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A whole-moon thermal history model of Europa: Impact of hydrothermal circulation and salt transport

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ABSTRACT

A whole-moon numerical model of Europa is developed to simulate its thermal history. The thermal evolution covers three phases: (i) an initial, roughly 0.5 Gyr-long period of radiogenic heating and differentiation, (ii) a long period from 0.5 Gyr to 4 Gyr with continuing radiogenic heating but no tidal dissipative heating (TDH), and (iii) a final period covering the last 0.5 Gyr until the present, during which TDH is active. Hydrothermal plumes develop after the initial period of heating and differentiation and transport heat and salt from Europa's silicate mantle to its ice shell. We find that, even without TDH, vigorous hydrothermal convection in the rocky mantle can sustain flow in an ocean layer throughout Europa's history. When TDH becomes active, the ice shell melts quickly to a thickness of about 20 km, leaving an ocean 80 km or more deep. Parameterized convection in the ice shell is non-uniform spatially, changes over time, and is tied to the deeper ocean–mantle dynamics. We also find that the dynamics are affected by salt concentrations. An initially non-uniform salt distribution retards plume penetration, but is homogenized over time by turbulent diffusion and time-dependent flow driven by initial thermal gradients. After homogenization, the uniformly distributed salt concentrations are no longer a major factor in controlling plume transport. Salt transport leads to the formation of a heterogeneous brine layer and salt inclusions at the bottom of the ice shell; the presence of salt in the ice shell could strongly influence convection in that layer.

1. Introduction

Data returned by the Galileo spacecraft provide considerable evidence that Jupiter's satellite Europa possesses a liquid ocean beneath its solid icy outer shell. The evidence for a subsurface ocean is largely based on magnetometer measurements that require a highly electrically conducting layer beneath the ice (Khurana et al., 1998; Kivelson et al., 2000; Zimmer et al., 2000). The complex geology of Europa's surface lends additional support for a subsurface ocean (Carr et al., 1998; Pappalardo et al., 1999). In particular, high-resolution images of Europa's surface have revealed chaotic terrain interpreted as disrupted ice overlying liquid water (Greenberg et al., 1999). The Galileo measurements of Europa's gravitational field indicate that the satellite is most likely differentiated into a metallic core surrounded by a silicate mantle and a water ice-liquid outer shell of approximately 100–170 km thickness (Anderson et al., 1998; Schubert et al., 2004). However, the gravity measurements cannot distinguish between the liquid and solid phases of water, and the thickness of the outer ice shell and the depth of an ocean remain uncertain.

The uncertainty of the ice thickness has helped fuel debate over the formation mechanism for regions of chaos on Europa. Two end-member models have been proposed to describe the development of chaos features. The first model assumes a layer of ice tens of kilometers thick. Solid-state convection within the thick ice shell induces diapirism. Chaos regions then form over upwelling diapirs of warm ice (Pappalardo et al., 1998). The second model suggests that the ice shell is only a few kilometers thick. In this case, areas of chaos result from the melt-through of the thin ice shell (Greenberg et al., 1999). Melt-through events could be driven by localized tidal heating in the ice (McKinnon, 1999) or focused heating from Europa's silicate mantle to the base of the ice shell (Thomson and Delaney, 2001; O'Brien et al., 2002). However, localized tidal heating as a mechanism for melt-through is a self-limiting process since tidal dissipation decreases as the ice is thinned and replaced by liquid (Ojakangas and Stevenson, 1989; Collins et al., 2000). Therefore, attention has been focused on determining the efficiency of hydrothermal plumes in transmitting heat from the rocky interior through the ocean to the base of the ice shell.

A number of studies examining the ability of a hydrothermal plume to melt through the Europan ice shell have resulted in

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widely different conclusions (Collins et al., 2000; Thomson and Delaney, 2001; Goodman et al., 2004; Lowell and DuBose, 2005). Thomson and Delaney (2001) provide the first detailed description of how a plume originating from the heated seafloor rises to the ice-liquid water interface. They argue that the heat delivered by the plume is sufficient to melt through the ice and cause chaos-type features. However, Collins et al. (2000), Goodman et al. (2004), and Lowell and DuBose (2005) argue against the melt-through model due to the enormous power required to maintain liquid water at Europa's surface. To prevent freezing of liquid water at the surface, a subsurface heat source must provide at least 300 $\mathrm{W\,m^{-2}}$ (Collins et al., 2003; Goodman et al., 2003). This value is an order of magnitude greater than even the most generous estimates of the heat flux delivered to the base of the ice shell (O'Brien et al., 2002; Goodman et al., 2004). Goodman et al. (2004) explore the physical parameters of Europan hydrothermal plumes using scaling laws and laboratory experiments to visualize plume behavior in a Europa-like parameter regime. The relevant scaling laws for a buoyant hydrothermal plume describe the flow and geometry of the plumes (e.g., the critical height at which the plume changes from conical to cylindrical, the width of the cylindrical plume, the time to baroclinic instability, the width of the baroclinic cone at the onset of baroclinic instability, and the drift velocity of the shed eddies). In order to test their theoretical scaling laws, Goodman et al. (2004) also use tank experiments to measure the critical height, widths, time, and drift velocity. Finding acceptable agreement between theory and experiment, they suggest that the heat fluxes delivered by hydrothermal plumes to the base of the ice shell are too weak to allow complete melt through.

