THERMO-MECHANICAL PLANETARY EVOLUTION OF ICE SHELLS AND INTERIORS OF THE JUPITER ICY MOONS/GALILEAN SATELLITES

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Abstract

Europa, Ganymede, and Callisto represent a broad range of icy satellite interior evolution, ranging from active tidal dissipation and rapid resurfacing on Europa to intrinsic magnetism and a layered interior on Ganymede, and comparatively limited resurfacing and internal differentiation on Callisto. We present three-dimensional thermo-mechanical convection simulations designed to investigate how variations in ice-shell thickness, internal heating (radiogenic and tidal), temperature-dependent viscosity, and buoyancy structure influence convective planform, heat transport, and the chemical differentiation of icy shells. Our modeling framework employs two-dimensional Cartesian simulations of convection over a range of parameter values listed above. Time-dependent velocity and temperature fields are analyzed to track the persistence of impurities in parts of the icy shell that remain cold enough to prevent brine segregation. Impurities are generally preserved only in the rigid upper boundary layer, which is structured by the dynamic convection in the layer beneath. Depending on the relevant brine segregation temperature, different degrees of brine preservation are observed. These simulations provide a quantitative framework for interpreting surface geology, assessing ocean longevity, and constraining heat flow in the context of current and upcoming mission observations, particularly those from the ESA JUICE and NASA Europa Clipper missions.

Introduction

Europa, Ganymede, and Callisto are a natural three-body comparison for studying icy moon convection because they occupy different thermal and geologic regimes within the same Jovian system. Europa is associated with recent resurfacing and strong evidence for ocean-shell interaction, Ganymede preserves evidence of internal evolution and tectonic activity, and Callisto appears to retain a colder and more weakly evolved outer shell.

A useful first-order way to compare these bodies is through ice-shell convection. In planetary ice shells, convection depends on whether buoyancy forces are strong enough to overcome viscous resistance and thermal diffusion. The parameter that captures this balance is the Rayleigh number. Once the Rayleigh number exceeds a critical threshold, convective heat transport becomes possible and may exceed conduction alone.

The goal of this paper is to frame Europa, Ganymede, and Callisto in terms of the parameters that matter most for convection: Rayleigh number, heating, and viscosity. The emphasis here is on a comparison that is consistent with the broader direction of icy-moon planetary and thermal-evolution work.

Background: Ice-Shell Convection

Heat can be transported through an icy shell by conduction, convection, or some combination of the two. Conduction dominates when the shell is too cold, too thin, or too viscous to overturn efficiently. In that limit, the temperature gradient is largely set by Fourier heat transport, and the shell behaves as a stagnant conductive lid.

For a simplified shell, the convective potential may be written in terms of the Rayleigh number Equation as follows:

$$Ra = \rho g \alpha \Delta T d^3 / \kappa \eta \qquad (1)$$

where ρ is density, g is gravity, α is thermal expansivity, ΔT is the temperature contrast across the shell, d is shell thickness, κ is thermal diffusivity, and η is viscosity. This equation shows that convection is strongly favored by thicker shells, larger temperature contrasts, and lower viscosities. The thermal evolution of the shell is then described by the Energy Equation as follows:

$$\frac{\partial T}{\partial t} + u \cdot \nabla T = \kappa \nabla^2 T + H \qquad (2)$$

where T is the temperature, t is time, u is the velocity field, ∇T is the temperature gradient, $\kappa \nabla^2 T$ represents thermal diffusion, and H is the internal heating term. The left-hand side describes temporal temperature change and advective transport, while the right-hand side accounts for conductive heat redistribution and volumetric heating within the shell. To represent the strong temperature dependence of ice rheology, viscosity is written as

$$\eta(T) = \eta_0 \, exp(E_\eta / T) \tag{3}$$

where η_0 is the reference viscosity and E_η is an activation parameter controlling the sensitivity of viscosity to temperature. This relation captures the fact that colder ice is much stiffer, while warmer basal ice is weaker and more capable of convective flow. Internal heating may be nondimensionalized as

$$H = Qd^2 / k\Delta T \tag{4}$$

Where Q is the volumetric internal heating rate, d is the shell thickness, k is the thermal conductivity, and ΔT is the temperature contrast across the layer. This parameter provides a convenient way to compare how strongly internal heat production modifies the shell thermal structure and convective regime.

