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Supporting Information for

Temporal changes in Europa's ice shell thickness: Insights from models of convection

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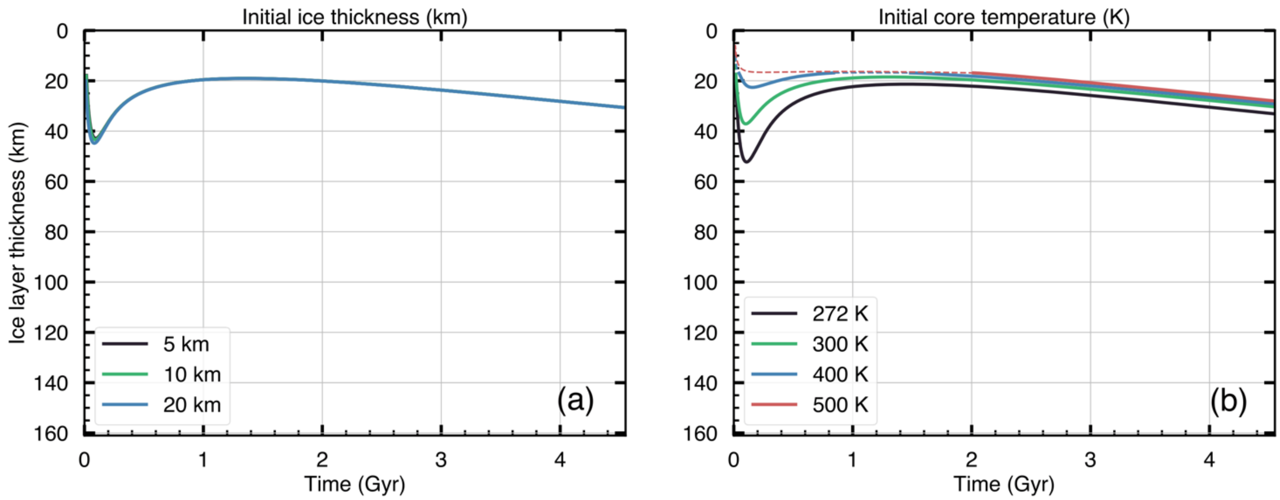

Figure S1. (a) Evolution of the ice shell thickness as a function of time for three values of initial ice thickness: 5 km, 10 km and 20 km. (b) Evolution of the ice shell thickness as a function of time for four values of initial ice temperature: 272.5 K (corresponding to the temperature at the bottom of a 10 km thick outer ice shell), 300 K, 400 K and 500 K. In all calculations, the ice reference viscosity and initial fraction of ammonia are set to 10^{14} Pa·s and 1.5 wt%, and the tidal heating is constant and fix to 1.0 TW. The dashed parts of the curves indicate that the system is not animated by convection.

