Ocean stratification impedes particulate transport to the plumes of Enceladus

Article

Supplemental Material

Supplementary material

Parameter	Value
Ice shell surface radius (r_s)	252 km
Core radius (r_c)	192 km
Ocean thickness (H_o)	40 km
Ice thickness (H_i)	20 km
Ice density (ρ_i)	925 kg m^{-3}
Gravity at ice shell surface (g)	0.113 m s^{-2}
Ocean mean salinity (S_ref)	5, 10, 15, 17.5, 20, 22.5 g kg^{-1}
Ocean reference pressure (P_ref)	$\rho_\mathrm{i} \int_{H_\mathrm{i}}^{0} g(z)\, dz$
Ocean reference temperature (T_ref)	Freezing temp at P_ref and S_ref
Ocean reference density (ρ_0)	Density at T_ref, P_ref and S_ref
Core density (ρ_core)	2370 kg m^{-3}
Rotation rate (Ω)	5.307 x 10^{-5} s^{-1}
Core total heat output (F_tot)	20 GW
Specific heat capacity (c_p)	4000 J kg^{-1} K^{-1}
Eddy diffusivity (κ_GM)	1 m^2 s^{-1}
Vertical diffusivity (κ_z)	10^{-5}, 10^{-4}, 10^{-3} m^2 s^{-1}
Prandtl number ($\frac{\nu}{\kappa}$)	10
Ice melting viscosity (η_melt)	10^{-14} Pa s

Table S1: Key parameters used in default numerical simulations and in computation of boundary forcings.

