Heat flow and thickness of a convective ice shell on Europa for grain size-dependent rheologies

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Received 20 June 2006; revised 10 November 2006

Available online 11 April 2007

Abstract

Although it is mostly accepted that the lower part of the ice shell of Europa is actively convective, there is still much uncertainty about the flow mechanism dominating the rheology of this convective layer, which largely depends on the grain size of the ice. In this work, we examined thermal equilibrium states in a tidally heated and strained convective shell, for two rheologies sensitive to grain size, grain boundary sliding and diffusion creep. If we take a lower limit of 70 mW m^{-2} for the surface heat flow, according to some geological features observed, the ice grain size should be less than 2 or 0.2 mm for grain boundary sliding or diffusion creep respectively. If in addition the thickness of the ice shell is constrained to a few tens of kilometers and it is assumed that the thickness of the convective layer is related to lenticulae spacing, then grain sizes between 0.2 and 2 mm for grain boundary sliding, and between 0.1 and 0.2 mm for diffusion creep are obtained. Also, local convective layer thicknesses deduced from lenticulae spacing are more similar to those here derived for grain boundary sliding. Our results thus favor grain boundary sliding as the dominant rheology for the water ice in Europa's convective layer, since this flow mechanism is able to satisfy the imposed constraints for a wider range of grain sizes.

Keywords: Europa; Jupiter, satellites; Thermal histories; Tides, solid body

1. Introduction

There is currently certain consensus that the ice shell of Europa floats on an internal ocean (e.g., Kivelson et al., 2000), is some tens of kilometers thick (e.g., Schenk, 2002; Schilling et al., 2004), and that its lower part is convective (e.g., McKinnon, 1999; Hussmann et al., 2002; Nimmo and Manga, 2002; Ruiz and Tejero, 2003; Tobie et al., 2003; López et al., 2003; Barr et al., 2004; Showman and Han, 2004; Mitri and Showman, 2005; Moore, 2006).

From the geological structures on the surface of Europa, it have been estimated a surface heat flow of ~70–200 mW m^{-2} (e.g., Ruiz and Tejero, 2000; Ruiz, 2005; Dombard and McKinnon, 2006). This value is an order of magnitude higher than that inferred from radioactive dissipation in the rock and metal core (~6–8 mW m^{-2}; e.g., Cassen et al., 1982; Spohn and Schubert, 2002). A thermally conductive shell, heated from below and in a thermal equilibrium with a heat flow of ⩾70 mW m^{-2} and a surface temperature of 100 K, should be at most 8 km thick, which is clearly thinner than the minimum values of ~19−25 km (Schenk, 2002) deduced from the morphology and characteristics of the major impact structures on Europa: this implies convection in the shell. Convection could start in the shell for heat flows under 45 mW m^{-2} (the exact value depends on the particular model; e.g., McKinnon, 1999; Hussmann et al., 2002; Ruiz and Tejero, 2003), such that most surface heat flow would be the result of tidal heating in the convective sublayer. Accordingly, any convection model for Europa's ice shell should be (roughly at least) consistent with surface heat flows deduced from geological structures.

In addition, for a model of convection in Europa, it would be useful to predict an ice shell thickness of several tens of

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kilometers at most, given that this would be consistent with the minimum thickness inferred from impact craters (Schenk, 2002), and with the ~20 km of depth until the internal ocean suggested by the magnetic evidence (Schilling et al., 2004). If it is admitted that the origin of the areas of microchaos and features known as lenticulae (including domes, pits and dark spots) is related to diapirs from a convective layer (e.g., Pappalardo et al., 1998; Nimmo and Manga, 2002; Sotin et al., 2002), a shell several kilometers thick would also be consistent with the thickness of the convective layer of ~7–18 km proposed from their spacing (Spaun et al., 2004). Note that all the thicknesses mentioned herein could vary locally.

One of the main uncertainties in the works that investigate convection in the ice shell of Europa arises from water ice rheology. Indeed, ice flow is a complex phenomenon involving several deformation mechanisms (e.g., Duval et al., 1983; Weertman, 1983; Budd and Jacka, 1989; Durham and Stern, 2001; Goldsby and Kohlstedt, 2001), both Newtonian (such as volume and grain boundary diffusion creep) and non-Newtonian (dislocation creep, grain boundary sliding and basal slip), which contribute to different extents depending on the temperature, the applied stress and grain size. Grain boundary sliding is the observed flow mechanism that should be dominant in the conditions in the convective layer of the Europa's shell (Pappalardo et al., 1998; McKinnon, 1999), although basal slip (Duval and Montagnat, 2004), and even a role for dislocation creep (Durham and Stern, 2001), have also been proposed. Newtonian flow of water ice has not been experimentally observed, but it could possibly be important (maybe dominant) in the low stress and strain rate environment typical of planetary convective layers. In fact, many authors prefer to use a Newtonian viscosity (Hussmann et al., 2002; Tobie et al., 2003; Showman and Han, 2004; Mitri and Showman, 2005) to investigate convection in the ice shell of Europa.

In this work, we explore thermal equilibrium states in a convective shell tidally heated and strained for grain boundary sliding and volume diffusion creep, as a function of a reasonable range of grain sizes. Our objective is to compare the obtained values of heat flow, thickness of the actively convective layer, thickness of the stagnant lid, and total thickness of the ice shell obtained for both flow mechanisms. The consistency between the results and the available information about these parameters should provide insights regarding the dominant flow mechanism and the probable range of grain sizes in the convective layer. In the work by Ruiz and Tejero (2003), this kind of analysis was made to several temperature-dependent regimes of grain boundary sliding and dislocation creep, and grain sizes of 0.1 and 1 mm (for grain boundary sliding, since dislocation creep is insensitive to grain size). Since the calculations are performed for a range of grain size, we should be able to identify tendencies, dues to the variation of this parameter, on the state of a convective shell for grain size-sensitive rheologies. Local variations in the state of the ice shell according to local variations in temperature and tidal strain are also analyzed.

