

COUPLED CONVECTION AND TIDAL DISSIPATION IN EUROPA'S ICE SHELL: 2. NON-NEWTONIAN VISCOSITY. L. Han¹ and A.P. Showman², ¹Planetary Science Institute, 1700 E Fort Lowell, Suite 106, Tucson, AZ 85719. han@psi.edu, ²Department of Planetary Sciences, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721.

Introduction: Europa's surface displays a wide range of tectonic features — uplifts, pits, chaos, and ridges. Heterogeneous tidal heating coupled with thermal convection has been suggested as a mechanism to generate these features [1-3]. Many authors have performed numerical simulations of convection to study thermal evolution in Europa's ice shell [2-6]. Most of these simulations consider tidal heating as a constant or dependent only on local temperature, estimated by an isothermal Maxwell model [3-6]. However, the tidal dissipation depends not only on local temperature, but also on surrounding temperature [7]. To self-consistently determine how convection interacts with tidal heating, Han and Showman (2009) [8] coupled simulation of oscillatory tidal flexing (using Tekton) to long-term simulations of thermal convection (using ConMan) assuming a Newtonian rheology. Their results show that heterogeneous tidal heating can significantly influence the long-term thermal evolution.

The viscous rheology of ice follows a power-law relationship [9-10]. Thermal convection (without tidal heating) in icy satellites can be very complicated if non-Newtonian rheology is used [11-12]. However, previous studies of convection using non-Newtonian rheology have not included tidal dissipation. Non-Newtonian rheology can strongly impact the tidal dissipation due to the non-linear relationship between strain rate and stress. Here, we present fully coupled simulations of convection and tidal heating [8] to understand the impacts of non-Newtonian rheology on convection and tidal heating.

Model and Methods: Our simulations include two processes: thermal convection and oscillatory tidal flexing, which we self-consistently couple (see the detailed description in [8]). We run the simulations in 2D Cartesian (rectangular) geometry. Cartesian geometry is appropriate for regional studies of Europa's ice shell because Europa's ice-shell thickness is much smaller than its radius.

To model the convective evolution, we use the finite-element code ConMan [13] to solve the dimensionless equations of momentum, continuity, and energy for a viscous fluid. The viscous rheology of ice can be defined as a power-law relationship [9-10].

$$\dot{\epsilon} = A \frac{\sigma^n}{d^p} \exp\left(-\frac{Q}{RT}\right) \quad (1)$$

where $\dot{\epsilon}$ is strain rate, A is a material constant, σ is stress, n is the stress exponent, d is grain size, p is the grain-size exponent, Q is the activation energy, R is the gas constant, and T is temperature. Here we focus on non-Newtonian mechanisms: grain boundary sliding (GBS), basal slip, and dislocation creep. See Table 1 for the rheological parameters. We explore grain sizes of 0.1–10 mm, spanning a range of estimates [14-15].

We use the two-dimensional finite-element code Tekton [16] to determine the oscillatory tidal stress, strain, and tidal-heating rate according to the temperature structure outputted by

the thermal convection model. We adopt viscoelastic rheology, which is appropriate because Europa's tidal period is close to the Maxwell time. We choose a Young's modulus of 10^{10} Pa and Poisson ratio of 0.25 [17]. The viscous part follows the power-law relationship as Eq. (1).

We run the oscillatory tidal flexing simulation for 5 tidal cycles with each tidal cycle being resolved with 85 timesteps [8]. We then calculate the tidal dissipation rate at each cell of the 2D domain by integrating stress times strain rate over a tidal cycle, yielding a heating rate per volume:

$$q = \frac{1}{\Delta\tau} \oint \sigma_{ij}(t) \dot{\epsilon}_{ij}(t) dt \quad (2)$$

where q is tidal heating rate, σ_{ij} is stress tensor, $\dot{\epsilon}_{ij}$ is the strain-rate tensor, t is time, and $\Delta\tau$ is the tidal cycle period. Subscripts correspond to the x and z coordinate axes; repeated indices imply summation.

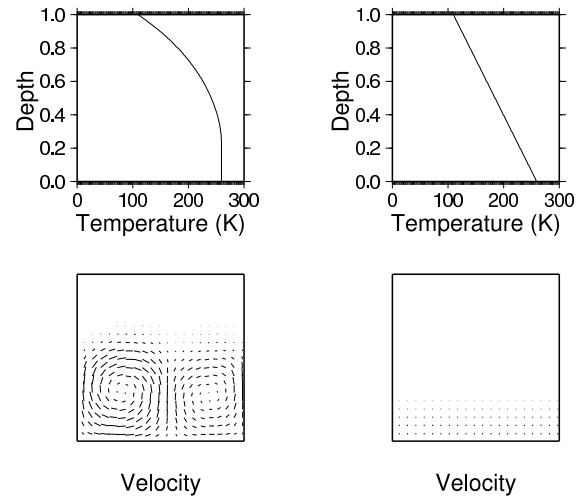


Figure 1: *Velocity and temperature.* Left panels: A fully coupled model of thermal convection and tidal dissipation with a tidal strain of 10^{-5} . Right panels: A thermal convection model without tidal dissipation. The models have a thickness of 30 km. Basal Slip rheology is used. Magnitude of initial temperature perturbation is 4.5 K

