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Coupled convection and tidal dissipation in Europa's ice shell using non-Newtonian grain-size-sensitive (GSS) creep rheology

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ABSTRACT

We present self-consistent, fully coupled two-dimensional (2D) numerical models of thermal evolution and tidal heating to investigate how convection interacts with tidal dissipation under the influence of non-Newtonian grain-size-sensitive creep rheology (plausibly resulting from grain boundary sliding) in Europa's ice shell. To determine the thermal evolution, we solved the convection equations (using finite-element code ConMan) with the tidal dissipation as a heat source. For a given heterogeneous temperature field at a given time, we determined the tidal dissipation rate throughout the ice shell by solving for the tidal stresses and strains subject to Maxwell viscoelastic rheology (using finite-element code Tekton). In this way, the convection and tidal heating are fully coupled and evolve together. Our simulations show that the tidal dissipation rate can have a strong impact on the onset of thermal convection in Europa's ice shell under non-Newtonian GSS rheology. By varying the ice grain size (1–10 mm), ice-shell thickness (20–120 km), and tidal-strain amplitude ($0–4 \times 10^{-5}$), we study the interrelationship of convection and conduction regimes in Europa's ice shell. Under non-Newtonian grain-size-sensitive creep rheology and ice grain size larger than 1 mm, no thermal convection can initiate in Europa's ice shell (for thicknesses <100 km) without tidal dissipation. However, thermal convection can start in thinner ice shells under the influence of tidal dissipation. The required tidal-strain amplitude for convection to occur decreases as the ice-shell thickness increases. For grain sizes of 1–10 mm, convection can occur in ice shells as thin as 20–40 km with the estimated tidal-strain amplitude of 2×10^{-5} on Europa.

1. Introduction

Elucidating the interaction of convection with tidal heating is important for unraveling the geology and thermal histories of several icy satellites, including Europa, Ganymede, Titan, and Enceladus, among others. Unlike the case of radiogenic heating, which tends to be spatially homogeneous and decays steadily in time, tidal heating depends nonlinearly on the three-dimensional viscoelastic state of the ice shell and can exhibit strong spatial and temporal variations. This coupled interaction enables an array of interesting feedbacks that may affect the production of surface landforms (e.g., Sotin et al., 2002; Tobie et al., 2003; see Barr and Showman (2009) for a review).

Convection in the ice shell of Europa has received significant attention (McKinnon, 1999; Sotin et al., 2002; Tobie et al., 2003; Barr et al., 2004; Barr and Pappalardo, 2005; Showman and Han, 2004, 2005; Han and Showman, 2005, 2008; Mitri and Showman, 2005; see Barr and Showman (2009) for a review). In these studies, the tidal heating (if any) was assumed to be constant or to depend only on local temperature, following the predictions of an isothermal Maxwell model with zero spatial dimensions. However, tidal dissipationat a given location depends not only on local temperature, but also on the surrounding temperature (Mitri and Showman, 2008; Han and Showman, 2010; Behounkova et al., 2010). Han and Showman (2010) performed the first coupled numerical simulations of convection and oscillatory tidal flexing to show that tidal heating, self-consistently calculated with the heterogeneous temperature structure, has a strong impact on thermal evolution in Europa's ice shell. Their results support the idea that spatially variable tidal dissipation could lead locally to high temperatures, partial melting, and play an important role in the formation of ridges, chaos, or other features (Nimmo and Gaidos, 2002; Han and Showman, 2008).

For simplicity, most of the above convection studies—including Han and Showman (2010)—assumed a temperature-dependent Newtonian (diffusion creep) rheology, relevant to small grain sizes of ∼0.5 mm or less. However, for grain sizes exceeding ∼1 mm, non-Newtonian creep mechanisms become dominant depending on the temperature, grain size, and stress (Durham et al., 1997; Goldsby and Kohlstedt, 1997, 2001; Durham and Stern, 2001).

