HYDROTHERMAL FLOW WITHIN ENCELADUS. B. J. Travis[1] and G. Schubert[2], [1]Computational Geosciences Group, EES-16/MS-J535, Los Alamos National Laboratory, Los Alamos, NM 87545, bjtravis@lanl.gov; [2]Earth and Space Sciences Dept. and IGPP, University of California, Los Angeles, CA, schubert@ucla.edu.

Introduction: Results of our previous differentiation study of Enceladus [1] indicate that if TDH (tidal dissipative heating) were operating throughout Enceladus' history, the interior, although now much cooler than immediately after differentation, could remain unfrozen to the present time. Those simulations use radiogenic heating, a simple TDH model and thermal transport, but do not include any fluid flow processes. A numerical simulation using a recently-developed whole-moon simulator [2] indicates that hydrothermal flow in the interior of Enceladus could dramatically change the ice shell thickness resulting in a restricted region of convective flow at each pole. The simulation described here is part of a recently-begun study to estimate under what conditions, if any, an ocean layer could persist on Enceladus, with or without TDH.

Baseline Simulation: The simulation geometry is 2-D spherical (radius and latitude). The global density of Enceladus is low. If Enceladus began as a 'dirty snowball', the porosity would have been high. After differentation, a silicate core of about 160 km radius, overlain by an H_2O layer out to 250 km radius, results [1]. Our model includes porous flow in the silicate core. Gravity is a function of radius. Surface gravity is very low, about 0.11 m/s^2. Peak pressures in the interior should therefore be low, not exceeding roughly 150 bars. That corresponds in the earth to a depth of only about 0.7 km. Permeability and porosity would not be expected to diminish much under such weak gravity, and are assumed constant in this model. We assume a porosity of 10% and a permeability of 0.1 darcy as baseline values for the core. Flow in the ocean is represented by a simplified Navier-Stokes model. Surface temperature distribution approximates observed values, and includes the anomalously high temperature at the south pole. In this 'cool' model, the initial temperature of the silicate core is only 100 C, and the initial ocean temperature is 1 C. Flow is triggered by a random perturbation to the initial temperature field. In this baseline simulation, TDH is operative. Our TDH model is simpler than the detailed computations described in [3], but does include a latitudinal dependence and a radial dependence. Ice viscosity is temperature dependent, and each radial grid cell is further subdivided into five thinner zones to capture viscosity variation. Thermal conductivities in the ice shell and ocean layer are parameterized by effective Rayleigh numbers. Radiogenic heating in the silicate core from long-lived radionuclides produces about 0.3 GW in the model, in agreement with estimates for Enceladus [3]. Salts and/or NH3 may be present in the interior of Enceladus, and strongly influence freezing; our model includes salt transport. We are using $CaCl_2$, a low-temperature (-52 C) eutectic salt, as an analog for NH_3 or whatever salt combinations might be present. The initial salt concentration in the ocean layer and the core pore water is set to 5%, but gradually increases to around 25% as the interior cools and the ocean volume contracts (the eutectic concentration for $CaCl_2$ is 32%). The ice shell is assumed to be 15 km thick initially. The ice shell is not required to remain fixed, but can change dynamically, both radially and latitudinally in response to local thermodynamics.

Simulation results: Initially, a flow field develops characterized by sinking flow at the equator and rising plumes at the poles. By 20 Myr after start-up, a quasi-steady condition has developed. A broad thickening of ice in the equatorial region occurs, so much so that flow is gradually restricted to the polar regions, with the south pole flow stronger than at the northern pole, because of the higher surface temperature imposed at the south pole. A feedback develops; cooler, sinking flow at the equator results in thickening of the ice there which in turn tends to isolate flow to the deeper ocean+core region at the poles. Figures 1 and 2 plot the temperature and ice fraction in the model domain at 50 Myr after start-up. Except at the surface, a nearly cylindrical region from north to south through the model remains fluid. The presence of salt allows liquid conditions and flow even though the ocean temperature is well below 0 C. The transition from ice shell to liquid ocean is not sharp; a thin slushy brine layer is present at the base of the ice shell. The amount or species of salt and degree of radiogenic heating would impact the rate at which the ice shell freezes, but would likely not change the patterns seen here, only their timing. Further, if the core were initially hot enough to melt, a latent heat reservoir would have existed, slowing the cooling of the interior. An approximately 70 km thick difference in ice thickness exists between equator and poles. However, due to the low gravity of Enceladus, this would give rise to a buoyant pressure difference of only about 5 bars. If the ice is anchored at the equator, as it appears to be, at least partially, it is not clear what the mechanical implications are of this ice thickness differential. After 50 Myr, the ice shell is continuing to thicken in the equatorial regions, but only very slowly. As the interior cools further over time, the salt concentration in the ocean and core pores will increase towards the eutectic, resisting the advancing freezing front. The core is slowly cooling, and eventually the ocean may freeze completely, but it is clear, at least in this model, that it will take a very long time for that to happen, on the order of 100-200 Myr or more. If episodes of strong TDH occurred on that time scale or shorter, a polar ocean might then persist indefinitely.