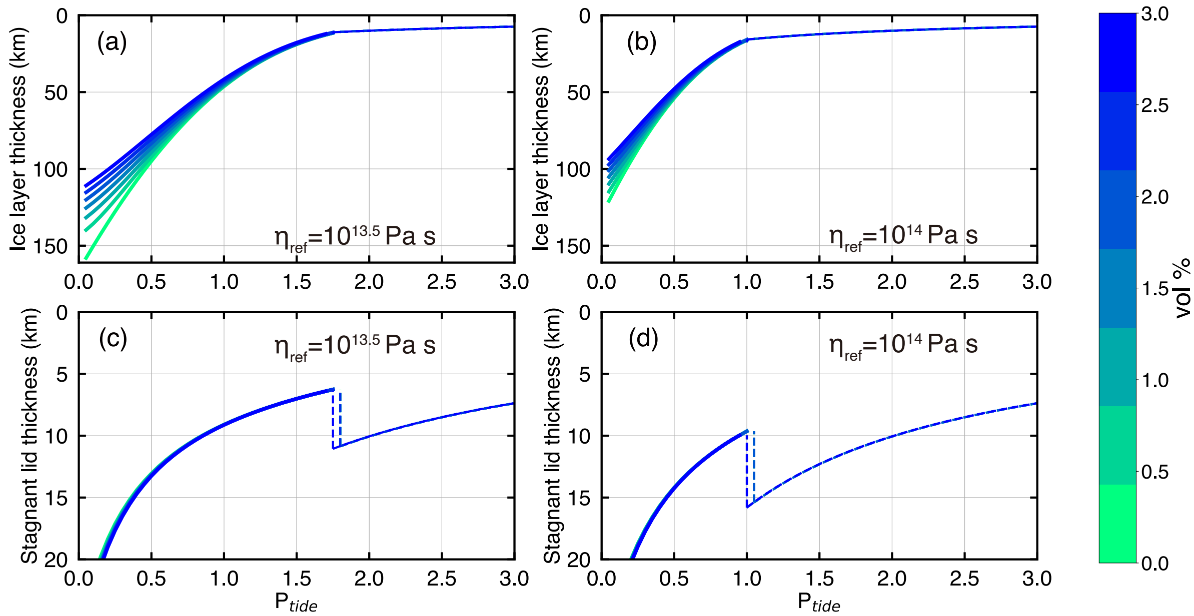

Figure S2. Thickness of ice shell (a) (b) and stagnant lid (c) (d) at 4.55 Gyr as a function of the tidal power and for seven values of the initial ocean composition (vol% ammonia). Two values of the bulk viscosity are considered, (a) (c) $10^{13.5}$ Pa·s and (b) (d) 10^{14} Pa·s. The dashed line parts of the curves indicate that the system is not animated by convection.

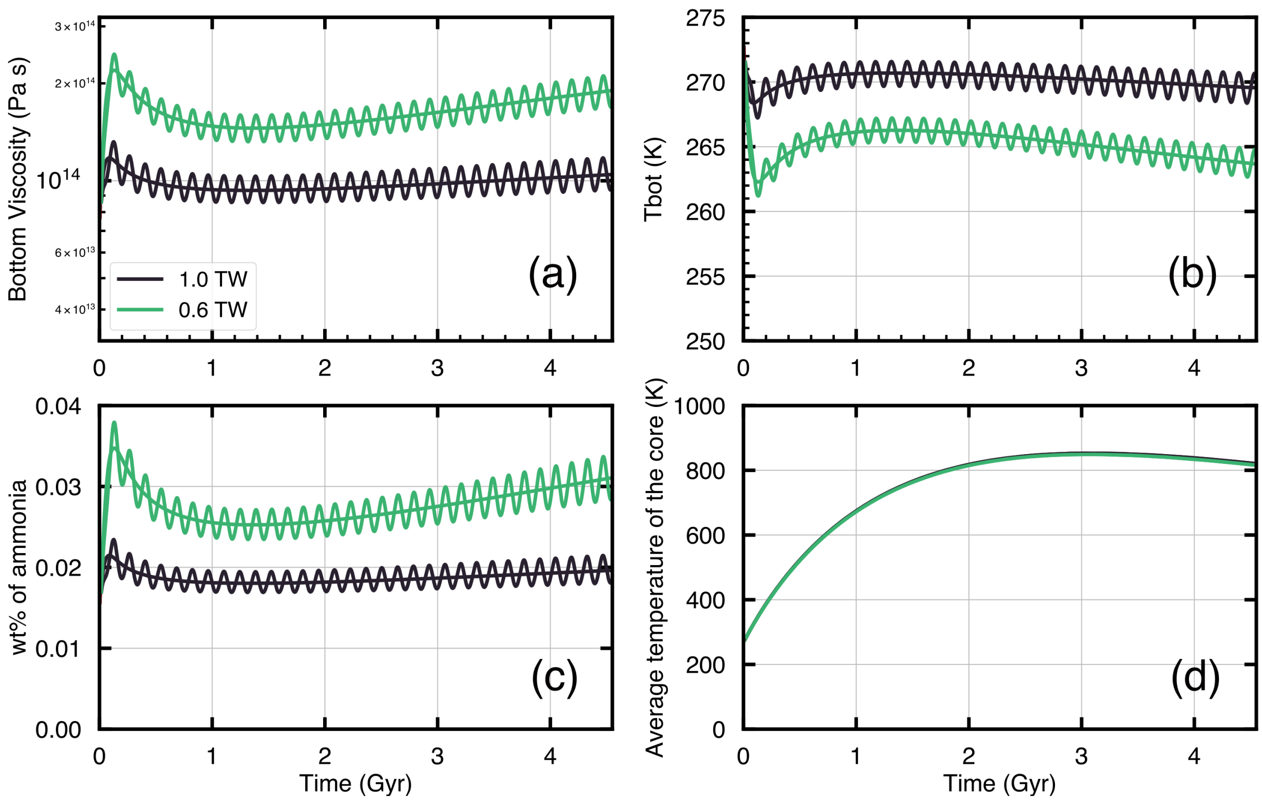

Figure S3. Evolution of (a) the viscosity of bottom ice shell, (b) the temperature of bottom ice shell, (c) the fraction of ammonia in the ocean and (d) the average temperature of the core as a function of time and for bulk viscosity $\eta_{ref} = 10^{14}$ Pa·s, initial fraction of ammonia x_{NH3} = 1.5 % and tidal power P_0 = 1.0 TW and 0.6 TW for time dependent tidal heating with 10 % variation in the orbital eccentricity and 0.14 Gyr period.