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Although grain sizes in icy satellites are highly uncertain, values of 1–10 mm are common in terrestrial glaciers (Budd and Jacka, 1989; Thorsteinsson et al., 1997; De La Chapelle et al., 1998), and recent estimates suggest that these sizes may also be appropriate for icy satellites (Barr and McKinnon, 2007). If so, then non-Newtonian creep mechanisms could control the rheology. The most relevant for convective flow in icy satellites is a non-Newtonian grain-size-sensitive (GSS) creep regime, with a stress exponent n of 1.8, which dominates ice creep over a wide range of temperature for grain sizes larger than 1 mm and stresses <1 MPa appropriate for planetary conditions (Goldsby and Kohlstedt, 1997, 2001). Goldsby and Kohlstedt (2001, 2002) argued that the deformation in this regime is controlled by grain boundary sliding (GBS), although debate exists over the precise mechanism (Duval and Montagnat, 2002). We henceforth refer to this regime as non-Newtonian GSS creep.

Despite the relevance of non-Newtonian rheology to icy satellites, no previous studies of icy satellites have investigated convection with non-Newtonian rheology in the presence of tidal heating. To date, the only numerical studies of convection in icy satellites that adopt non-Newtonian rheology are Barr et al. (2004) and Barr and Pappalardo (2005), who investigated the onset of convection in the absence of internal heating. However, internal (tidal) heating can greatly alter the conditions for convective onset, so it must be included for a robust assessment of the conditions for convective onset on tidally heated icy satellites.

Here, we present two-dimensional (2D) fully coupled simulations of convection and oscillatory tidal flexing to quantify how tidal heating influences the onset and equilibrated state of convection under non-Newtonian grain-size-sensitive (GSS) rheology in the ice shells of large icy satellites. This extends the study of Han and Showman (2010) to the non-Newtonian case. In Section 2, we describe the method to couple the long-term thermal evolution and high-frequency tidal flexing. In Section 3, we present the results from our coupled models. Section 4 discusses the geophysical implications.

2. Models and methods

We study the problem of thermal convection with tidal heating in a 2D Cartesian geometry, which is appropriate for large icy satellites because the ice-shell thickness is much smaller than the satellite radius. The specific parameters of Europa are adopted. We use the finite element code ConMan (King et al., 1990) to solve the two-dimensional governing dimensionless momentum, continuity, and thermal-energy equations, subject to the Boussinesq approximation and neglecting inertia:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + Ra\theta k_i = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

$$\frac{\partial \theta}{\partial t} + u_i \frac{\partial \theta}{\partial x_i} = \frac{\partial^2 \theta}{\partial x_i^2} + q' \tag{3}$$

where σ_{ij} is the stress tensor, u_i is velocity, Ra is basal heating Rayleigh number, θ is temperature, q' is internal tidal heating rate, k_i is the vertical unit vector, t is time, x_i and x_j are the spatial coordinates, and i and j are the coordinate indices. All variables are dimensionless. Repeated spatial indices imply summation. The model parameters are presented in Table 1.

To calculate the tidal heating rate q' in Eq. (3), we couple the convective evolution (Eqs. (1)–(3)) to a model of the oscillatory tidal flexing for a given temperature distribution. We adopt Maxwell viscoelastic rheology, which is important because the tidal period is close to the Maxwell time in Europa's ice shell. We use the two-dimensional finite-element code Tekton (Melosh and Raefsky, 1980) to solve for the tidal stress, tidal strain, and tidal heating rate with the temperature distribution from Eq. (3). See Han and Showman (2010) for the detailed description of calculations.

Table 1
Model parameters.

