THE POTENTIAL FOR DOUBLE-DIFFUSIVE CONVECTION IN EUROPA'S OCEAN.
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Introduction: From Galileo magnetometer measurements, it is now widely accepted that Jupiter's icy moon Europa contains a global subsurface ocean [1]. Salt deposits on the surface of Europa also imply interaction between a geologically active ice shell and the underlying ocean [2]. Understanding the dynamics of Europa's ocean is crucial to determine how material might be transported between the silicate mantle and the icy shell, an exchange process that is important to consider for habitability. Numerical thermal convection models of Europa's ocean show that the ocean is well-mixed, with strong zonal jets and Hadley-like circulation cells [3]. In this study, we investigate how salinity variations in Europa's ocean might affect previously proposed thermal convection models. Towards this end, we estimate the compositional Rayleigh number and compare it to the thermal Rayleigh number. These dimensionless parameters quantify the thermal and compositional buoyancy of the system with respect to diffusion.

With the potential significance of compositional stratification due to salt content increasing with depth [4] in addition to thermal convection driven by the temperature contrast between the underlying mantle and overlying ice shell [3], we investigate the possibility of a double-diffusive system within Europa's ocean. Double-diffusive convection occurs in a fluid with two or more density gradients, each with different diffusivities [5]. In the case of Europa's ocean, there are two density gradients determined by the temperature and salinity gradients. The diffusivity of heat in water is two orders of magnitude higher than the diffusivity of salt [6]. The density stability ratio, R_ρ, determines if a system can develop double-diffusive convection, where $R_\rho = \beta \Delta S / \alpha \Delta T$. The change in salinity and temperature in Europa's ocean are ΔS and ΔT, respectively. $\beta = 8.3\times10^{-4}$ psu^{-1} is the saline contraction coefficient [5], and $\alpha = 2\times10^{-5}$ K^{-1} is the thermal expansion coefficient [7]. For double diffusive convection to occur, the density stability ratio needs to be roughly between 1 and 10 [8]. A density stability ratio less than 1 indicates a dynamic ocean driven primarily by temperature, with Rayleigh-Bénard convection. A density stability ratio greater than 10 indicates an ocean with dominantly salinity-driven dynamics.

Calculations: Due to the lack of direct observations of Europa's ocean, the salinity gradient of the ocean is not well constrained. Recent estimations put the change in salinity throughout Europa's ocean in a range of [10^{-4}, 10^{-1}] psu [9]. We use this salinity range to calculate the compositional Rayleigh number, finding values between 6×10^{22} and 1×10^{26}. Using a range of temperature contrasts across Europa's ocean of [0.4×10^{-3}, 96×10^{-3}] K [10], we calculate that the thermal Rayleigh number is between 7×10^{18} and 2×10^{22}.

The salinity and temperature contrasts are used to calculate the density stability ratio R_ρ of Europa's ocean. Due to the wide range of salinity and temperature changes, there is a wide range of possible density stability ratios, spanning from less than unity to more than 10^4 (Table 1). The dynamics may, therefore, be thermally dominated ($R_\rho < 1$), double diffusive ($1 < R_\rho < 10$), or compositionally dominated ($R_\rho > 10$). Consequently, we are unable to conclude the dynamical nature of Europa's ocean from this value alone. While some of the calculated values of R_ρ are much greater than 10, the ocean of Europa may not be stratified due to the high thermal Rayleigh numbers that would tend to mix the ocean's composition and reduce salinity gradients (ΔS). We, therefore, focus on the double diffusive regime.

Table 1: ***Calculated Values of R_ρ***

	$\Delta S=10^{-4}$ psu	$\Delta S=0.2$ psu	$\Delta S=3\times10^{-3}$ psu
$\Delta T=0.4\times10^{-3}$ K	10	2.1×10^4	328
$\Delta T=96\times10^{-3}$ K	0.04	86	1
$\Delta T\approx7.7\times10^{-3}$ K	0.1	172	3

Table 1. Calculated values of the density stability ratio for the ranges of salinity and temperature contrasts, including their intermediate values.

