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New scaling laws for stagnant lid convection with a composite ice rheology: Application to Ganymede and Titan

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The persistence of subsurface oceans in icy moons primarily depends on the efficiency of heat transfer through the outer ice shell. Scaling laws for heat transfer have already been determined by previous studies. These consider however a simplified rheology assuming a single creep mechanism, often using a linearized version of the temperature-dependent viscosity law (called Frank-Kamenetskii approximation). In the present study, we test the influence of ice rheology on the efficiency of heat transfer by considering a more realistic composite viscosity law, including diffusion creep, grain boundary sliding, basal slip and dislocation creep. In order to establish heat transfer scaling laws, we performed a large number of numerical simulations of thermal convection in the stagnant lid regime using a 2-D spherical annulus geometry geometry, varying the curvature f ($0.92 < f < 0.99$) and the grain size (10^{-5} m $< d_g < 10^{-2}$ m). From these simulations, we derive new scaling relationships taking into account the grain size and apply them to the of modeling the thermal evolution of Ganymede and Titan.

1. Rheology

The convective dynamics of planetary mantle strongly depend on the viscosity of the materials, here ice, which is known to be a strong function of temperature T. Viscosity is described by an Arrhenius-type law:

$$\eta = \frac{d_g^m}{A\ \sigma_{II}^{n-1}}\ \exp\left(\frac{E_a}{RT}\right) \tag{1}$$

where d_g and σ_{II} are respectively the grain size and the second invariant of the deviatoric stress tensor. A, m, n and E_a are the creep parameters, depending on the material and on the creep mechanism occurring in the layer [1, 2]. But this formulation takes into account only one mechanism whereas four creep mechanisms have been identified for ice-I: diffusion creep, dislocation creep, grain boundary sliding and basal slip. Several Arrhenius viscosity laws should be considered simultaneous to properly predict the rheology of polycrystalline ice. Here, we use the formulation proposed by [1]

$$\frac{1}{\eta_{tot}} = \frac{1}{\eta_{diff}} + \frac{1}{\eta_{disl}} + \frac{1}{\eta_{gbs} + \eta_{bas}}, \tag{2}$$

which has the merit to combine the four creep mechanisms in a composite flow law. η_{diff}, η_{disl}, η_{gbs} and η_{bas} are the viscosities associated with each creep mechanism and are determined by an Arrhenius-type law (eq. 1).

The rheological parameter γ_{rh} corresponds to the inverse of the viscous temperature scale, proposed by [3], and is defined as

$$\gamma_{rh} = -\frac{\partial\eta/\partial T}{\eta}. \tag{3}$$

γ_{rh} is computed with eq. 3 from the time averaged temperature and viscosity profiles in the instable part of the cold thermal boundary layer (called the rheological sublayer).

All simulations are time-dependent and have reached a thermal equilibrium, in which heat flux is quasi-constant through time.

2. Results

As seen before (Eq. 2), the composite rheology involves four different creep mechanisms. The dynamics of the total layer is mainly controlled by the dominant creep mechanism occurring in the rheological sublayer, which is mostly determined by grain size (1). We find that for grain sizes lower than ~3.6 mm, diffusion creep is the dominant mechanism. For coarser grains (see Fig.1), a combination of grain boundary sliding and basal slip prevails in the rheological sublayer.

Our results lead to the Nu-Ra relationship $Nu = 0.65\ Ra_i^{1/3}\ (c_g\gamma_{rh})^{-4/3}$ (Fig. 2). The parameter c_g takes into account the dominant creep mechanism in the rheological sublayer which controls the heat transfer: c_g=1.25 for cases where a combination of grain

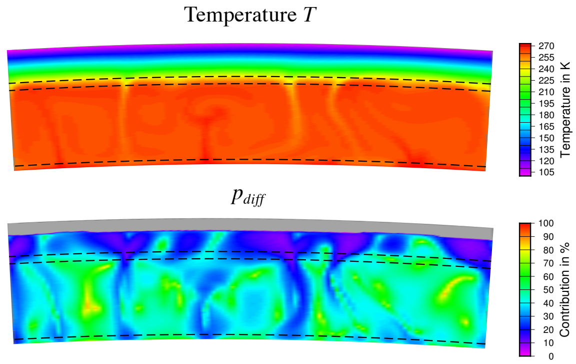

Figure 1: Snapshots of fields of temperature and contribution in percent of diffusion creep in the total deformation rate for simulation with d_g = 10 mm (f = 0.97 and R_{ext} = 2576 km). Dashed lines represent, from top to bottom, depths of the base of the stagnant lid (d_{sl}), of the cold thermal boundary layer (δ_0) and of the top of hot thermal boundary layer (δ_1). The gray region at the top of the layer is the part affected by the viscosity cutoff.

boundary sliding and basal slip is the dominant mechanism, while c_g=1 when diffusion creep is the main creep mechanism.

We find that the conductive lid thickness can be estimated by $d_{sl} = 0.82Nu^{-1}$. d_{sl} is ~15% thicker with a composite rheology than for the commonly-used Frank-Kamenetskii approximation.

The thickness of the lower thermal boundary layer δ_1 is related to the Nusselt number and γ_{rh} [4]. Our data yield $\delta_1 = 1.12Nu^{-1}(c_g\gamma_{rh})^{-1}$. In the same way as for the Nu-Ra relationship, γ_{rh} has to be weighted by c_g.

3. Conclusions

Our results show that the dynamics of the ice shell is mainly controlled by the dominant creep mechanism in the rheological sublayer (the unstable lower portion of the cold boundary layer beneath the stagnant lid), which is mostly determined by grain size. For grain sizes lower than ~3.6 mm, diffusion creep is the dominant creep mechanism in the rheological sublayer, while a combination of grain boundary sliding and basal sliding prevails for coarser grains. This threshold in grain size is reflected in the efficiency of heat transfer: we derive new scaling relationships that practically account for the dominant creep mechanism (from diffusion to grain boundary sliding/basal slip), thus allowing for a more accurate quantification of the

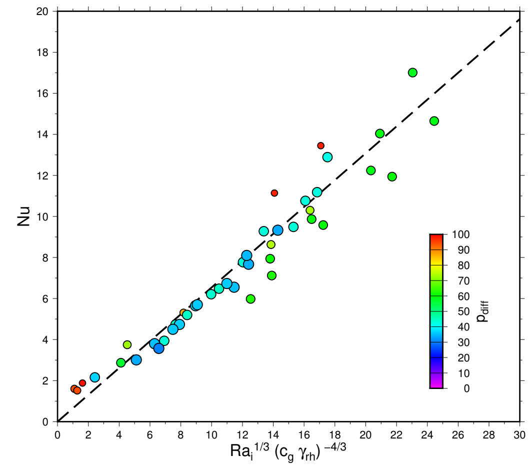

Figure 2: Nusselt-Rayleigh relationship for composite rheology. The color denotes the contribution of diffusion creep to the inverse of the total viscosity p_{diff} (in%). The symbol size indicates the grain size, ranging from 0.1 to 10 mm.

temperature profile in the ice shell and cooling rate of the internal oceans. Taking into account the specificity of ice rheology when modeling the thermal profile of ice shell and its temporal evolution is crucial to interpret the future geophysical data collected by JUICE on the ice shell structure and dynamics of Ganymede. Applications of these new scaling laws for the evolution of Ganymede and Titan will be presented at the conference.

Acknowledgements

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