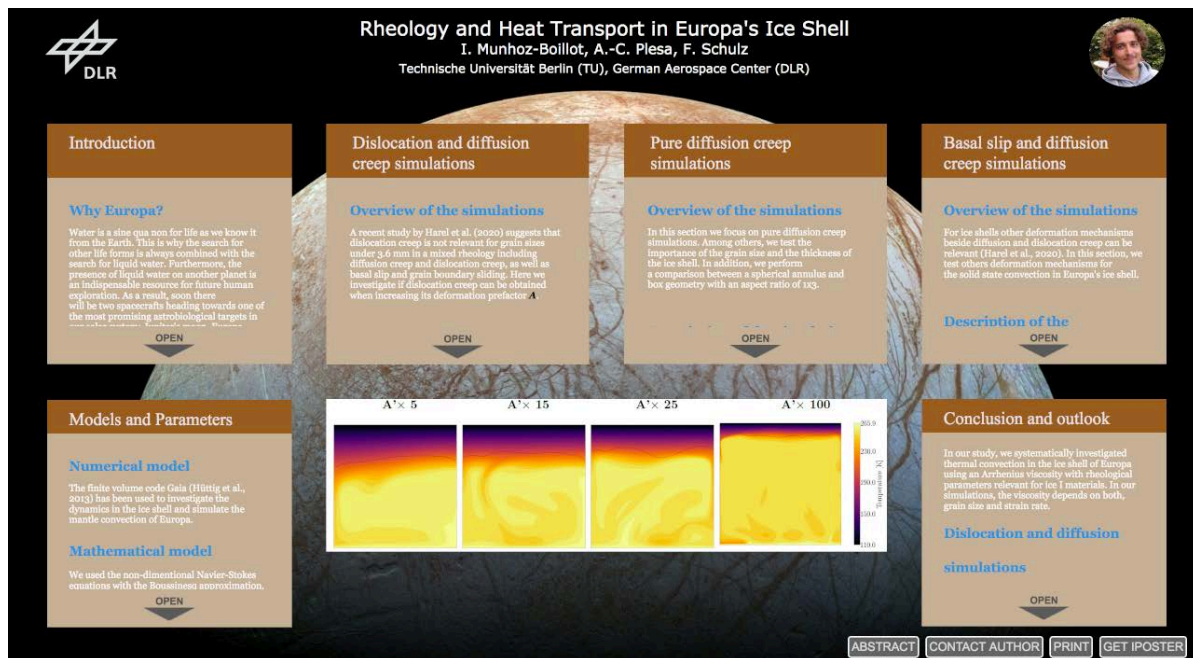


Rheology and Heat Transport in Europa's Ice Shell



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INTRODUCTION

Why Europa?

Water is a *sine qua non* for life as we know it from the Earth. This is why the search for other life forms is always combined with the search for liquid water. Furthermore, the presence of liquid water on another planet is an indispensable resource for future human exploration. As a result, soon there will be two spacecrafts heading towards one of the most promising astrobiological targets in our solar system: Jupiter's moon, Europa.

The Europa Clipper (NASA, Phillips and Pappalardo, 2014) and JUICE (ESA, Grasset et al., 2013) spacecrafts will carry instruments to probe beneath Europa's surface ice. There is strong evidences from the images of the Hubble Space Telescope suggesting the presence of an ocean hidden beneath the ice shell covering Jupiter's moon. Due to the gravitational interaction of Europa with Jupiter and the other jovian moons, tidal heat is being released and prevents the water from freezing (Sotin et al., 2002; Durham and Stern, 2001; Běhouňková et al., 2010; Showman and Han, 2004).

Why investigate the ice shell?

Although current models predict ice thicknesses ranging from 15 to 100 km (Showman and Han, 2004; Tobie et al., 2003), not suitable for drilling with current instruments, liquid water reservoirs may be located close to the surface in form of subsurface water lenses (Schmidt et al., 2011), which translates in domes on the outside of the ice shell (Allu Peddinti and McNamara, 2015; Pappalardo and Barr, 2004; Sparks et al., 2017).

The subsurface ocean on Europa is an important environment where life could have developed and exist today. Its evolution is intimately related to the evolution of the ice shell and hence a better understanding of the latter will help to place constraints on the subsurface water ocean.

The evolution of the ice shell depends on the heat transport and rheology. Both parameters shape the ice shell dynamics. When comparing the solid state convection (slow creep of material or macro-scale deformation due to defects in the crystalline structure at atomic level) in the ice shell with the one in silicate mantles, it turns out that the ice shell shows a much lower viscosity (Tobie et al., 2003; Barr et al., 2004; Harel et al., 2020).

Deformation mechanisms

Despite different viscosity values, the mechanisms governing the mantle deformation in icy moons are assumed to be the same as the ones in terrestrial planets: the main mechanisms are the diffusion and the dislocation creep (Karato and Jung, 2003; Hirth and Kohlstedt, 2003). Diffusion creep is a Newtonian, grain size dependent mechanism, usually acting for small grain sizes with a low stress.

On the other hand, dislocation creep is a non-Newtonian mechanism, primarily active for greater grain sizes and higher stresses. Contrary to the former mechanism, dislocation creep has a nonlinear stress/strainrate relation (Kaminski et al., 2004; Blackman and Kendall, 2002).

Although often neglected in numerical convection models (usually to ease the convergence of linear solvers), a non-linear rheology can significantly influence the heat transport. In this iPoster, we investigate the influence of linear and non-linear rheologies on the thermal convection in the ice shell of Europa.

DISLOCATION AND DIFFUSION CREEP SIMULATIONS

Overview of the simulations

A recent study by Harel et al. (2020) suggests that dislocation creep is not relevant for grain sizes under 3.6 mm in a mixed rheology including diffusion creep and dislocation creep, as well as basal slip and grain boundary sliding. Here we investigate if dislocation creep can be obtained when increasing its deformation prefactor A .

Description of the simulations

When started with dislocation creep as the only deformation mechanism, using the prefactor listed in the Parameters Section, the simulations entered systematically in a conductive state.

However, since the deformation prefactor A is a poorly known parameter, we further tested its influence on dislocation creep occurrence.

For this purpose, we investigated a large number of simulations with an enhanced prefactor A , using a mixed rheology with diffusion creep as the second mechanism, a grain size $d = 1 \text{ mm}$ and a ice thickness $D = 70 \text{ km}$.