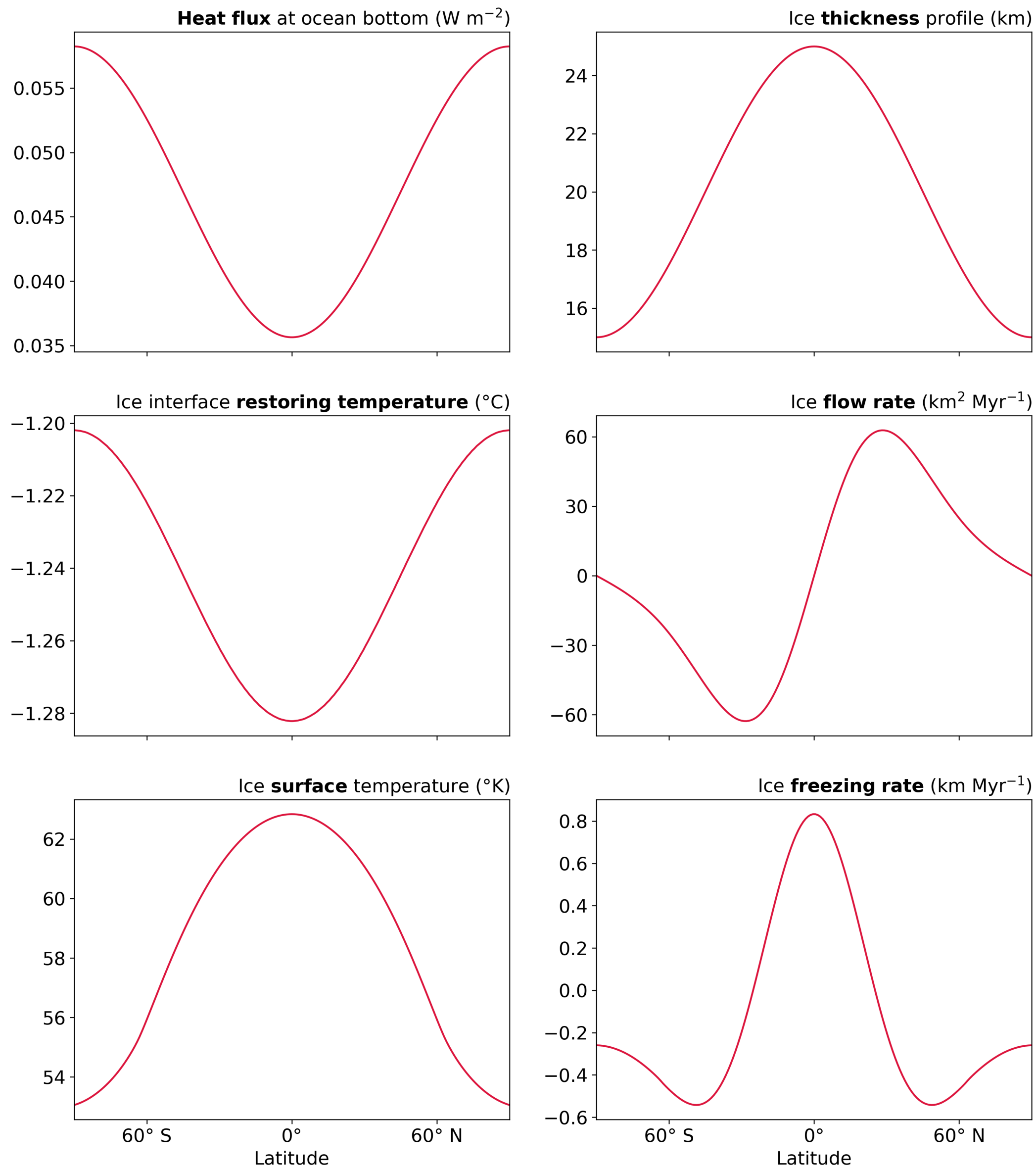

Figure S1: **Top Left**: Bottom heating profile used in simulations (W m^{-2}), assuming a total global core heat output of 20 GW. **Middle left**: An example restoring temperature (^{o}C) profile at the ocean top (ice-interface) used in simulations at 20 g kg^{-1} - corresponding to the pressure and salinity dependant freezing temperature. **Bottom left**: Surface temperature (^{o}K) of ice used to compute ice flow rate in middle right panel. **Top right**: Idealised ice thickness profile (km) used to compute the ice-interface restoring temperature and ice flow rate (for use in computation of ice freezing rate). Note the topography itself is not used in simulations, which assume a flat ocean top. **Middle right**: Ice flow rate (km^2 per million years) used for computing the freshwater flux at the ocean top, in turn computed from the idealised geometry of the top right panel, assuming a steady state Enceladus ice shell thickness profile. **Bottom right**: Freshwater flux (km per million years) profile applied at the ocean top in simulations, computed using the ice flow rate in the middle right panel.