2. Steady-state, tidally heated, convection in the ice shell

Convection in the outer shell of icy satellites operates in the stagnant lid regime (e.g., McKinnon, 1998; Freeman et al., 2006), in which a cold and essentially immobile lid develops above the actively convective sublayer. Although the viscosity contrast across the entire ice shell can be very large, the viscosity variation within the convective sublayer is typically of one order of magnitude (see Grasset and Parmentier, 1998, and references therein). Grasset and Parmentier (1998) have shown that convective parameterization laws derived for constant viscosity convection are applicable if the boundary conditions are properly defined. In fact, this procedure has been previously used for the case of icy satellites (e.g., Hussmann et al., 2002, 2006; Ruiz and Tejero, 2003). This is useful for Europa, because tidal heating is strongly temperature-dependent (Ojakangas and Stevenson, 1989), and it is largely restricted to the warmest ice. In these conditions, tidal heating is negligible in the stagnant lid, which can be treated separately (Hussmann et al., 2002; Ruiz and Tejero, 2003). However, parameterizations for internally heated stagnant lid convection considering the same heating rate in both the stagnant lid and the convective sublayer are not a good analogous for the case of the ice shell of Europa.

Thus, here we consider a steady-state convective layer heated from within, Schubert et al. (2001) find the relation

$$\Theta = \frac{k(T_i - T_t)}{H b_c^2} = 1.70 Ra_{\mathrm{H}}^{-1/4}, \quad (1)$$

where Θ is the dimensionless temperature ratio, k is the thermal conductivity, T_i is the temperature of the well-mixed convective interior, T_t is the temperature of the top of the convective layer, H is the volumetric heating rate, b_c is the thickness of the actively convective layer, and Ra_{H} is the Rayleigh number defined for an internally heated layer,

$$Ra_{\mathrm{H}} = \frac{\alpha \rho g H b_c^5}{k \kappa \eta_i}, \quad (2)$$

where, in turn, α is the thermal expansion coefficient, ρ is the density, g is the gravity (1.31 $\mathrm{m\,s^{-2}}$ for Europa), κ is the heat diffusion coefficient, k is the thermal conductivity, and η_i is the effective viscosity calculated for $T = T_i$. Several terms of Eqs. (1) and (2) are functions of temperature. Thus, $k = k_0 T^{-1}$, $\alpha = \alpha_0 T$, and $\kappa = \kappa_0 T^{-2}$, where the constants are 567 $\mathrm{W\,m^{-1}}$ (Klinger, 1980), and $\alpha_0 = 6.24 \times 10^{-7}\ \mathrm{K^{-2}}$ and $\kappa_0 = 9.1875 \times 10^{-2}\ \mathrm{m^2\,K^2\,s^{-1}}$ (Kirk and Stevenson, 1987); these functions are calculated for $T = T_i$, since most of the convective layer is nearly isothermal. In turn, ice density varies slightly with temperature and pressure (e.g., Lupo and Lewis, 1979), yet adopting a constant value does not alter the results significantly; here this value is taken as 930 $\mathrm{kg\,m^{-3}}$. The heat flow out of the convective layer can be obtained by combining Eqs. (1) and (2)

$$F_c = H b_c = 0.49 k \left[\frac{\alpha \rho g (T_i - T_t)^4}{\kappa \eta_i} \right]^{1/3}. \quad (3)$$

To adequately define the temperature at the top of the convective layer, in order to use isoviscous convection equations for the convective sublayer, we use the relation (Grasset and Parmentier, 1998)

$$T_t = T_i - 2.23\frac{RT_i^2}{Q}, \tag{4}$$

where Q is the activation energy for creep deformation determining the viscosity.

Equations (1)–(3) work if the convective layer is only heated from within, and so a lower boundary layer does not exist. However, Europa's ice shell must also be heated from below by tidal and radioactive heating in the rocky core. In a layer heated both from within and below, the general pattern of heat transfer would not be very different to that occurring in a layer heated from within (Sotin and Labrosse, 1999), but there is a lower boundary layer. Moreover, if the lenticulae have effectively formed related to convective processes it is necessary the presence of a lower boundary layer to nucleate thermal plumes. There is not a parameterized formulation for a convective layer heated from within and from below. Here we take into account the effect of the presence of the lower boundary layer in the temperature of the well-mixed convective interior using (see, for example, Deschamps and Sotin, 2001)

$$T_i \approx \left(\frac{Q^2}{4R^2} + \frac{QT_b}{R}\right)^{1/2} - \frac{Q}{2R}, \tag{5}$$

where T_b is the temperature at the shell base, given by the water ice melting point, which depends on pressure P as (Chizhov, 1993)

$$T_b = 273.16\left(1 - \frac{P\ (\text{MPa})}{395.2}\right)^{1/9}. \tag{6}$$

The pressure at the ice shell base is given by $\rho g b$, where b is the total shell thickness. The stagnant lid, which is thermally conductive and heated from below, contributes to the total ice shell thickness. For a temperature-dependent thermal conductivity the thickness of the stagnant lid is

$$b_{\text{sl}} = \frac{k_0}{F_c}\ln\left(\frac{T_t}{T_s}\right), \tag{7}$$

where T_s is the surface temperature.

Finally, to calculate tidal heating rates, we assume that under tidal stresses ice behave like a viscoelastic (Maxwell) material: thus, the tidal volumetric dissipation rate can be calculated according to (Ojakangas and Stevenson, 1989)

$$H = \frac{2\eta\dot{\varepsilon}^2\mu^2}{\mu^2 + \omega^2\eta^2}, \tag{8}$$

where η is the viscosity, $\dot{\varepsilon}$ is the strain rate, $\mu = 4 \times 10^9$ Pa is the ice rigidity, ω is the frequency of the forcing, which can be equated with Europa's mean motion, $2.05 \times 10^{-5}\ \text{rad}\,\text{s}^{-1}$. We take $H = H_i$, which somewhat overestimates tidal dissipation within the upper boundary layer (where temperatures are lower than T_i). But the contribution of the lower boundary layer (where temperatures are higher than T_i) is not calculated, which, in turn, somewhat underestimates total tidal heating. We thus consider our tidal dissipation rate calculations to be representative for the convective layer. Moreover, although a certain amount of heat enters the ice shell from below the method here described can be used as an approximation, since surface heat flow of Europa must be mostly generated in the warm ice of the convective sublayer (Ruiz, 2005).