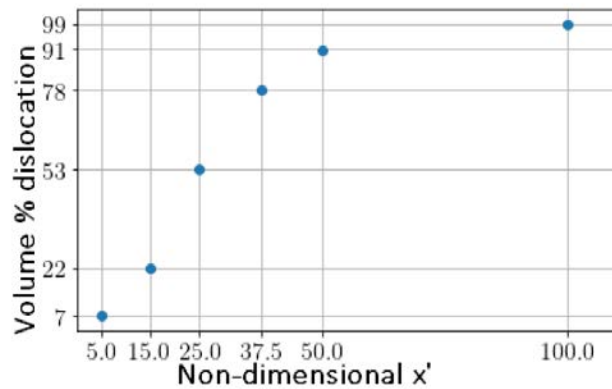
Since the Gaia Code uses non-dimensional values, the dimensional prefactor A for each deformation mechanism had to be converted to a non-dimensional prefactor A' .

Then, the prefactor A' for dislocation creep was multiplied by different x' , as summarized below:

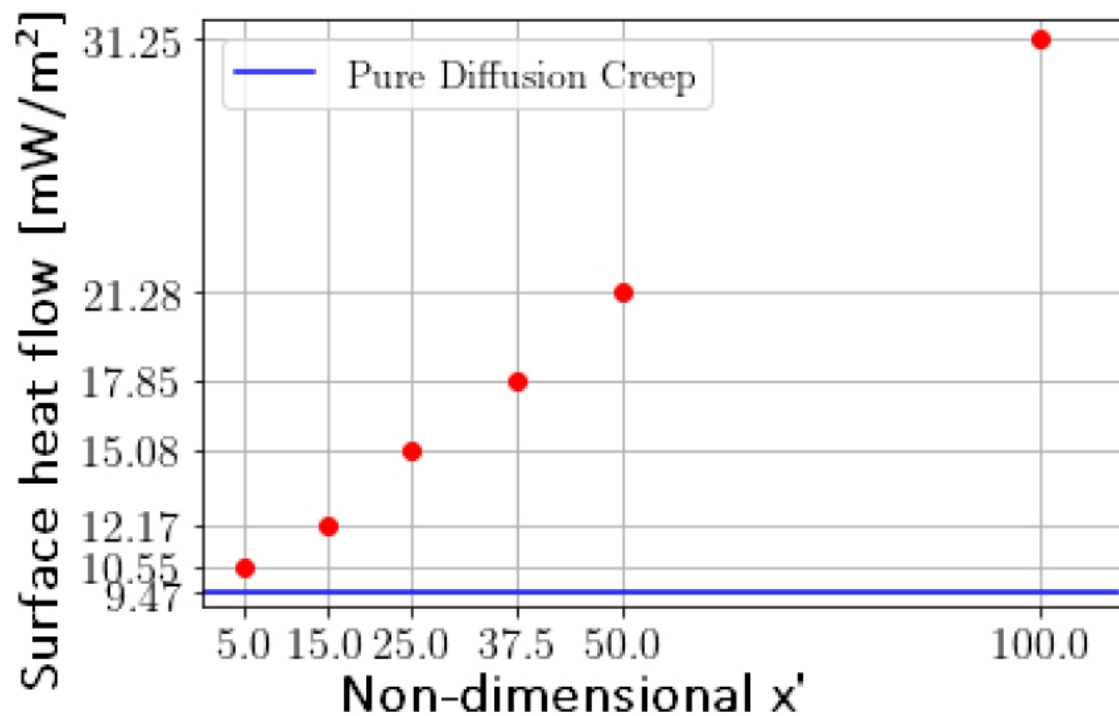
$A' \cdot x'$ (Non-dim)	$A \cdot x$ (Dim)
$x' = 5$	$x = 6.25 \times 10^2$
$x' = 15$	$x = 5.06 \times 10^4$
$x' = 25$	$x = 3.91 \times 10^5$
$x' = 37.5$	$x = 1.98 \times 10^6$
$x' = 50$	$x = 6.25 \times 10^6$
$x' = 100$	$x = 1 \times 10^8$

Results

Volume percent of dislocation fraction shown for each of the prefactors that were tested for the dislocation creep rheology:



Surface heat flow in [mW/m^2], shown for each of the prefactors that were tested for the dislocation creep rheology and for a pure diffusion simulation in a 1×1 box:



SEE SLIDE SHOW BELOW FOR MORE RESULTS

- 1- Steady state distribution of the ratio of dislocation creep to diffusion creep viscosity
- 2- Distribution of temperature
- 3- Distribution of the strain rate
- 4- Distribution of the viscosity

PURE DIFFUSION CREEP SIMULATIONS

Overview of the simulations

In this section we focus on pure diffusion creep simulations. Among others, we test the importance of the grain size and the thickness of the ice shell. In addition, we perform a comparison between a spherical annulus and box geometry with an aspect ratio of 1x3.

Description of the simulations

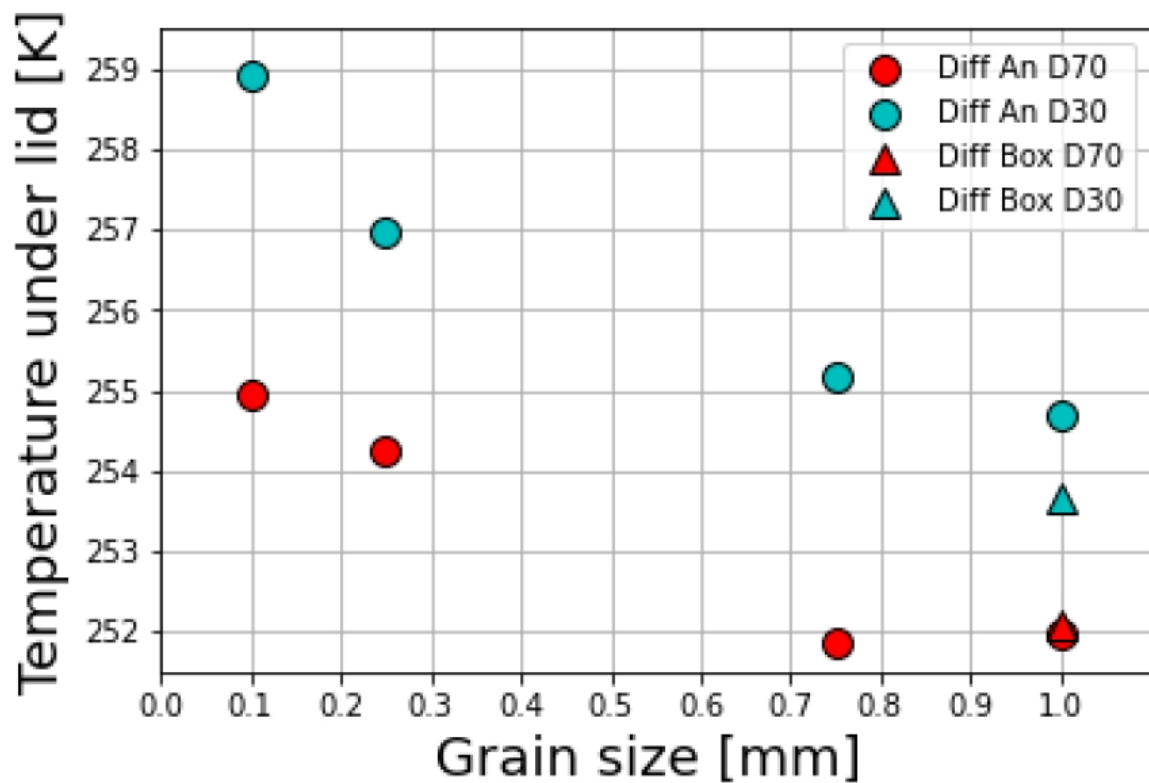
The simulations were started for 2 different ice thicknesses :

$D = 30 \text{ km}$ and $D = 70 \text{ km}$.