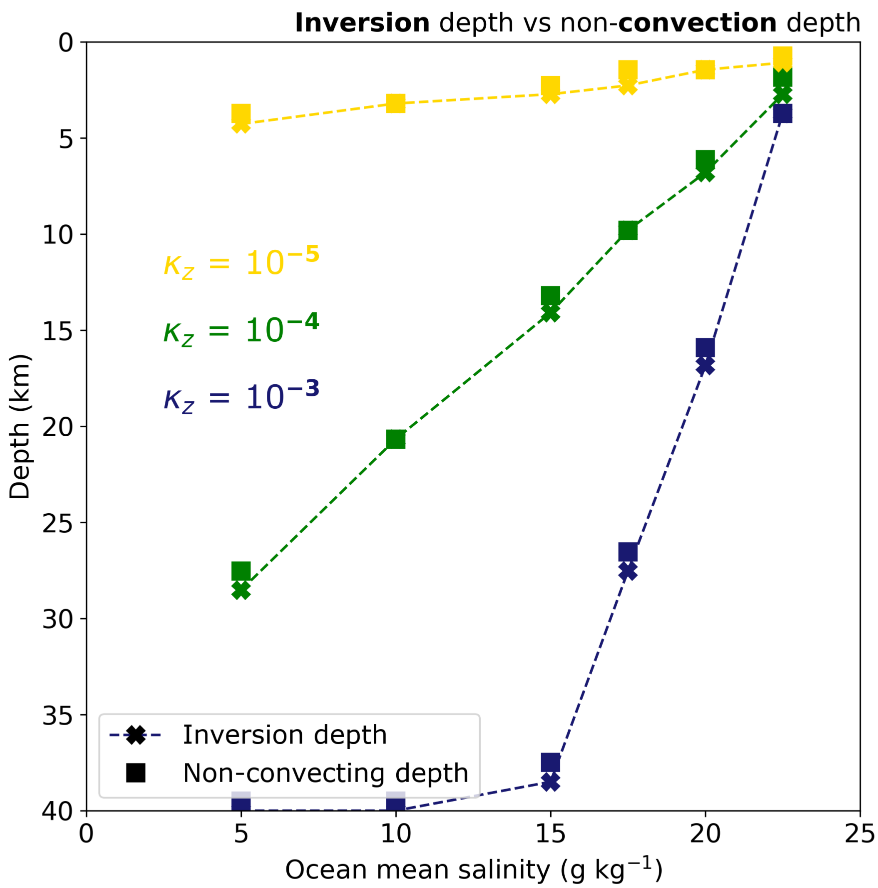

Figure S2: Numerical solution for the inversion depth (km - cross, dashed line - depth at which the thermal expansion coefficient α_T becomes negative) across a range of ocean mean salinity (g kg^{-1}) for three values of κ_z (m^2 s^{-1}), denoted with different colours, as in Fig. 2 of the main text. Here the inversion depth is plotted alongside the depth at which model convection extending from the ocean bottom stops (km - squares), defined as the depth at which the laterally-averaged convecting time falls below 0.01% of model time. Markers at 40 km depth denote where there is no inversion depth (meaning α_T remained negative across the whole ocean) or non-convecting depth (meaning no convection extended from the ocean bottom) respectively.

