MODELING THE DYNAMICS OF ICY SATELLITE SUBSURFACE OCEANS WITH FOCUS ON IMPLICATIONS FOR SPACECRAFT OBSERVABLES. E.M.A. Chen[1], G.A. Glatzmaier[1], and F. Nimmo[1], [1]Department of Earth and Planetary Sciences, University of California Santa Cruz, Santa Cruz, CA 95064, (echen@pmc.ucsc.edu).

Introduction: Observations from the *Galileo* and *Cassini* spacecraft suggest that subsurface global water oceans are likely present on multiple icy satellites of Jupiter and Saturn. With the exception of Titan, the main evidence for satellite subsurface oceans arises from the induction signature generated by the presence of a conductor (presumably a saline ocean) in a time-varying magnetic field [1]. With flyby measurements alone, it is difficult to characterize the subsurface oceans further.

The effect of tides on the icy satellites have been studied extensively in the context of tidal heating in the ice shell [2,3]. However, the effect of a time-varying tidal potential on the behavior of the ocean underneath the ice shell has been looked at only in limited contexts [4]. We have modeled the large-scale ocean behavior subject to a time-varying tidal potential in 2-D using classical nonlinear shallow water theory [5] and in 3-D using a numerical magnetohydrodynamics code [6]. We analyze the results of these models in the context of spacecraft observables: the spatial and temporal variation in the magnetic and gravitational fields, and variability in ice shell rotation.

Models:

Numerical 3-D MHD model. We employ a model that solves a coupled nonlinear system of equations that describes conservation of mass, momentum and energy and the induction of the magnetic field. While there is the ability to account for density stratification, we have presently made the Boussinesq approximation in the model. We calculate the 3-D time-dependent fluid velocity, magnetic field, density, pressure and temperature within the ocean. This solution provides the ability to analyze the aforementioned fields both spatially and temporally.

Characteristics of subsurface oceans are currently fairly unconstrained. Thus, the model has been run with varying parameters (e.g. heat flux, buoyancy, density stratification, conductivity) to determine the effects on the observables.

Semi-analytic 2-D shallow water model. Because the ocean depth is likely relatively small compared to the radius of any of the icy satellites, we have also employed a 2-D (integrated in the radial direction) shallow water model, similar to [5], but with an additional tidal forcing term and an optional viscous drag. Weak nonlinearity is introduced as the product of forced solutions as in [7]. The primary objective of this approach is to understand the spatial and temporal behavior observed in the full 3-D simulations.

Magnetic Fields: Both Jupiter and Saturn have strong magnetic fields. The Gailean satellites are subject to a time-varying magnetic field because Jupiter's magnetic axis is not aligned with the orbital plane. This variability induces a magnetic field in the satellites that has been detected by *Galileo* [1]. In theory, the induced field in the subsurface ocean should also have an additional component, following from the induction equation:

$$\frac{\partial \underline{B}_{ind}}{\partial t} = \underline{\nabla} \times (\underline{v} \times (\underline{B}_P + \underline{B}_{ind})) - \underline{\nabla} \times (\eta \underline{\nabla} \times \underline{B}_{ind}) - \frac{\partial \underline{B}_P}{\partial t}$$

The first term on the right hand side is the induction contribution due to the moving fluid ($\underline{v}$ represents the fluid velocity); the second terms represents diffusion, where η is a magnetic diffusivity; the third term is the time-varying external field. The third term dominates in the case of the field of the Galilean satellites; however, Saturn's magnetic field is nearly aligned with its rotation axis, and thus, this term contributes less significantly to any induced field for the Saturnian satellites.

While the fluid motion is small, the frequency of the field signal is different from the dominant signal. The fluid flows are driven primarily at the orbital frequency, while the external field varies on the primary's rotational period. Current spacecraft data are unable to give insights into the frequency content of satellite magnetic fields; however, future orbiters, like the proposed *Jupiter Europa Orbiter*, will likely be able to provide more continuous data. Preliminary results from simulations show that in the case of Europa, the induced field is composed primarily of an equatorial dipole that oscillates with the rotation period of Jupiter, as expected [1]. There is also an additional signal, albeit with much smaller amplitude, due to ocean circulation (see Figure 1).

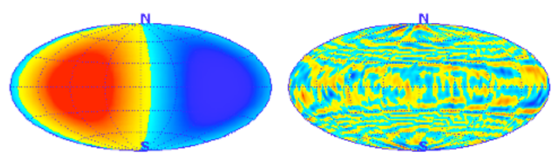

Figure 1: Snapshots of the radial component of the induced magnetic field at Europa's surface. (left) Equatorial dipole due to Jupiter's rotation (9.5 nT) (right) Non-dipole component due to ocean circulation (0.3 nT).

Shape variability: For subsurface oceans, the tidal forcing occurs at two spherical harmonic modes, the *m=0*, *l=2* mode and the *m=2*, *l=2* mode [8]. In general, the tidal potential will deform the shape of the satellite in these modes and in the ice shell and the silicate core, this will lead to tidal heating. The ocean will similary react to the tidal potential, but additionally, due to Coriolis forces and nonlinear advection, there will be deformation and flow in other modes. Results from shallow water dynamics (see Figure 2) show that the time-varying tidal potential can generate gravity waves that alter the shape of the ocean. These short-period gravity waves originate in the forcing modes and are coupled via Coriolis forces to other modes.