Name	Symbol	Value
Acceleration of gravity	g	$1.3\ \mathrm{m\ s^{-1}}$
Density	ρ	$930\ \mathrm{kg\ m^{-3}}$
Thermal expansivity	α	$1.1 \times 10^{-4}\ \mathrm{K^{-1}}$
Thermal diffusivity	κ	$10^{-6}\ \mathrm{m^2\ s^{-1}}$
Specific heat	c_p	$1250\ \mathrm{J\ kg^{-1}\ K^{-1}}$
Surface temperature	T_t	110 K
Bottom temperature	T_b	260 K
Angular frequency	ω	2×10^{-5}
Tidal-strain amplitude	ϵ	$0–4 \times 10^{-5}$
Young's modulus	E	10^{10} Pa
Poisson ratio	μ	0.25
Activation energy	Q	$49{,}000\ \mathrm{J\ mol^{-1}}$
Stress exponent	n	1.8
Grain size exponent	p	1.4
Ice grains size	d	1–10 mm
Thickness of ice shell	D	20–120 km

The viscous rheology of ice can be described using a power-law relationship (Durham et al., 1997; Goldsby and Kohlstedt, 2001)

$$\dot{\epsilon} = A\frac{\sigma^n}{d^p} \exp\left(-\frac{Q}{RT}\right) \tag{4}$$

where $\dot{\epsilon}$ is strain rate, A is a material constant, σ is stress, n is stress exponent, d is grain size, p is grain-size exponent, Q is activation energy, R is the gas constant, and T is temperature. Here, we focus on non-Newtonian GSS creep rheology with $n = 1.8$ and $p = 1.4$ as suggested by Goldsby and Kohlstedt (2001).

While the grain sizes are unknown, estimates have suggested 0.1–10 mm (Kirk and Stevenson, 1987; Barr and McKinnon, 2007). Ice grain sizes in terrestrial glaciers have been estimated at 1–10 mm (Budd and Jacka, 1989; Thorsteinsson et al., 1997; De La Chapelle et al., 1998). To bracket this range, studies should explore ice grain size values spanning 0.1–10 mm. In our previous paper (Han and Showman, 2010), we have explored the impact of tidal heating on convection under diffusion-creep rheology (i.e., ice grain size range of 0.1–0.5 mm). Here, we focus on non-Newtonian GSS rheology with ice grain sizes of 1–10 mm. See Table 1 for the rheological parameters used in the models. For the present study, we neglect pre-melting, which could lead to a viscosity drop and greater strain rates near the melting temperature than are captured in Eq. (4) (e.g., Dash et al., 1995; Duval, 1977; De La Chapelle et al., 1999; Tobie et al., 2003). For simplicity, we also neglect the possible dynamic growth of ice grain size in Europa's ice shell (Barr and McKinnon, 2007; Tobie et al., 2006).

All the models are performed with aspect ratio (ratio of width to depth) of 1. The resolution is 100 elements in both vertical direction and horizontal direction. Galileo data indicate that Europa's H_2O layer is ~100–150 km thick (Anderson et al., 1998); however, the thickness of solid ice layer over the liquid water ocean is uncertain. We vary the ice-shell thickness from 20 to 120 km in different models to bracket the range of plausible values.

In the thermal convection models, the velocity boundary conditions are periodic on the sides and free-slip rigid walls on the top and bottom. To facilitate comparison with previous work on convective initiation in satellite ice shells, we implement similar temperature boundary and initial conditions to those in Barr et al. (2004) and Barr and Pappalardo (2005). We fix the bottom boundary to a temperature of 260 K, representing the melting temperature. The top surface is maintained at 110 K. We pin the temperature to prevent it from rising above the melting temperature. The temperature was initialized as a linear function of depth (i.e., a conductive profile), with an initial temperature disturbance as follows:

$$T = T_0 - \Delta T \frac{y}{D} + \delta T \cos\left[\pi \frac{x}{D}\right] \sin\left[\pi\left(1 - \frac{y}{D}\right)\right] \qquad (5)$$

where T_0 is melting temperature, ΔT is temperature contrast between the top and bottom boundaries, δT is initial temperature disturbance amplitude, x is horizontal coordinate, and y is vertical coordinate.