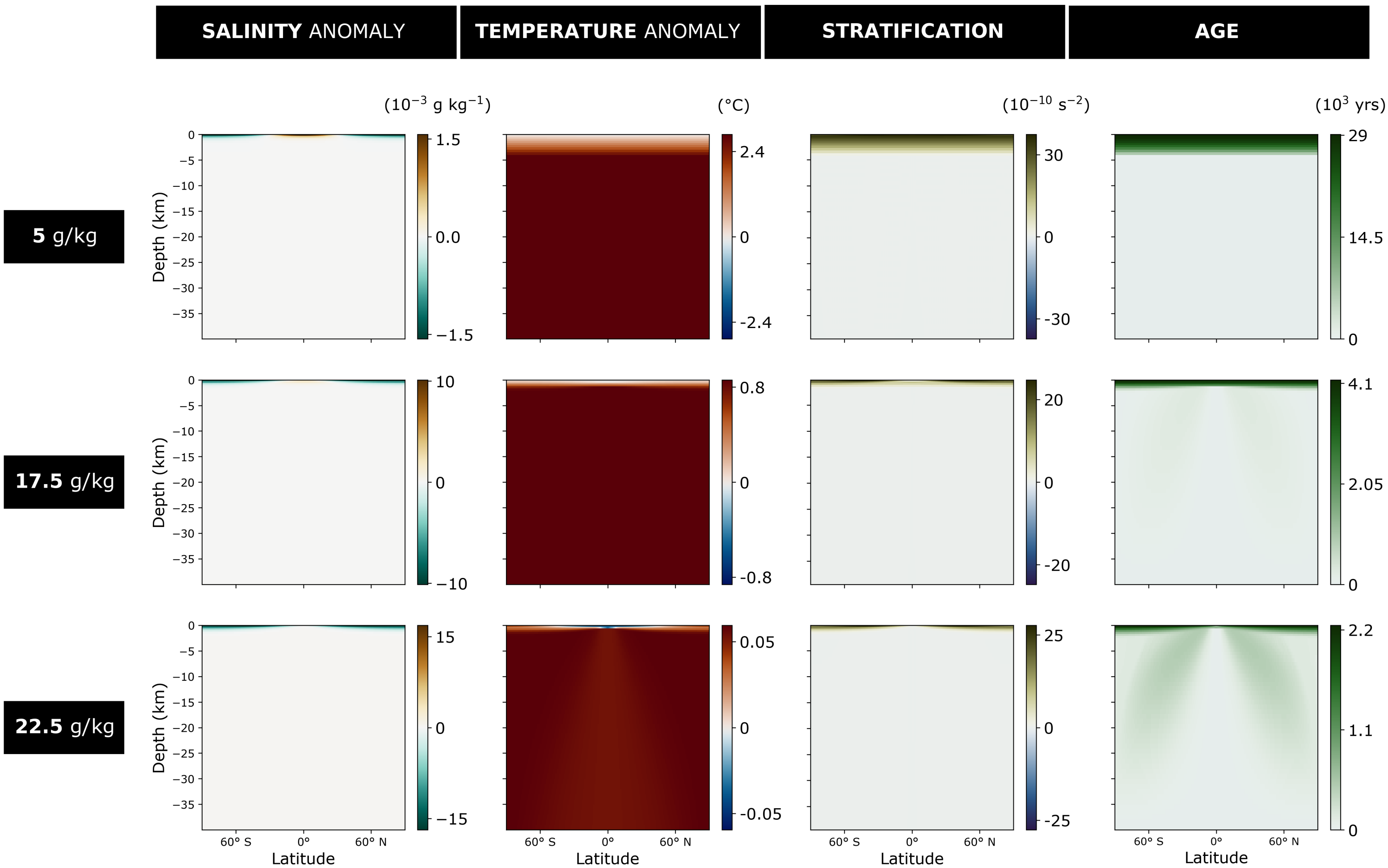

Figure S3: Numerical solutions with effective vertical diffusivity $\kappa_z = 10^{-5}$ m^2 s^{-1}, across three different mean ocean salinities of 5 (top), 17.5 (middle), and 22.5 (bottom) g kg^{-1}, highlighting stratification regimes at a lower κ_z than presented in the main text. Note colour bar scales are saturated and vary throughout. **First column**: Salinity anomaly (g kg^{-1}) taken about the mean salinity. **Second column**: Potential temperature anomaly (° C) taken about the simulation reference temperature T_{ref} (freezing temperature computed under 20 km mean ice thickness) of -0.433 (top), -1.106 (middle) and -1.379 (bottom) ° C. **Third column**: Buoyancy frequency N^2 (s^{-2}) indicating stratification. **Fourth column**: Ideal age of tracers (years), sourced from the ocean bottom.