In planetary ice shells, however, viscosity is strongly dependent on temperature. The cold near-surface ice may remain extremely stiff, while warmer deep ice is much weaker. Because of that contrast, stagnant-lid convection is often more realistic than whole-layer overturn. The effective behavior, therefore, depends not only on bulk parameters but on the depth dependence of rheology across the shell. To examine these effects in a consistent framework, Figures 1–4 present the reference convection state and the sensitivity of that state to the primary control parameters in this study. Figure 1 shows the baseline convection regime, while Figures 2–4 illustrate how variations in internal heating (H), activation energy (E_η), and the Rayleigh number (Ra)modify the structure and vigor of the convecting ice shell.

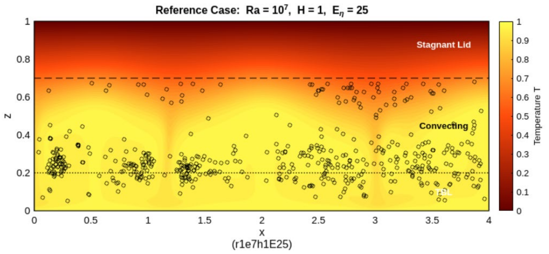

Figure 1: Reference Case Dynamics (Ra $= 10^7$, H = 1). A detailed cross-section of the simulated ice shell showing the distinct transition from the conductive stagnant lid to the convecting sublayer. Passive tracers are concentrated within the upwelling plumes, demonstrating the primary mechanism for mass transport across the shell's thermal boundary layers.

Figure 1 shows the reference convection case used as the baseline framework for this study. The model domain consists of a cold, mechanically stiff stagnant lid overlying a warmer convecting interior. Passive tracers illustrate material transport and thermal cycling within the shell, while the flow structure highlights the presence of focused upwelling and broader return flow. This reference state provides the basis for interpreting how changes in internal heating, viscosity contrast, and buoyancy forcing alter the overall convection regime.

Key Parameters

Heating

Heating may be supplied by radiogenic decay, tidal dissipation, secular cooling, or combinations of these. Europa is the clearest case of strong present-day tidal influence because its orbital resonance maintains eccentricity and deformation. Ganymede likely experienced less tidal heating but still retains heat through its larger size and interior evolution. Callisto is generally expected to have the weakest effective heating of the three, which reduces the likelihood of sustained vigorous convection.

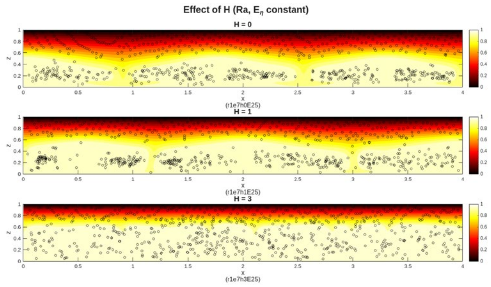

Figure 2: Effect of Internal Heating: As dimensionless internal heating (H) increases, the ice shell interior warms, causing convective plumes to become more diffuse. This shift impacts how effectively material (tracers) is cycled between the deep interior and the stagnant lid.

Figure 2 illustrates the effect of varying the nondimensional internal heating parameter H. As internal heating increases, the thermal structure of the shell becomes more strongly modified from within, which affects plume development, lid thickness, and the distribution of convective activity. Higher internal heating tends to promote warmer interior conditions and can change the balance between basal forcing and volumetric heating, producing noticeable changes in convection style and transport efficiency.

Rayleigh Number

The Rayleigh number is the clearest first-order measure of convective potential. Because it scales with d^3, shell thickness has a major influence on whether convection occurs. A modest change in shell thickness can therefore shift a moon from a conduction-dominated regime to a convection-favorable regime even if the other parameters remain similar.

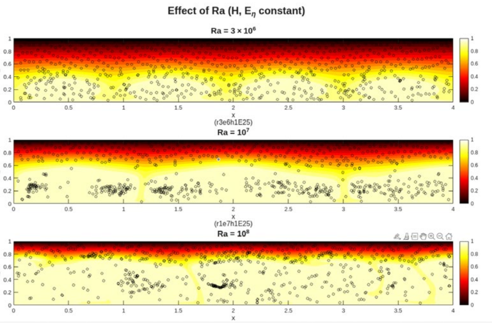

Figure 3: Convective morphology as a function of Rayleigh number (Ra). As the Rayleigh number increases from $3 * 10^6\ to\ 10^8$, the buoyancy-to-viscosity rises, resulting in a transition from broad, steady-state cells to narrower, more vigorous upwelling plumes. This high Ra regime (bottom panel) is characterized by increased lateral mobility within the shell and a significant thinning of the thermal boundary layers at both the stagnant lid (z = 1) and the ice-ocean interface (z = 0).

