

# *Ocean stratification impedes particulate transport to the plumes of Enceladus*

Article

Supplemental Material

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## Supplementary material

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| 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 ( $\rho_i$ )                         | $925 \text{ kg m}^{-3}$                                             |
| Gravity at ice shell surface ( $g$ )             | $0.113 \text{ m s}^{-2}$                                            |
| Ocean mean salinity ( $S_{\text{ref}}$ )         | 5, 10, 15, 17.5, 20, 22.5 g kg $^{-1}$                              |
| Ocean reference pressure ( $P_{\text{ref}}$ )    | $\rho_i \int_{H_i}^0 g(z) dz$                                       |
| Ocean reference temperature ( $T_{\text{ref}}$ ) | Freezing temp at $P_{\text{ref}}$ and $S_{\text{ref}}$              |
| Ocean reference density ( $\rho_0$ )             | Density at $T_{\text{ref}}$ , $P_{\text{ref}}$ and $S_{\text{ref}}$ |
| Core density ( $\rho_{\text{core}}$ )            | $2370 \text{ kg m}^{-3}$                                            |
| Rotation rate ( $\Omega$ )                       | $5.307 \times 10^{-5} \text{ s}^{-1}$                               |
| Core total heat output ( $F_{\text{tot}}$ )      | 20 GW                                                               |
| Specific heat capacity ( $c_p$ )                 | $4000 \text{ J kg}^{-1} \text{ K}^{-1}$                             |
| Eddy diffusivity ( $\kappa_{\text{GM}}$ )        | $1 \text{ m}^2 \text{ s}^{-1}$                                      |
| Vertical diffusivity ( $\kappa_z$ )              | $10^{-5}, 10^{-4}, 10^{-3} \text{ m}^2 \text{ s}^{-1}$              |
| Prandtl number ( $\frac{\nu}{\kappa}$ )          | 10                                                                  |
| Ice melting viscosity ( $\eta_{\text{melt}}$ )   | $10^{-14} \text{ Pa s}$                                             |