The grain size was varied from 0.1 to 1 mm (based on literature values).

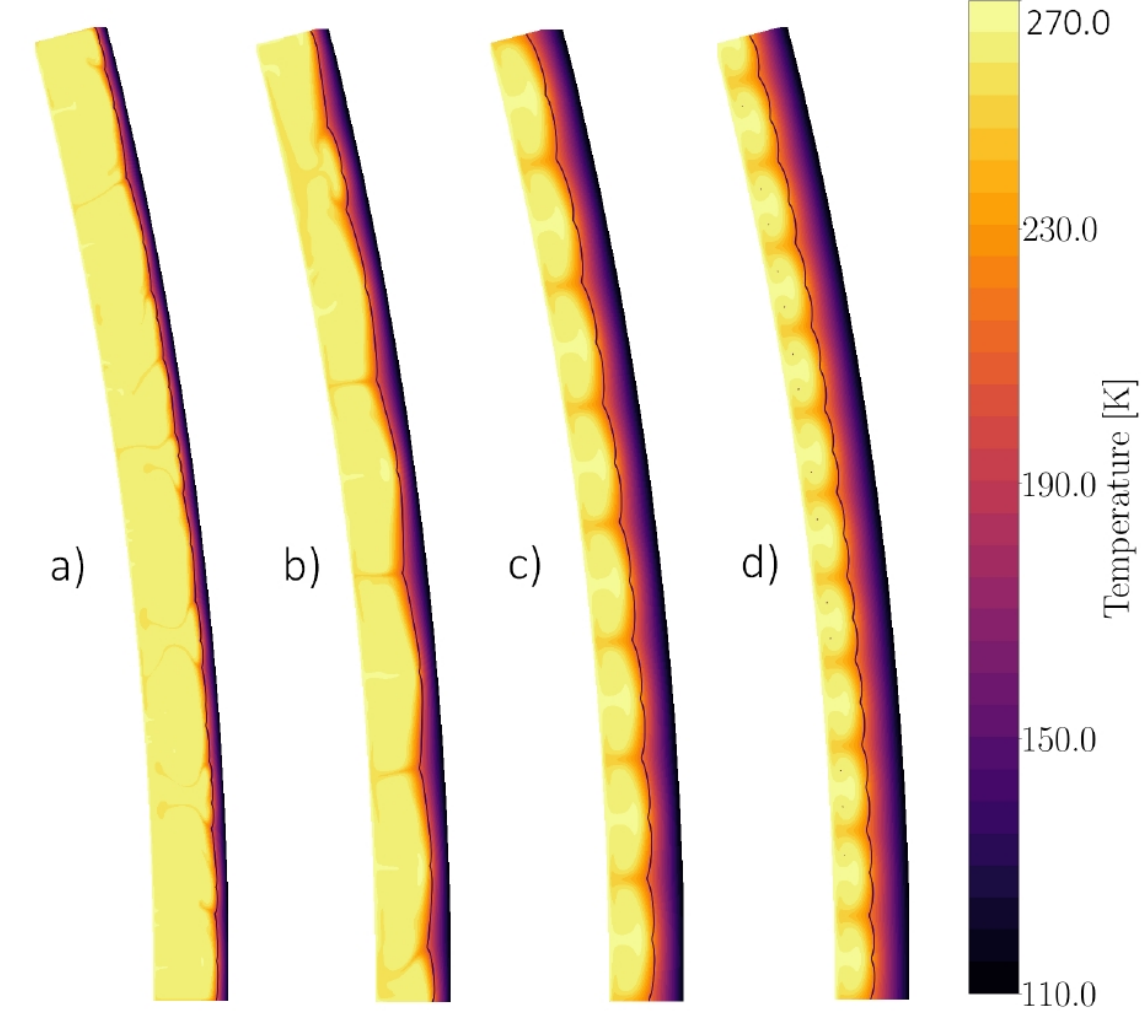
Results

Below we show the mean temperature under the lid, in steady state, over the grain size range. The simulations with a $D = 30 \text{ km}$ are marked in red and with a $D = 70 \text{ km}$ in blue. Circles stand for simulations with a spherical annulus geometry and the triangles for the simulations in a 1x3 box:

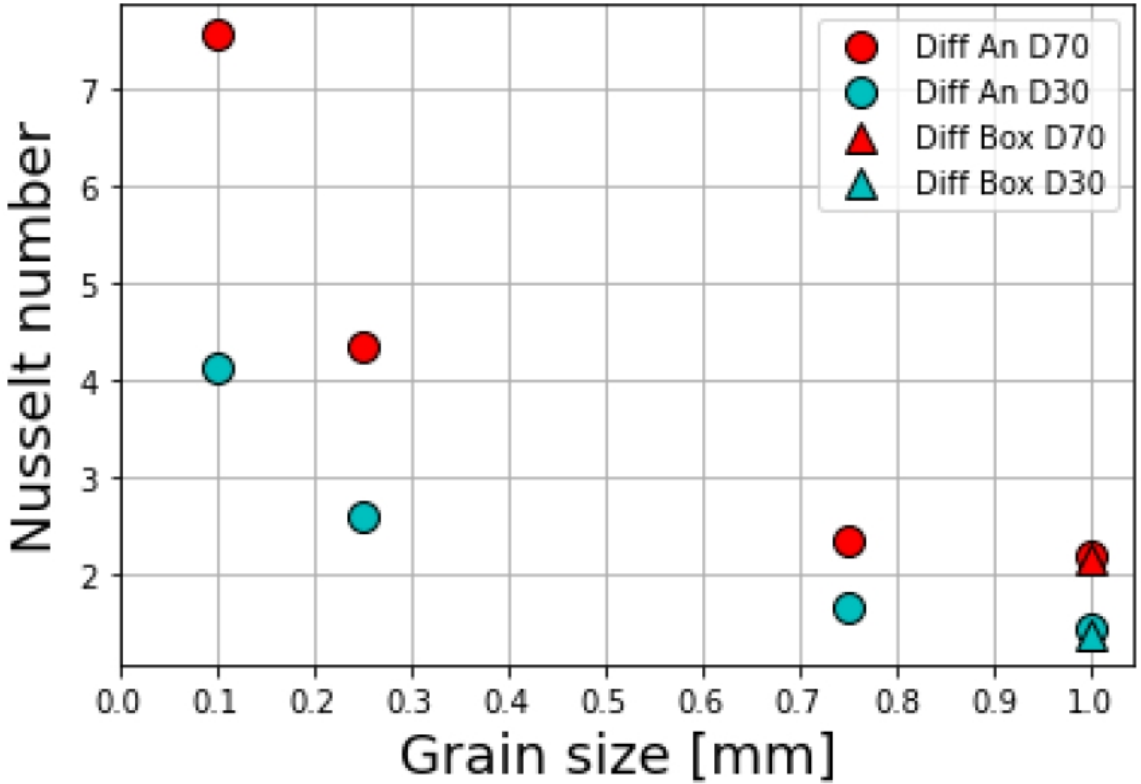


Temperature distribution in steady state with a spherical annulus geometry and a depth $D = 30 \text{ km}$ for a) $d = 0.1 \text{ mm}$, b) $d = 0.25 \text{ mm}$, c) $d = 0.75 \text{ mm}$ and d) $d = 1 \text{ mm}$.

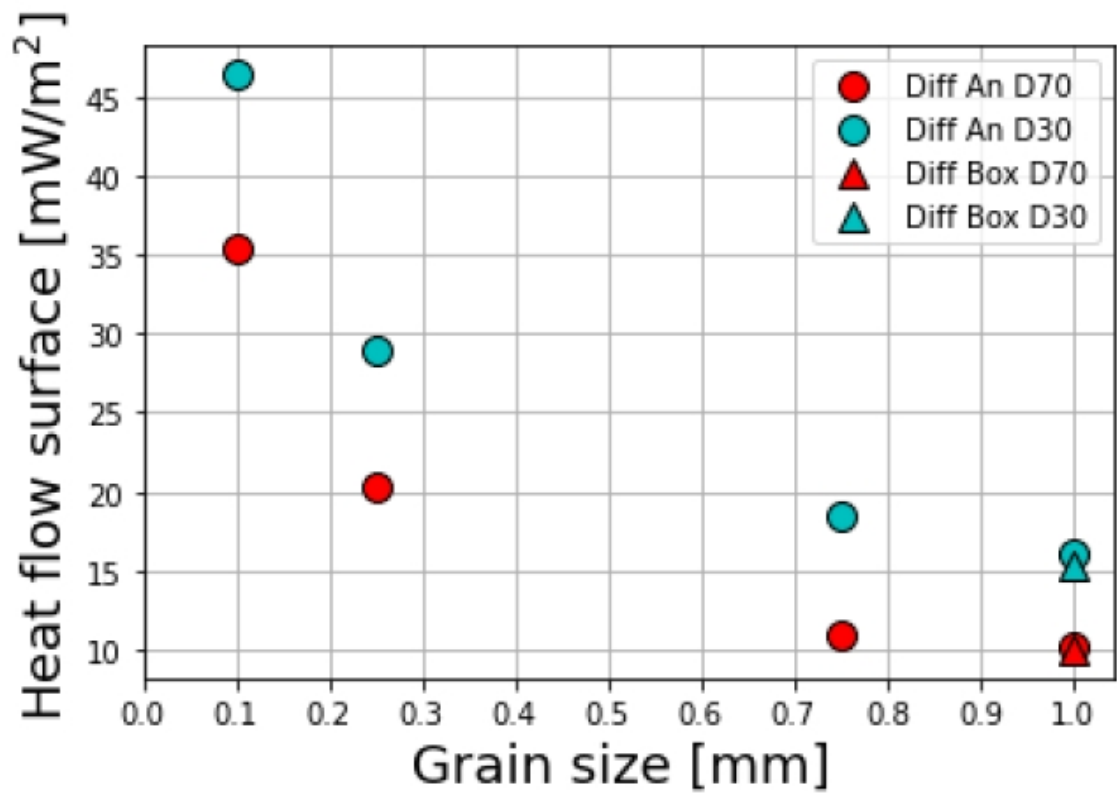
The black lines show the stagnant lid (the immobile layer at the top of the simulation domain):



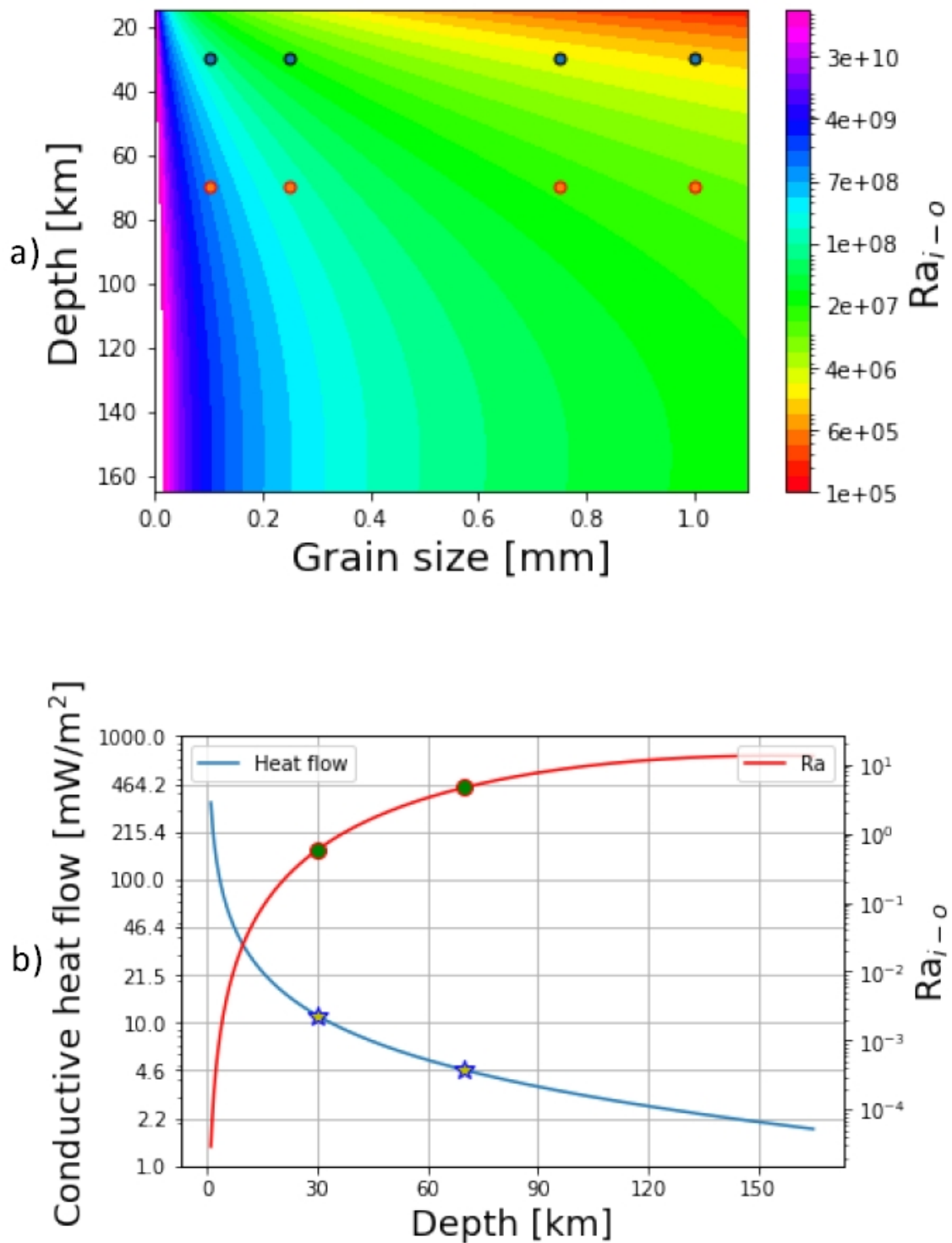
Nusselt number (non-dimensional heat flow), in steady state, over the grain size range:



Surface heat flow in [mW/m²], shown for different grain sizes:



Rayleigh number as a function of grain size and depth:



a) Rayleigh number computed at the ice-ocean interface over the grain size range for depths from **20 km** to **160 km**.

The red dots are the simulations with $D = 70$ km and the blue dots the simulations with $D = 30$ km.

b) Conductive heat flow (blue line + stars) in $[W/m^2]$ and Rayleigh number (red line + circles), in steady state, for depths from **0 km** to **150 km**. The symbols mark the cases simulated in this work.

The Rayleigh number was calculated at the ice-ocean interface with a varying viscosity, depending on the temperature, the grain size and the ice shell thickness. The temperature at the ice-ocean interface was set to the solidus temperature using the equation in Chizhov (1993).

BASAL SLIP AND DIFFUSION CREEP SIMULATIONS

Overview of the simulations

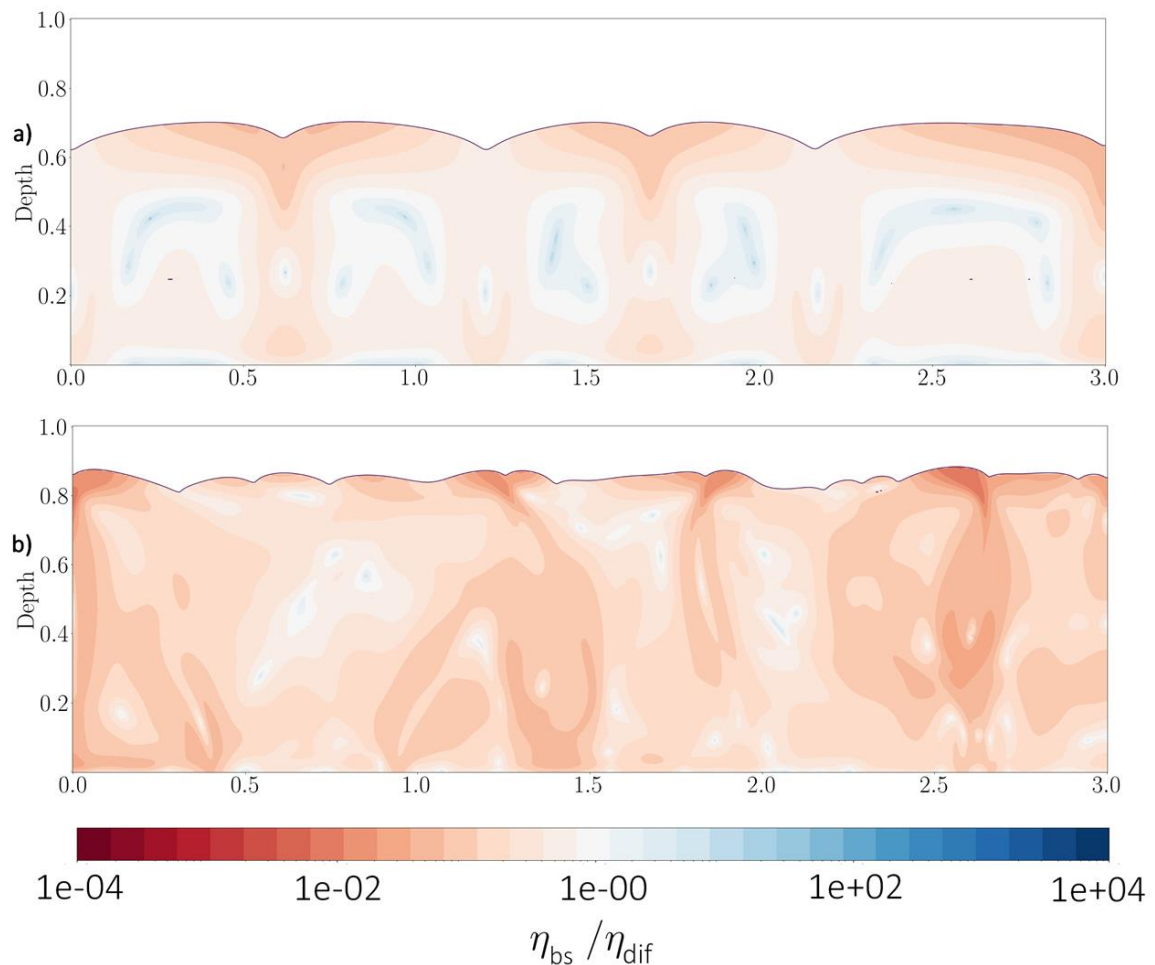
For ice shells other deformation mechanisms beside diffusion and dislocation creep can be relevant (Harel et al., 2020). In this section, we test others deformation mechanisms for the solid state convection in Europa's ice shell.