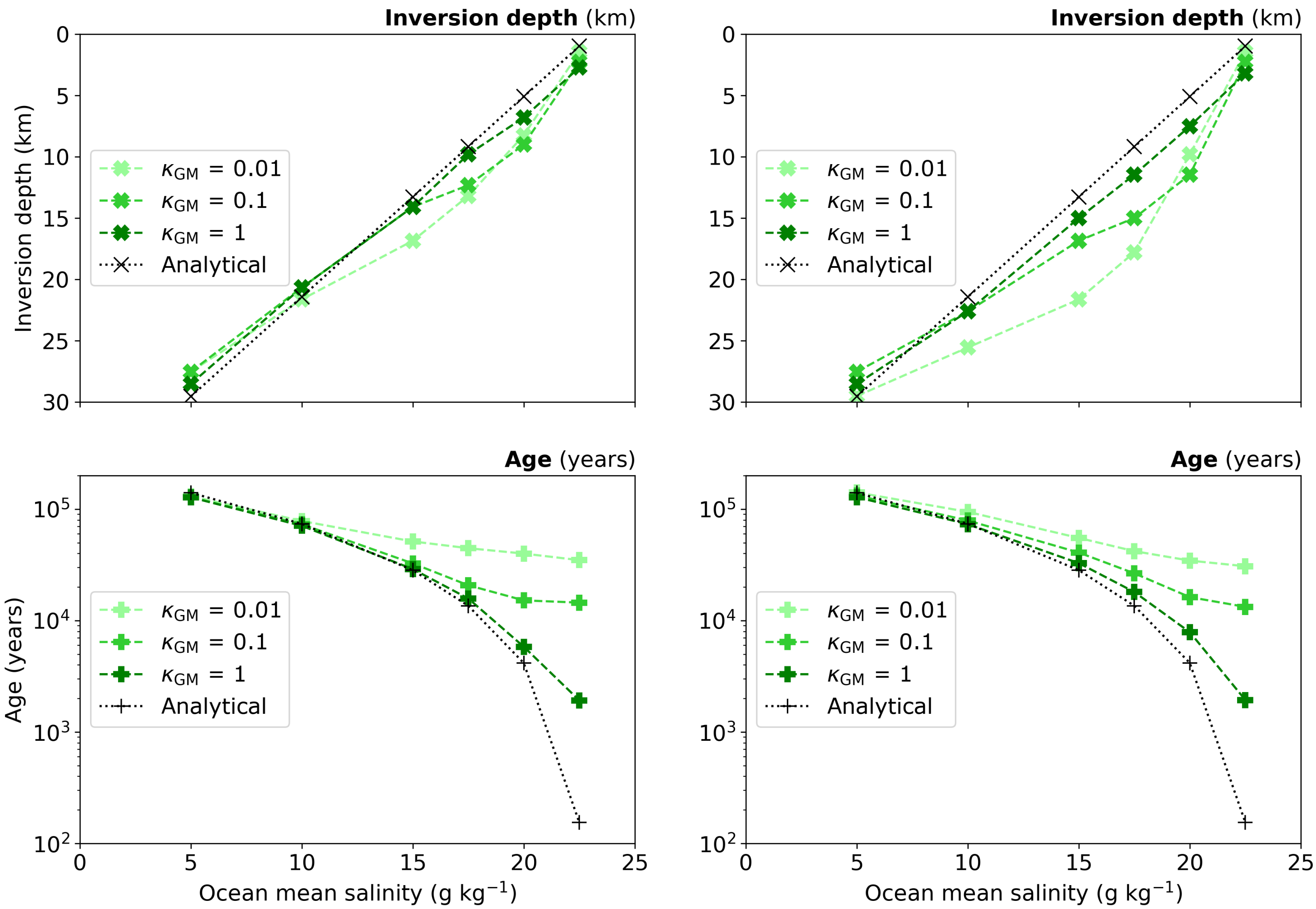

Figure S4: **Top**: Numerical solution for the inversion depth (km - depth at which the thermal expansion coefficient α_T becomes negative), as in Fig. 2 of the main text across a range of ocean mean salinity (g kg^{-1}), but plotted for three different values eddy diffusivity κ_{GM} (m^2 s^{-1}), indicated with varying shade of green, for constant vertical diffusivity $\kappa_z = 10^{-4}$ m^2 s^{-1}. The analytical solution (black) using Eq. (5) is plotted alongside for comparison. **Bottom**: Corresponding numerical solution for the ideal age at the south polar ocean-ice interface, plotted alongside the analytical solution (Eq. (6)). **Left**: Solutions at a melting viscosity $\eta_{\mathrm{melt}} = 10^{-14}$ Pa s as used in default simulations of the main paper. **Right**: solutions with $\eta_{\mathrm{melt}} = 2\mathrm{x}10^{-13}$ Pa s, which creates a 5 times larger magnitude of ice melting and freezing at the ocean top. Note increasing discrepancies relative to analytical solution at higher salinity and lower κ_{GM}, due to the formation of freshwater lenses at the ocean-ice interface at the poles.