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

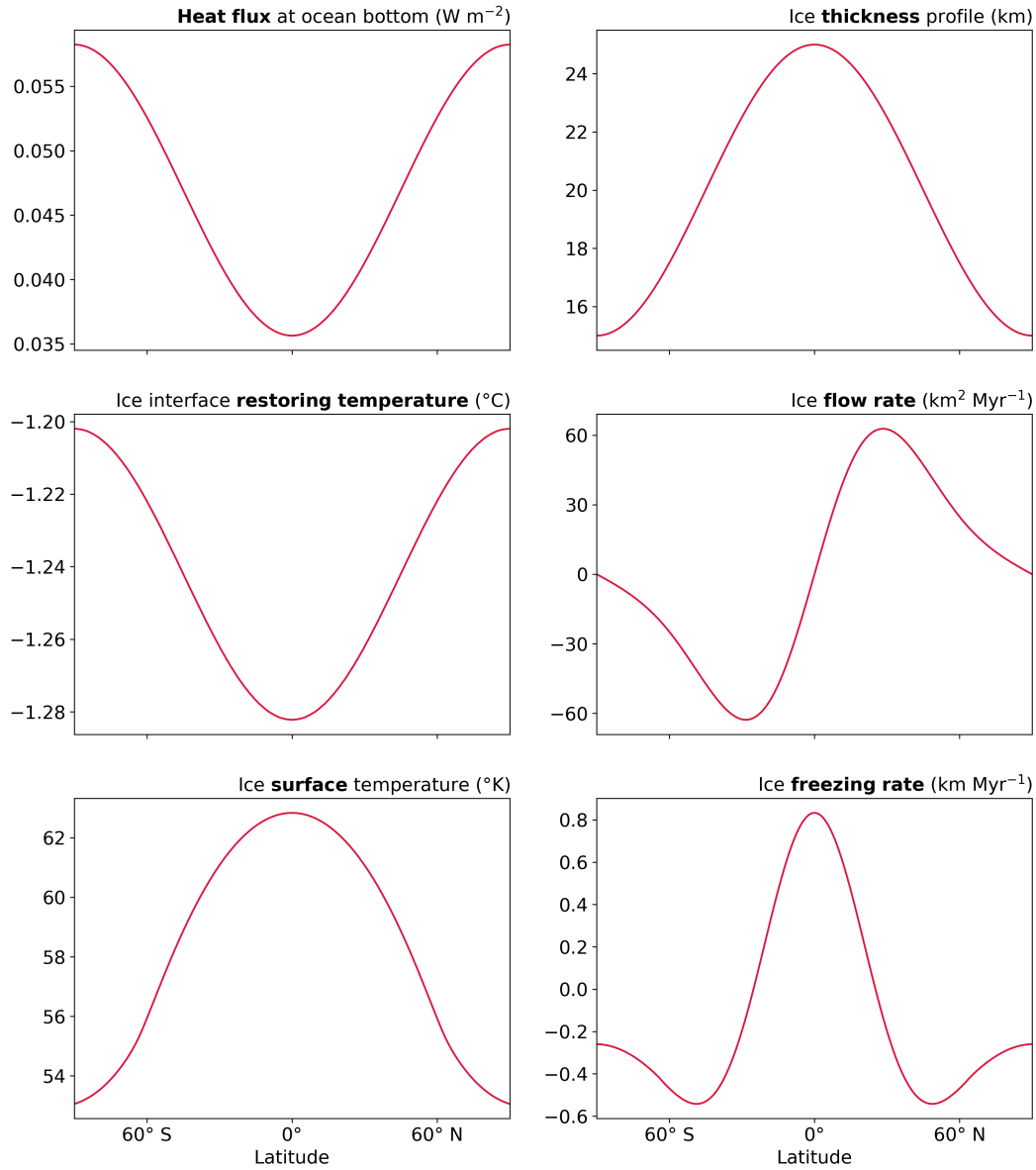


Figure S1: **Top Left:** Bottom heating profile used in simulations ( $\text{W m}^{-2}$ ), assuming a total global core heat output of 20 GW. **Middle left:** An example restoring temperature ( $^{\circ}\text{C}$ ) profile at the ocean top (ice-interface) used in simulations at  $20 \text{ g kg}^{-1}$  - corresponding to the pressure and salinity dependant freezing temperature. **Bottom left:** Surface temperature ( $^{\circ}\text{K}$ ) 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 ( $\text{km}^2$  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 ( $\text{km}$  per million years) profile applied at the ocean top in simulations, computed using the ice flow rate in the middle right panel.