We calculated shell structure and heat flow by simultaneously solving Eqs. (3)–(8). The total ice shell thickness is taken as $b = b_{\text{sl}} + b_c$ in Eq. (6). Heat transfer through the lower boundary layer is difficult to describe in a simple way (e.g., Sotin and Labrosse, 1999; Nimmo and Stevenson, 2000), although this transfers heat principally by conduction, and thus its thickness is dependent on heat flow at the base of the ice shell. This heat flow is very difficult to estimate, but it should be at least equal to the radiogenic contribution from the rocky core. For a basal heat flow of 6–$8\ \text{mW}\,\text{m}^{-2}$ a reasonable upper limit for the lower boundary layer thickness can be obtained, which, for typical temperatures in the well-mixed interior, is $\leqslant 4$ km (Ruiz and Tejero, 2003). So, including the lower boundary thickness in Eq. (6) causes a difference in calculating T_b no greater than one degree, and therefore does not imply substantial variation in calculating F_c and b_c (Ruiz and Tejero, 2003).

There are two effects that parameterized convective models cannot to address. Temperature-dependent tidal heating could vary by a factor 4 across the convective sublayer, including potential hot and cold plumes (e.g., Tobie et al., 2003; Mitri and Showman, 2005), whereas Eqs. (1)–(3) are appropriate for homogeneous heat dissipation rates. The grain size could similarly be heterogeneous in the ice shell, due to variations in ice contaminants or to differential temperature-enhanced crystal growth or dynamical re-crystallization (Tobie et al., 2006; Barr and McKinnon, 2006). Although these effects can be incorporated to numerical models, parameterized formalisms have the advantage of more easily to explore of the influence of varying the rheology on the convective heat transfer. So, although it is worth to remind respective limitations, both kinds of methodologies should be considered as complementary.

3. Calculation of ice viscosity

For grain sizes much larger than the grain boundary width, the viscosity for diffusion (Newtonian) creep can be calculated from

$$\eta = \frac{d^2}{2B}\exp\left(\frac{Q}{RT}\right), \tag{9}$$

where d is the grain size, Q is the activation energy for creep deformation, $R = 8.3145\ \text{J}\,\text{mol}^{-1}\,\text{K}^{-1}$ is the gas constant, and T is the absolute temperature, and

$$B = \frac{42V_m D_{\text{ov}}}{3RT}, \tag{10}$$

where in turn V_m is the molar volume and D_{ov} is the volume diffusion pre-exponential coefficient. Diffusion creep has not been experimentally observed in water ice, although Goldsby and Kohlstedt (2001) proposed a theoretical flow law for this deformation mechanism based on the values of the constants involved. These values are $Q = 59.4\ \mathrm{kJ\,mol^{-1}}$, $V_m = 1.97 \times 10^{-5}\ \mathrm{m^3}$, and $D_{ov} = 9.1 \times 10^{-4}\ \mathrm{m^2\,s^{-1}}$ (see Goldsby and Kohlstedt, 2001, and references therein).

On the other hand, the viscosity of a non-Newtonian material can be calculated from the strain rate according to the equation

$$\eta = \frac{1}{3}\left(\frac{d^p}{A\dot{\varepsilon}^{n-1}}\right)^{1/n} \exp\left(\frac{Q}{nRT}\right), \tag{11}$$

where p, A, and n are experimentally established constants depending on the creep mechanism; for grain boundary sliding, $Q = 49\ \mathrm{kJ\,mol^{-1}}$, $A = 3.9 \times 10^{-3}\ \mathrm{MPa^{-n}\,m^p\,s^{-1}}$, $p = 1.4$, and $n = 1.8$ (Goldsby and Kohlstedt, 2001). The flow of a non-Newtonian material is dependent on both magnitude and direction of applied stresses. If mean tidal strain rates are used in Eq. (11), a non-Newtonian viscosity related to tidal stresses, η_{tidal}, is obtained. In the ice shell of Europa convective stresses are significantly less than fluctuating tidal stresses. McKinnon (1999) has shown that in these conditions an average effective viscosity can be calculated from

$$\eta_{\mathrm{eff}} = \eta_{\mathrm{tidal}} n^{-1/2}, \tag{12}$$

according to McKinnon (1999), this average effective viscosity may be treated as Newtonian, and therefore it can be used in Eqs. (2), (3), and (7).

4. Heat flow and layers thicknesses

In this section, we calculate the convective heat flow, the thickness of the actively convective layer, the thickness of the stagnant lid, and the whole thickness of the ice shell, as a function of grain size. The surface temperature is taken as 100 K, a value considered as representative of the mean temperature at Europa's surface (e.g., Ojakangas and Stevenson, 1989).

Elastic tidal strain rates in the ice shell of Europa were estimate by Ojakangas and Stevenson (1989) to be between $1.2 \times 10^{-10}\ \mathrm{s^{-1}}$ at the sub- and anti-jovian points and $2.5 \times 10^{-10}\ \mathrm{s^{-1}}$ close to the poles. Ojakangas and Stevenson (1989) argued that these values are independent of the rheology considered, since a thin shell must adopt the hydrostatic figure of the fluid beneath it. Similarly, Tobie et al. (2003) found, for a viscoelastic rheology, slightly slower tidal strain rates between 1 and $2 \times 10^{-10}\ \mathrm{s^{-1}}$. In our calculations we use end member tidal strain rates of 1 and $2.5 \times 10^{-10}\ \mathrm{s^{-1}}$, such that the range of strain rates is overestimated.

For grain size, we selected a range between 0.1 and 10 mm. This interval comprises the values generally used for the ice shell of Europa (Pappalardo et al., 1998; Ruiz and Tejero, 2000; Dombard and McKinnon, 2006). Based on polar glacial ice observations, a grain size smaller than 0.1 mm is unlikely (McKinnon, 1999), at least if there are no impurities limiting crystal growth. For tidal stresses and grain sizes greater than 10 mm the dominant flow mechanism should be dislocation creep (see Durham and Stern, 2001), not considered in this work. Finally, grain size values must be taken as averages, since this parameter could be very heterogeneous both vertically and horizontally (Tobie et al., 2006; Barr and McKinnon, 2006).

