

Different ice shell geometries on Europa and Enceladus due to their different sizes: impacts of ocean heat transport. W. Kang¹, Malte Jansen², ¹ Earth, Atmospheric and Planetary Science Department, Massachusetts Institute of Technology, Cambridge, MA 02139. ² Department of Geophysical Sciences, University of Chicago, IL 60637

Introduction: On icy worlds, the ice shell and subsurface ocean form a coupled system -- heat and salinity flux from the ice shell induced by the ice thickness gradient drives circulation in the ocean, and in turn, the heat transport by ocean circulation shapes the ice shell. Understanding how the ocean circulation and heat transport varies with ice topography, ocean salinity, gravity, rotation rate would allow us to infer the properties of the hidden ocean layer from the ice shell geometry from observation [1], or to put constraints on the equilibrium ice shell geometry knowing the orbital parameters [2,3]. Here, we present theoretical predictions for the ocean heat transport (OHT) driven by the ice topography in absence of bottom heating and use this to predict the equilibrium equator-to-pole ice thickness difference for an arbitrary icy satellite. **Specifically, we highlight that OHT increases with the size of icy moons. This finding allows us to predict that the ice thickness variations on large icy moons (e.g., Europa, Ganymede and Callisto) are likely much strongly damped than those on small icy moons (e.g., Enceladus, Uranus satellites).**

Ocean circulation driven by ice topography: Since we assume that the ice shell is the only heat source, and the dissipation rate is polar amplified [4], the polar ice shell is likely thinner the equator, so we take the following form to represent the ice thickness profile as a function of latitude φ

$$H(\varphi) = H_0 + \Delta H \cdot P_2(\sin \varphi).$$

In direct contact with ice, the ocean temperature at the water-ice interface will be relaxed toward the local freezing point T_f , which is lower under a thick ice shell because of the high pressure

$$T_f(S, P) = c_0 + b_0 P + a_0 S. (b_0 < 0)$$

Meanwhile, assuming ice shell is in mass equilibrium, equatorial freezing and polar melting is required to prevent the ice shell from being flattened by the pressure-driven ice flow [5,6]. The freezing/melting will then induce salinity exchange with the subsurface ocean. Under these forcings, water over the poles become warmer and fresher than the water at low latitudes. The resultant density variations drive ocean circulation and eddies, which can be represented by a residual circulation Ψ^\dagger . Ψ^\dagger transports heat down-gradient from the poles to the equator, which in turns affect the heat budget of the ice shell. In equilibrium, this budget should be in balance.

Difference between small and large icy moons:

Using parameters relevant for Enceladus [1], the circulation driven by surface heat and salinity fluxes can go either direction depending on the ocean salinity: in the low-salinity limit, temperature-induced density variation dominates, and the warm polar water would sink because fresh water contracts upon warming ($\alpha < 0$, anomalous expansion); whilst in the high-salinity limit, the anomalous expansion is suppressed, and both salinity- and temperature-induced density gradients contribute to downwelling at low-latitudes.

When considering icy satellites larger than Enceladus (most of the icy satellites of interest are), the following changes are expected:

- The thermal expansion coefficient will become more positive, and eventually anomalous expansion will be completely suppressed even if the ocean is relatively fresh. Without anomalous expansion, ocean circulation on large icy moons always sink over the equator, regardless of the ocean salinity.
- The temperature difference under the ice shell between the equator and the pole $\Delta T = \Delta T_f = b_0 \Delta P = b_0 \rho_i g \Delta H$ increases due to the stronger gravity. Here, ρ_i is the ice density, g is gravity.
- Salinity forcing will weaken. In equilibrium state, the freezing rate q ought to balance the divergence of ice flow. Since ice flow behaves like diffusion [5,6], which is proportional to $\Delta H/a^2$, where a is satellite radius.
- The same density gradient will drive a stronger ocean circulation and heat transport as a result of the stronger gravity.

Given the above reasoning, one can see that, on larger icy moons, the OHT is likely to be 1) more efficient in flattening the ice shell and 2) dominantly controlled by temperature variations.

Theoretical prediction for OHT:

Overtaking circulation and eddies driven by meridional density gradient has been intensively studied in the context of earth atmosphere and ocean. Geostrophic turbulence theory is found to be able to predict the heat transport reasonably well [7,8]. We apply the theory to icy moons and found the equatorward OHT \mathcal{F} forced by an equator-to-pole ice thickness gradient ΔH should follow

$$\mathcal{F} \sim 2\pi\rho C_p \Delta T \left(\frac{a^4}{4f^2} \right)^{2/7} (\alpha g \Delta T)^{3/7} \kappa_v^{5/7} \\ \propto a^3 \Delta H^{10/7} f^{-4/7} \kappa_v^{5/7}$$

in the low- κ_v (vertical diffusivity) regime. In the above formula, C_p is the heat capacity of water, f is the Coriolis coefficient and ΔH is the equator-to-pole ice thickness difference. As shown in Fig. 1, the theoretical prediction (lines) matches reasonably well with the OHT diagnosed from numerical simulations.