Description of the simulations

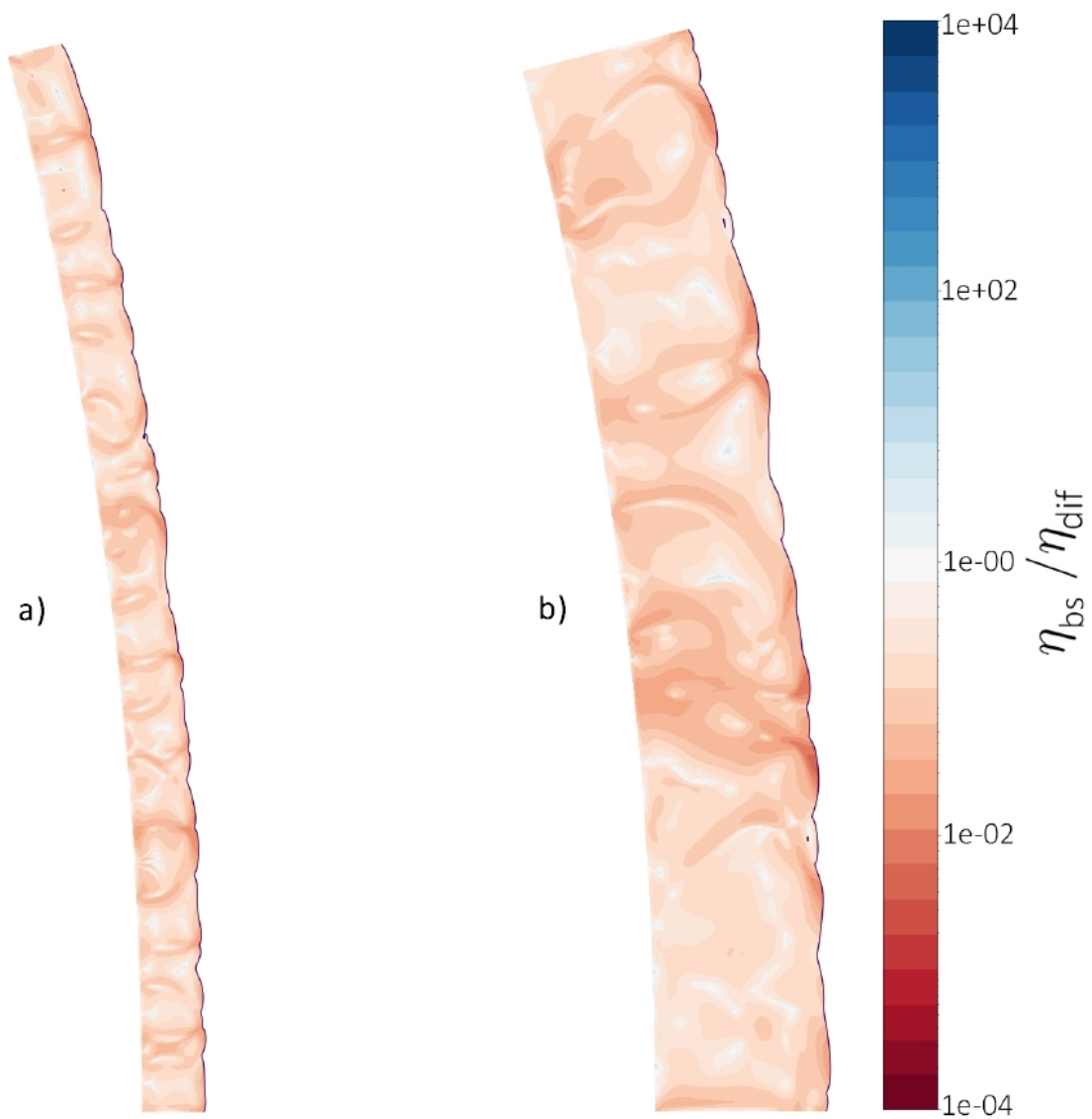
We chose to investigate the possibility of a mixed - basal slip and diffusion creep- rheology as well as possible differences between the 1x3 aspect ratio box and the spherical annulus geometries, for a grain size of **1 mm**.

Results

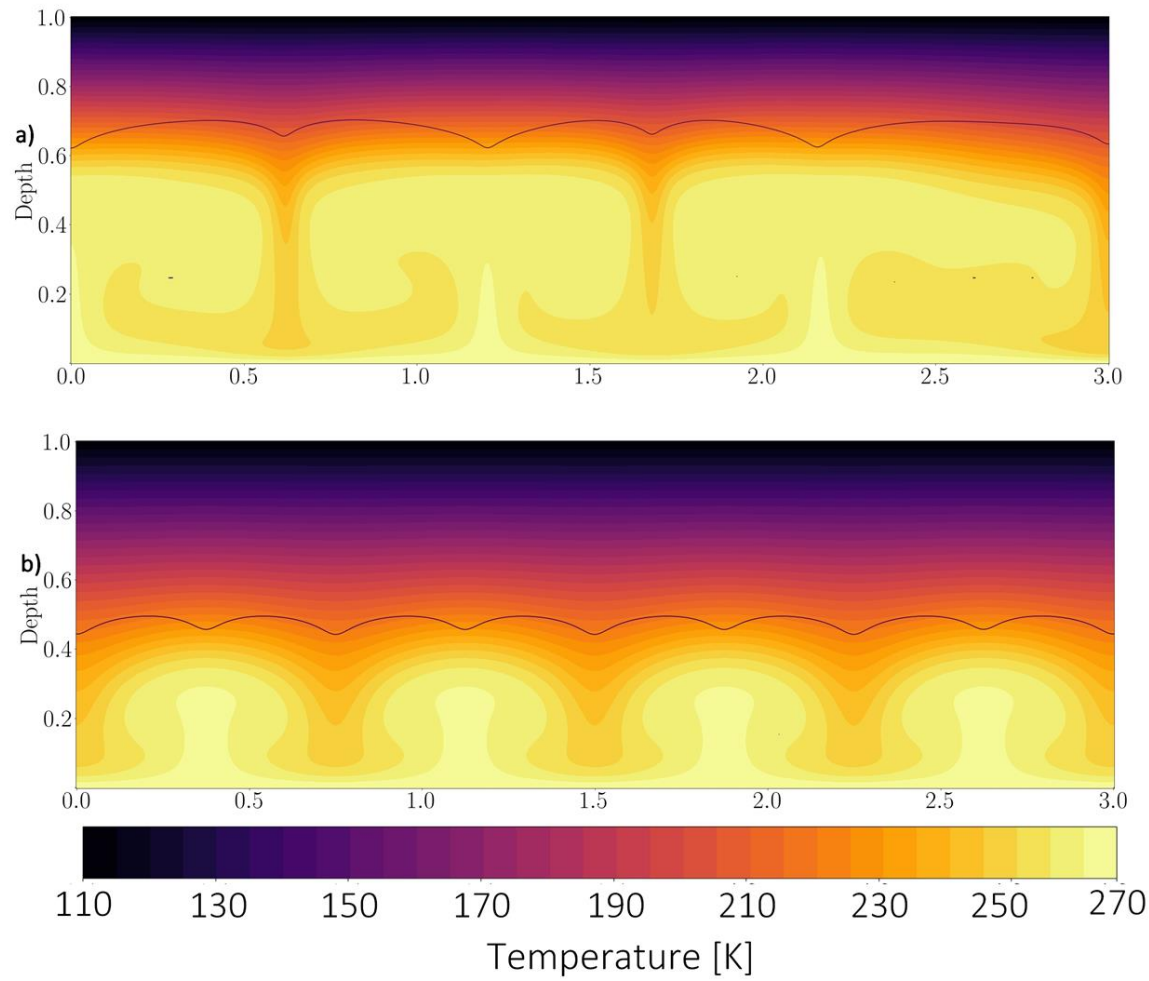
Below, we show the volume fraction of basal slip in a mixed -basal slip and diffusion creep- simulation, in steady state, in an 1x3 box geometry, and compare ice shell thicknesses of **$D = 30 \text{ km}$ (a)** and **$D = 70 \text{ km}$ (b)**:



Volume fraction of basal slip in a mixed -basal slip and diffusion creep- simulation, in steady state, in an annulus geometry with **$D = 30 \text{ km}$ (a)** and **$D = 70 \text{ km}$ (b)**:



Steady state distribution of the temperature for a mixed diffusion creep-basal slip rheology **(a)** and for a pure diffusion creep simulation **(b)** in a 1x3 box geometry and a depth $D = 30 \text{ km}$:



Parameters for basal slip (BS) and diffusion creep simulations for different geometries:

<div>Parameter</div> <div>Geometry</div>	BS volume fraction [%]	Temperature [K]	Nusselt number [1]	Surface heat flow [mW/m ²]
Annulus, $D = 30$ km	99	256.94	2.66	29.86
Annulus, $D = 70$ km	99	252.96	4.69	21.93
Box, $D = 30$ km	83	255.03	2.04	22.92
Box, $D = 70$ km	99	253.98	4.44	20.77

MODELS AND PARAMETERS

Numerical model

The finite volume code Gaia (Hüttig et al., 2013) has been used to investigate the dynamics in the ice shell and simulate the mantle convection of Europa.

Mathematical model

We used the non-dimensional Navier-Stokes equations with the Boussinesq approximation, as well as the equations for rheology defined in Karato and Jung, 2003; Hirth and Kohlstedt, 2003.

The equation below shows the viscosity for each (i) deformation mechanism:

$$\eta_i = \frac{\dot{\epsilon}^{\frac{1-n_i}{n_i}} \cdot d^{\frac{m_i}{n_i}}}{2A_i^{\frac{1}{n_i}}} \exp\left(\frac{E_i + PV_i}{n_i RT}\right)$$

where $\dot{\epsilon}$ is the strain rate, d is the grain size, A is the deformation prefactor, E is the activation energy, R is the gas constant, P is the pressure and V the activation volume. The grain size and stress exponents (m_i , n_i) are defined for each mechanism in the table with the model parameters below.

The effective viscosity η_{eff} , which depends on various deformation mechanisms, is defined as follow:

$$\eta_{\text{eff}} = \left(\sum_i \frac{1}{\eta_i} \right)^{-1}$$

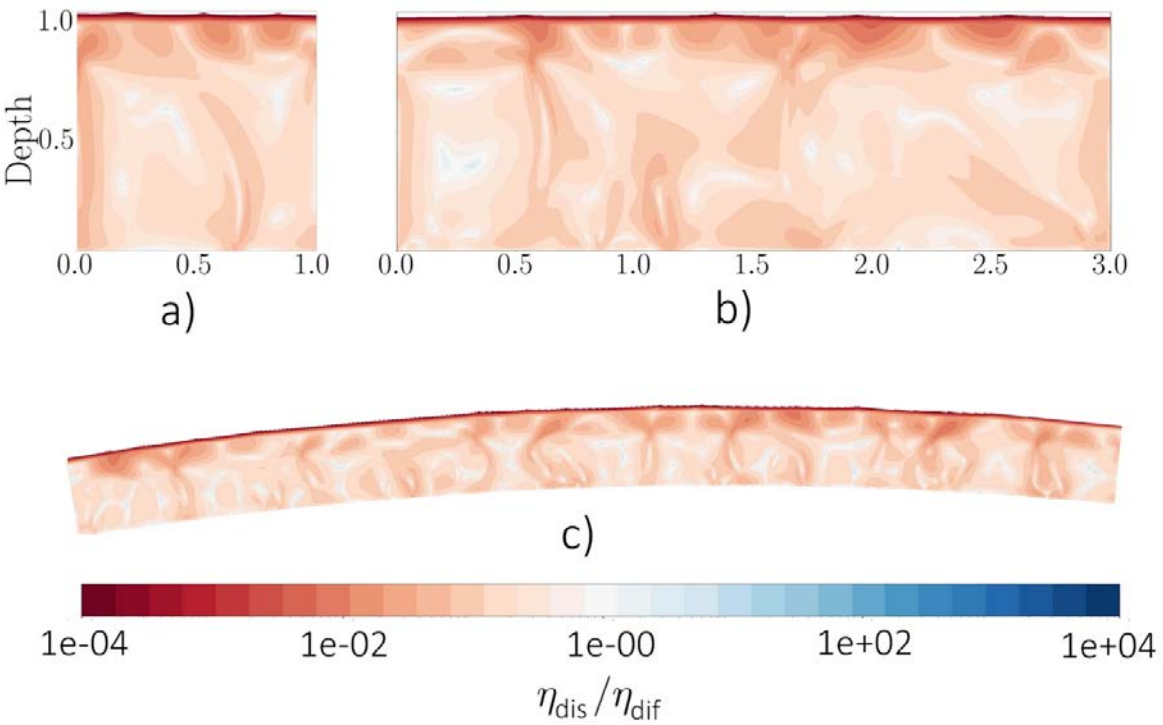
Geometry

Three different geometries have been investigated:

a) A Cartesian box geometry with a 1x1 aspect ratio to determine under which circumstances dislocation creep appears, while avoiding the higher computational costs associated with the spherical annulus geometry.

b) A Cartesian box geometry using a 1x3 aspect ratio with a mixed rheology, in order to not "force" the convection pattern to one convection cell, as it is often the case in a 1x1 box.

c) A spherical annulus geometry with a mixed rheology. Both annulus and 1x3 box geometries have been compared to determine the relevance of the box 1x3 geometry.



(Example with the fraction of diffusion viscosity divided by dislocation viscosity)

Model parameters

The parameters for the 3 deformations mechanisms that are investigated in this iPoster (diffusion creep, dislocation creep, basal slip) were gathered from Goldsby and Kohlstedt (2001); Barr et al. (2004); Harel et al. (2020).

