THE STRUCTURE AND EVOLUTION OF EUROPA'S OCEAN AND ICE SHELL IN THE PRESENCE OF AQUEOUS MGSO$_4$. S. Vance[1], J. C. Goodman[2], [1]Jet Propulsion Laboratory, Caltech (svance@jpl.nasa.gov), [2]Wheaton College, Massachusetts.

Introduction: We use numerical methods to evaluate the coupled thermal and compositional evolution of Europa's ocean and ice shell. Our focus is constraining vertical density and thermal structure, and related transport of material and heat between a rocky seafloor and the near surface of an ice shell. Heat and salt flux values considered are consistent with changes in average heat flux to the entire ocean, and also with more intense localized plumes generated by hydrothermal activity. Consistent with previous studies, we find that ocean temperature is governed by the ice shell's pressure- and composition-dependent freezing point. A non-convecting stratosphere layer forms below the ice shell for thickness less than 17 km and $MgSO_4$ salinity less than 0.3 mol/kg$_{H2O}$. Double-diffusive convection is found to regulate heat transfer at the ice shell, and can lead to warming of the lower ocean by tens of degrees over Myr time scales.

Model Description. We use a single-column convection model identical to those used in meteorology and oceanography [1]. Upper or lower boundary forcing can be specified in terms of heat and salt flux. We model a vertical column of Europa seawater, nominally 100 km deep, representing it as forty 2.5 km thick finite volumes. This 1-D model is complmentary to recent work examining the development 3D of hydrothermal plumes in Europa's ocean [2].

We step forward in time using a simple Euler forward scheme. We write the model's finite-difference scheme as an explicit matrix operator, and step the model forward in time using an Euler-backward fully implicit scheme. Since the model's physical dynamics are governed by slow transfers of heat at the boundaries but its numerical stability is limited by the rapid flow of heat through actively-convecting regions, an implicit scheme allows us to take large steps forward in time (up to 2560 days) without compromising accuracy. For the models considered here, our time step is 4 terrestrial days.

Convective mixing is parameterized as a vertical diffusive process, as per common oceanographic practice [1]. When adjacent volumes are convectively unstable, their contents are mixed using a large diffusion constant (k = 0.5 m s^{-2}, assuming an eddy velocity of 1 cm s^{-1} and a mixing length of 50 m).

Double Diffusive Convection. Even when the water column is convectively stable, transfer of heat and salt can occur through double diffusion [3]. If warm, salty water stably overlies cold, fresh water, the transfer of heat leads to the creation of downward-penetrating salt fingers, which cross the interface, transferring heat and salt. If cold fresh water overlies warm salty liquid, heat transfer sharpens the layer interfaces, creating diffusive layers, which increases the rate of molecular diffusion and conduction across them. Salt and heat are transferred across a stable interface in both cases. These processes occur on centimeter scales, but can affect the whole ocean structure. Double diffusion is parameterized as per [4]. Separate diffusivities for heat and salt are calculated.

Boundary Conditions. We assume steady-state thermal conduction for the ice shell, with fixed top and bottom temperatures [5]. With these assumptions, the heat flux through the base of the ice is strictly proportional to the ice thickness:

$$F_{base} = \frac{b_1 \ln(T_f/T_s) + b_0(T_f - T_s) + \frac{1}{2}c(T_f^2 - T_s^2)}{h} \quad (1)$$

[6] where h is the ice shell thickness, T_s=102 K is Europa's mean surface temperature [7], T_f =273 K is the melting point, b_1=632 W m^{-1}, b_0=0.38 W m-1 K^{-1} c=-0.00197 W m^{-1} K^{-2} [8]

At the boundary between ice and water, we compare the heat flow upward into the ice from the equation above with the heat flow upward from the ocean. Any difference between these must be accounted for by latent heat, leading to freezing or melting the ice base. This allows us to step the ice thickness forward in time:

$$\frac{dh}{dt} = \frac{F_{base} - F_{ocean}}{\rho_i L} \quad (2)$$

where ρ_i is the density of ice and L is the latent heat of fusion. F_{ocean} is set to ensure that the topmost layer of the ocean is always at the melting point.

Most of Europa's ice shell is at temperatures that promote the exclusion of salt [9]. For the slow rates of melting and freezing considered here, salt is also strongly rejected from the warmer lower ice as it freezes. To find the effect of ice melting and freezing on salinity at the top of the ocean, we treat the real freshwater flux as a virtual salt flux into the top of the ocean [10]:

$$\frac{dS_{top}}{dt} = \frac{S_{top}}{\Delta z}\frac{\rho_i}{\rho_w}\frac{dh}{dt} \quad (3)$$

where ρ_i and ρ_w are the densities of ice and water, and Δz is the thickness of the topmost model layer.

Results. The included figure shows results for a model run beginning with an unstratified 0.1 molal (~1 Wt%) ocean with constant seafloor heat flux of 0.190 W m^{-2}—an the upper limit for estimates of tidal input [11], but about half the upper limit for heat from a hydrothermal source [12]. Salinity and temperature are displayed as a function of depth and time in the upper left and middle panels; zero-km depth is at the ice-water interface. The ocean is initially isothermal, and constant flux of dissolved $MgSO_4$ 10^{-7} mole m^{-2} s^{-1} is specified. Starting ice shell thickness (upper right panel) is 10 km. Convection and double diffusive mixing (lower left and middle panels) are established in the upper and lower ocean as the ice shell thickens for the first 100 kyr. As the calculation progresses, the ice shell thins toward its equilibrium thickness of 3 km, but slowly as the influx of meltwater separates it from heat flux from below. A sawtooth pattern of melting and refreezing is established, with a period of roughly a thousand years. Much of the heat and salt flux from the seafloor is retained in the lower 10 km, separated by a stratified double-diffusive boundary (lower middle and right panels).

Discussion and Conclusions. Downward-penetrating double-diffusive convection slows changes in ice shell thickness by impeding convective heat transfer from the ocean upon thinning and speeding it through increased salinity when the ice thickens. Diffusive-mode double diffusive convection in the lower ocean—due to flux of dissolved salt from the seafloor presumed to occur due to water-rock interaction—can warm the lower ocean tens of degrees above the freezing temperature of water over Myr time scales. Disruption of this lower layer leads to rapid thinning of the ice shell, the effects of which might be discernable in Europa's surface geology.

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