Lowell and DuBose (2005) address the physics of hydrothermal flow on Europa by assuming that hydrothermal processes on Europa are analogous to those on Earth. They estimate the global hydrothermal heat flux on Europa and the heat output of an individual high-temperature plume. They also determine that Europan seafloor plumes are relatively weak and unlikely to cause melt-through events. Recently, Goodman and Lenferink (2009) and Goodman (2010) use 3-D numerical simulation to study hydrothermal plumes driven from hot spots on the seafloor, considering thermal buoyancy only. Results are similar to those of previous tank experiments and theory, except that plume temperature varies with depth. Turbulent mixing and entrainment occurs when plumes reach 20–35 km in diameter. Typical large-scale currents near plumes flow at 1.5–5 $\mathrm{cm\,s^{-1}}$, and temperature anomalies are very small.

In addition to studying the transport of heat by these plumes, one must consider the conditions under which buoyant plumes from the ocean–mantle interface reach the base of the ice shell. If the plumes and the ocean water are not compositionally different and the ocean is not stratified, plume buoyancy is controlled by the difference in temperature between it and the surrounding ocean. In this case, warmer plumes are less dense and should rise through the unstratified ocean to the water ice-liquid interface. The high Rayleigh numbers characterizing Europa's ocean should help maintain a well-stirred ocean with homogeneous temperature. However, it is still possible that the ocean is stratified, due to compositional or thermal variations (Collins et al., 2000; Goodman et al., 2004; Melosh et al., 2004; Vance and Brown, 2005). Such stratification of the ocean can halt the ascent of plumes before they reach the ice shell. In a stratified fluid, a hydrothermal plume rises until it reaches a level (the neutral buoyancy level) where its density equals that of the surroundings. Whether or not a plume remains buoyant over the entire depth of the ocean therefore depends on factors such as the salt concentration and temperature profile of the plume and ambient ocean.

Several studies have discussed the effect of salinity on plume buoyancy in Europa (Collins et al., 2000; Thomson and Delaney, 2001; Goodman et al., 2004; Melosh et al., 2004; Vance and Brown, 2005). Vance and Brown (2005) assess plume buoyancy in a dilute ocean and in a saturated eutectic ocean to determine the effect a plume's salinity relative to the surrounding ocean has on its rise height. In a more dilute ocean, Vance and Brown (2005) assume enhanced salinity of the plumes as a result of interactions with surrounding mantle rock. The excess salinity in the plume due to uptake below or at the seafloor shifts the density anomaly profile in the direction of neutral buoyancy well before reaching the base of the ice shell. However, it is also possible that the difference in salt concentration between the plume and ocean is approximately zero or that Europa's ocean is unstably stratified (Speer and Rona, 1989; Vance and Brown, 2005). Under either of these conditions it is possible for the plume to reach the ice shell. For example, an unstable salinity gradient (i.e., seawater salinity increases with height) in the Atlantic Ocean results in plume penetration heights greater than those of plumes in the Pacific Ocean where the salinity decreases with height. In the Atlantic, even after the temperature of the plume equals that of the background, the plume remains buoyant due to its salinity deficit relative to the ambient seawater (Speer and Rona, 1989). Additionally, mid-ocean ridge hydrothermal systems are known to vent fluids with salinities substantially different from that of seawater (reported salinities range from 10% to 200% seawater) as a result of phase separation and segregation of the resulting vapor and brine phases (Bischoff and Rosenbauer, 1989; Fontaine and Wilcock, 2006). Some of these systems have vented fluids with salinities well below seawater for decades.

The work presented here builds upon previous studies by investigating the generation of hydrothermal systems and the subsequent transport of heat and solute mass into a Europan ocean and mixing and transport therein. The mechanics of plume generation are investigated using a whole-moon numerical model integrated over Europa's history. These simulations allow us to better characterize and quantify the kind of hydrothermal flows that might develop under Europan conditions by determining the nature of hydrothermal convection in Europa's outer mantle, its impact on overall heat transport, and the global ice shell thickness. In addition, the impact of mantle pore water convection throughout much of Europa's history is considered, to determine if it could sustain an ocean. This study also investigates the evolution of salt transport into an ocean and interaction of a salty ocean with freezing and melting processes at the ocean–ice shell interface. Consequently, this work provides additional constraints on the conditions, properties, and evolution of hydrothermal plumes in Europa.

2. Model description and simulation parameters

2.1. Model description

Europa is assumed to be composed of four zones, a metallic core, an overlying silicate mantle, an ocean layer and an ice shell. Europa's history naturally divides into three phases – the first 0.5 Gyr, marked by differentiation of the core and mantle, the middle period from 0.5 to 4.0 Gyr, in which tidal dissipative heating (TDH) may not have occurred, and the most recent phase covering the past 0.5 Gyr in which TDH heats the ice shell. Appendix A summarizes the processes included in each phase for each region of Europa. The numerical simulations of this study use the computer code MAGHNUM (Travis et al., 2003), a model that includes thermal diffusion, water-ice phase changes, radiogenic and tidal heating, and convection in porous permeable rock, the ocean layer and the ice shell. The code solves the time-dependent governing equations of mass, momentum and energy conservation in 3-D spherical coordinates (but limited here to a 2-D radial, latitudinal geometry) for a radially varying gravity field. Mathematical descriptions of the