The Structure and Evolution of Europa's Ocean and Ice Shell in the Presence of Aqueous $MgSO_4$

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Abstract

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 a non-convecting stratosphere layer forms below the ice if the ocean's salinity is very low. 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 million-year time scales.

1) Motivation

—Long-term evolution of global ocean

- Evidence for liquid oceans on icy worlds of the outer solar system is well-established
- Little is known about long-term evolution of these oceans
- Studies of local, short-term behavior related to hydrothermal plume events, of considerable geological and astrobiological interest, made broad assumptions about ocean global mean structure (Collins et al. 2000, Thomson and Delaney 2000, Goodman et al. 2004, Vance and Brown 2005, Nimmo and Giese 2005, Schmidt et al. 2011)

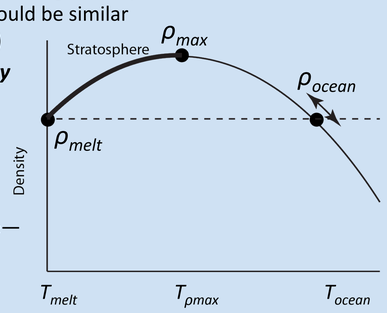
—Long-term response to hydrothermal plumes, including turbulent convection vs depth and time (only)

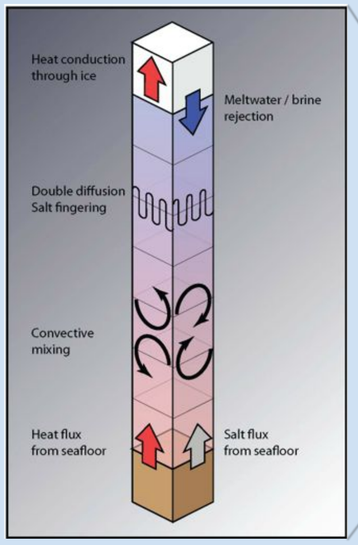
—Effects of salinity

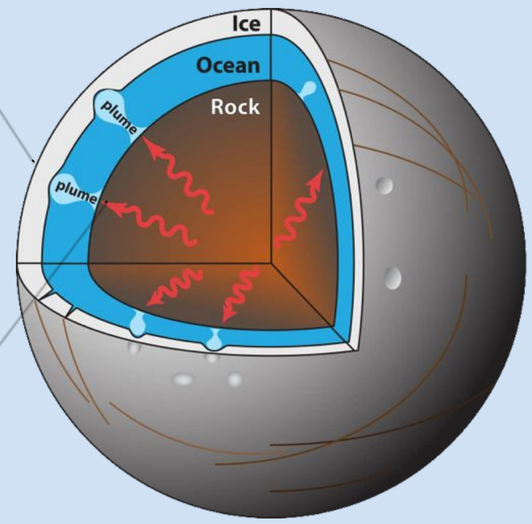
- Conductivity of icy world oceans (Zimmer et al. 2000) suggests they contain salt
- Exact composition and concentrations are unknown
- $MgSO_4$ is a likely solute given satellites' compositions (Zolotov and Kargel 2009)
- Phenomenology using e.g., NaCl, KCl (Brown and Hand 2013) should be similar
- Ocean salinities considered: freshwater to 1 molal (120.4 kg/m^3)

—Salinities discussed here span an important dynamical boundary

- At low salinity and pressure, thermal expansivity, $\alpha<0$
  →cold water is buoyant.
- At higher salinity (>1 molal) or pressure (>20 MPa), $\alpha>0$
- Melosh et al. (2004) note $\alpha<0$ would lead to a non-convecting buoyant cold water layer in contact with the ice/water interface—a ***"Melosh stratosphere"***







2) Model Features

—Aqueous $MgSO_4$ thermodynamics: Equation of state based on Vance & Brown (2013)

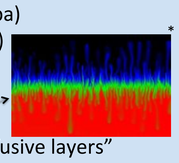
- Broad validity: T: 253 to 373 K; P: 0.1-700 MPa (0.1MPa = 1 bar = 1 atm) ; m: 0-2.5 molal ($MgSO_4$/kg H_2O)
- Self-consistent density (ρ), thermal expansivity (α), specific heat capacity (C_P)

—Single-column convection model

- Vertical column ocean, 100 km deep, divided into 2.5 km thick finite volumes
- Measure convective instability, parameterize convective mixing as a diffusion process
- Implicit timestepping scheme allows evolution of model for 10-20 Myr
- Ice-ocean interface: heat and salt fluxes from meltwater release, brine rejection
- Assume ice shell in conductive equlibrium for simplicity, $T_{surface}$ = 102 K (average for Europa)
- Seafloor heat flux: background heating (0.05 W/m^2) or hydrothermal plume (0.375 W/m^2)
- Seafloor salt flux permitted