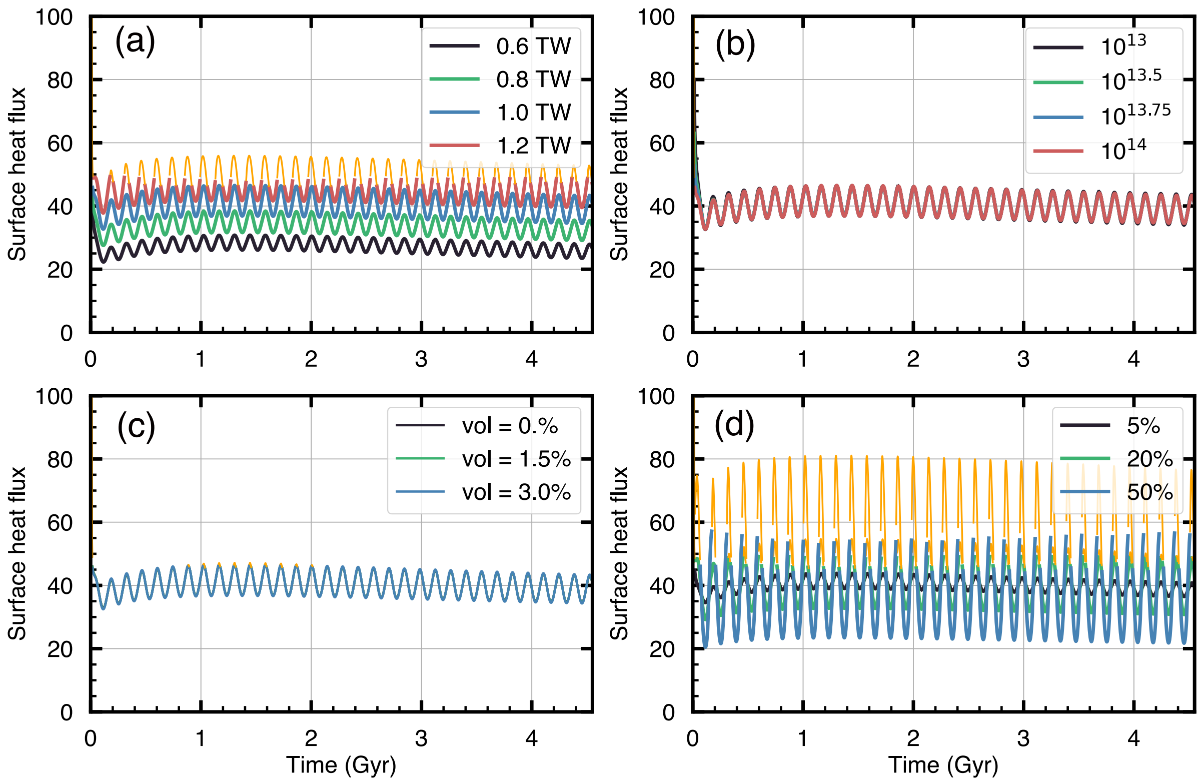

Figure S4. Evolution of the surface heat flux as a function of time for several values of the (a) tidal power, (b) bulk ice viscosity, (c) initial volume fraction of ammonia in the ocean, and (d) amplitude of variations in orbital eccentricity. The reference tidal power, bulk ice viscosity, initial fraction of ammonia and amplitude of eccentricity variations are respectively equal to 1.0 TW, 10^{14} Pa·s, 1.5 % and 10 %. The yellow line parts of the curves indicate that the system is not animated by convection.