If double-diffusive convection were to form in the ocean of Europa, it would develop layers of convecting fluid. This is the 'diffusive' regime of double-diffusive convection, which occurs when cold fresher water overlays warm saltier water. In these double diffusive layers, the salinity change stabilizes the system while the temperature change destabilizes the system [9]. The layers naturally evolve until they reach a certain height h_c, which can be found with the following expression [11];

$$h_c = \left(\frac{\nu R_c}{64 g \kappa^2}\right)^{\frac{1}{4}} H_*^{\frac{3}{4}} S_*^{-1}$$

where,

$$H_* = \frac{-g\alpha H}{\rho C_p}; \; S_* = -\frac{1}{2} g\beta \left(\frac{dS}{dz}\right)$$

In the above equations, ν is the kinematic viscosity, g is the acceleration due to gravity, R_c is the critical thermal Rayleigh number, κ is the thermal diffusivity, α is the thermal expansion coefficient, H is the heat flux, ρ is the density, C_p is the specific heat capacity, and β is the saline contraction coefficient. The vertical salinity gradient (*dS/dZ)* was estimated by dividing the ΔS used to calculate the density stability ratio by the height of Europa's ocean.

Using these parameters, we estimate that the height of the diffusive layers h_c would be on the order of 10^5 km each. To estimate this height, the thermal Rayleigh number and salinity change ΔS that correspond to a R_ρ in the double diffusive regime where used. Obviously, double-diffusive convection with 10^5 km layer heights is not possible in the ~100 km deep Europan ocean. By plotting the layer height h_c, versus ocean depth, we show that Europa's ocean would need to be two orders of magnitude shallower for double-diffusive layers to form. This plot is shown in Figure 1. The black dotted line in Figure 1 shows where the double-diffusive layer height equals the height of the ocean. Below the black line, diffusive layers can form. Above the black line, diffusive layers cannot form. Figure 1 shows plots for both Europa's ocean and the Red Sea. Double-diffusive layers have been observed in the bottom of the Red Sea on the order of tens of meters [12]. This agrees with the Red Sea line in Figure 1, as it is well below the black dotted line at the actual depth of the Red Sea (~2000 m). At the actual height of Europa's ocean, ~10^5 m, the plot for Europa's ocean is well above the black line, indicating that double-diffusive layers cannot form in Europa's ocean.

Conclusion: The high thermal Rayleigh number for Europa's ocean concur with a well-mixed turbulent ocean if stable salinity gradients are sufficiently small. Because of the wide range of estimates for the change in salinity in Europa's ocean with depth, the density stability ratio cannot be well constrained, but demonstrates that double-diffusive convection is possible. However, when estimating the layer height in a double-diffusive Europan ocean, we find that the ocean is too deep to maintain double-diffusive layers. We, therefore, conclude that convection in Europa's ocean would likely cause both temperature and salinity to be well mixed away from the boundary layers.

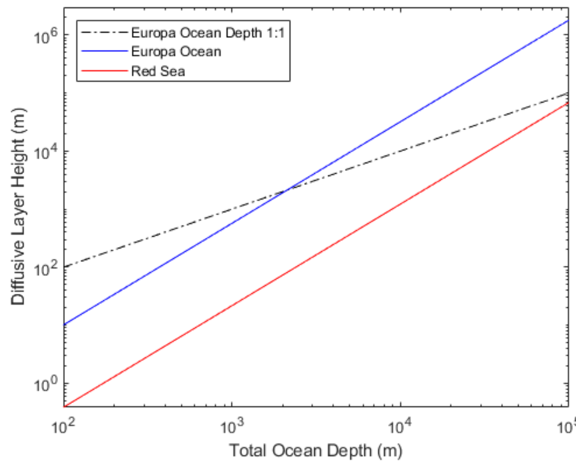

Figure 1. Log scale plot of the diffusive layer height estimates versus ocean depth for Europa's ocean (blue line) and the Red Sea (red line). The dotted black line shows where the diffusive layer height equals the ocean depth. Above the black line, double-diffusive layers cannot form. Below the black line, double-diffusive layers can form.

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