Fig. 1 shows that convective heat flow diminishes with increasing grain size for both grain boundary sliding and diffusion creep, although it is more pronounced for the later flow mechanism. The dependence of the heat flow on the tidal strain rate is relatively limited. Taking $70\ \mathrm{mW\,m^{-2}}$ as a reasonable lower limit for the heat flow of Europa (Ruiz, 2005; see also Dombard and McKinnon, 2006), it may be noted that diffusion creep only satisfies this condition for grain sizes less than 0.2 mm, while grain boundary sliding yields results appropriate for grain sizes under 2 mm.

Fig. 2 indicates how for both flow mechanisms, the curves for the thickness of the convective in terms of grain size, layer has a minimal value, which depends on the strain rate. Also, faster strain rates imply thicker convective layers. The curves for grain boundary sliding are smoother. If it is accepted that lenticulae spacing is a reasonable indicator of the thickness of the convective layer, this thickness should not exceed ∼20 km.

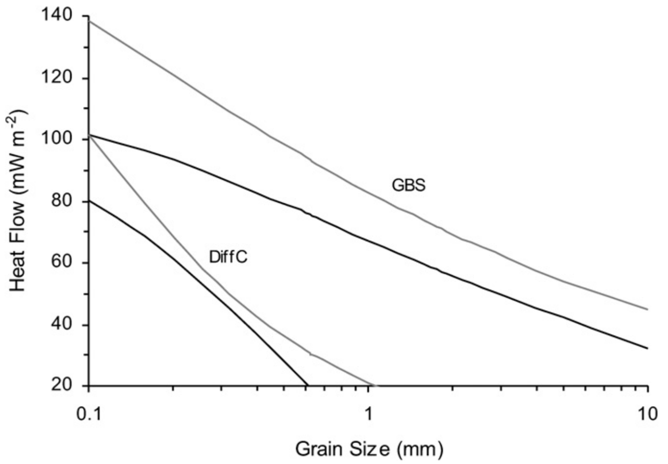

Fig. 1. Convective heat flow show in terms of the grain size. DiffC and GBS and indicates diffusion creep and grain boundary sliding, respectively. Black and gray curves show results for $\dot{\varepsilon} = 10^{-10}\ \mathrm{s^{-1}}$ and $\dot{\varepsilon} = 2.5 \times 10^{-10}\ \mathrm{s^{-1}}$, respectively.

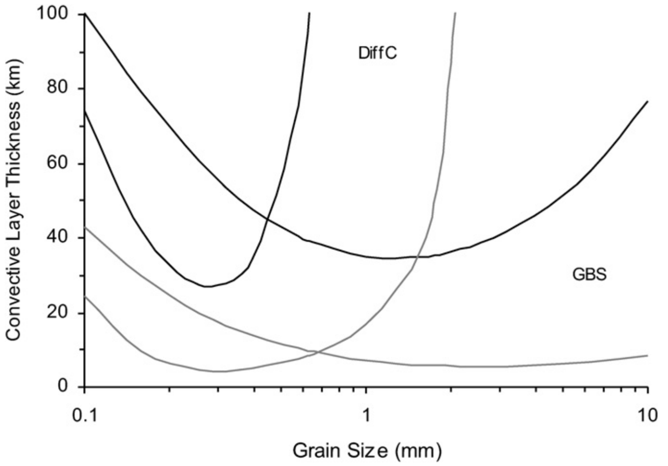

Fig. 2. Convective layer thickness in terms of the grain size. DiffC and GBS and indicates diffusion creep and grain boundary sliding, respectively. Black and gray curves show results for $\dot{\varepsilon} = 10^{-10}\ \mathrm{s^{-1}}$ and $\dot{\varepsilon} = 2.5 \times 10^{-10}\ \mathrm{s^{-1}}$, respectively.

For grain boundary sliding, this condition is fulfilled for grain sizes larger than 0.25 mm, while for diffusion creep, it only holds for sizes in the range between 0.12 and 1.1 mm, although it should be highlighted that this constraint is less solid than that imposed by heat flow. Fig. 3 shows the thickness of the stagnant lid, which is inversely related to the heat flow. Consequently, the stagnant lid is always thinner for grain boundary sliding.

Fig. 4 shows the total thickness of the shell calculated as $b_{sl} + b_c$, as indicated in Section 2. Once again, the curves for grain boundary sliding are smoother as a consequence of the also smoother curves obtained, for this flow mechanism, for the thicknesses of both the convective layer and stagnant lid. It may be observed that the shell has a minimum thickness in (depending on the strain rate) ~13–40 km for both rheologies, which is the consequence of the trend observed for the thickness of the convective layer, although slightly shifted towards smaller grain sizes. An ice shell no more than a few tens of kilometers thick is consistent with a broader range of grain sizes for grain boundary sliding. For example, a shell thinner than ~30 km can be obtained for $d \geqslant 2$ mm and $d = 0.1$–0.75 mm for grain boundary sliding and diffusion creep, respectively.

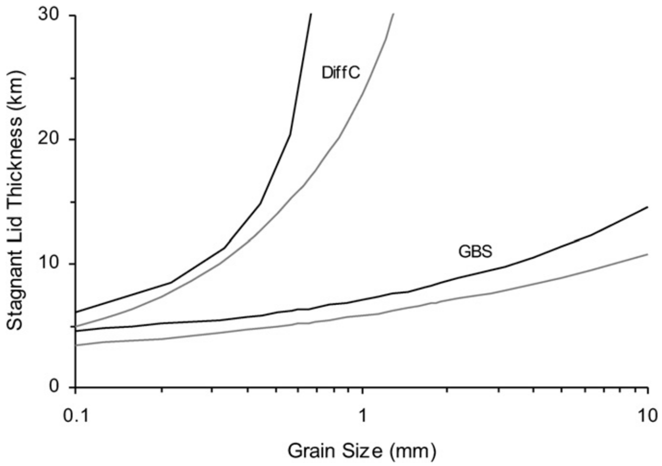

Fig. 3. Stagnant lid thickness in terms of the grain size. DiffC and GBS and indicates diffusion creep and grain boundary sliding, respectively. Black and gray curves show results for $\dot{\varepsilon} = 10^{-10}$ s^{-1} and $\dot{\varepsilon} = 2.5 \times 10^{-10}$ s^{-1}, respectively.