In the thermal convection model, we use impermeable, free-slip velocity boundary conditions on the top, bottom, and sides. The initial condition comprises a linear conductive temperature profile with a weak superposed disturbance following [11-12]. In the tidal oscillation models, we use free-slip boundary conditions on the top and bottom. The side boundaries undergo a specified periodic (sinusoidal) displacement in

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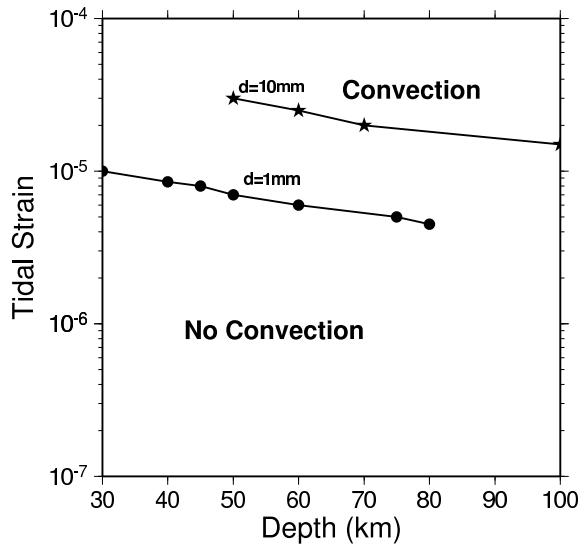


Figure 2: Convection versus non-convection regime with various tidal strain rates, depths of ice shell, and ice grain sizes. GBS rheology is implemented. The star line shows the simulations with ice grain size of 10 mm. The circle line shows the simulations with ice grain size of 1 mm.

Table 1: Rheological Parameters (See [9-10])

Creep Mechanism	$\log(A)$	n	p	$Q(\text{kJ/mol})$
Basal Slip	7.74	2.4	0	60
GBS	-2.4	1.8	1.4	49
Dislocation	5.1	4.0	0	61

time, with a period equal to Europa's 3.5-day orbital period, to simulate the tidal oscillation process in Europa's ice shell.

Results. Heterogeneous tidal heating strongly influences the conditions under which convection can occur. In particular, we find that sufficiently strong tidal heating can allow convection to occur in thinner ice shells than would be possible with weaker (or no) tidal heating. To illustrate, Fig. 1 depicts the temperature and velocity fields from two simulations that are identical except that one includes tidal heating and the other does not. The models were run with an ice-shell thickness of 30 km, initial temperature disturbance magnitude of 4.5 K, and basal slip rheology. In the absence of tidal heating, no convection occurs in the 30-km thick ice shell (right panels in Fig. 1). However, thermal convection is triggered in the model with realistic tidal dissipation calculated from the time-evolving temperature structure (left panels in Fig. 1). This convection occurs despite the fact that the basal Rayleigh number (defined using the temperature contrast between the top and bottom boundaries) is substantially lower

than the critical value for a system without internal heating. Once the convection is well developed, the temperature under the stagnant-lid is almost uniform, with a temperature close to melting temperature.

We performed numerous simulations to map out the regimes under which convection can initiate as a function of ice-shell thickness, domain-mean tidal-flexing amplitude, grain size, and amplitude of the thermal perturbation used in the initial condition. The simulations adopt fully self-consistent coupling between convection and oscillatory tidal heating as described previously. Figure 2 depicts the results for GBS rheology for ice-grain sizes of 1 and 10 mm (bottom and top curves, respectively) and an initial thermal perturbation of 4.5 K. Convection occurs above the relevant curve but not below it. Considering the $d = 1$ mm case, for example, in the absence of tidal heating, convection can not occur for ice-shell thicknesses thinner than ~ 85 –90 km. But with a mean tidal-flexing amplitude of 10^{-5} relevant to Europa, the critical shell thickness for convection drops to 30 km. When $d = 10$ mm, convection can occur in ice shells thinner than 50 km if the mean tidal-flexing amplitude is 3×10^{-5} or greater. In the absence of tidal heating, the critical ice-shell thickness depends on the amplitude of the initial thermal perturbation [11-12], but this dependence seems to weaken with increasing amplitude of tidal heating.

Summary. Under the influence of non-Newtonian rheology relevant to Europa, the presence of realistic tidal heating can significantly decrease the ice-shell thicknesses at which convection can initiate for a given grain size. These simulations support the possibility of convection under conditions relevant to Europa and other large icy satellites.

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