In the tidal flexing simulations, we implement a displacement boundary condition where the sidewall positions at $x = D/2$ and $-D/2$ vary in time as $\xi_0 \sin \omega t$ and $-\xi_0 \sin \omega t$, respectively, with a displacement amplitude ξ_0 specified to give a desired spatial-mean, peak-to-peak tidal-flexing amplitude. ξ_0 is systematically varied in different simulations so that the spatial-mean tidal-strain amplitude (i.e., ξ_0/D) ranges from 0 to 4×10^{-5} in any given case, bracketing the range of tidal-flexing amplitudes expected for Europa, Ganymede, and Titan. The oscillation period is 3.5 Earth days, appropriate to Europa. This boundary condition forces the domain to experience a temporally periodic cycle of extension/contraction.

3. Results

We first ran models of thermal evolution in Europa's ice shell without tidal heating. Fig. 1 shows the results from a model with an ice shell thickness of 99 km, ice grain size of 1 mm, and an initial temperature disturbance amplitude (δT) of 37.5 K. Our simulation results are consistent with previous studies without tidal heating and verify previous conclusions that the onset of basal-heating-only convection in an ice shell depends on ice grain size, ice-shell thickness, and the initial temperature disturbance distribution and amplitude (Barr et al., 2004; Barr and Pappalardo, 2005). The minimum ice-shell thickness (i.e., critical ice-shell thickness) for convection to occur—with basal heating alone—is larger if the initial temperature disturbance is smaller. For an ice grain size of 1 mm and initial temperature disturbance amplitude of 15 K, the critical ice-shell thickness in the absence of internal heating is 119 km. The critical ice-shell thickness for basal-heating-only convection increases as the ice grain size increases, and for a grain size of 10 mm, no convection can occur in the absence of internal heating even for the maximum ice-shell thicknesses relevant to Europa (120–150 km). In this case, the ice shell transports heat solely by thermal conduction.

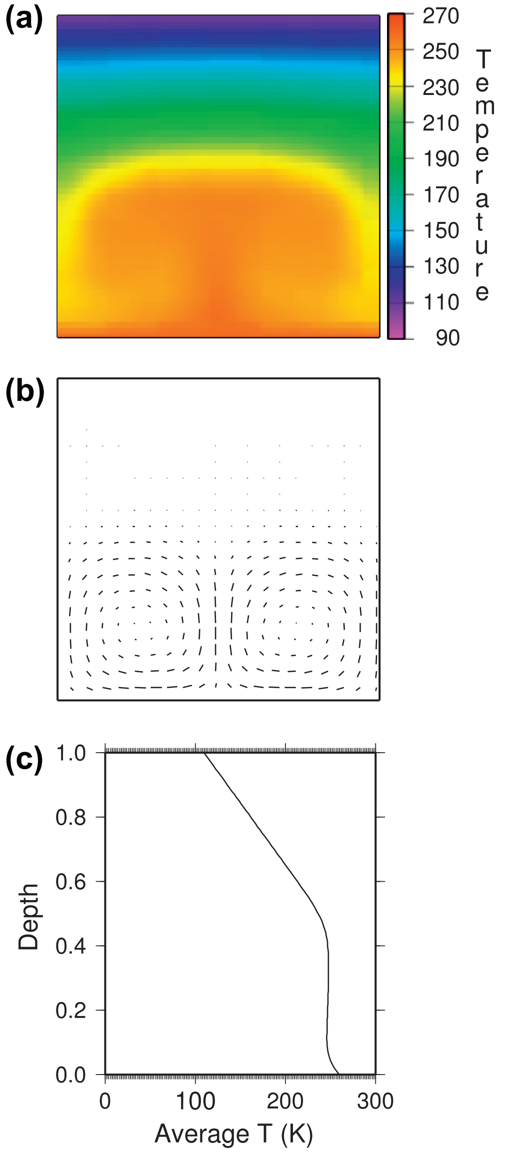

Fig. 1. Results from a thermal convection model without tidal heating. (a) Temperature field. (b) Flow field. (c) Average temperature versus depth. The thickness of the ice shell is 99 km and the ice grain size is 1 mm. The model has an initial temperature disturbance amplitude of 37.5 K.