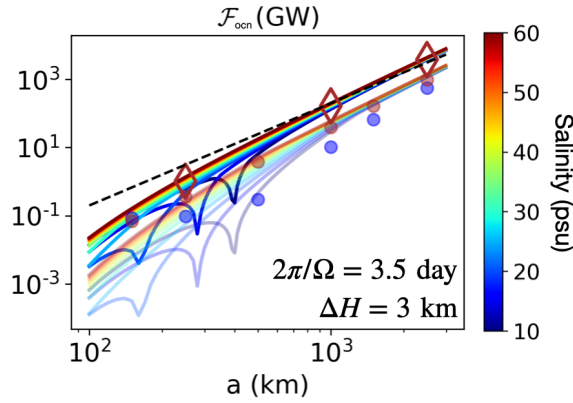


Figure 1. Scaling of ocean heat transport (OHT) as a function of satellite radius a , taken from [3]. The lines in highly saturated colors present the 3D scaling given by [3], and lines in lighter colors present the 2D scaling given by [2]. Scattered on top are the diagnosed OHT from 3D numerical experiments (diamond markers) and 2D numerical experiments (dots). Different colors are used to differentiate different ocean salinities: from blueish color to reddish color, salinity increases. The dashed line shows the scaling $\mathcal{F} \propto a^3$.

Equilibrium ice thickness gradient: The dependence of \mathcal{F} on orbital parameters and ΔH can be used to predict the equilibrium ice thickness variation using the fact that the ice shell heat budget should be closed:

$\Delta \mathcal{H}_{ice} + \Delta \mathcal{H}_{latent} + \mathcal{F}(\Delta H)/(\pi a^2) = \Delta \mathcal{H}_{cond}$, where \mathcal{H}_{ice} denotes the heat produced in the ice, \mathcal{H}_{latent} denotes the latent heat associated freezing/melting, \mathcal{H}_{cond} denotes the conductive heat loss and Δ denotes the difference between equator and the pole. Since $\Delta \mathcal{H}_{ice}$, $\Delta \mathcal{H}_{latent}$, $\Delta \mathcal{H}_{cond}$ are all functions of ΔH , the equilibrium equator-to-pole ice thickness difference ΔH can be solved from the above equation.

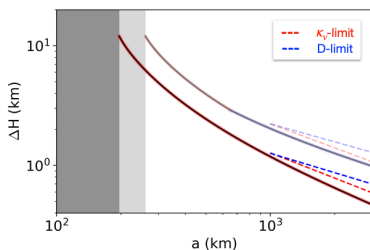


Figure 2. Predicted equator-to-pole ice thickness difference ΔH using heat budget. Rotation period is set to 3.5 days.

Fig. 2 shows the ΔH solution as a function of satellite radius. Since OHT is stronger on large icy moons, the equilibrium ice topography is much flatter there. This is consistent with the fact that Enceladus's ice shell exhibits strong thickness variations [9], but Europa's ice shell seems to be much flatter based on shape measurement [10].

Finally, to drive the point home, we substitute the analytical OHT expression into the ice evolution model by Kang & Flierl 2020 [6], where ice thickness at each latitude is evolving in response to the heating terms (\mathcal{H}_{ice} , \mathcal{H}_{cond} , \mathcal{F}) and the ice flow. As shown in Fig. 3, using Enceladus parameters, the ice shell tends to develop significant thickness variations (some cases even developed hemispheric asymmetry). To the contrary, when Europa parameter is used, the ice shell tends to be rather flat unless the OHT is completely suppressed (last row).

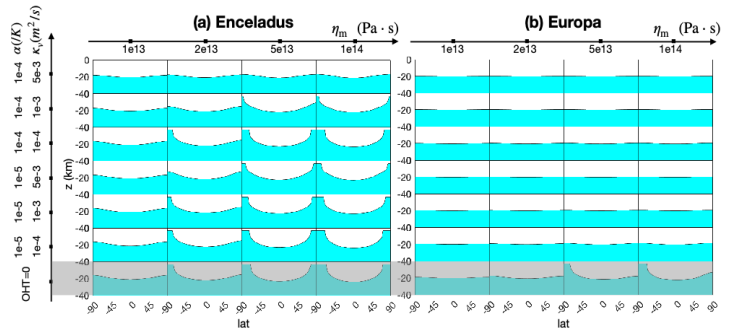


Figure 3. Equilibrium ice thickness profile for Enceladus and Europa obtained using an ice evolution model [6]. Various combinations of ocean diffusivity, thermal expansivity and ice viscosity is examined. The last row has OHT set to zero.

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References:

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