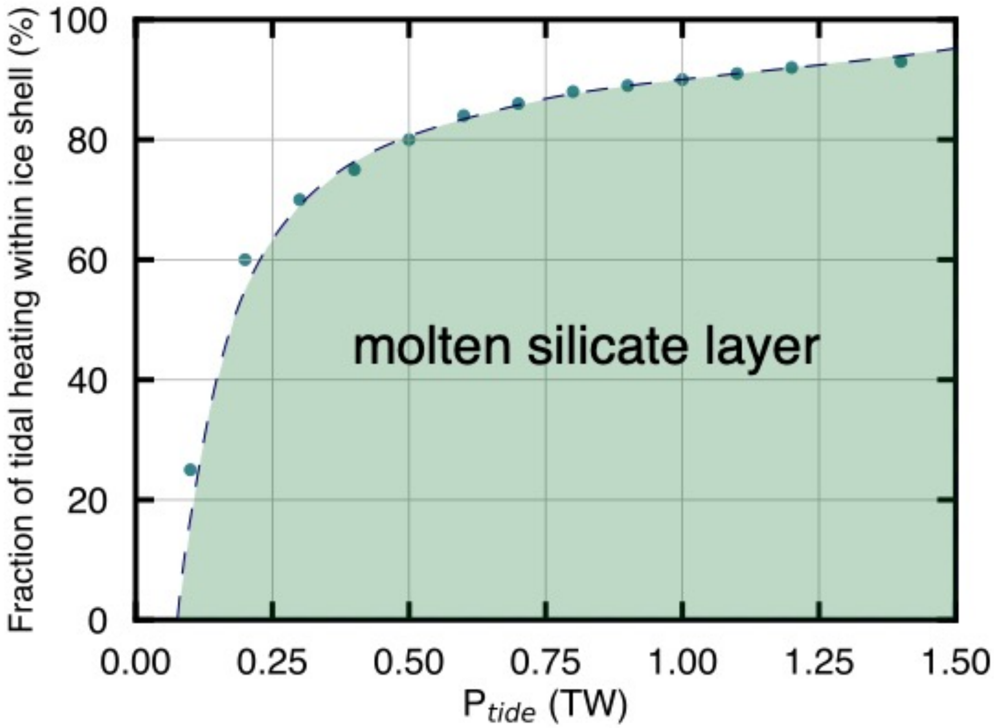

Figure S5. Relationship between internal power and the fraction of tidal dissipation in the ice shell leading to melting of the silicate layer.