Our solutions show that tidal heating has a strong impact on the conditions allowing convection in an ice shell. To quantify this dependence, we performed a sequence of integrations with differing tidal-flexing amplitude to determine, for a given grain size and shell thickness, the minimum tidal-flexing amplitude that allows convection to occur. When the tidal-flexing amplitude is small, the resulting tidal heating does not significantly alter the thermal state. However, the thermal evolution changes dramatically as the tidal-strain amplitude increases. For example, for an ice-shell thickness of 50 km, grain size of 1 mm, and initial temperature disturbance amplitude of 15 K, convection cannot occur if the tidal-strain amplitude is less than 0.5×10^{-5}. However, Fig. 2 shows that convection does occur for a tidal-strain amplitude of 0.75×10^{-5}. A cold conductive layer forms at the top of the domain, and the temperature in the bottom half is nearly uniform at the melting temperature. The flow field, consisting of broad, laminar upwellings and downwellings (Fig. 2d), is typical of convection at modestly supercritical Rayleigh numbers. The average temperature within the convective layer is almost uniform and close to the temperature at the base (Davaille and Jaupart, 1993; Grasset and Parmentier, 1998; Schubert et al., 2001; Moore, 2008); no significant lower boundary layer develops, as expected for convection when internal heating dominates over that conducted through the base. The tidal-strain amplitude of 0.75×10^{-5} is the minimum tidal-strain amplitude for convection to occur in an ice-shell thickness of 50 km and ice grain size of 1 mm, so we call it the critical tidal strain amplitude for ice-shell thickness of 50 km and ice grain size of 1 mm. We note that the critical value of 0.75×10^{-5} is obtained numerically.

For larger ice grain sizes, we find that larger critical tidal-strain amplitudes are required to initiate convection in an ice shell of a given thickness. For example, at a grain size of 10 mm, a minimum tidal strain amplitude of 2.25×10^{-5} is required to initiate convection in an ice shell 50 km thick. This critical tidal-strain amplitude is almost 3 times larger than that with the same parameters but an ice grain size of 1 mm.

Fig. 3 summarizes how the critical tidal-strain amplitude for convection depends on a wide range of parameters. Initial temperature disturbance amplitudes of 3, 15, and 30 K are depicted in black, red, and green curves, respectively. Each panel shows the critical tidal strain amplitudes (dashed-dotted curves) versus ice-

