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Key Points:

- New ice formed at phase boundary is transported toward surface via convection
- New ice uptaken by ice plumes is progressively mixed into convecting ice shell
- New ice that could capture trace ocean chemistry is blocked by viscous lid

Supporting Information:

- Text S1 and Figures S1–S3

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Material transport across Europa's ice shell

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Abstract Jupiter's moon Europa exhibits a deformed icy surface with salt deposits concentrated along the varied geological features. The topographic alignment of salt deposits has been speculated to indicate an endogenic sourcing of the material. Two-way transport of salts from a liquid-water ocean beneath the ice shell to the surface, and vice versa, has been speculated. We present dynamical models that demonstrate the incorporation of newly frozen ice into convective plumes within the ice shell, caused by convection within the ice shell that drives dynamic topography along the ice-ocean boundary. The new ice that forms at the freezing front can be transported by the rising ice plumes toward the surface until it is blocked by a high-viscosity lid at the surface. Weakening of the lid by tidal or tectonic forces could then lead to the surface detection of ocean trace chemistry captured in the newly formed ice.

1. Introduction

The detection of oceanic chemistry [*Zolotov and Kargel*, 2009] on the surface of Europa could have profound implications in evaluating its astrobiological potential [*Kargel et al.*, 2000; *Greenberg et al.*, 2000]. Surface detection of a potential biosignature from the deep ocean relies upon the material transport through the ice shell, and the thickness of the ice shell [*Billings and Kattenhorn*, 2005] would determine the time scale and mechanism of this process. Previous studies [*McKinnon*, 1999; *Pappalardo et al.*, 1998; *Barr and McKinnon*, 2007] identify that a thick ice shell is expected to undergo solid state convection. However, irrespective of thickness of the shell, two important aspects would govern the chemical transfer across the system. One is a mechanism to break through the viscous lid [*McKinnon*, 1999] of the ice shell in order to reach the surface. Second, for any oceanic material to reach the surface, it must first be transferred across the solid-liquid phase boundary between the ice shell and the ocean. The latter aspect is particularly important for a thick ($> \sim$20–30 km) convecting ice shell [*Pappalardo and Head*, 2001] which is the model we explore in this study. The phase boundary between solid ice (i.e., the ice shell) and liquid water (i.e., the subshell ocean) produces a high-viscosity contrast and marks a dynamical boundary. The low-viscosity water exhibits more vigorous convection than the solid state convection in ice. Thus, the high-viscosity contrast between the solid ice and liquid water effectively decouples the two layers and the resultant H_2O system consists of two convecting layers—a convecting ice shell over a convecting liquid ocean. In our study, we aim at exploring the convective material transport across this two-phase system.

In the H_2O system, increasing pressure decreases the melting temperature. Hence, pressure-induced melting occurs at depth. In terrestrial glaciology, "ice-pump" mechanism is described [*Lewis and Perkin*, 1986; *Fricker et al.*, 2001; *Robin et al.*, 2014], where ice growth or accretion at the base of the ice shelves occurs by the supercooling of the water (produced by melting at depth) in the immediate vicinity of the ice surface [*Lewis and Perkin*, 1986; *Cook et al.*, 2006]. It has also been suggested that advective motion and ocean currents would augment the melting and deposition process at the base of the ice shelves. The rate of melting and deposition at the ice-water interface would be constant in a steady state ice pump. Previous studies [*Vance and Goodman*, 2009; *Soderlund et al.*, 2014] have suggested that the ice-pump accretion mechanism could be operating in Europa's ice-ocean system. Hence, new ice could be forming at the base of the ice shell in Europa aided by topography generated by ocean currents at the ice-ocean interface.