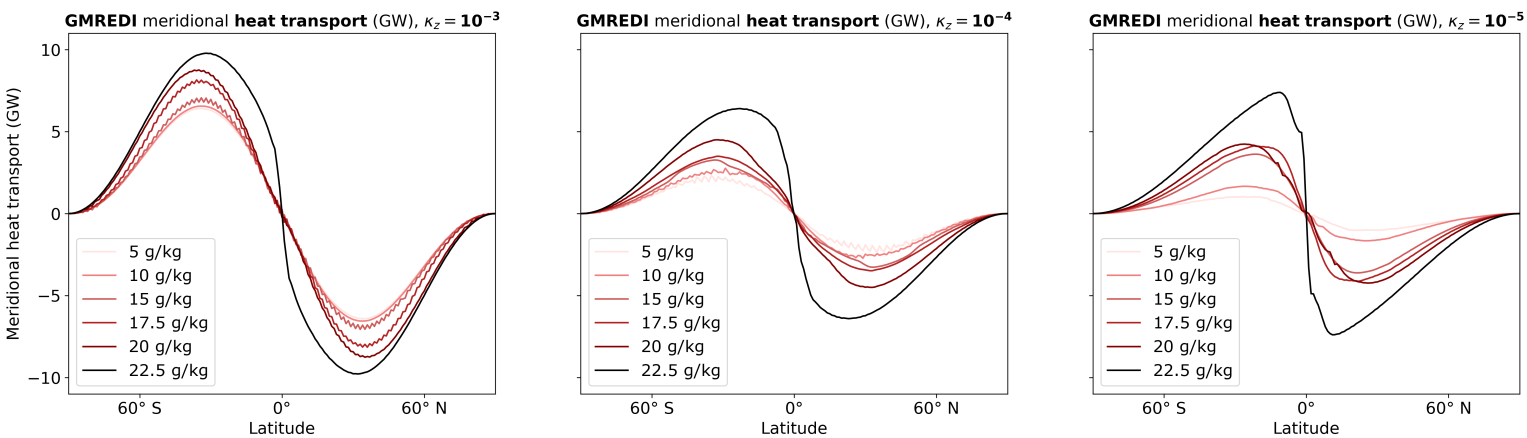

Figure S5: Vertically-integrated global meridional heat transport (GW) achieved by parameterised eddies (GMREDI) in numerical solutions. Plotted across modelled ocean mean salinity at a modelled effective vertical diffusivity κ_z of 10^{-3} (left), 10^{-4} (middle), and 10^{-5} (right) m^2 s^{-1}. The eddy diffusivity $\kappa_{\rm GM} = 1$ m^2 s^{-1} for the presented solutions. Note the heat transports shown here are scaled up by a factor 360 to be representative of the global ocean (as the 2D simulations are based on a 1 degree wide single box in the zonal direction).