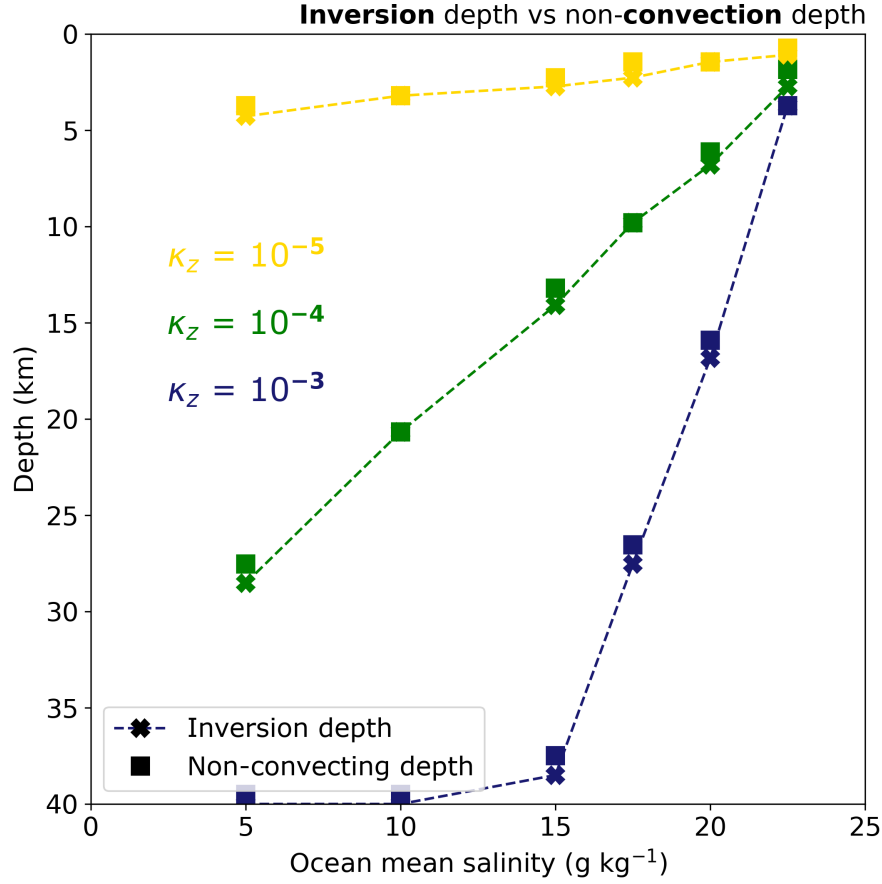


Figure S2: Numerical solution for the inversion depth (km - cross, dashed line - depth at which the thermal expansion coefficient  $\alpha_T$  becomes negative) across a range of ocean mean salinity ( $\text{g kg}^{-1}$ ) for three values of  $\kappa_z$  ( $\text{m}^2 \text{s}^{-1}$ ), denoted with different 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  $\alpha_T$  remained negative across the whole ocean) or non-convecting depth (meaning no convection extended from the ocean bottom) respectively.

