LATITUDE-DEPENDENT ICE THICKNESS OF EUROPA: EFFECTS OF CONVECTION AND RIFTING.

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Summary: The thickness of the ice shell of Europa is related to heat generated in the satellite's interior, especially by tidal heating, and the mode of heat transport [1]. We present models of the steady-state ice shell thickness assuming stagnant lid convection. The shell is partitioned into a nearly isoviscous core heated from inside and from below, overlain by a conductive thermal boundary layer. We include the temperature dependence of thermal conductivity and viscosity.

We report here how ice thickness may vary with latitude due to differences in heat generation and surface temperature [2], as well as the effect of rifting [3] on ice thickness. The model predicts significant variations with latitude, and the shutdown of convection near the pole or upon rifting. Active bands are deeper at the pole than at the equator but recently inactive bands may stand higher than surrounding plains.

These models can be tested against the distribution of possible convective features such as pits and domes [4,5], the shape of the ice [6], and the relief of bands [7, 8]. The maximum variation of ice thickness of 7 km advocated by [6] appears inconsistent with the more than 25 km difference in ice thickness predicted here.

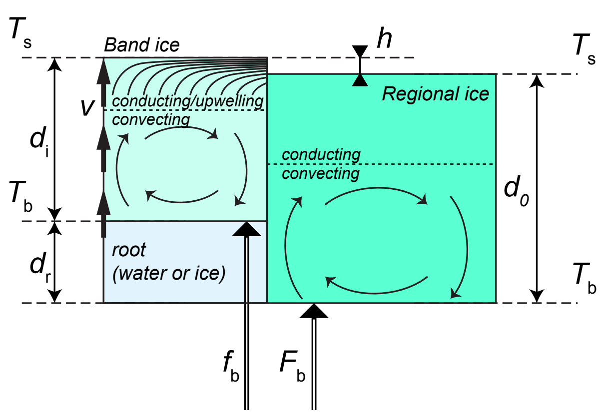

Figure 1: Schematic diagram of the thermal structure of the ice shell inside and outside an isostatically-supported band (left and right).

Method: The ice shell is partitioned into a nearly isothermal convective cell (if needed) and a conductive stagnant lid, across which most of the temperature drop takes place (Figure 1). Both domains are heated from inside by tidal dissipation and by a basal heat flux. We consider that heat conductivity, viscosity, and tidal heat generation are function of temperature.

Rifting imparts an upwelling velocity V to the shell. Here, we consider that V increases linearly with depth in the conductive lid. Rifting appears in two aspects of the calculation described here. 1) It changes the shape of the temperature profile in the conducting ice layer. 2) The basal heat flow increases as water crystalizes to compensate for the thinning ice: $f_b = F_\mathrm{b} + \rho L V$, where L is the latent heat of crystallization and F_b is the heat flux from radioactive decay in Europa's rocky core and tidal dissipation in the liquid internal ocean.

Convecting Ice Core: The thermal structure of the convecting ice core is determined from the simultaneous solution of a set of scaling equations obtained by [9] for an isoviscous layer with both internal and basal heating.

The intensity of convection is given by the Rayleigh number $Ra \equiv \frac{\alpha\rho g\,\Delta T\, b^3}{\kappa_\mathrm{i}\eta_\mathrm{i}}$ where g is the acceleration of gravity, ΔT the temperature drop across the layer, b is the thickness of the convecting layer, κ is the diffusivity, and η is the viscosity. Both η and κ are evaluated at the internal temperature T_i, which is itself given by

$$T_\mathrm{i} = T_\mathrm{b} + \Delta T \left[\frac{1}{2} + a\left(\frac{Hb^2}{k\Delta T}\right)^{3/4} Ra^{-1/4}\right]$$

where T_b is the temperature at the base of the layer, set to the melting point of ice, k is the thermal conductivity, and $a = 1.236$ [9].

The heat flux across at the top of the convecting core is given by $f_\mathrm{t} = 0.3446\, Ra^{1/3}\theta^{2/3}k\Delta T/b$ [9]. For consistency, $f_\mathrm{t} = f_\mathrm{b} + Hb$.

These equations are combined to provide an estimate of the temperature drop across the core:

$$\Delta T = 2k^{-\frac{3}{4}}\left(\frac{\alpha g\rho}{\kappa\eta}\right)^{-\frac{a}{4}}\left[\left(\frac{f_\mathrm{b} + Hb}{c}\right)^{\frac{3}{4}} - a(Hb)^{\frac{3}{4}}\right]$$

For each candidate convective cell thickness, we determine the interior temperature for which the various quantities above are mutually consistent. Then, we retain the thickness for which the viscosity contrast between the top and the interior of the convecting core is $\exp(2.23)$ [10]. However, we consider that there is no convecting core if no value of b results in the appropriate viscosity ratio or the thickness of the boundary layers exceeds b. At very low basal heat flux it is possible that the interior temperature exceeds the melting point of ice but we ignore this rare issue.