—Double diffusion

- Can transport heat and salt even when water column is convectively stable
- Differing diffusivities of heat and salt lead to formation of cm-scale "salt fingers" and "diffusive layers"
- Zhang et al. (1998) parameterization from Earth oceanography



*fluidflowvisualization.sandia.gov

3) Freshwater Ocean

- Initially isothermal
- Heated from below: 0.05 W/m^2 (1.5 TW globally)

—Adiabatic convection homogenizes ocean interior

- Water is compressible
  →temperature (1a,2a) increases with depth (just as in a compressible planetary atmosphere)
- Convection (c) mixes almost entire water column

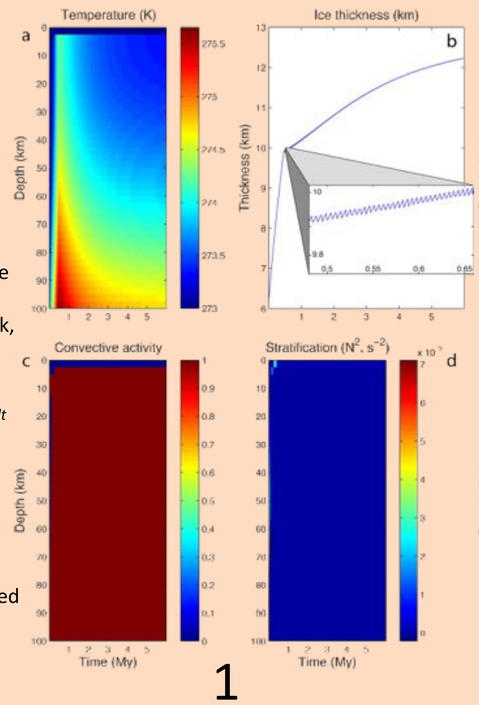
—Melosh stratosphere forms

- Negative temperature jump at uppermost model layer (1a,2a), where thermal expansion coefficient is negative
- In the Melosh et al. (2004) description, this layer transfers heat by conduction, and is only tens of m thick, smaller than model resolution of 2500 m
- Heat reaches model ice-ocean interface intermittently: rising T_{ocean} lowers ocean density until $\rho_{ocean}<\rho_{melt}$
- leads to ice thickness oscillations (inset 1b)

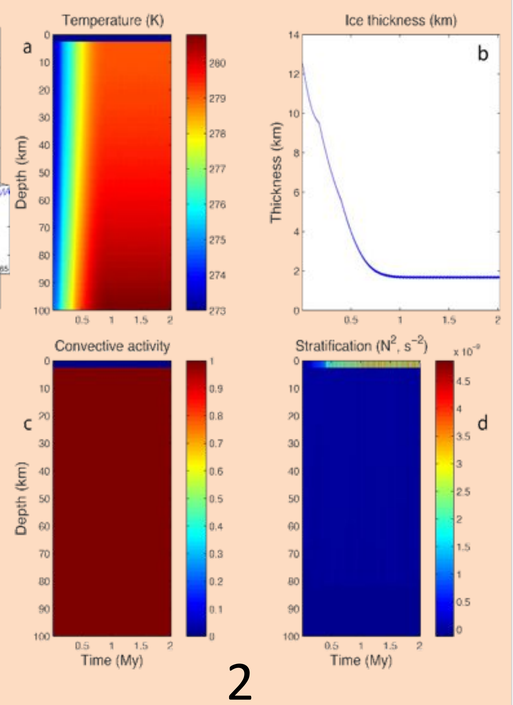
—Freshwater plume steadily thins ice

- 0.375 W/m^2 (100 MW over an 18 km circle)
- Use end-state of previous run as an initial condition
- Ice shell thins, but ocean remains adiabatic
- Melosh stratosphere remains, becoming more stratified (2d) due to intensifying temperature gradient

Initialization of freshwater ocean model



Introduction of freshwater hydrothermal plume



4) Salty Ocean

- Initial salinity of 1 molal
- Apply 0.05 W/m^{2}background heating (figure not shown)
- Model ocean reaches adiabatic profile with continual top-to-bottom convection and no Melosh stratosphere
- Now apply hydrothermal plume heat flux of 0.375 W/m^2

—Freshwater melt layer

- As ice melts, a buoyant layer of fresh meltwater forms.
- Convection cannot penetrate this layer
  →heat accumulates in ocean interior
- Double-diffusive mixing carries heat across the stable layer, continuing melting process, but ocean warms by more than 50 K!