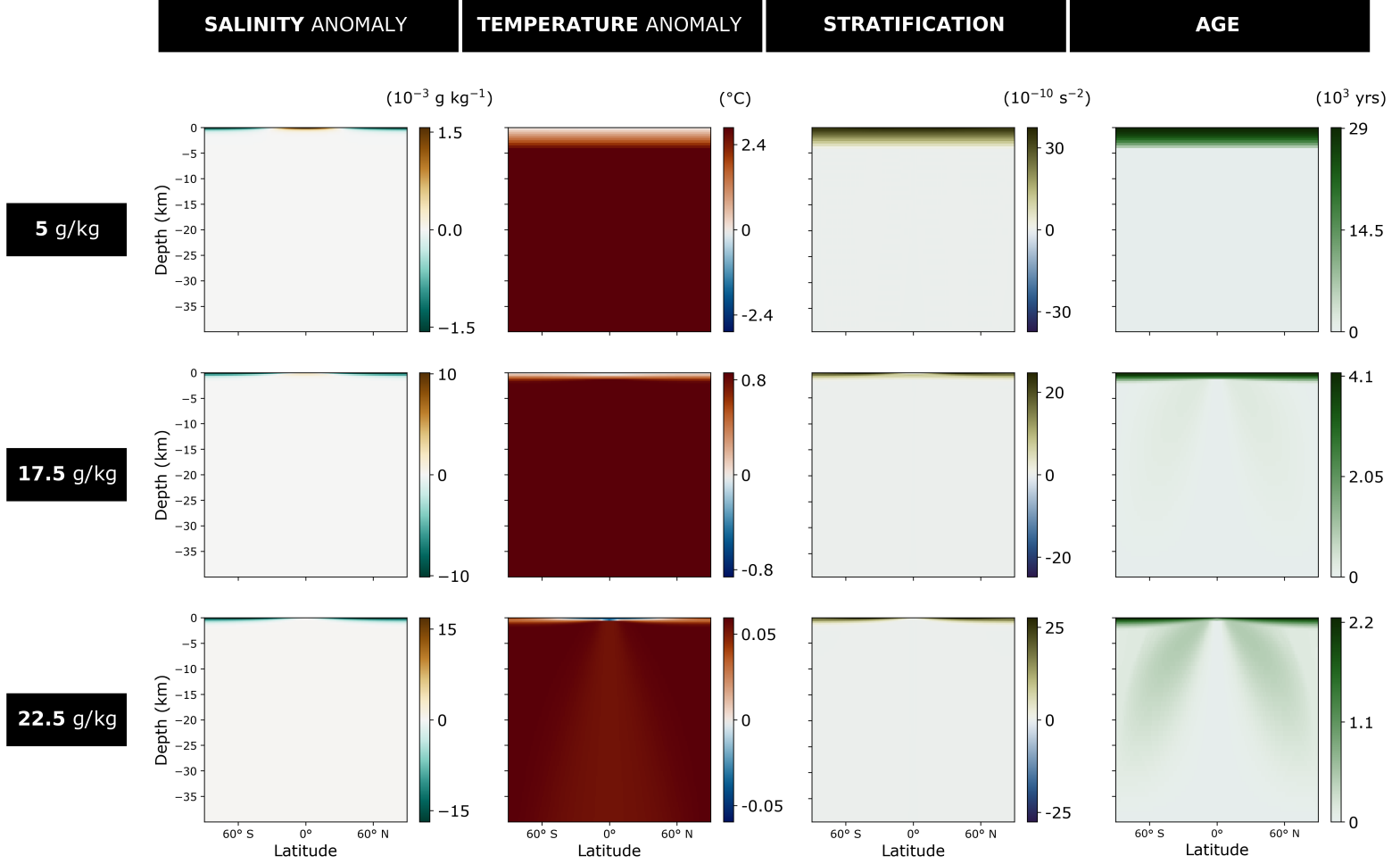


Figure S3: Numerical solutions with effective vertical diffusivity  $\kappa_z = 10^{-5} \text{ m}^2 \text{ s}^{-1}$ , across three different mean ocean salinities of 5 (top), 17.5 (middle), and 22.5 (bottom)  $\text{g kg}^{-1}$ , highlighting stratification regimes at a lower  $\kappa_z$  than presented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