Although ice pump may be an important mechanism, in this study, we simply explore the process of formation and transport of the newly frozen ice from the ocean through the ice shell by convective ice plumes. We hypothesize that ice is continually being created (by freezing) at the base of the ice shell, beneath upwelling regions within the ice. If so, trace amounts of aqueous compounds from the ocean could be captured by freezing in the newly formed ice at the phase boundary and then be incorporated into

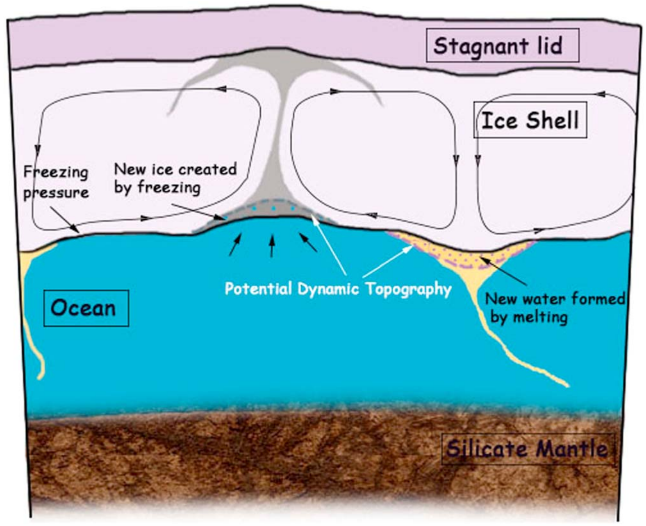

Figure 1. Hypothesis for formation and transport of new ice and new melt across the ice-ocean system. Sketch of upper few hundreds of kilometers of Europa that shows the ice-ocean system (~100–150 km) with highly exaggerated phase boundary topography showing the convecting ice shell (pale purple) over the convecting ocean (blue) separated by the phase change boundary (bold black line). The viscous lid that forms atop the ice shell is also shown (darker purple), and the entire ice-ocean system overlies the silicate mantle (brown shaded region) that extends downward. Convection cells are represented by arrows. Relatively warmer plumes form within the convecting ice shell, driving dynamic topography that would be developed if the ice/ocean boundary was a compositional boundary instead of a phase boundary. Ocean water fills this newly created void space (blue/grey stippled region), freezing to form new ice (grey) that is incorporated into the convecting ice shell. Similarly, new water forms by melting (purple yellow dotted matrix) as the cold ice plumes push ice downward and the cold water plumes (yellow) mix this newly melted water down into the convecting ocean. We hypothesize that if any trace chemistry from the ocean can be trapped into the newly frozen ice, it could be circulated across the system by means of the dynamic process schematically presented here. Furthermore, if chemistry from the surface gets incorporated into the convecting ice shell, some of it should be expelled in the melt formed at the base of the downwellings into the ocean below.

the warmer thermal plumes within the ice shell. The rising ice plumes could thus potentially lead to surface detection of the entrapped oceanic chemistry. Figure 1 shows a conceptual sketch of this process within the two layered convecting system. The base of the ice shell is self-consistently defined by the freezing/melting pressure of H_2O. This freezing/melting pressure increases with decreasing temperature [e.g., *Dunaeva et al.*, 2010], so the base of the ice shell will be deeper beneath colder, downwelling ice and shallower beneath warmer, upwelling ice (as exaggeratedly shown by a thick bold line in Figure 1). This is determined by the equation [*Dunaeva et al.*, 2010]

$$T(P) = a + bP + c \ln P + d/P + e\sqrt{P}$$

$$a = 273.0159,\ b = -0.0132,$$
$$c = -0.1577,\ d = 0.0,\ \text{and } e = 0.1516$$

where T is the temperature in kelvin; P is the pressure in bar; and coefficients a, b, c, d, and e are obtained from experimental data.