We consider this simulation as suggestive of possible dynamics and tendencies. The present model, with flow, results in a colder interior than our previous no-flow study [1]. Convective flow will transport heat faster from the interior than just conduction, but the trade-off here is the very non-uniform ice thickness that results. Our model does not provide a mechanism for restricting dynamics to just the south pole; here we see restriction of flow to both poles, with a somewhat stronger flow at the south pole reflecting the temperature anomaly there. Previous model studies (such as [3]) apparently fix the ice shell thickness to a uniform value. Here, where it is free to respond to changing local as well as global conditions, flow induces a dramatic change in the ice distribution. That could strongly affect TDH production. This numerical simulation is a baseline in a larger study to explore under what conditions, if any, an ocean could persist on Enceladus.

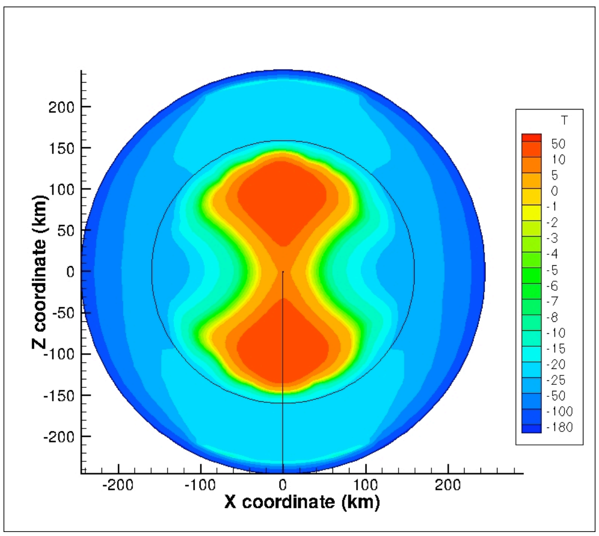

Figure 1 Temperature distribution in Enceladus model at 50 Myr after start-up. A quasi-equilibrium state has developed. Residual heat plus radiogenic heating in the core plus inclusion of salt allow convective flow through the ocean and permeable core to continue for a long period of time, even at sub-zero temperatures.

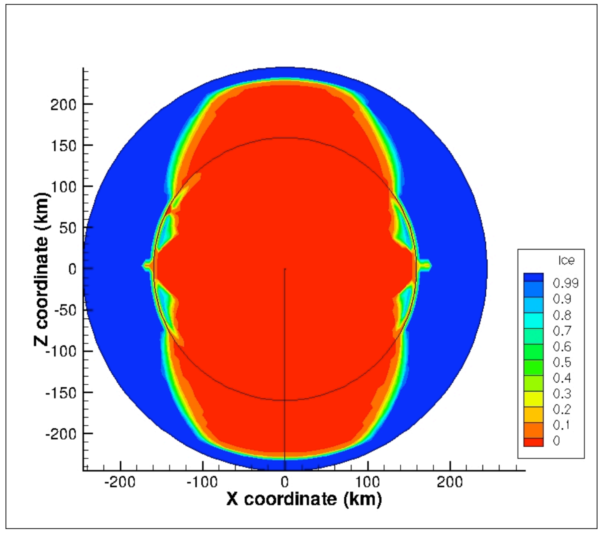

Figure 2 Ice distribution in our Enceladus model at 50 Myr after start-up. In this quasi-equilibrium state, only the polar ocean regions are unfrozen except near the surface. The equatorial region is frozen almost down to the core/mantle interface. The silicate core is ice free, except for small regions near the equator.

References: [1] Schubert et al (2007) *Icarus 188,* 345-355. [2] Travis B. J., Palguta J. and Schubert G. (2012) *Icarus,* submitted. [3] Roberts J. H. and Nimmo F. (2009) *Icarus 194,* 675-689.