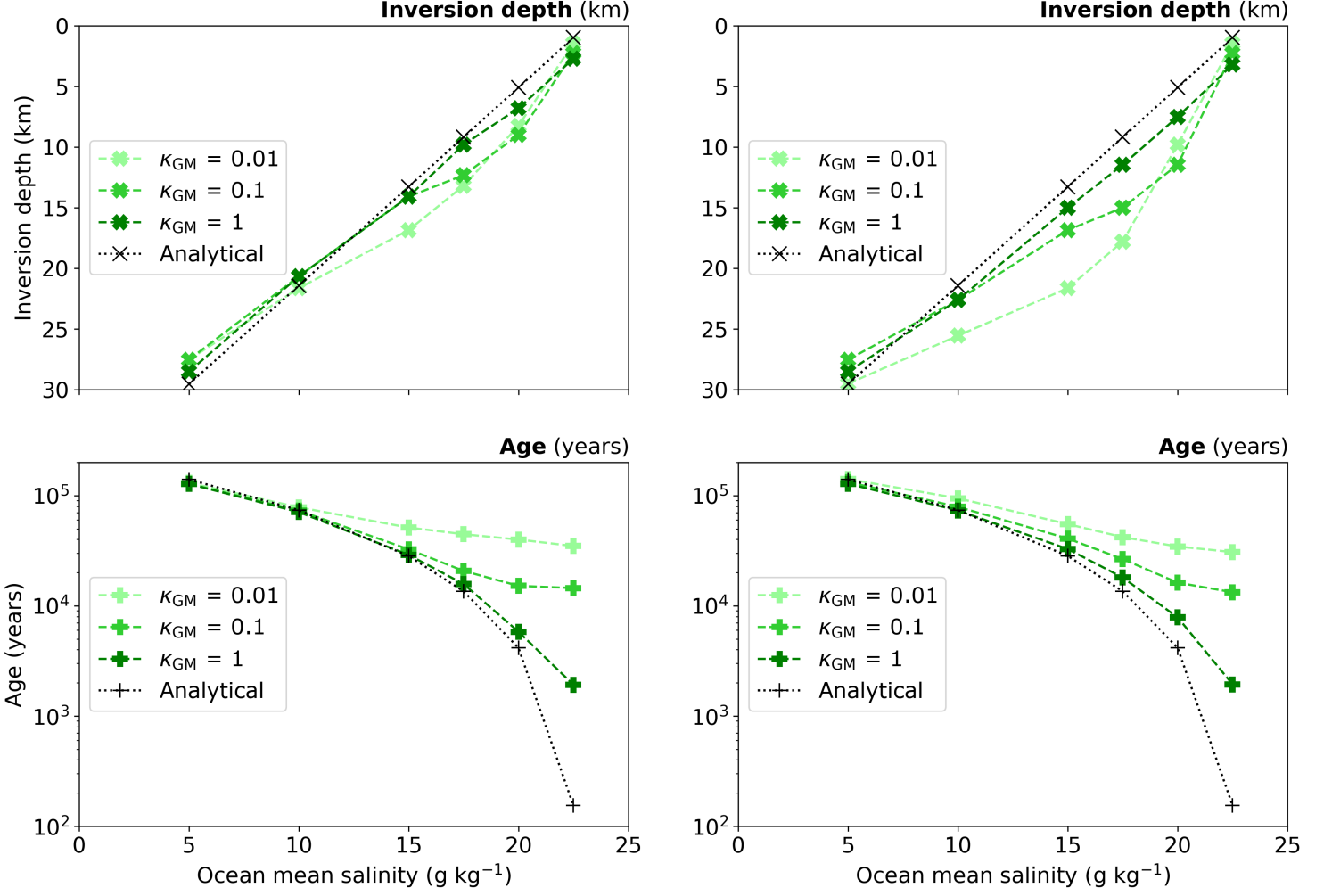


Figure S4: **Top:** Numerical solution for the inversion depth (km - depth at which the thermal expansion coefficient  $\alpha_T$  becomes negative), as in Fig. 2 of the main text across a range of ocean mean salinity (g kg<sup>-1</sup>), but plotted for three different values eddy diffusivity  $\kappa_{GM}$  (m<sup>2</sup> s<sup>-1</sup>), indicated with varying shade of green, for constant vertical diffusivity  $\kappa_z = 10^{-4}$  m<sup>2</sup> s<sup>-1</sup>. 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  $\eta_{melt} = 10^{-14}$  Pa s as used in default simulations of the main paper. **Right:** solutions with  $\eta_{melt} = 2 \times 10^{-13}$  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  $\kappa_{GM}$ , due to the formation of freshwater lenses at the ocean-ice interface at the poles.

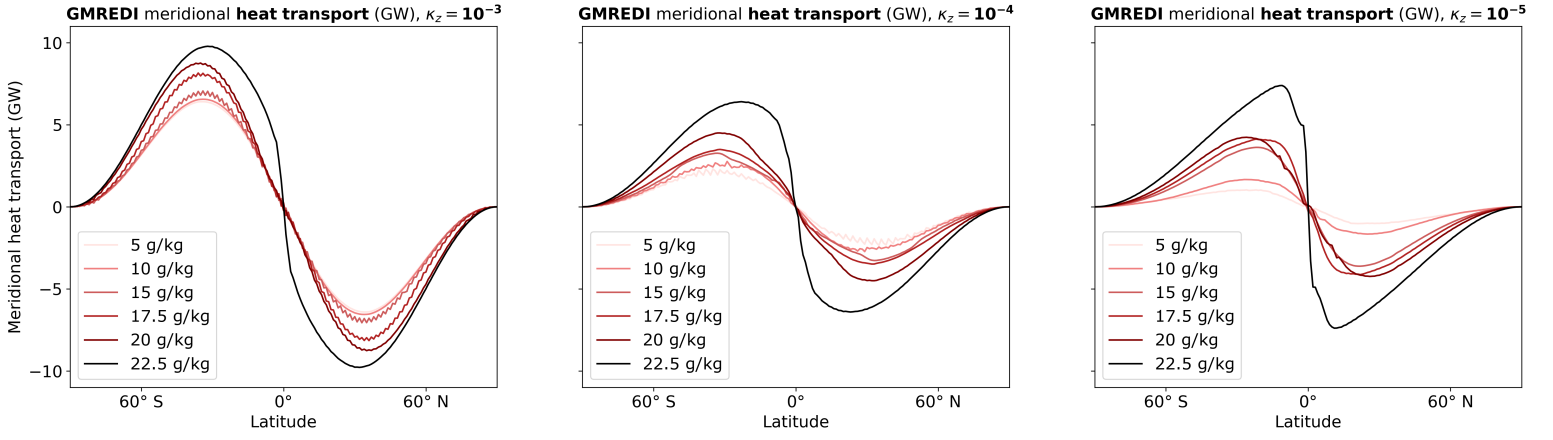


Figure S5: Vertically-integrated global meridional heat transport (GW) achieved by parameterised eddies (GMREDI) in numerical solutions. Plotted across modelled ocean mean salinity at a modelled effective vertical diffusivity  $\kappa_z$  of  $10^{-3}$  (left),  $10^{-4}$  (middle), and  $10^{-5}$  (right) m<sup>2</sup> s<sup>-1</sup>. The eddy diffusivity  $\kappa_{GM} = 1$  m<sup>2</sup> s<sup>-1</sup> 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).