Furthermore, convection within the ice generates radial stresses on the top and bottom boundaries of the ice shell. At the top surface, which is a compositional boundary, these radial stresses drive the formation of dynamic topography [e.g., *Han and Showman*, 2005]. However, because the bottom of the ice shell is defined by a phase boundary (the freezing/melting pressure), the radial stresses act to drive the material across the freezing pressure. Therefore, there is no actual dynamic topography generated. Upwellings within the ice shell generate radial stress that pulls the base of the ice shell upward to lower pressure. Any liquid water that fills that space will therefore cross into the solid phase due to decompression freezing. This new ice can then be incorporated into the warm rising plumes and be transported across the ice shell toward the surface. Conversely, downwellings within the ice shell generate radial stresses that push the base of the ice shell deeper to higher pressure. As this ice is exposed to higher pressure than the freezing/melting pressure, it will melt into the liquid ocean below.

When water from the ocean freezes to form new ice, some trace chemistry could be captured into it in the interstices of pure ice or as clathrates [*Zolotov and Kargel*, 2009]. This could result in transport of trace ocean chemistry into and across the ice shell as the rising plumes capture the newly formed ice and stir it into the convecting ice shell. Similarly, if surface chemistry gets incorporated into the convecting ice shell, some of it could ultimately enter the ocean across the phase boundary as ice melts beneath downwellings. Thus, chemical circulation from the surface to the ocean and back across the ice shell in between could be plausible in this two-phase convecting system.

Table 1. Parameter Values Used in the Models

Parameter	Value
Gravitational acceleration (g)	$1.3\ m\ s^{-2}$
Temperature at the surface (T_s)	95 K
Melting temperature of ice (T_m)	Function of pressure (~270 K)
Melting viscosity of ice (η_m)	10^{16} Pa s
Density of ice (ρ_i)	$917\ kg\ m^{-3}$
Density of water (ρ_w)	$1000\ kg\ m^{-3}$
Thermal expansivity of ice (α_i)	$1.6 \times 10^{-4}\ K^{-1}$
Thermal expansivity of water (α_w)	$2.0 \times 10^{-5}\ K^{-1}$
Thermal diffusivity of ice (κ_i)	$1.0 \times 10^{-6}\ m^2\ s^{-1}$
Thermal diffusivity of water (κ_w)	$1.33 \times 10^{-7}\ m^2\ s^{-1}$

2. Modeling

We test the hypothesis that convection-induced dynamic topography on the bottom of the ice shell can drive the transfer of material across the phase boundary by performing numerical thermochemical convection calculations of the entire two-phase H_2O layer. We adapt our thermochemical version of the two-dimensional mantle convection code, Citcom [*Moresi and Gurnis*, 1996; *McNamara et al.*, 2010], that solves the dimensionless equations for conservation of mass, momentum, and energy under the Boussinesq approximation (supporting information). The fixed parameters used for ice convection are listed in Table 1. A temperature-dependent ice viscosity is used [e.g., *Showman and Han*, 2004; *Mitri and Showman*, 2005] in our calculations. We explore three cases that differ in their temperature dependence of ice viscosity. All other parameters remain fixed (Table 1). The viscosity of the ice shell is determined by

$$\eta = \eta_m \exp\left(A\left(\frac{T_m}{T} - 1\right)\right)$$

where η (Pa s) is the viscosity, η_m (Pa s) is the melting viscosity fixed here at 10^{16} Pa s (supporting information for further discussion of ice viscosity), A is the activation coefficient, T_m (K) is the melting temperature, and T (K) is the temperature. A controls the temperature dependence of ice viscosity. We vary the values of A (supporting information) in our study. We employ a modest temperature dependence and a high melting viscosity in our models in order to improve the computational efficiency of the models.