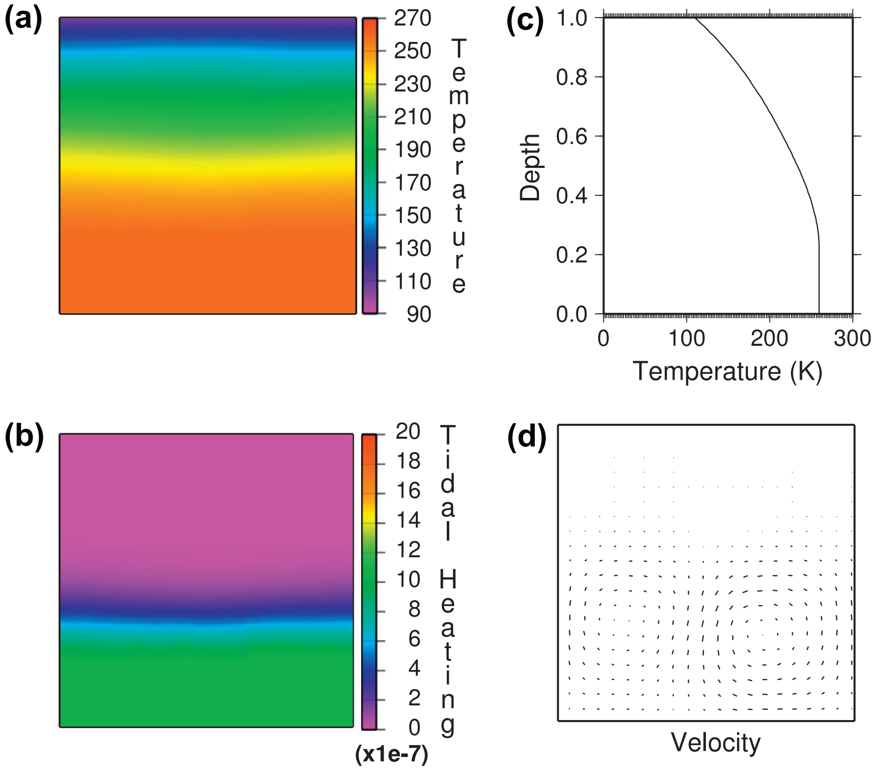

Fig. 2. Results from a fully coupled ConMan/Tekton model of thermal convection and oscillatory tidal flexing. (a) Temperature field. (b) Tidal dissipation rate. (c) Average temperature versus depth. (d) Velocity field. The model implements a domain-averaged tidal-flexing amplitude of 0.75×10^{-5} and tidal period of 3.5 days. The thickness of the ice shell is 50 km and the ice grain size is 1 mm, The model has an initial temperature disturbance amplitude of 15 K.

shell thickness for a given ice grain size, corresponding to 1 mm in panel (a) and 10 mm in panel (b). Convection occurs only for combinations of tidal-strain amplitude and shell thickness that lie above, or to the right of, the relevant curve. First consider Fig. 3a, corresponding to a grain size of 1 mm. Without tidal heating, convection can occur only for ice shells thicker than 99 km or 119 km for initial temperature perturbations of 30 or 15 K, respectively; if the initial temperature perturbation is 3 K or less, convection does not occur without tidal heating for any of the shell thicknesses explored here.

Tidal-strain amplitudes smaller than $\sim 0.3 \times 10^{-5}$ do not alter the minimum ice-shell thickness needed for convection. Once the tidal-strain amplitude exceeds 0.4×10^{-5}, however, convection can occur in progressively thinner ice shells, and for values of 1.5×10^{-5}, convection can occur in ice shells as thin as 20 km. This factor-of-six reduction in the shell thickness needed for convection emphasizes the dramatic effect that tidal heating exhibits on conditions allowing convection. Since Europa's average tidal-strain amplitude is 2×10^{-5} and its ice-shell thickness is often estimated at tens of km, Fig. 3 therefore suggests that convection via non-Newtonian grain-size-sensitive creep ($n = 1.8$) is possible on Europa if the grain size is 1 mm.

The critical tidal-strain amplitude depends strongly on ice grain size. Fig. 3b shows the critical tidal-strain amplitude as a function of ice-shell thickness if a grain size of 10 mm is used. Red, and green curves again correspond to initial temperature disturbance amplitudes of 15, and 30 K. Our models show that, without tidal heating, convection cannot occur even for Europa's thickest plausible ice shells (120 km) if the grain size is 10 mm. Convection can occur in thinner ice shell if tidal heating is present. However, for a given ice-shell thickness, the critical tidal-strain amplitude is ~ 3 times larger for a grain size of 10 mm than for a grain size of 1 mm. Our simulations show that thermal convection can occur in an ice shell thicker than 40 km with ice grain size of 10 mm if Europa's strain deformation is as large as 2.25×10^{-5}.

The amplitude, δT, of the initial temperature disturbance influences the onset of basally heated convection (without tidal heating) under non-Newtonian grain-size-sensitive (GSS) creep rheology. The required ice-shell thickness for the onset of convection with basal heating alone decreases as the initial disturbance amplitude (δT) increases up to several tens of K (Barr et al., 2004). However, our simulations show that the initial temperature disturbance amplitude (δT) has very little impact on the onset of convection when tidal heating is included (Fig. 3). Our simulations show that the critical tidal-strain amplitude remains constant for models of the same ice-shell thickness but with different initial temperature disturbance—that is, the curves in Fig. 3 all overlap for the entire range of parameters explored in panel (b) and for shell thicknesses less than ~ 100 km, and tidal-strain amplitudes exceeding ~ 0.3–0.4×10^{-5}, in panel (a).

