NUMERICAL SIMULATIONS OF NON-NEWTONIAN CONVECTION IN ICE: APPLICATION TO EUROPA.

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Introduction: Numerical simulations of solid-state convection in Europa's ice shell have so far been limited to consideration of Newtonian flow laws, where the viscsoity of ice is strongly dependent upon temperature, predicting that a stagnant lid should form at the top (10-40%) of a convecting ice shell [1, 2]. Such large thicknesses seem to contradict estimates of the effective elastic thickness of Europa's ice shell during its geologically active period [3, 4]. Recent laboratory experiments characterize the rheology of ice as the sum of contributions from several temperature and strain rate-dependent creep mechanisms [5]. We present the results of numerical simulations of convection within Europa's ice shell using the finite-element model Citcom [6], applying the non-Newtonian rheology of grain boundry sliding. Our calculations suggest a shallower brittle/ductile transition and larger interior convective velocities compared to Newtonian rheology. The flow field is time-dependent, with small, localized upwellings and downwellings at the thermal boundary layers that have minimal topographic expression at the surface.

Geological Setting: The surface of Europa is geologically young, with an inferred crater age of ~50 Myr [7, 8]. Despite its young age, Europa displays a rich variety of surface features that are inferred to form from the effects of tidal forcing on the shell and/or from convective upwellings [3, 9]. Convection has been suggested to drive the formation of three classes of features observed on Europa for which formation by upwelling of warm ice seems to best explain their mophologies: bands; large-scale chaos regions; small-scale pits, spots, and domes (collectively, "lenticulae"). The apparent lack of obvious compressional features on Europa's surface also constrains the surface expression of convective downwellings.

A nominal value of the elastic thickness of Europa's lithosphere at the time of active surface deformation is ~2 km [9]. The elastic plate thickness has a somewhat imprecise definition but we adopt the T=180 K isotherm as the base of the elastic lithosphere, and seek to compare our calculated thermal structures with those inferred for Europa.

Rheology: Based on laboratory experiments [5], the rheology of ice has been characterized as a sum of contributions from four different creep mechanisms: diffusional flow, basal slip accomodated grain boundary sliding, grain boundary sliding, and dislocation creep. Each of the flow laws has a different stress and temperature dependence. Different creep mechanisms control the flow of ice in different portions of the ice shell, and no single creep mechanism can adequately describe motion of ice within the entire shell.

The purpose of our study is to determine whether the convective style operational within Europa's shell differs from the style predicted by Newtonian rheologies. In this preliminary work, we provide a first glimpse of the differences in convective style between Newtonian and non-Newtonian convection within Europa's shell by adopting only the grain boundary sliding (GBS) term. Grain boundary sliding has the smallest n of non-linear terms in the combined flow law; therefore, this rheology provides a conservative view of how a non-linear rheology might affect the convection within Europa's shell. A summary of parameters used in the Newtonian and non-Newtonian convection simulations is shown in Table 1.

To simplify our numerical model, we construct an approximated GBS flow law:

$$\eta_{eff} = \eta_o (\dot{\varepsilon})^{-(n-1)/n} \exp(\gamma (T_o - T)) \qquad (1)$$

where η_o=7x10^{16} Pa s, γ=$Q^*/(nRT_{ad}^2)$=14, n=1.8, and T_o=180 K. The Rayleigh number evaluated at these reference values and the approximate tidal strain rate of 10^{-10} s^{-1} is 2x10^3. Computational constraints of Citcom limit the range of viscosities between the surface (T=100 K) and basal (T=260 K) ice that we can accurately model to 10^9. Therefore, our estimates of behavior at the cold surface of the convecting region should be interpreted with caution.

Results: Results from a Newtonian model with a rheology appropriate for diffusional flow and results of the non-Newtonian simulation with grain boundary sliding rheology in eq. (1) are shown in Figure 1. Table 2 compares bulk properties of both flow fields.

The non-Newtonian model has a lower average interior temperature and predicts a thinner stagnant lid and elastic lithosphere than the Newtonian model. If GBS were the dominant creep mechanism operational in Europa's shell and the viscosity contrast between the surface and basal ice was ≤10^9, the elastic lithosphere thickness is 3 km, which is closer to the observed values than the Newtonian estimate of 5 km.

In the non-Newtonian model, we find a time-dependent flow field with localized high-velocity upwellings. The bottom thermal boundary layer generates instabilities of size ~1 km. This is smaller than the measured size of lenticulae on Europa, but whether these high-velocity upwellings might correspond to intrusive doming events is unclear, since the observed topographic heights depend on the uncertain Young's modulus of the surface ice.

The top thermal boundary layer generates localized downwellings as well (Fig. 1b), which are expected to have little topographic expression at the surface. If this is the style of convection occuring within Europa's shell, these small instabilities might draw the overlying lithosphere downward to help balance the ubiquitous extension observed on the surface.

In the high-velocity (~20 cm/yr) upwellings, material can be transported from the bottom thermal boundary layer to the base of the lithosphere in ~10^4 years. The vertical mass flux within a single plume ρu_z is 10^9 kg/year. This material is delivered to the base of the stagnant lid, which is 7 km thick. Geological events involving movement of material in solid state such as eruptive diapirism or ridge formation are required to move material to the surface.