To establish a self-consistent two-phase system, the phase diagram of water ice Ih [*Dunaeva et al.*, 2010] was incorporated into the model to produce a temperature- and pressure-dependent phase change. The extreme viscosity contrast between ice and water is computationally challenging to model; however, for this problem it is only necessary to resolve the convection within the ice shell and adequately reproduce the viscous decoupling between ice and liquid ocean. Hence, our numerical model employs a low-viscosity proxy fluid to represent the ocean layer. Although the viscosity of this proxy fluid is higher than that of liquid water, it remains much lower than that of solid ice and allows a viscously decoupled, self-consistent phase boundary. Such a low-viscosity approximation has also been used in terrestrial mantle convection studies to represent a realistic scenario of free surface plates over the mantle [*Crameri et al.*, 2012]. By performing an extensive set of initial comparison calculations (examining different viscosities of the proxy fluid), we found that proxy fluid viscosity that is a thousand times lower than that of the lowest viscosity in the ice was sufficient to provide adequate viscous decoupling of the layers and further reduction in viscosity did not produce a noticeable change in dynamics of the ice portion of the system (details in the supporting information).

In order to design a simple experiment to test this hypothesis, we do not yet include the effects of tidal heating [*Tobie et al.*, 2003; *Han and Showman*, 2010] which is considered to be an important source of heat generation in Europa. Therefore, the heat balance of our model is controlled by the prescribed temperature contrast across the system (from the bottom of the ocean to the surface) which we control in order to reach a steady state ice-shell thickness over time (supporting information for more details). We staged our system to be at thermal equilibrium, such that the average ice-shell thickness neither grows nor shrinks.

3. Results and Conclusions

Case 1 employs a relatively moderate temperature dependence of viscosity ($A = 5.0$, leading to a viscosity contrast of ~100X across the ice shell). A time sequence of three snapshots for this case is shown in Figure 2. For each snapshot, phase and temperature are shown in the left and right panels, respectively. The temperature panels for each of these times reveal vigorous convection occurring within the ice shell, with warm upwelling

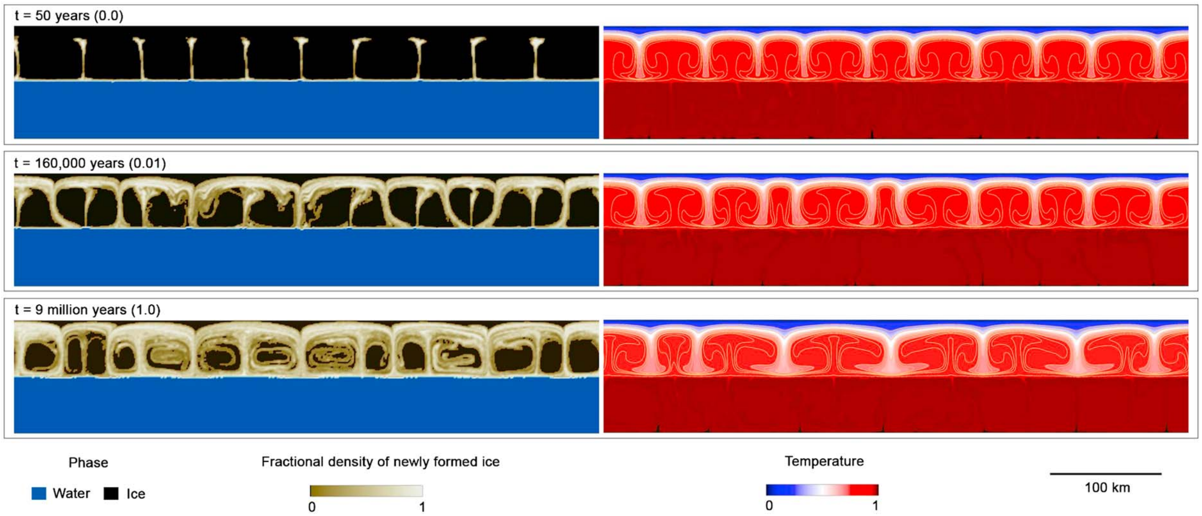

Figure 2. Time evolution of Case 1. The composition (phase) and temperature fields are shown for three time snapshots in the calculation, each as an individual row. Panels on the left display composition, and panels on the right display temperature. In the composition panels, blue represents the proxy fluid (the liquid ocean) and black represents solid ice. The fractional density of newly formed ice is superimposed on the black background (as green to white). The three rows are identified by the dimensional times and the nondimensional times within parentheses relative to the first step shown in the first row at time, $t = 0.0$, when we start tracking the new ice in a convectively equilibrated system.