Parameters	Diffusion creep	Dislocation creep	Basal slip
Activation energy	$E_{\text{diff}} = 59.4 \text{ kJ} \cdot \text{mol}^{-1}$	$E_{\text{disl}} = 61 \text{ kJ} \cdot \text{mol}^{-1}$	$E_{\text{bs}} = 60 \text{ kJ} \cdot \text{mol}^{-1}$
Grain size exponent	$m_{\text{diff}} = 2$	$m_{\text{disl}} = 0$	$m_{\text{bs}} = 0$
Stress exponent	$n_{\text{diff}} = 1$	$n_{\text{disl}} = 4$	$n_{\text{bs}} = 2.4$
Deformation prefactor	$3.5 \times 10^{-10} \text{ m}^2 (\text{Pa} \cdot \text{s})^{-1}$	$5 \times 10^{-18.9} (\text{Pa}^4 \cdot \text{s})^{-1}$	$2.2 \times 10^{-7} (\text{Pa}^{2.4} \cdot \text{s})^{-1}$

CONCLUSION AND OUTLOOK

In our study, we systematically investigated thermal convection in the ice shell of Europa using an Arrhenius viscosity with rheological parameters relevant for ice I materials. In our simulations, the viscosity depends on both, grain size and strain rate.

Dislocation and diffusion simulations

For a depth of $D = 70 \text{ km}$, when dislocation creep is the only deformation mechanism, the simulations enter systematically in a conductive state.

Simulations with dislocation creep can be started when using an enhanced non-dimensional dislocation prefactor $\alpha' A'$. However, the value of the enhanced prefactor needs to be significantly larger than the value allowed by uncertainties of rheological experiments.

Thus, this first series of simulations showed that dislocation creep can be neglected when analyzing solid-state convection in Europa's ice shell with the chosen parameters.

Pure diffusion simulations

An important aspect of the pure diffusion simulations is that although the Nusselt number is larger for a thick ice shell, the dimensional surface heat flow obtained for a thin ice shell is larger than for a thicker one. This is caused by the rescaling of the Nusselt number to a dimensional heat flow.

Furthermore, the comparison of the spherical annulus and a 1×3 Cartesian box geometry, showed that when considering a pure diffusion scenario for depths $D = 30 \text{ km}$ and $D = 70 \text{ km}$ and a grain size of 1 mm , the box geometry leads to the same results as the spherical annulus.

This makes the box geometry an interesting alternative for future studies, due to its lower computing time.

Basal slip and diffusion simulations

Simulations showed that in addition to diffusion creep, basal slip can be considered as an important, if not dominant, deformation mechanism when studying solid-state convection in the ice shell of Europa with a grain size of 1 mm .

However, the box with an aspect ratio 1×3 might not be suitable to use with a mixed rheology and thin ice shells, since a steady-state convection pattern may be affected by geometrical effects. A larger box aspect ratio resembling more to the aspect ratio used in the spherical annulus could be relevant.

Outlook

In future studies, the effects of tidal heating need to be accounted for. It could play a non-negligible role in the thermal convection of icy moons.

Moreover, the implementation of heat sources could, among others, lead to changes in the temperature distribution, as well as to a local decrease of the viscosity.

Additionally, a grain size evolution should be considered in future studies, as this will determine the dominant deformation mechanism, which in turn affects the dynamics of the ice shell.

ABSTRACT

The efficiency of heat transfer in the outer shell of icy satellites is important to determine the evolution and thermal state of their interior with major implications for the cooling behavior of an internal ocean.

In this study, we systematically investigate thermal convection in the ice shell of Europa using an Arrhenius viscosity and accounting for ice I material that is dependent on both grain size and strain rate. To this end, we employ the geodynamical code GAIA [1] with a mixed rheology approach similar to [2], and perform calculations in a 2D Cartesian box and spherical annulus geometry for two values of the ice shell thickness (i.e., 30 and 70 km). In our simulations, we test various constant grain size values (Fig. 1).

In a first serie of simulations, we tested the importance of the dislocation creep mechanism for modeling convection in Europa's ice shell. Our results show that, in a mixed diffusion-dislocation creep rheology, diffusion creep is the dominant heat transfer mechanism, similar to the study of [3]. A pure dislocation creep rheology leads to a conductive ice shell. Dislocation creep may become dominant if its rheological prefactor increases by about 5 orders of magnitude, which even taking into account the uncertainty associated with rheological measurements is considered unrealistic.

Additional simulations that use a mixed diffusion-basal slip rheology show that for ice shells, basal slip may be a relevant deformation mechanism in addition to diffusion creep (Fig. 1).

Another important aspect is that the efficiency of heat transfer is larger for a thick ice shell (70 km, Fig. 1a compared to a thinner one (i.e., 30 km)). However, the dimensional surface heat flow obtained for a thin ice shell is larger than for a thicker one, as shown in Fig. 1b. This is caused by the rescaling of non-dimensional parameters to a dimensional heat flow.

References: [1] Hüttig et al., PEPI 2013; [2] Schulz et al., GJI 2019; [3] Harel et al., Icarus 2020.

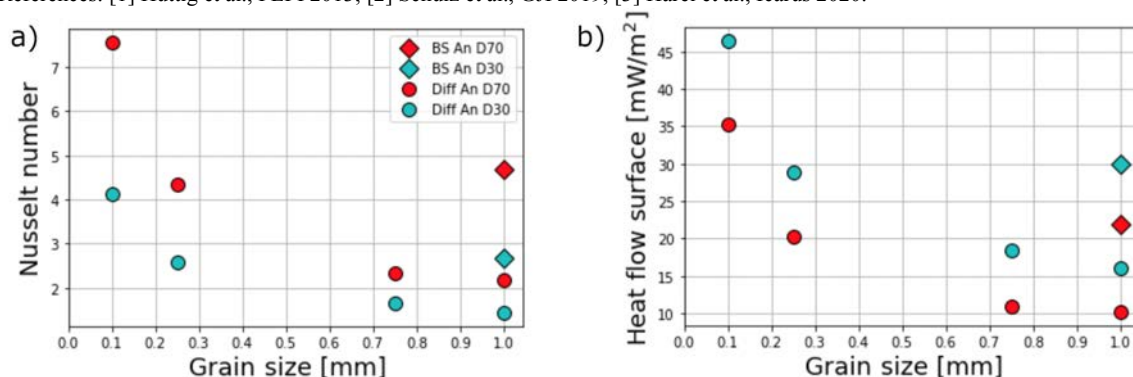


Fig. 1: Nusselt number and dimensional surface heat flow as a function of grain size and deformation mechanism for calculations performed in a spherical annulus geometry. Panel a): Nusselt number for pure diffusion creep calculations using various grain sizes. For comparison a mixed diffusion-basal slip simulation is shown for a 1mm grain size. Panel b): similar to Panel a) but showing the dimensional surface heat flow.

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