4. Conclusions and discussions

We performed numerical simulations of coupled convection and oscillatory tidal flexing to study the interrelationship between tidal dissipation and the thermal evolution of Europa's ice shell. Adopting a Maxwell viscoelastic rheology for the ice shell, we calculate the tidal dissipation rate by solving for the stress and strain throughout the oscillatory tidal flexing cycle for a specified temperature structure. We couple the convective evolution and tidal dissipation by including the dissipation as an internal heating source in the convection equations. Han and Showman (2010) implemented diffusion creep (Newtonian temperature-dependent) viscosity and focused on exploring ice grain size range of 0.1–1 mm. Here, we implemented the non-Newtonian grain-size-sensi-

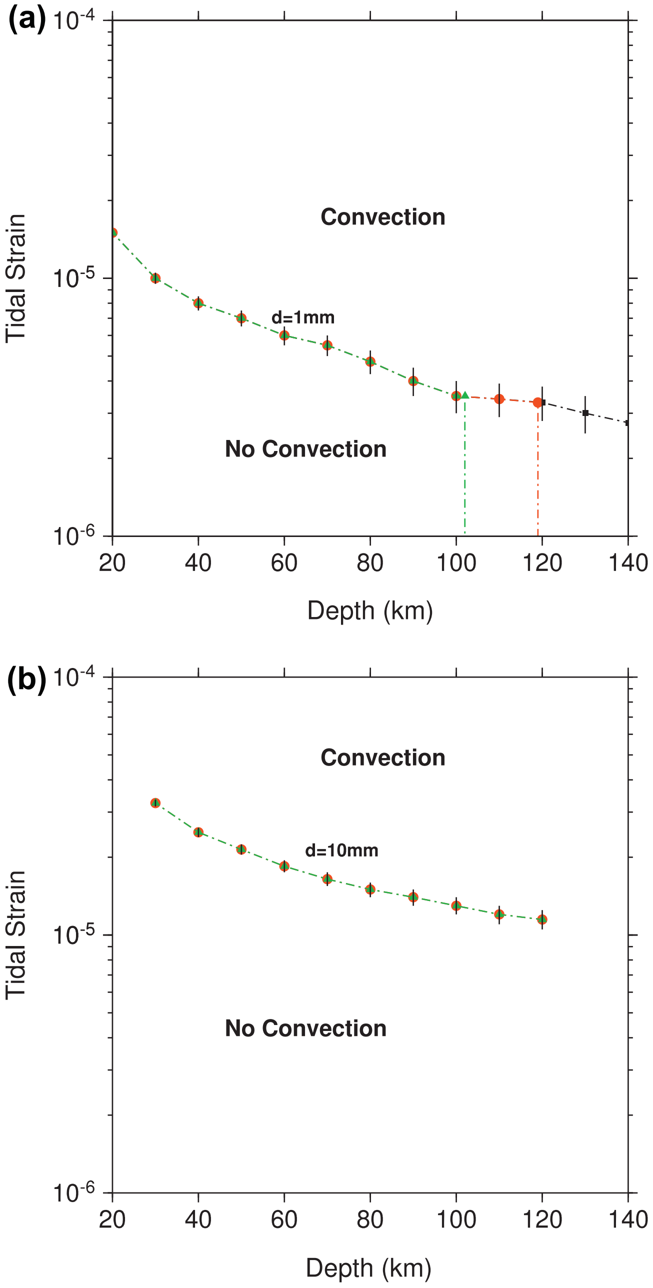

Fig. 3. Summary plot of interrelationship of convection and conduction regimes under different ice-shell thickness, ice grain size, and tidal-strain amplitude. The dashed-dotted lines represent the critical tidal strain amplitude for convection to occur as function of ice-shell thickness. Different colors represent simulations initialized with different amplitudes of the initial thermal perturbation δT; black, red, and green correspond to δT of 3, 15, and 30 K, respectively. (The curves overlap except toward the right side of the top plot.) (a) Ice grain size of 1 mm. (b) Ice grain size of 10 mm. In the limit of zero tidal flexing, the minimum ice-shell thickness allowing convection to initiate depends on δT, but this dependence disappears for sufficiently thin shells and sufficiently large tidal-strain amplitudes. Convection can occur in Europa's ice shell as thin as 20–40 km with an average tidal-strain amplitude of 2×10^{-5} if ice grain size ranges from 1 mm to 10 mm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tive (GSS) creep mechanism and explored ice grain size range of 1–10 mm.

Our models show that tidal heating strongly influences the onset of thermal convection in Europa's ice shell under non-Newtonian grain-size-sensitive (GSS) rheology. The minimum tidal-strain amplitude required for convection to occur decreases with ice-shell thickness. For an ice grain size of 1 mm, the minimum shell thickness allowing convection is 100 km in the absence of tidal heating, but it decreases to 20 km for tidal-strain amplitudes of 1.5×10^{-5}. For an ice grain size of 10 mm, convection cannot occur in the absence of tidal heating for any ice-shell thickness plausible for Europa; however, tidal strain amplitudes reaching 2×10^{-5} allow convection to occur in shells as thin as 40 km. Mean tidal-strain