plumes surrounded by cooler downwellings. In the phase panels, blue represents the proxy fluid (liquid ocean) and black represents the solid ice. As new ice is formed by freezing of water crossing the phase boundary, we track it by changing the color of the element that contains it. In other words, elements that contain newly formed ice are colored white green, the shade of which is determined by the fraction of new ice that the element contains. The snapshots clearly show that the newly formed ice is then advected up along the plume axis until the plume is deflected by the viscous lid at the surface. The newly formed ice is subsequently stirred into the convecting ice shell beneath the viscous lid.

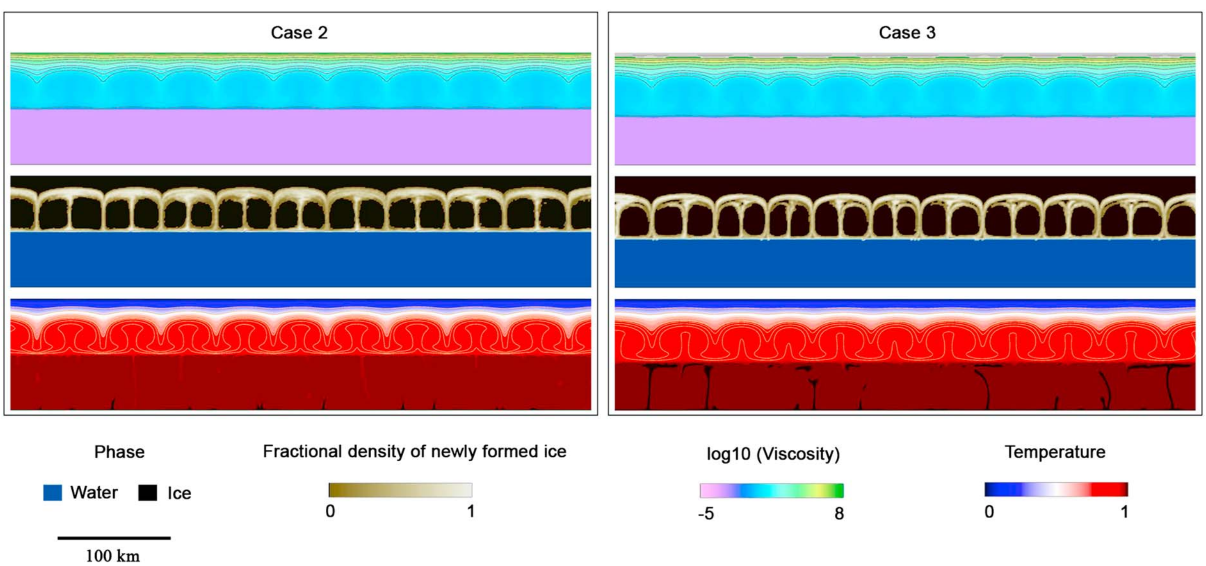

Figure 3. Demonstration of new ice formation for Cases 2 and 3. Top panels display the logarithm of viscosity with contours shown for every order of magnitude increase. Middle panels display composition (phase) in which blue represents the proxy fluid (liquid ocean) and black represents solid ice. The fractional density of newly formed ice is superposed on the black background (as green to white). Bottom panels represent temperature. The two cases shown here have higher temperature dependence of ice viscosity across the shell than case 1 with case 2 representing a viscosity contrast of 10,000X ($A = 10.0$) and case 3 representing a viscosity contrast of 1,000,000X ($A = 13.8$) across the ice shell, respectively. The snapshots in cases 2 and 3 are taken at approximately 5 Myr and 13 Myr, respectively.