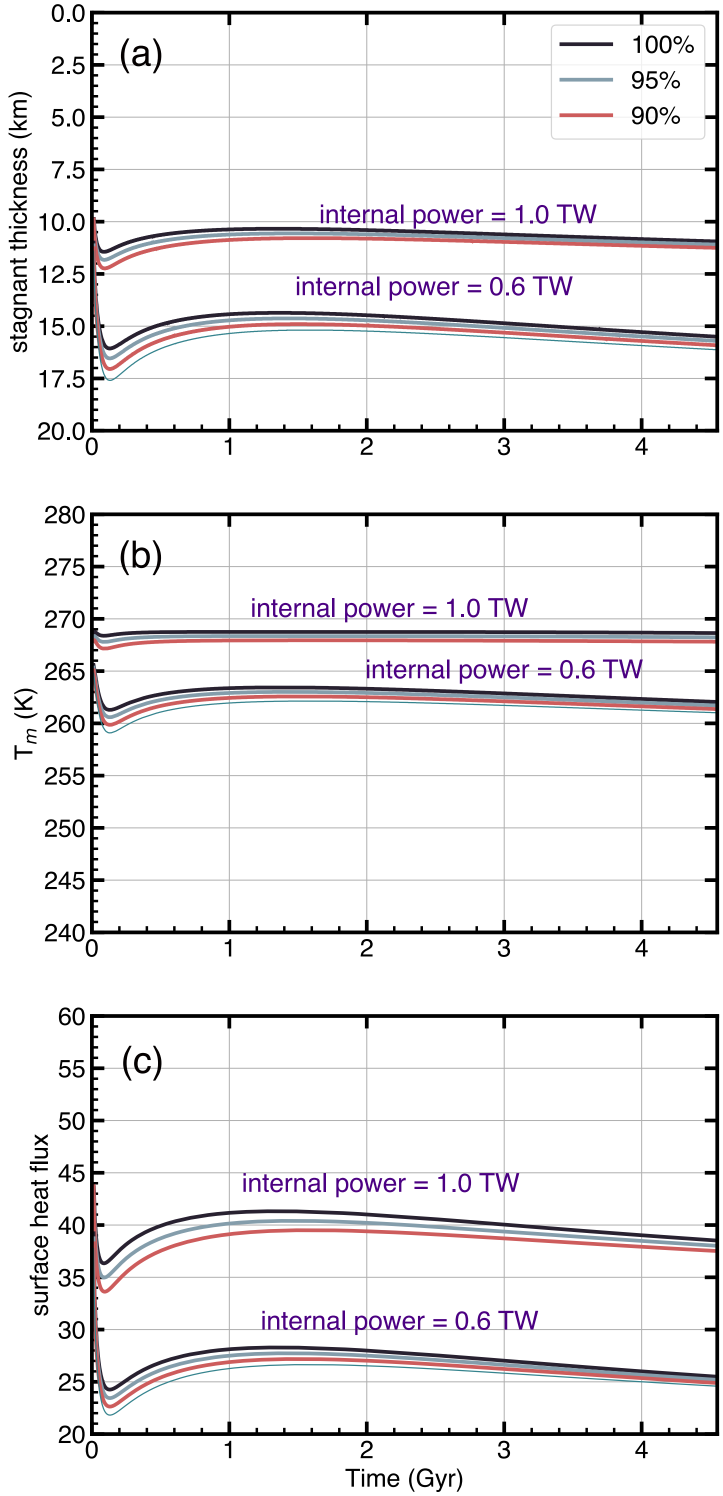

Figure S6. Evolution of the ice shell thickness as a function of time for several repartitions of the tidal heating between the ice shell and the core (with dissipated fraction in the shell equal to 100%, 95%, 90% and 85%). The tidal heating is constant in time and two values are considered, 0.6 TW and 1.0 TW. The bulk ice viscosity is η_{ref}=10^{14} Pa·s, and the initial fraction of ammonia x_{NH3} = 1.5 vol%. (a) Stagnant lid thickness. (b) Interior temperature. (c) Surface heat flux.

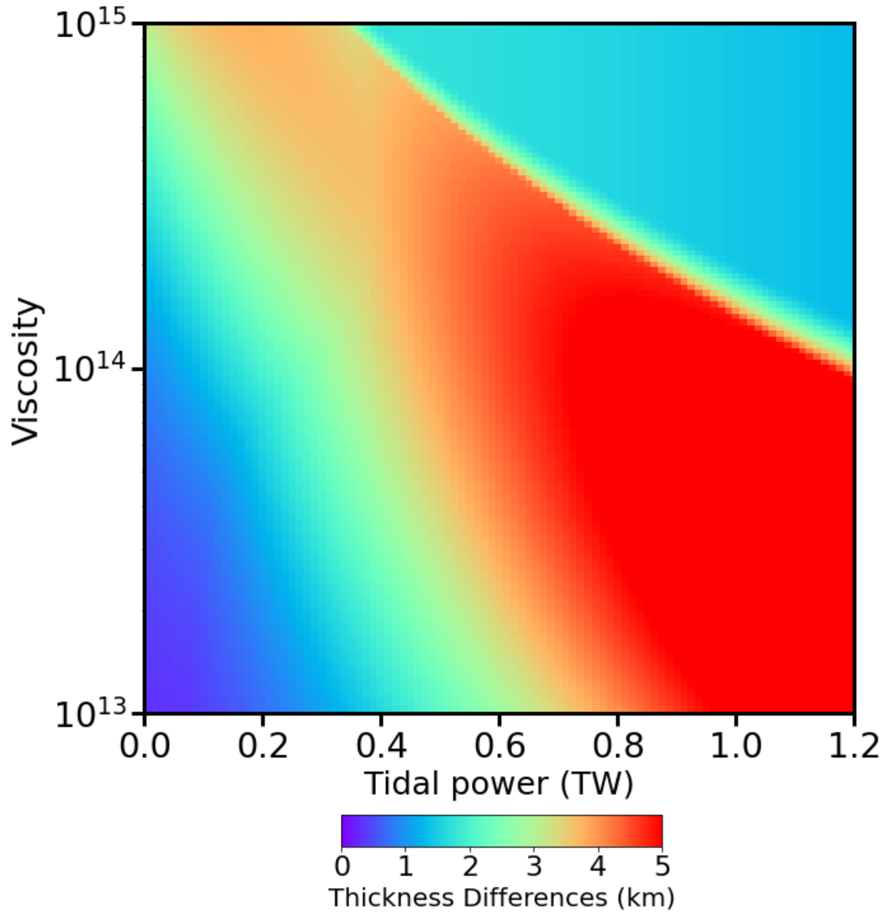

Figure S7. Difference between average and minimum ice shell thicknesses over the last 0.5 Gyr as a function of reference ice viscosity and tidal power, assuming a 10% variation in orbital eccentricity and an initial ammonia concentration of 1.5 vol%. This figure complements Figure 10 by illustrating the range of temporal variability in ice shell thickness under different thermal and tidal regimes, helping to assess the stability and evolution of the ice shell across modeled parameter spaces.