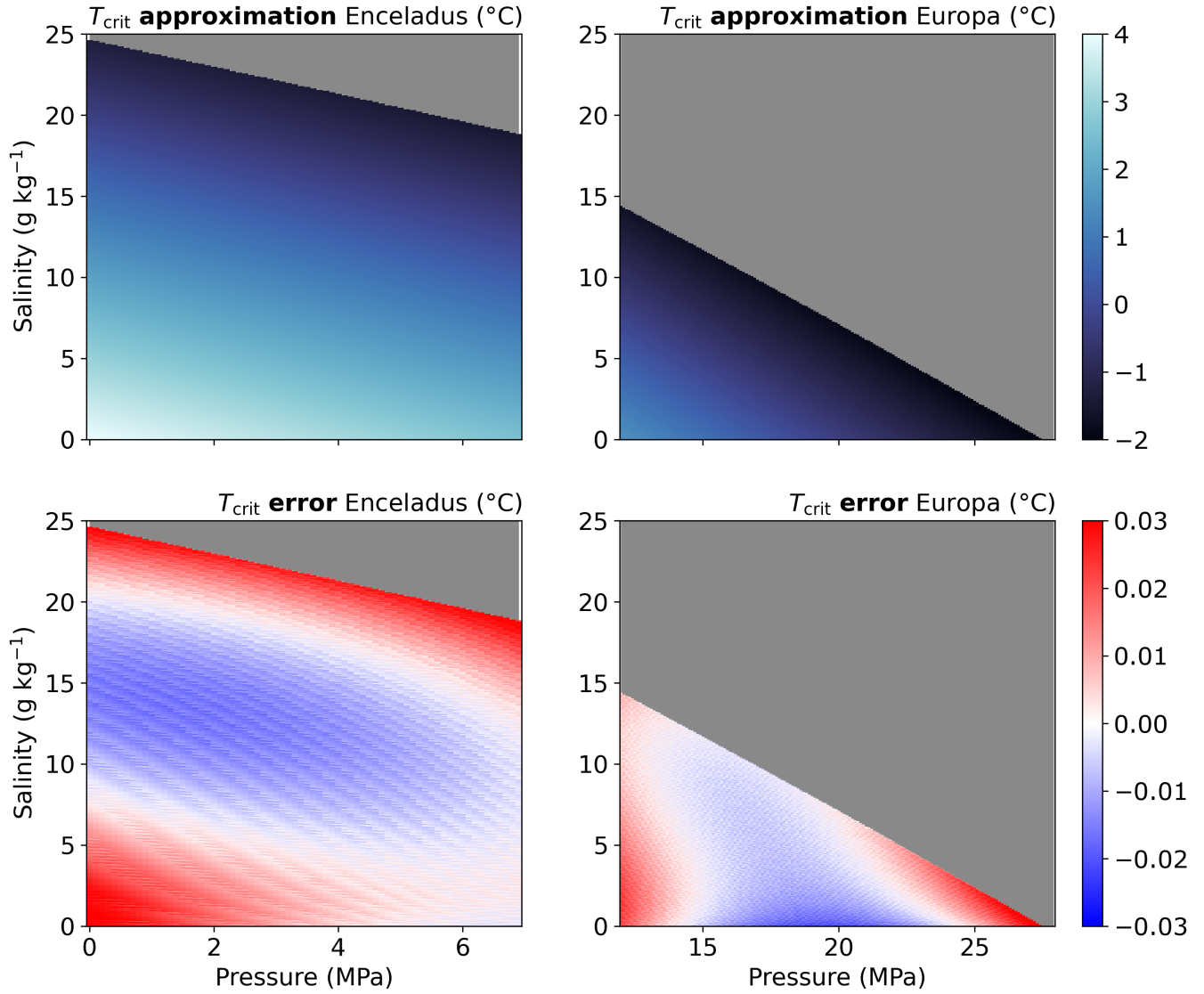


Figure S6: **Top:** Linearly approximated critical temperature ( $T_{\text{crit}}$  - °C) - defining the temperature at which the thermal expansion coefficient ( $\alpha_T$ ) changes sign - as a function of pressures (MPa) and salinity ( $\text{g kg}^{-1}$ ) plausible for Enceladus (left) and Europa (right) respectively. Grey shading denotes where  $T_{\text{crit}}$  does not apply because  $\alpha_T$  cannot become negative for the given salinity and pressure.

**Bottom:** Error of linear approximation of critical temperature (°C) relative to reference computation described in the main text.