Conclusions and Future Work: Estimates of total thickness and elastic thickness of Europa's ice shell are beginning to converge toward convective thermal structures. We have provided an initial assessment of the effects of a non-linear rheology on the thermal structure and deformation style of Europa's ice shell. It should be noted that in order to consider the effects non-linear rheology within Europa's ice shell in a geophysically self-consistent manner, one must apply the tidal strain rate to the ice shell because the thermal structure within the shell due to tidal heating and convection are linked to the applied tidal force through the non-linear viscosity field. In future work, these effects must be treated simultaneously.

References: [1] Barr, et al., absract #1545, LPSC XXXIII, 2001; [2] McKinnon, W. B., M. Gurnis, abstract #2058, LPSC XXX, 1999; [3] Pappalardo, R. T. et al., *Nature* 193, 365-367, 1998; [4] Nimmo, et al., *Geophys. Res. Lett.* submitted, 2002. [5] Goldsby and Kohlstedt, *JGR* 106, 11,017-11,030; [6] Zhong, S. M., et al., *JGR* 103, 15,255-15268, 1998; [7] Zahnle, K., abstract #1699, LPSC XXXI, 2001; [8] Zahnle, K., et al., *Icarus* 136, 202-222, 1998; [9] Pappalardo, et al., *JGR* 104, 24,015 -24,055, 1999.

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Table 1.

Parameter	Newtonian Model	Non-Newtonian Model
Ra_o	2×10^3	2×10^3
η_o	7×10^{16} Pa s	7×10^{16} Pa s
Q^*	52 kJ/mol	49 kJ/mol
n	1.0	1.8
γ	0.0938	0.0873

Table 2.

Parameter	Newtonian Model	Non-Newtonian Model
$T_{ad} \sim$ isothermal interior temperature	248 K	236 K
δ_o, top thermal boundary layer thickness	8 km	7 km
δ_{180}, average depth to brittle/ductile transition	5 km	3 km
$max(V)$, maximum convective velocity	48 cm/yr	74 cm/yr

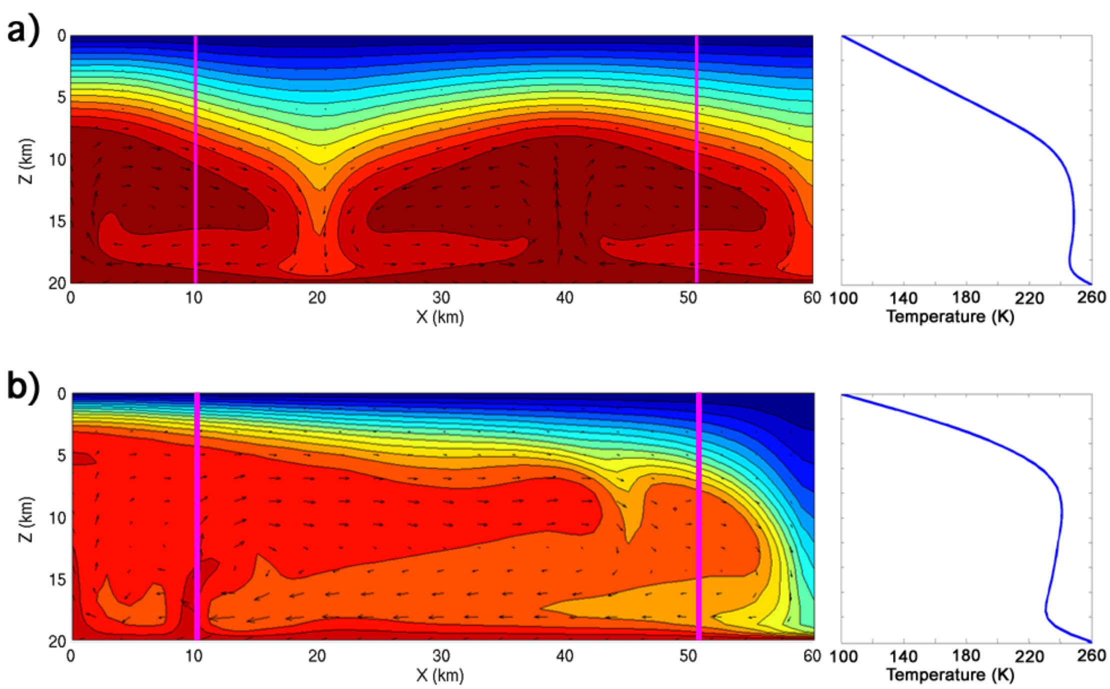

Figure 1. a) Isotherm diagram and thermal profile resulting from the Newtonian rheology of diffusional flow (n=1, Q^*= 52 kJ/mol, η_o= 7x10^{16} Pa s, Ra$_o$= 2x10^3). b) Isotherm diagram and thermal profile resulting from the non-Newtonian rheology of grain boundary sliding (n=1.8, Q*=49 kJ/mol, η_o=7 x 10^{16} Pa s, Ra$_o$=2x10^3). Free-slip boundary conditions of the model cause strong upwellings and downwellings at the sides of the box in the non-Newtonian case. Bulk properties of the flow field were calculated in both cases excluding data from the 10 km at the left and right edges (indicated by horizontal lines at x=10, x=50 km).