Figure 3 shows how convective morphology changes as the Rayleigh number increases from $3 \times 10^6$to 10^8. At lower Ra, convection is broader and steadier, with relatively diffuse circulation cells and thicker thermal boundary layers. As Ra increases, buoyancy forcing becomes more effective relative to viscous and diffusive resistance, producing narrower, more vigorous upwelling plumes and stronger lateral variability within the shell. In the highest Ra case, the thermal boundary layers at both the stagnant lid and the basal ice-ocean interface become noticeably thinner, indicating more efficient heat and material transport through the convecting layer. While the Rayleigh number captures the overall vigor of buoyancy-driven overturn, the resulting flow geometry also depends strongly on how viscosity varies with temperature throughout the shell. In planetary ice shells, this rheological contrast is especially important because the cold near-surface lid can remain mechanically stiff even when the deeper shell is actively convecting.

Viscosity

Viscosity is one of the most important controls and one of the largest uncertainties. Small temperature changes can produce large viscosity contrasts within the shell, especially between the upper cold lid and the lower warm ice. High viscosity suppresses convective motion, while reduced deep-shell viscosity promotes overturn and enhances vertical heat transport.

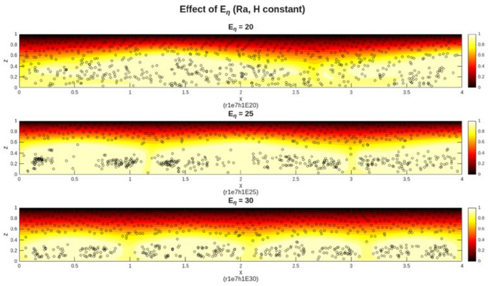

Figure 4: Role of Temperature-Dependent Viscosity: Higher activation energy (E_η) creates a sharper contrast in ice stiffness. This results in tightly focused, powerful upwellings (bottom panel) compared to the broader, more uniform flow seen at lower E_η values.

Figure 4 illustrates the role of temperature-dependent viscosity through variation in activation energy (E_η). As $E_\eta$increases, the viscosity contrast across the shell becomes stronger, so the cold near-surface lid remains more rigid while the warmer lower shell becomes relatively more mobile. This leads to a more clearly developed stagnant lid and increasingly localized plume structures. In the lower- E_η cases, the convective circulation is broader and more laterally distributed, whereas the higher-E_η cases show narrower, more vertically focused upwellings and sharper thermal gradients between the lid and the convecting interior. These results indicate that rheology strongly controls plume geometry, boundary-layer thickness, and the efficiency with which material is cycled between the deeper shell and the overlying stagnant lid.

Parameter Coupling and Convective Regime Interpretation

Although Rayleigh number, internal heating, and temperature-dependent viscosity can each be discussed separately, the convective state of an icy shell is determined by their combined interaction. The energy equation governs how temperature evolves through advection, diffusion, and internal heat production, while the viscosity relation determines how that thermal structure translates into resistance to flow. Internal heating modifies the shell's temperature distribution, which in turn changes the viscosity contrast between the cold stagnant lid and the warmer convecting interior. The Rayleigh number then provides a first-order measure of whether buoyancy forces are sufficient to overcome viscous and diffusive resistance. In this way, H, E_η, and Rado not act independently, but together determine stagnant-lid thickness, plume localization, boundary-layer structure, and the overall efficiency of heat and material transport through the shell.

This coupling is especially important for icy satellites because small changes in thermal state can produce large rheological changes. A shell with modest internal heating but strong viscosity contrast may remain sluggish or strongly lid-dominated, whereas a shell with both favorable heating and sufficiently high Rayleigh number can develop more vigorous overturn and plume-driven transport. The parameter sensitivity shown in Figures 1–4, therefore, provides a framework for interpreting how similar ice-rich bodies can evolve into very different thermal and geologic states.

Comparative Discussion

Europa

Europa is the strongest candidate for active or recent ice-shell convection. Strong tidal heating, probable ocean-shell exchange, and its geologically young surface all imply a relatively warm and mobile shell. Within a Rayleigh-number framework, Europa is favored both by enhanced heating and by lower effective viscosity at depth. Even if the upper shell behaves as a cold stagnant lid, deeper convection remains plausible and consistent with the surface expression of tectonic bands and disrupted terrain.