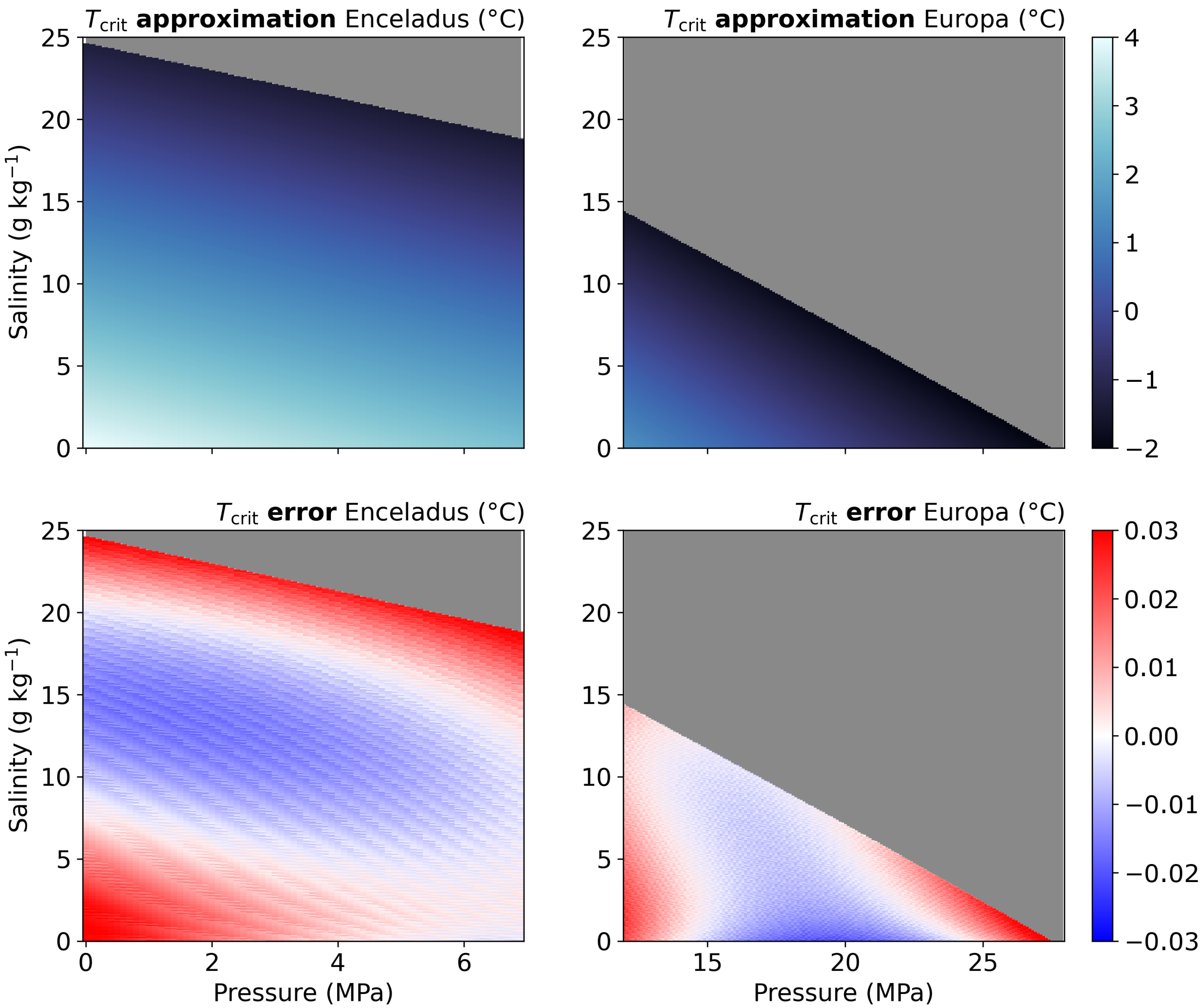

Figure S6: **Top:** Linearly approximated critical temperature (T_{crit} - ^{o}C) - defining the temperature at which the thermal expansion coefficient (α_T) changes sign - as a function of pressures (MPa) and salinity (g kg^{-1}) plausible for Enceladus (left) and Europa (right) respectively. Grey shading denotes where T_{crit} does not apply because α_T cannot become negative for the given salinity and pressure.
Bottom: Error of linear approximation of critical temperature (^{o}C) relative to reference computation described in the main text.