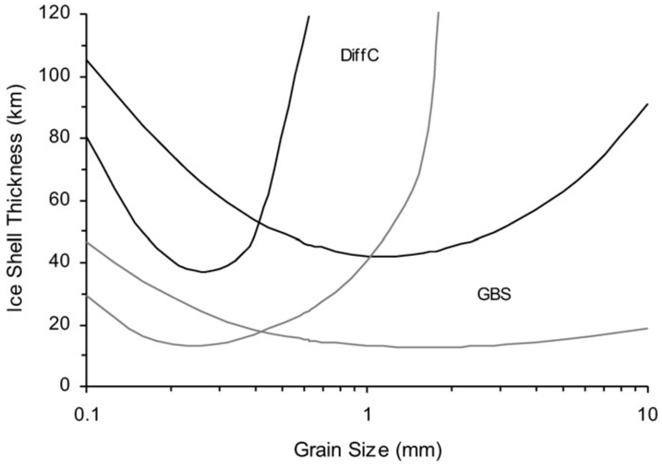

Fig. 4. Total ice shell thickness in terms of the grain size. DiffC and GBS and indicates diffusion creep and grain boundary sliding, respectively. Black and gray curves show results for $\dot{\varepsilon} = 10^{-10}$ s^{-1} and $\dot{\varepsilon} = 2.5 \times 10^{-10}$ s^{-1}, respectively.

It must be noted that the ice shell thickness cannot be thicker than ~ 80–170 km, which is the total thickness of the outer water crust (liquid plus ice) suggested by Galileo flybys (Anderson et al., 1998; see also Kuskov and Kronrov, 2005). For thicker shells the entire water crust should be solidified and the internal ocean would not exist, which is in disagreement with data provided by the Galileo magnetometer (see Kivelson et al., 2000). Complete freezing of the shell is therefore inevitable if the grain size is out of the range ~0.02–2 mm for diffusion creep, or ~7 μm–0.8 m for grain boundary sliding.

Collectively, our results obtain that for grain boundary sliding as the dominant rheology, a grain size between 0.25 and 2 mm is in good agreement with the available constraints. For diffusion creep, however, there is only a narrow range of situations compatible with such constraints, for grain sizes between 0.1 and 0.2 mm. In conclusion, our results favor grain boundary sliding as the dominant rheology in the convective layer of the ice shell of Europa, since this flow mechanism is capable of satisfying the requirements of heat flow, ice shell thickness and thickness of the actively convective layer for a clearly broader range of grain sizes.

Finally, the heat flow and convective layer thickness are relatively insensitive to the exact value of the surface temperature (Ruiz and Tejero, 2003). The stagnant lid thickness (and hence the total ice shell thickness) is dependent on the surface temperature. This effect is important near the poles, where surface temperatures are close to ~50 K. For a local surface temperature $T_{s(\mathrm{local})}$, the thickness of the stagnant lid must be increased, with respect to the value in Fig. 3, in an amount approximately equal to $(k_0/F_c)\ln(100\mathrm{K}/T_{s(\mathrm{local})})$. As an example, for $F_c \geqslant 70$ mW m^{-2} and $T_{s(\mathrm{local})} = 50$ K, the stagnant lid is at most ~6 km thicker than the corresponding value shown in Fig. 3. In any case, this is only important close to the poles, and therefore for the fastest strain rates. The same increasing is also applicable to the total ice shell thickness values shown in Fig. 4.

5. Local variations

In this section we analyze local variations in the heat flow, the thickness of the actively convective layer, the thickness of the stagnant lid and the total shell thickness. For this purpose, we use tidal strain rates estimated by Ojakangas and Stevenson (1989) (see their Fig. 1), as a function of latitude and longitude. The range of strain rates in Tobie et al. (2003) is similar, but these authors only give end-members values.

The surface temperature is calculated following the procedure of Ojakangas and Stevenson (1989), but without taking into account the obliquity of the orbit, such that it depends on latitude according to (see also Tobie et al., 2003)

$$T_s = \left[\frac{(1-A)(F_{\mathrm{solar}})}{\sigma}\left(\frac{\cos\theta}{\pi}\right)\right]^{1/4}, \tag{13}$$

where θ is the latitude, A is the albedo of the ice, F_{solar} is the solar flux at Jupiter's orbit, and $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}

is the Stefan–Boltzmann constant. We use $A = 0.55$ (Spencer et al., 1999) and $F_{solar} = 50.6\ \mathrm{mW\,m^{-2}}$ (for solar constant and orbital parameters as in de Pater and Lissauer, 2001); herein Eq. (13) can be written simply as

$$T_s = 106.3 \cos^{1/4}\theta, \tag{14}$$

this is in accordance with the equatorial and seasonal mean surface temperature of 106 K reported by Spencer et al. (1999).

Calculations have been performed for grain sizes of 0.15 and 1 mm for diffusion creep and grain boundary sliding respectively. These values are within the ranges obtained in the previous section for the corresponding rheologies. Also, they give similar convective heat flows, what is useful for comparative purposes.

Results are shown in Figs. 5–8. General trends are relatively similar to these obtained for Newtonian viscosity in Tobie et al. (2003) (see their Fig. 12), because the dependence of tidal heating on the locally-dependent tidal straining, but concrete values are very different, as a consequence of our different treatment (including the imposition of satisfying constraints for heat flow and layer thicknesses). In Fig. 5 it can be seen that the total variation in convective heat flow is lower for diffusion creep (between 74 and 82 $\mathrm{mW\,m^{-2}}$) than for grain boundary sliding (between 70 and 83 $\mathrm{mW\,m^{-2}}$). The highest heat flows are obtained for high latitudes, where tidal strain rates are the faster (and hence tidal heating more intense); the lowest heat flows are located in the sub- and anti-jovian points, where strain rates are slower (Ojakangas and Stevenson, 1989).