Ganymede

Ganymede is better viewed as an intermediate case rather than simply a scaled-up Europa. Its larger size changes its thermal evolution, but its present tidal forcing is weaker. Convection in Ganymede's ice shell is therefore more sensitive to the assumed shell thickness, basal temperature, and contrast with viscosity. Under favorable conditions, convective heat transport remains plausible and may help explain tectono-thermal modification associated with grooved terrain and long-term interior evolution.

Callisto

Callisto likely represents the least convectively active endmember. Its older, more heavily cratered surface and apparently weaker degree of internal modification suggest that conduction may have dominated for much of its history, or that convection was limited to sluggish overturn. In Rayleigh-number terms, weaker heating and colder shell conditions raise viscosity and reduce the likelihood of vigorous convection.

Implications for Europa, Ganymede, and Callisto

Europa is the clearest high-priority case for convection because tidal heating directly affects the thermal state of the lower shell. Ganymede is more ambiguous because its larger size favors long-term heat retention, but weaker present-day tidal forcing reduces the certainty of active overturn. Callisto remains the best low-activity comparison because it tests how far an icy shell can evolve toward a conduction-dominated state while remaining relevant to ocean-world studies. The combined parameter behavior described previously provides a useful framework for interpreting the different convective styles expected in Europa, Ganymede, and Callisto. Although all three moons contain substantial water ice, their present thermal states likely occupy different regions of parameter space because of differences in tidal heating, shell structure, and long-term thermal evolution.

Brine Drainage, Brine Separation, and Cryovolcanic Implications

Brine drainage and brine separation are important consequences of thermal and structural evolution in icy shells and are directly related to the convective environments examined here. As temperature gradients, internal heating, and rheological contrasts reorganize material within the shell, dissolved impurities and brine-rich components may become segregated from the surrounding ice. This separation can modify local density structure, weaken portions of the shell, and create compositionally distinct regions that are relevant to later-stage transport processes. In that sense, the convection and parameter-space analysis presented here provides a useful physical framework for understanding how brine-bearing regions may develop within Europa-, Ganymede-, or Callisto-like shells.

These processes are also relevant to cryovolcanism, since brine accumulation and separation can help establish the conditions needed for later mobilization of volatile-rich material. However, implementation of cryovolcanism itself requires a different class of models than the convection-focused framework used here. For that reason, cryovolcanic transport is best treated as a follow-on stage of this work rather than as part of the present model's results. The current study, therefore, focuses on the thermal-convective regime that may prepare or precondition the shell for later cryovolcanic development.

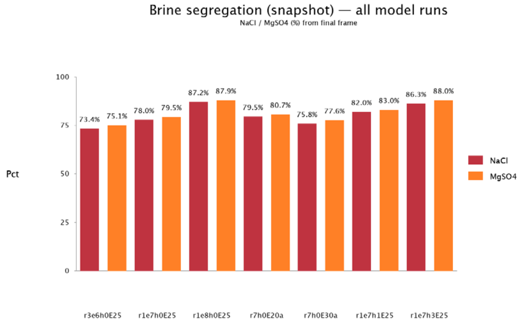

Figure 5: Final brine segregation across multiple ice-shell model runs for NaCl and $MgSO_4$ bearing cases. Bars show the percentage of tracer/brine concentration segregated by the final model frame for each run. In all cases, $MgSO_4$ exhibits slightly stronger segregation than NaCl, while the highest segregation occurs in the more vigorous convective cases. These results indicate that convection-driven transport efficiently redistributes brine-bearing material and that compositional differences can systematically affect the magnitude of separation.

Figure 5 summarizes the net brine segregation outcome across the full model suite. The final-frame comparison shows that both NaCl and $MgSO_4$ bearing cases undergo substantial segregation, generally reaching values of about 75–88%, with $MgSO_4$ consistently slightly higher than NaCl for the same run. The strongest segregation occurs in the more vigorous convective cases, indicating that plume-driven transport and boundary-layer cycling are effective mechanisms for redistributing compositionally distinct material. This result supports the interpretation that thermo-mechanical convection provides a physically plausible pathway for brine drainage and chemical partitioning within icy shells.