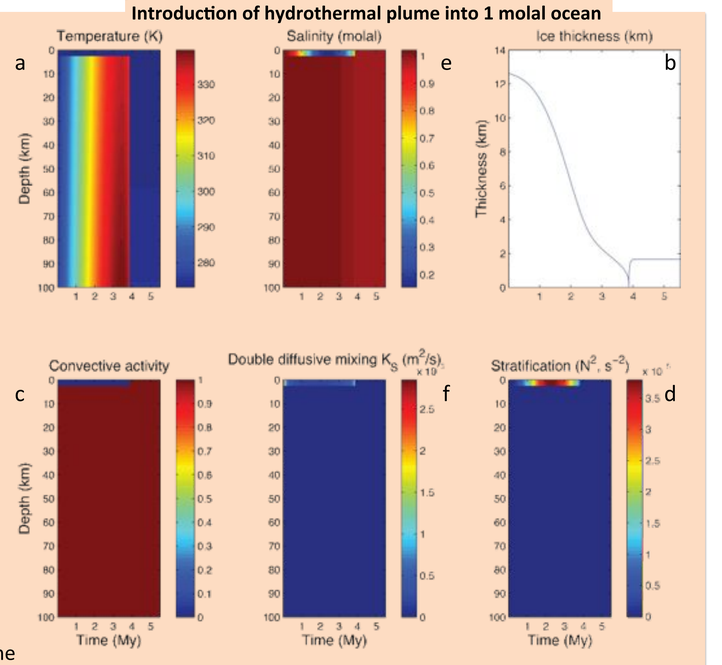
—Melt-through events occur for the salty ocean but are not periodic

- At 3.8 Ma, lower ocean becomes warm enough to convectively mix with cold fresh layer
- Burst of heat delivered to the ice sheet, melting it to <1 m thickness
- With meltwater cap gone, model reaches new adiabatic equilibrium with top-to-bottom convection

—Melt-through event is probably unrealistic

- 1D model forces heat to flow through ice
- Real-world plume transfers heat laterally (Goodman and Lenferink 2012)
- Meltwater cap forces intense local heating to spread out in space and time

Introduction of hydrothermal plume into 1 molal ocean



5) Salty Plumes

- Repeat of Part **4**, but assume hydrothermal source emits salt (300 nanomol/(s-m^2)) as well as heat

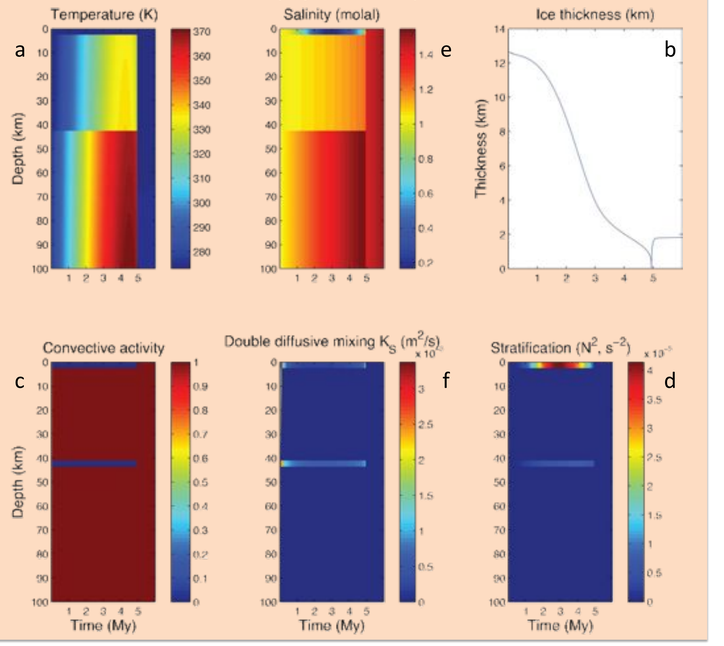
—Stagnant plume

- Relative importance of heat vs salt on density depends on pressure: hydrothermal fluid buoyant only up to 50 km, where it initially stagnates

—Double diffusive mixing drives plume dynamics

- Carries the plume heat across stagnant interface to ice-water interface
- Melts ice to form stable meltwater layer, as in Part **4**
- Heat accumulates in both layers
- Eventually meltwater layer destabilizes as in Part **4**, leading to melt-through event that homogenizes entire water column

Introduction of salty hydrothermal plume into 1 molal ocean



6) Implications for Icy World Oceanography and Geology

—Non-convecting layers impede heat transport, protect ice from local melting

- Several types: Melosh stratosphere (Part **3**), meltwater cap (Part **4**) stagnant salty plume (Part **5**)
- Penetration of these layers would cause massive heat flux and ice thinning
- But real-world plumes probably carry heat sideways instead
- Convective break-through events are not periodic

—Double diffusion is key to maintaining thermal equilibrium

—Habitability: biochemical barriers or energetic interfaces?

- Layers impede vertical transport of nutrients / organisms
- But layers may act as ecological "niches", disequilibrium boundaries

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Acknowledgements

This work was supported by the NASA Astrobiology Institute, Icy Worlds Initative