The volumetric tidal heating rate is lower for diffusion creep and $d = 0.15$ mm ($H \approx 5\ \mathrm{\mu W\,m^{-2}}$) than for grain boundary sliding and $d = 1$ mm ($H \approx 8\ \mathrm{\mu W\,m^{-2}}$). So, for diffusion creep the thickness of the convective layer, where tidal heating is generated, must be proportionally larger in order to equilibrate a similar heat flow, with local variations also larger; this effect is observed in Fig. 6. Fig. 7 shows that local variations in stagnant lid thickness are little, due to the moderate variations in convective heat flow. As a consequence of the previously mentioned, variations in total thickness of the ice shell are larger for diffusion creep (Fig. 8). Viscous flow of warm ice in the shell base would tend to smooth local variations in total thickness (Stevenson, 2000), but it is not clear the importance of this process for an actively convective shell.

Currently there are not clear observational evidences on local variations in ice shell thickness. Spaun et al. (2004) relate differences in lenticulae spacing with local variations in the thickness of the convective layer. Local trends proposed by these authors are generally consistent with both large-scale variations in ice shell thickness obtained by (Ojakangas and Stevenson, 1989) (their model only takes into account thermal conduction, not convection), Tobie et al. (2003), and this study (Fig. 8), and with trends in variation of the convective layer thickness shown in Fig. 7. Moreover, the absolute convective layer thicknesses here obtained for grain boundary sliding (Fig. 7b) are

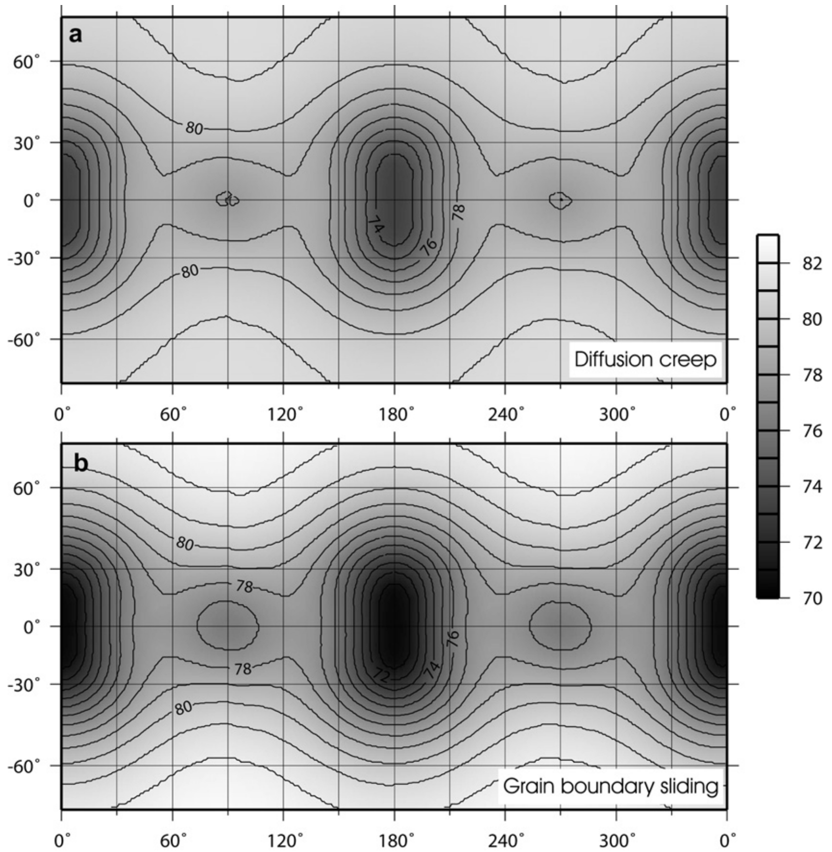

Fig. 5. Maps of convective heat flow for (a) diffusion creep, and (b) grain boundary sliding. The calculations use latitude- and longitude-dependent strain rates after Ojakangas and Stevenson (1989), and latitude-dependent surface temperatures as given by Eq. (14).

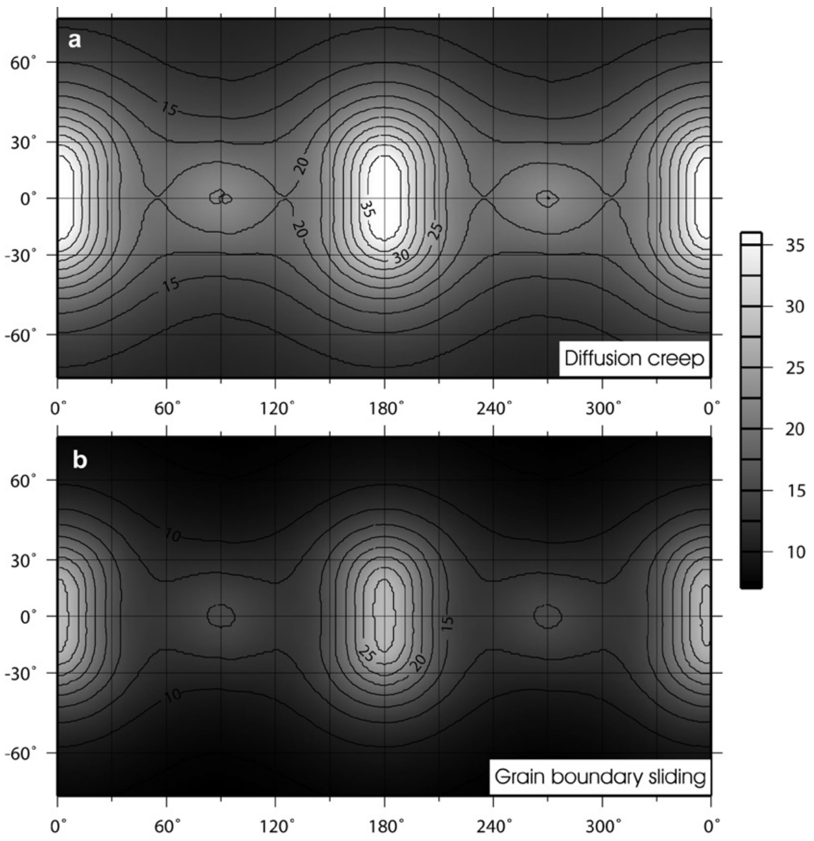

Fig. 6. Maps of convective layer thickness for (a) diffusion creep, and (b) grain boundary sliding. Strain rates and surface temperatures as in Fig. 2.