Conducting Ice: The heat conservation equation contains contributions from upwelling, at a predefined velocity V, and heat generation, H:

$$\frac{dF}{dz} - \frac{V}{\kappa}F - H = 0$$

The equation is solved under the condition that the temperature and heat flux at the base of the conductive layer are those at the top of the convective cell. Then, the temperature profile is obtained by integrating

$$\frac{dT}{dz} + \frac{F}{k} = 0$$

The solution is obtained by finite difference approximation (central differences), which makes it possible to incorporate temperature-dependent conductivity and heat production.

Finally, the thickness of conducting ice is determined by the condition that the temperature is at a predefined value T_s at the surface ($z = 0$).

Ice elevation: Elevation is assumed to be hydrostatic. We integrate $\rho_0[1 - \alpha(T_0 - T_b)]$ over the shell (both convective and conductive portions) to obtain the weight of ice. That is supported by a root of 1) liquid water for the static ice shell (latitude variations) or the currently active band (elevation compared to surrounding ice, Figure 1) or 2) ice at 270K for the recently inactive band.

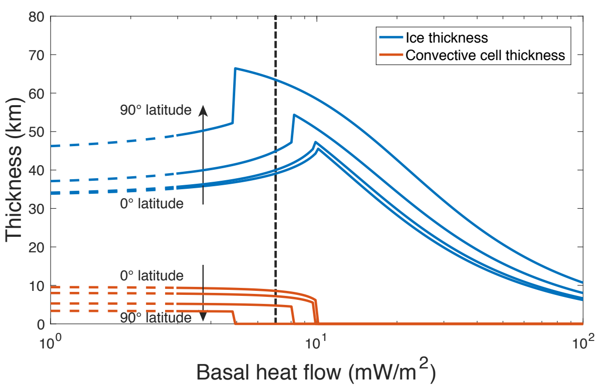

Figure 2: Ice thickness (blue) and thickness of the convective cell (orange) as a function of basal heat flow for conditions corresponding to various latitude. The dashed lines indicate that the convective cell should be melting. Heat generation is smaller but surface temperature is higher near the equator. The dashed black line indicates 7 mW/m^2.

Results: The thickness of ice shell for different latitudes is compared in Figure 2. Heat generation is higher at the poles [2], which decreases the thickness of the convective core (the heat flow at the top of the cell cannot accommodate the basal heat flow and the tidal heat generated over a thick convective cell). However, the shell is thicker at the pole because of the lower surface temperature at the poles, requiring a thick conductive lid

The variation of ice thickness predicted here exceeds 25 km, which is too large to be accommodated in the observed 3 km ellipticity of Europa [6]. A high basal heat flux, which prevents convection, would reduce this issue. Alternatively, long-range ice transport at the base of the shell would reduce the thickness variations [6].

The increased heat generation at the pole can shut down convection (Figure 2). In that case, we would expect that geological evidence for convection, such as a pits and domes [4, 5] would be absent close to the poles. Where this change takes place depends on basal heat flow and the reference viscosity of ice.

Rifting increases the basal heat flow as ice crystallizes at the base of the ice shell. As a result, it can also shut down convection. In a conductive shell, rifting thins the ice, which, if supported by a liquid water root (active band), should stand several kilometers lower than the surrounding plains. These depressions should be more pronounced near the poles (Figure 3). Conversely, the freezing of this root should lift the band to higher elevation at the poles than near the equator. High-resolution global topography would help testing whether this elevation cycle does take place on Europa.

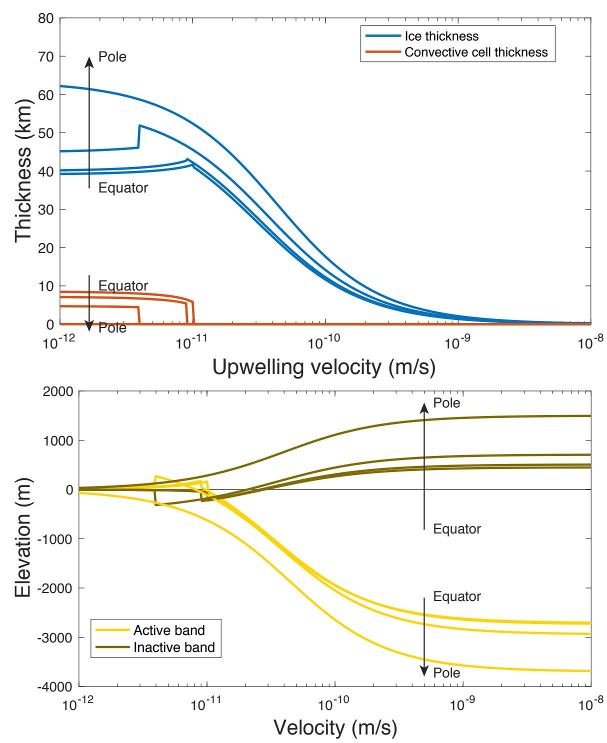

Figure 3: Ice thickness (blue), thickness of the convective cell (orange), and band elevation(yellow) against upwelling velocity for conditions corresponding to various latitude. The root underneath the band (Figure 1) is taken to be liquid water for an active band and ice at 270K for the inactive band.

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