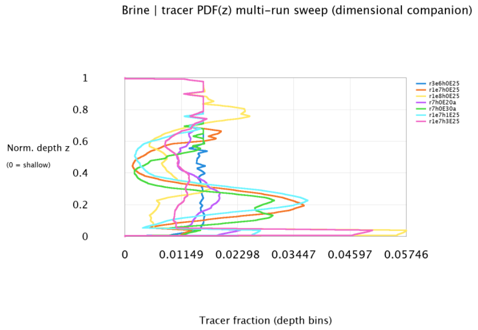

Figure 6: Vertical distribution of brine tracer with normalized depth, shown as the depth-binned tracer fraction $\mathrm{PDF}(z)$, where PDF denotes the tracer distribution as a function of normalized depth z. The profiles show that brine-bearing material is not uniformly mixed throughout the shell but instead becomes concentrated at preferred depth intervals that vary with convective regime. Peaks at deeper and intermediate levels indicate that plume transport and return flow reorganize segregated brine into vertically structured reservoirs.

Figure 6 builds on the bulk segregation results in Figure 5 by showing where the brine tracer ends up within the shell. Here, PDF stands for probability density function and represents the vertical distribution of tracer fraction with normalized depth z. Rather than remaining evenly mixed, the tracer develops clear concentration peaks at specific depth levels, showing that convection organizes brine-bearing material into structured zones. In several runs, the strongest concentrations occur in the deeper shell and at intermediate depths, which suggests that plume transport and recirculation are important controls on brine drainage and separation.

Implications for Icy Moon Evolution

The comparison among Europa, Ganymede, and Callisto shows that icy moon evolution cannot be understood from composition alone. All three bodies contain substantial water ice, but their thermal outcomes differ because convection is highly sensitive to parameter choice. Europa appears to lie most clearly in a regime where heating and viscosity conditions favor active heat transport. Ganymede may occupy an intermediate regime in which convection is plausible but more episodic or time dependent. Callisto likely lies closer to or below the threshold for sustained vigorous convection.

This comparative framework is useful in icy bodies in the outer solar system beyond the Galilean moons. The same first-order controls - Rayleigh number, internal heating, and viscosity structure also matter for other ocean worlds. As a result, studying these three moons together provides a physically motivated way to connect observed surface geology to otherwise inaccessible interior processes.

Conclusion

Europa, Ganymede, and Callisto provide a useful comparative framework for understanding convection in icy shells. Europa is the most favorable for active convection because of strong tidal heating and reduced effective viscosity at depth. Ganymede occupies an intermediate regime in which convection remains plausible but depends more sensitively on shell thickness and rheology. Callisto is the least favorable for vigorous overturn because weaker heating and colder conditions increase viscosity and suppress convective motion.

Overall, Rayleigh number, heating, and viscosity provide the clearest first-order explanation for why these moons evolved so differently despite sharing the same broad compositional class. This convection-based framework is therefore a useful foundation for continued observational and modeling work on icy ocean worlds.

Acknowledgements

This work was supported through the Virginia Space Grant Consortium. The author also acknowledges guidance from Hampton University faculty and ongoing discussions, which were very insightful and helpful to furthering this work from this year’s Lunar and Planetary Science Conference (LPSC) and beyond, related to icy moon interiors, convection, and planetary and thermal evolution.

References

1. Magnanini, Andrea, et al. "Joint analysis of JUICE and Europa Clipper tracking data to study the Jovian system ephemerides and dissipative parameters." Astronomy & Astrophysics 687 (2024): A132.
2. Steinbrügge, G., et al. "Brine migration and impact-induced cryovolcanoism on Europa." Geophysical Research Letters 47.21 (2020): e2020GL090797.
3. Durham, W. B., and L. A. Stern. "Rheological properties of water ice—Applications to satellites of the outer planets." Annual Review of Earth and Planetary Sciences 29.1 (2001): 295-330.
4. Tackley, Paul James. Three-dimensional models of mantle convection: Influence of phase transitions and temperature-dependent viscosity. California Institute of Technology, 1994.
5. Green, A. P., L. G. J. Montesi, and C. M. Cooper. "The growth of Europa's icy shell: Convection and crystallization." Journal of Geophysical Research: Planets 126.4 (2021): e2020JE006677.
6. Nagel, K., D. Breuer, and T. Spohn. "A model for the interior structure, evolution, and differentiation of Callisto." Icarus 169.2 (2004): 402-412.