**OCEAN-ICE SHELL COUPLING AND NONLINEAR TIDAL DISSIPATION IN OCEAN WORLDS** 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:** Ocean tides in icy moons can dissipate tidal energy through turbulence at the macroscale. This source of heating has been studied in the last decade while neglecting the effect of an ice shell [e.g., 1–4]. Here, we report on our recent study [5] where we numerically simulate subsurface ocean tides using *nonlinear* bottom drag, as is used on Earth [e.g., 6], and include the effects of an ice shell using the Love number theory from [7]. Our model was applied to icy satellites with evidence of subsurface oceans where we explore how coupling the ocean and ice shell impact ocean tidal heating.

**Numerical Model and Methods** We simulated subsurface ocean dynamics coupled to an elastic ice shell on Enceladus using our code Ocean Dissipation in Icy Satellites (ODIS) [4, 5]. The ocean and ice shell thickness were varied over a range of values to investigate the effect of the ice shell on energy dissipation. These results were then used to benchmark a series of energy dissipation scaling laws that we have extended from [3] to include coupling with an overlying ice shell [5].

**Results and Discussion:** The ocean responds very differently to eccentricity and obliquity forcing [e.g., 3, 5, 8]. Eccentricity-forcing predominately creates gravity waves at the ocean surface. The mechanical restoring force of the ice shell increases the propagation speed of these waves which reduces the phase lag between the tidal response and forcing. This lowers the amount of tidal dissipation. In contrast, the ocean response to obliquity forcing is through Rossby-Haurwitz waves [8]. These waves are largely non-divergent, so the ice shell can only affect such waves through self-gravity. This increases the amount of tidal dissipation in the ocean.

In Figure 1 we see that for the small satellites, Dione and Enceladus, the ice shell severely reduces eccentricity tide heating due to the ice shell's mechanical suppression. In contrast, obliquity tide heating increases with the addition of an ice shell, due to the satellite's enhanced self-gravity, although the increase is generally small.

For large satellites, the effective rigidity is small enough that the dominant ice shell effect is self-gravity, resulting in an overall increase in tidal dissipation for both eccentricity and obliquity forcing. Triton is the only satellite where this is not the case because its obliquity forcing is likely large enough to produce gravity waves in the ocean response, where the ice shell's mechanical suppression begins to take effect.

**Conclusions:** The two main ice shell effects, mechanical suppression (enhanced restoring force) and self-gravity, were shown to have opposite effects on subsurface ocean tidal dissipation. Mechanical suppression dominates on high rigidity small satellites like Enceladus and Dione where eccentricity tide heating is reduced, but is far weaker on large satellites, where eccentricity tide dissipation increases. In general, obliquity tides are unaffected by the shell's mechanical suppression which allows obliquity-forced heating to increase from self-gravity. Overall, we find that the amount of nonlinear tidal dissipation within these oceans is small, except for Triton and perhaps Titan. Obliquity tides remain [3] as the dominant source of fluid dissipation in icy satellites.

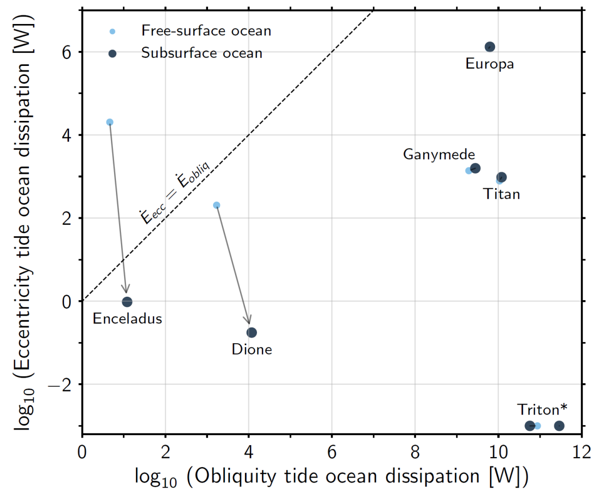


Figure 1: The ice shell effect on a variety of icy satellites. The ice shell is neglected in the blue dots, and included in the black dots. Note that Triton has zero eccentricity, but is plotted for illustration. Taken from [5].

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