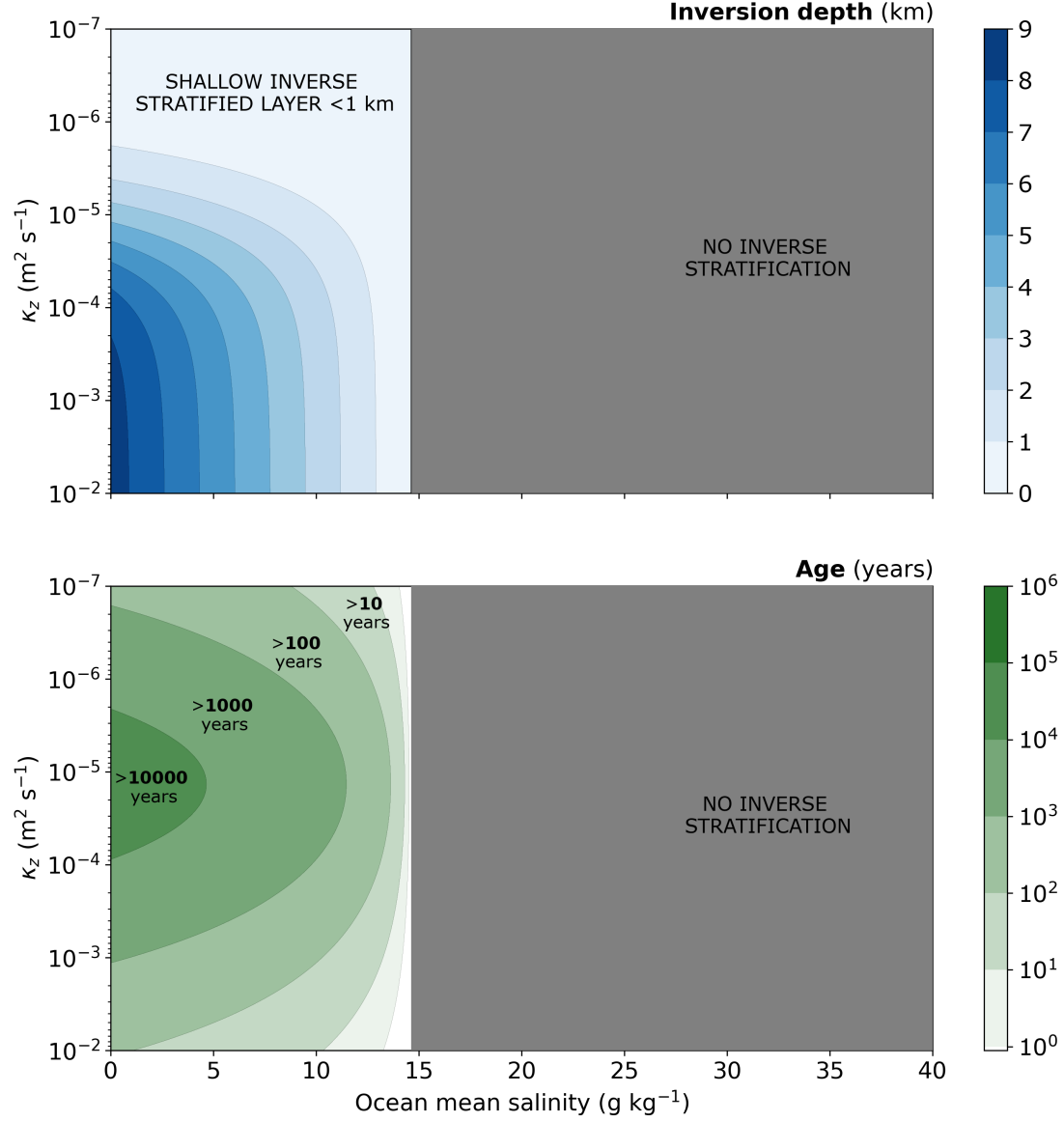


Figure S7: **Top:** Inversion depth  $H_{\text{strat}}$  (km - depth at which thermal expansion coefficient  $\alpha_T$  becomes negative, taken here to define the inverse layer thickness) plotted as a function of ocean mean salinity ( $\text{g kg}^{-1}$ ) and vertical diffusivity  $\kappa_z$  ( $\text{m}^2 \text{s}^{-1}$ ), for Europa - moon of Jupiter. Grey shading denotes where inverse stratification cannot occur, because  $\alpha_T$  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.