amplitudes of $\sim$1–2×10^{-5} have been estimated given Europa's expected internal structure (i.e., an ice shell, internal ocean, and silicate core) and current orbital eccentricity (Ojakangas and Stevenson, 1989; Ross and Schubert, 1987; Moore and Schubert, 2000). Thus, for plausible ice-shell thicknesses (20–40 km or more), convection via non-Newtonian GSS creep can occur in Europa's ice shell under modern-day tidal flexing conditions if the grain size is 1–10 mm.

Although we focused on ice grain sizes of 1–10 mm, Europa's ice grain size may extend beyond this range, and creep would no longer necessarily occur by non-Newtonian GSS creep. Smaller grain sizes promote diffusion creep, as explored by numerous authors. If ice grain size exceeds $\sim$10 mm, dislocation creep becomes the dominant creep mechanism, although convection is unlikely to occur in this case because the effective viscosities are large. In the future, composite rheology needs to be considered.

Although we emphasized Europa, our models also have implications for other icy moons, including Ganymede, Titan, Callisto, and Enceladus. Ganymede currently experiences minimal tidal heating but may have been tidally heated in the past during passage through a Laplace-like resonance (Malhotra, 1991; Showman and Malhotra, 1997; Showman et al., 1997; Bland et al., 2009). In contrast, Callisto has never experienced significant tidal heating. If Ganymede indeed experienced such an event, our models indicate that a much broader range of conditions (ice grain sizes and shell thicknesses) could have allowed convection in Ganymede than in Callisto. This might play a role in contributing to resurfacing on Ganymede but not on Callisto. Similarly, Titan experiences modest tidal heating due to its non-zero orbital eccentricity, which would modify the conditions allowing convection in its ice shell, with possible implications for long-term evolution and cryovolcanism (Mitri et al., 2008). On Enceladus, convection or diapirism has been suggested as a possible cause of the highly tectonized south polar terrains (Nimmo and Pappalardo, 2006; Barr, 2008), and tidal dissipation plays a major role in Enceladus' thermal convection or diapirism (Roberts and Nimmo, 2008; Tobie et al., 2008; Behounkova et al., 2010). Although our present models do not apply quantitatively to Enceladus (because of its much lower gravity than we considered), we expect that tidal heating could allow convection to occur over a broader range of conditions, promoting internal activity and resurfacing. We will explore these issues quantitatively in the future.

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