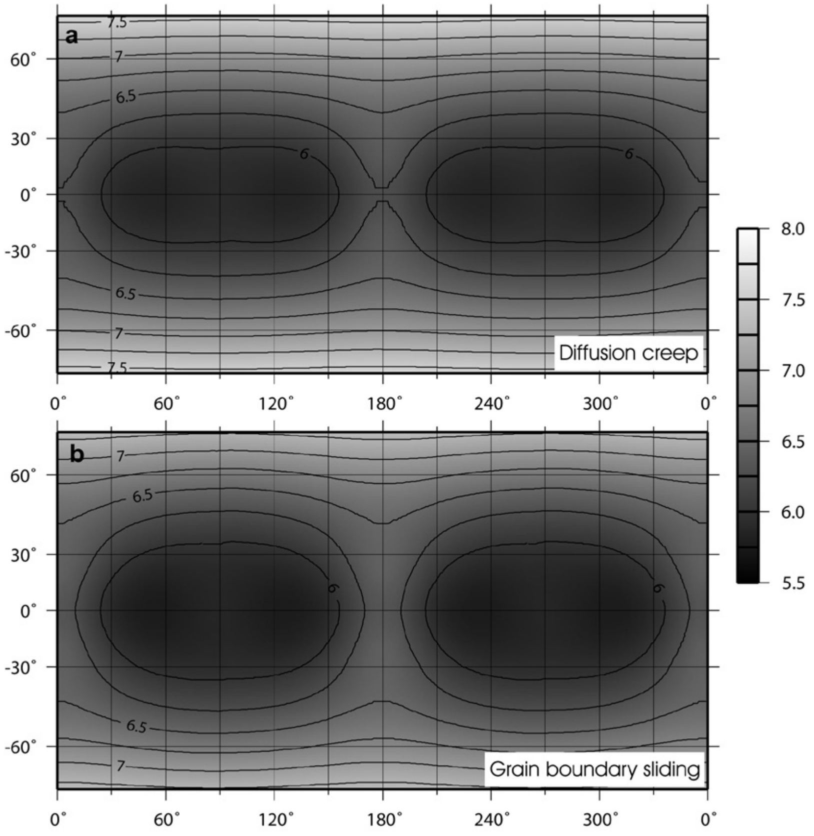

Fig. 7. Maps of stagnant lid thickness for (a) diffusion creep, and (b) grain boundary sliding.boundary sliding and diffusion creep. Strain rates and surface temperatures as in Fig. 2.

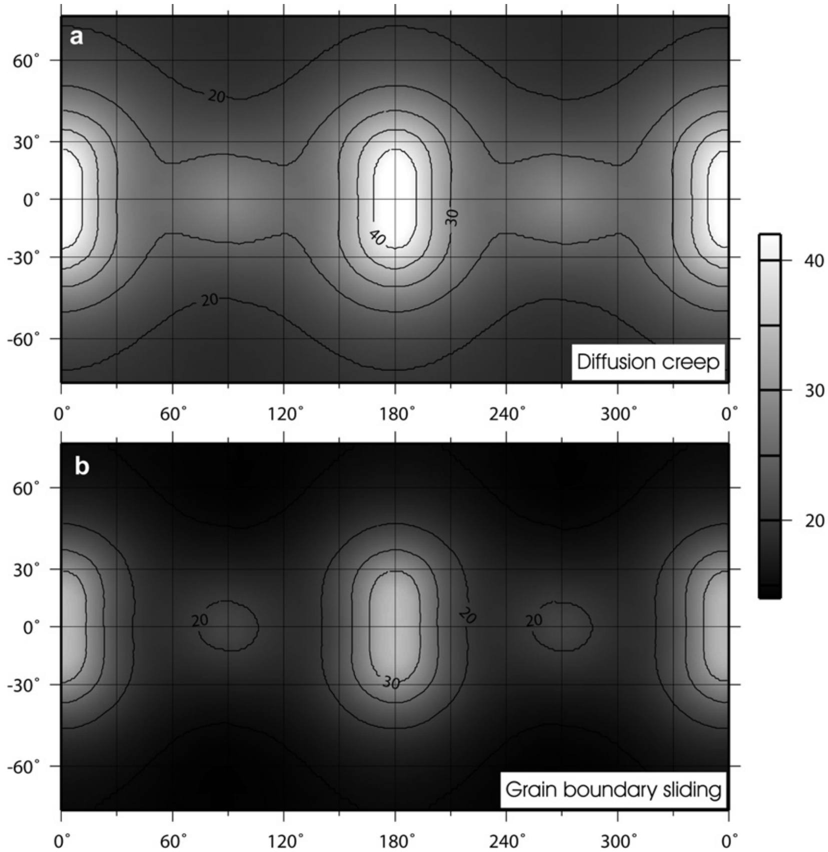

Fig. 8. Maps of total ice shell thickness for (a) diffusion creep, and (b) grain boundary sliding. Strain rates and surface temperatures as in Fig. 2.

more similar to those deduced from Spaun et al. (2004) than the equivalent ones for diffusion creep (Fig. 7a). Fig. 8b shows that for grain boundary sliding and $d = 1$ mm the ice shell could locally be thinner than 15 km, whereas Schenk (2002) proposed a shell at least 19–25 km thick from the relation between size and depth in large impact structures. However, in the same figure it can be observed that the ice shell would be 24 and 20 km thick at the localization of Callanish (16° S, 26° E) and Tyre (34° N, 214° E), respectively, the largest impact structures on Europa, in good agreement with Schenk's results.

