect of an overlying ice shell on the ocean flow and the corresponding dissipation of the ocean's kinetic energy. We consider tidal dissipation in a subsurface ocean of Enceladus; however, the formalisms are general enough to consider tidal dissipation in other satellites.

## Application to Enceladus

The heat flow emanating from Enceladus' south polar terrain has been estimated to be $15.8 \pm 3.1$ GW using Cassini infrared data [21]. A finite orbital eccentricity causes the tidal bulge to librate in longitude, and a finite obliquity causes the tidal bulge to librate in latitude. Thus, finite eccentricity, finite obliquity, or the combination of both results in dynamic displacements of the subsurface ocean. The orbit of Enceladus has a forced eccentricity, $e = 0.0047$, due to a resonance with Dione. Although there are no measurements of Enceladus' obliquity, under the assumption that energy dissipation has driven the spin pole to a Cassini state, the obliquity must be $< 0.0027°$ if the outer ice shell is decoupled due to a global subsurface ocean, or smaller if the outer ice shell is not decoupled [22]. We adopt $0.0027°$ as an upper limit.

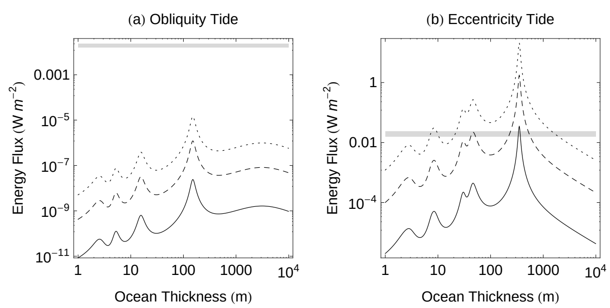


**Figure 1:** Average dissipated energy flux, $F$, due to the obliquity and eccentricity tides as a function of ocean thickness. Dotted, dashed, and solid lines correspond to overlying shell thicknesses $h_s = 0$ km, 10 km, and 100 km respectively. We assume $Q = 10$ in all cases. The shaded region highlights the observed, globally averaged, heat flux of $20 \pm 4$ mW m$^{-2}$ [21].

Figure 1 shows the dissipated energy averaged over the surface and the tidal periodflux as a function of ocean thickness for different ice shell thicknesses assuming a tidal quality factor $Q = 10$. The maxima correspond to ocean thicknesses for which the tidal flow is resonantly enhanced. The dissipated energy decreases as the thickness of the overlying ice shell increases, as expected since the tidal displacement is smaller for a thicker overlying ice shell.

Some of the resonant peaks in Figure 1b for the eccentricity tide have energy fluxes that are large enough to explain the observed average heat flux. However, as Chen and Nimmo [22] noted, tidal dissipation due to the obliquity tide is unlikely to explain the heat flux emanating from Enceladus' south polar terrain, even without an overlying ice shell (Figure 1a).

Figure 2 shows the average dissipated energy flux due to the obliquity and eccentricity tides as a function of

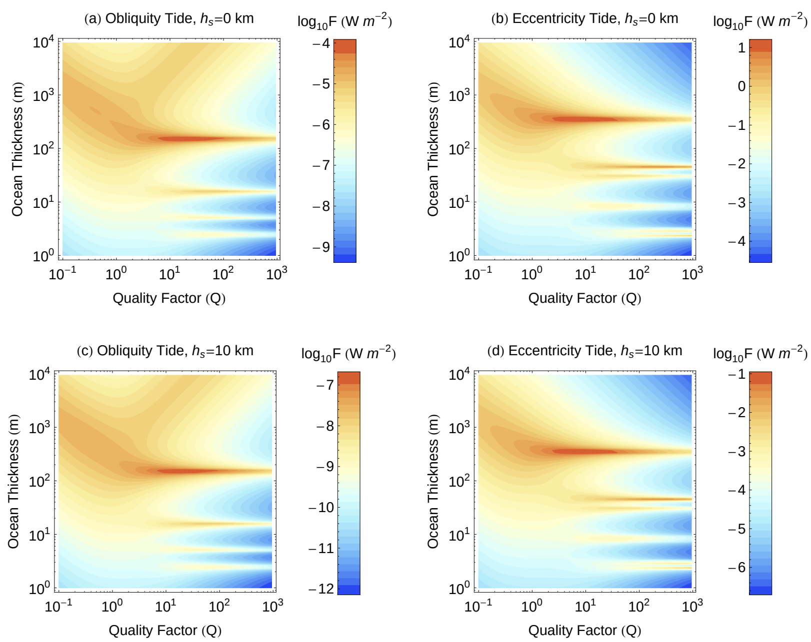


**Figure 2:** Average dissipated energy flux, $F$, due to the obliquity and eccentricity tides as a function of the quality factor and ocean thickness for different thicknesses of the overlying shell, $h_s$, as labeled on each panel.

the quality factor and ocean thickness. Once again, the maxima correspond to ocean thicknesses for which the tidal flow is resonantly enhanced, and the dissipated energy flux decreases if the presence of an overlying shell is taken into account. Somewhat counterintuitively given the definition of the tidal quality factor, the maximum energy flux does not correspond to the smallest quality factor. Energy is dissipated more efficiently as the quality factor decreases. However, fluid motions also decrease in this case, reducing the ocean's kinetic energy available for dissipation. The maximum energy flux corresponds to quality factors in the range $1 \lesssim Q \lesssim 100$. This range includes values similar to Earth's tidal effective $Q \sim 10$ [23].

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