Cases 2 and 3 employ higher-temperature dependence of viscosity, leading to viscosity contrasts of 10,000X and 1,000,000X across the ice shell, respectively. Snapshots from these cases are shown in Figure 3 which includes panels showing the logarithm of viscosity, phase, and temperature. We find that the main effect of increasing the temperature dependence of viscosity is to thicken the viscous lid at the top of the ice shell. Like in case 1, new ice is formed at the base of upwelling ice plumes, advected up along the plume axis, deflected by the viscous lid, and stirred into the convecting ice shell.

While the effects of internal heating, melting viscosity of ice, and numerical parameters such as grid resolution would affect the absolute amount of new ice that is formed, the physics of new ice formation at the phase boundary between the ice shell and the ocean established here is likely to be a dynamic process occurring in convecting ice shells over liquid-water oceans, including the ice-ocean system of Europa. However, it has been recognized that numerical representation of entrainment is a function of grid resolution [*Van Keken et al.*, 1997] and hence finer the grid, more accurate the estimate of the amount of new ice formed and incorporated. Therefore, the amount of new ice formed and transported demonstrated in this study should be treated as an upper limit of possible new ice formation. Our experiment is focused toward understanding material transport due to radial stresses from ice-shell convection pushing/pulling the material across the phase boundary. However, other mechanisms such as "ice pump" [*Lewis and Perkin*, 1986; *Fricker et al.*, 2001; *Robin et al.*, 2014] may provide additional material transport across the phase boundary.

Our Boussinesq formulation in this study does not include latent heat, adiabatic effects, viscous dissipation, and tidal heating. The rate of freezing is limited by the rate at which latent heat can be removed. However, most of the latent heat is expected to be advected away by ocean currents rather than conduct into the ice [e.g., *Warren et al.*, 2002]. Because the rate of new ice formation (controlled by convective velocities within the solid ice shell) is much slower than the rate at which heat can be advected away (controlled by the much higher convective velocities within the liquid ocean), latent heat is not expected to play a significant role in this process. Addition of compositional species (e.g., salts) may influence the freezing and melting of ice and change the estimates of new ice formed. In any case, our simple numerical experiments demonstrate the process of dynamic stress driving material across the phase boundary, which is expected to also occur in models with more complexities added.

The possibility of trace chemistry from the ocean being trapped into the freezing newly formed ice and its subsequent integration into rising ice plumes argues for its detection at the surface subject to breaking of the viscous ice lid capping the shell. It has been proposed that weakening of the lid can occur due to the tidal forces as well as convective stresses [*Sotin et al.*, 2002; *Pappalardo and Barr*, 2004; *Schmidt et al.*, 2011] and tectonic stresses [*Sullivan et al.*, 1998; *Greenberg et al.*, 1998; *Hoppa et al.*, 1999; *Prockter and Pappalardo*, 2000; *Nimmo and Gaidos*, 2002]. A recent study [*Kattenhorn and Prockter*, 2014] has also proposed the possible tectonic "subsumption" in the ice shell which would further facilitate transport of the newly formed ice that is advected by ice plumes toward the surface. Fracturing the lid could thus expose the rising new ice to the surface and potentially allow any captured oceanic material to be detected on the surface.

Our qualitative calculations support the convective-driven process of new ice formation in the two-phase convecting ice-ocean system as relevant to Europa. They also demonstrate that this new ice (from the ocean) can be integrated into the rising ice plumes, move toward the surface, and become progressively mixed into the convecting ice shell. However, the newly formed ice cannot penetrate the viscous lid of the ice shell; therefore, some mechanism is required to break the lid to expose it at the surface. Possible implications of these conclusions include transport of trace ocean chemistry on to the surface and from the surface down into the ocean below—an essential while not necessary indicator of any potential existence of life in the icy moon.

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