6. Discussion and conclusions

Our results favor grain boundary sliding, respect to diffusion creep, as the dominant rheology in the actively convective layer of Europa's ice shell. In a previous work, Ruiz and Tejero (2003) showed that grain boundary sliding is more feasible than dislocation creep as the rheology of the convective layer. Thus, the comparison of our values for convective heat flow, and convective layer, stagnant lid and whole ice shell thicknesses with the available constraints is consistent with the extrapolation of experimental data on ice deformation to the conditions of the convective layer of Europa (see Goldsby and Kohlstedt, 2001). Our results also favor grain sizes in the range between 0.2 and 2 mm.

Previous works on Newtonian convection in the ice shell have also yielded results that can be easily fitted to requirements related to the thickness of the shell or convective layer, but they are difficult to reconcile with the constraints for the heat flow. Most of these predict heat flows in the range 20 to 70 mW m^{-2} (Hussmann et al., 2002; Tobie et al., 2003; Showman and Han, 2004; Mitri and Showman, 2005), such that they are marginally consistent with the surface heat flows inferred for Europa from geological indicators (e.g., Ruiz, 2005). These models are useful for gain information about convective patterns, but they fix the viscosity of the ice at its melting point and not consider grain sizes. Otherwise, Nimmo and Manga (2002) found that convection by volume diffusion creep (calculating the viscosity according to the flow law in Goldsby and Kohlstedt, 2001) could explain the size of Europa's domes. In their model, the convective heat flow is 104–115 mW m^{-2}, and grain size 0.02–0.06 mm, requiring impurities limiting ice crystal growth.

Basal slip also has been proposed as the dominant deformation mechanism in the convective layer of Europa (Duval and Montagnat, 2004), on the basis of similar stresses and strain rates in both the ice shell and terrestrial polar ice sheets. But there is not consensus about the interpretation of ice deformation and fabric in ice sheets samples (e.g., Duval and Montagnat, 2002; Goldsby and Kohlstedt, 2002). If the creep parameters for basal slip ($Q = 60$ kJ mol^{-1}, $A = 5.5 \times 10^{-3}$ MPa^{-n} m^{p} s^{-1}, $p = 0$, and $n = 2.4$; Goldsby and Kohlstedt, 2001) are used following the methodology described in this paper it is obtained (for $\dot{\varepsilon} = 1{-}2.5 \times 10^{-10}$ s^{-1}) a heat flow of $\sim$100–150 mW m^{-2}, but the ice shell is very thick,

∼105−170 km (the upper ∼3–4 km corresponding to the stagnant lid), what does not seem convincing for Europa.

On the other hand, Moore (2006) used a composite flow law (with contributions from volume and grain boundary diffusion creep, grain boundary sliding, basal slip and dislocation creep) for water ice proposed by Goldsby and Kohlstedt (2001), obtaining volume diffusion creep as the dominant rheology of the actively convective layer, whose thickness is greater than ∼16 km. For grain sizes smaller than 1 mm, heat flow approached ∼100 $mW\,m^{-2}$ (see their Fig. 3), but shell thickness varied considerably depending on grain size. These results are very interesting, but that work does not take into account the effect of tidal stresses on non-Newtonian flow mechanisms [see McKinnon (1999) and Section 3]. If tidal straining is introduced in the composite flow law of Goldsby and Kohlstedt (2001) (correcting the diffusion creep flow law according to Barr and Pappalardo, 2005), then for $\dot{\varepsilon} = 1\text{–}2.5 \times 10^{-10}\ s^{-1}$ and $T = 260$ K (a typical temperature for the convective interior; McKinnon, 1999), it gives that grain boundary sliding dominates over diffusion creep for grain sizes larger than 0.2 mm (and over dislocation creep for grain sizes under ∼1.5–2 mm; 0.2–2 mm is similar to the preferred grain size range obtained in the present work for convection on Europa's ice shell by grain boundary sliding).

Dynamic recrystallization in convective layers of icy satellites could affect the distribution of grain sizes. This effect is poorly known, but preliminary works suggest that grain sizes in equilibrium with convection in icy satellites could vary largely, both vertically and laterally, and to be relatively large, between one millimeter and several centimeters (Barr and McKinnon, 2006; Tobie et al., 2006). These works do not account for the effect of tidal stresses: if tidal stresses in the ice shell of Europa, typically of ∼0.1 MPa (Greenberg et al., 1998), are considered, the grain size in dynamic equilibrium would be ∼4 mm (Barr and McKinnon, 2006). These grain sizes are mostly beyond the preferred range obtained by the present study for grain boundary sliding, and implies freezing of the entire water crust for diffusion creep. This suggest grain sizes not in dynamic recrystallization equilibrium (maybe due to the presence of impurities), at least at the time when the geological features used as heat flow indicators were formed, although further research is need.

In the calculations presented here, we only took into account the physical properties of water ice. Although the presence of salts or other substances could affect the thermal (e.g., Prieto-Ballesteros and Kargel, 2005) or rheological properties of the ice (Durham et al., 2005), it is not clear whether these substances occur in sufficient amounts to produce important effects; for example, Durham et al. (2005) found the flow of ice mixed with up to 20% mirabilite (a substance possibly close to some of the hydrated magnesium salts that could exist in Europa's ice shell) is practically indistinguishable of the pure water ice flow. Moreover, the ice shell of Europa could be heterogeneous [see Nimmo et al. (2005) and references therein], with temporal and local variations in the dominant rheology of the convective layer, perhaps in relation to changes in grain size or non-ice components abundance. This could explain, for instance, the low heat flow between 24 and 35 $mW\,m^{-2}$ deduced from the effective elastic thickness of the lithosphere in the area close to the Cilix crater (Nimmo et al., 2003; Ruiz, 2005). Thus, the results of current convection models should be interpreted in a general manner whereas future refinements are performed.

Acknowledgments

The authors thank the comments from two anonymous reviewers. J.R. was supported by a Contract I3P with the CSIC, financed for the Fondo Social Europeo. J.A.A.G. was supported by a grant of the Universidad Complutense de Madrid. N.S. was supported by a contract of the Programa Juan de la Cierva of the Spanish Ministerio de Educación y Ciencia.

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