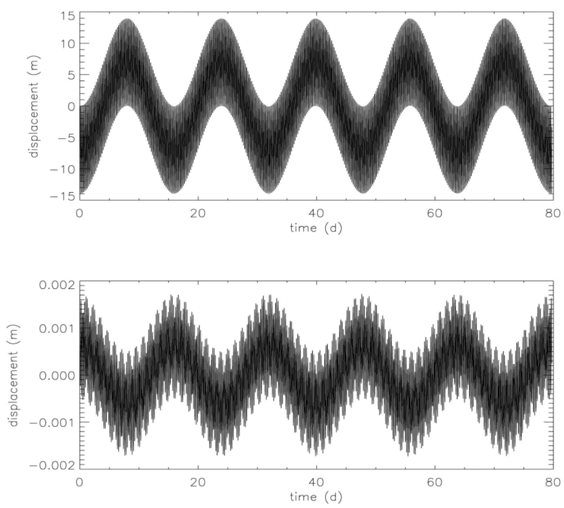

Figure 2: (top) Spherical harmonic mode *m=0, l=2* surface response to tidal forcing from the shallow water model for a subsurface ocean in Titan. A high-frequency surface gravity wave (period = 0.20 d) is superimposed on top of a wave oscillating with the orbital frequency (period = 15.95 d). (bottom) Spherical harmonic mode *m=0, l=4* surface response to tidal forcing only in the *m=0, l=2* mode. The two modes are coupled via Coriolis forces and exhibit the same peaks in their power spectra.

Torques on the Ice Shell: The presence of an ocean decouples the ice shell from the solid interior, and nonsynchronous rotation (NSR) of the ice shell relative to the interior is a possibility. It has been suggested that NSR may explain the fracture patterns on Europa [9]. Large-scale ocean circulation underneath the ice shell likely generates viscous torques and may affect the NSR of the ice shell.

From preliminary 3-D simulations, the spatially integrated torque on the ice shell due to the ocean circulation oscillates on the orbital period (see Figure 3). Additionally, time series analysis of the simulation data suggests that a nonlinear effect produces a variation of the torque on a longer timescale. Tidal torques or elastic torques may eventually force the total NSR towards zero [10,11], but ocean torques may force some NSR on shorter timescales and generate signficant .

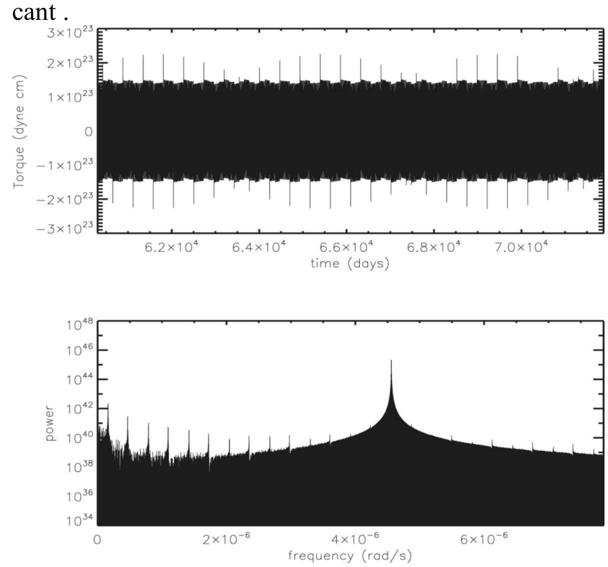

Figure 3: (top) Spatially averaged torque on the ice shell over 750 orbits. (bottom) Power spectrum for the torque, with peaks occurring at the orbital frequency and a longer frequency (~30 orbital periods, 1.6x10-7 rad/s).

Discussion and Future Work: Subsurface oceans within icy satellites are forced by a time-varying tidal potential and respond to this potential through the fluid dynamics equations. We have presented results from preliminary simulations, primarily to illustrate how spacecraft observables may be affected by subsurface ocean circulation. The circulation is likely to be indicative of important ocean parameters such as basal heat flow or ocean depth. We plan to carry out a full parameter exploration to quantify the response of a subsurface ocean to varying ocean parameters.

References: [1] Khurana K. K. et al. (1998) *Nature, 395*, 777-780. [2] Segatz M. et al. (1988) *Icarus*, *75*, 187-206. [3] Tobie G et al. (2005) *Icarus*, *177*, 534-549. [4] Tyler R. (2008) *Nature, 456*, 770-772. [5] Longuet-Higgins M. S. (1968) *Phil. Trans. R. Soc. Lond. A, 262,* 511-607. [6] Glatzmaier G. A. (1984) *J. Comput. Phys., 55,* 461-484. [7] Glatzmaier G. A. and Gilman P. A. (1982) *Astrophys. J. Suppl., 47,* 103-116. [8] Kaula W. M. (1964) *Rev. Geophys., 2,* 661-685. [9] Geissler P. E. et al. (1998) *Nature*, *391,* 368-370. [10] Greenberg R. and Weidenschilling S. J. (1984) *Icarus, 58,* 186-196. [11] Goldreich P. M. and Mitchell J. L. (2009) *Icarus,* submitted.