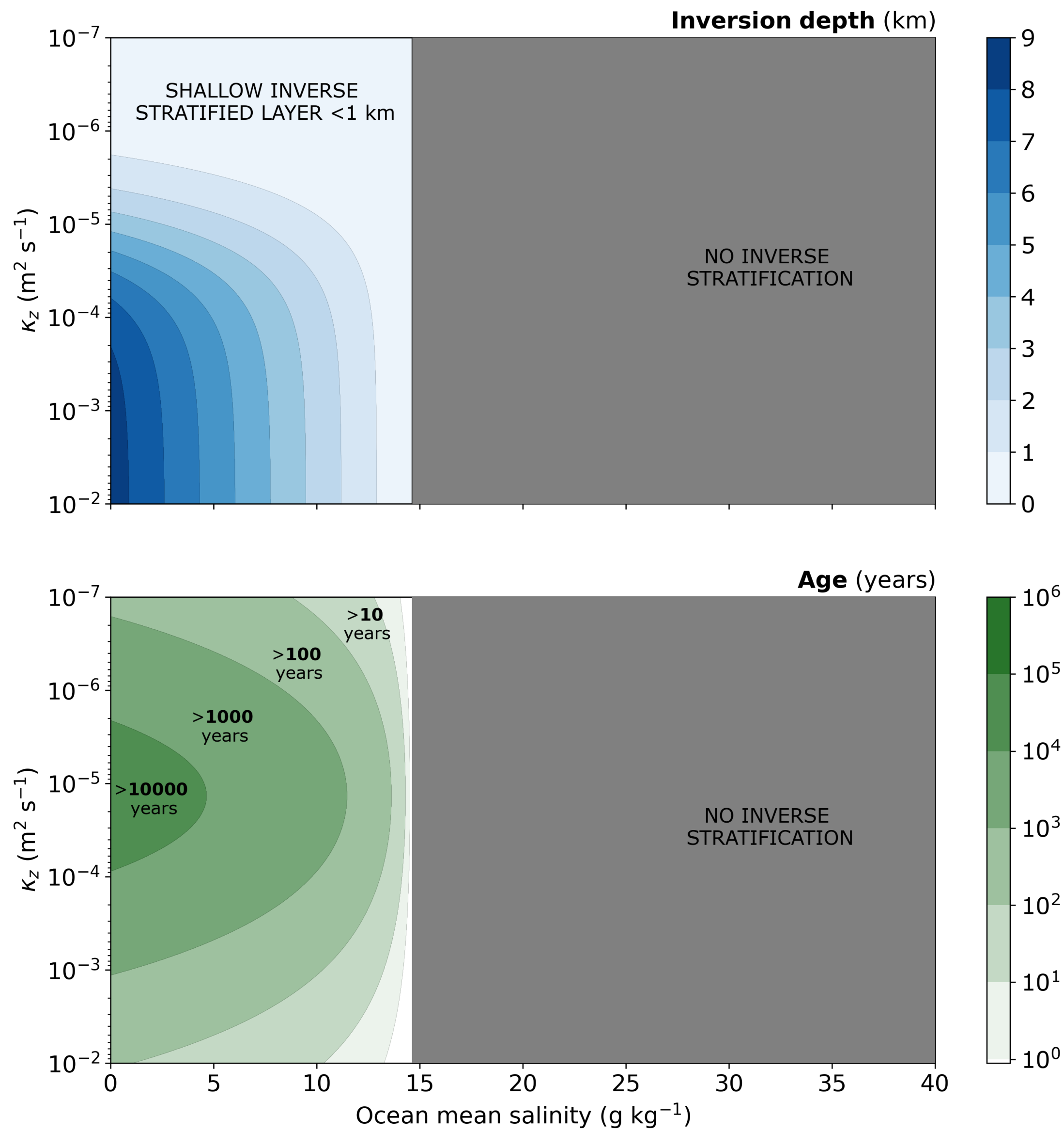

Figure S7: **Top**: Inversion depth $H_{\rm strat}$ (km - depth at which thermal expansion coefficient α_T becomes negative, taken here to define the inverse layer thickness) plotted as a function of ocean mean salinity (g kg^{-1}) and vertical diffusivity κ_z (m^2 s^{-1}), for Europa - moon of Jupiter. Grey shading denotes where inverse stratification cannot occur, because α_T cannot become negative at the ocean-ice interface pressure (computed under an assumed 10 km ice thickness). **Bottom**: Tracer age (years) at Europa's ocean-ice interface, computed using the theoretical model outlined in the main text. Note that age contours are logarithmic.