INTERACTIONS BETWEEN OCEAN CIRCULATION AND TOPOGRAPHY IN ICY WORLDS.

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Introduction: Topography at water-rock and ice-water interfaces is a major unknown in the study of icy world oceans. While future spacecraft missions may provide some clues[1], we must consider how far we can get without this information. To what extent does topography at the water-rock interface control the general circulation patterns of icy world oceans? And contrariwise, to what extent does ocean circulation control the topography at the ice-water interface (or interfaces, in the case of high-pressure icy worlds)?

Specifically, we review progress toward understanding three questions: 1) Does mechanical mixing due to topographic roughness at the seafloor control the most basic patterns and scales of ocean circulation? 2) Does liquid flow via the "ice pump" effect at the upper ice-water interface act to erase topography there? 3) Does liquid flow at the interface between liquid and high-pressure ices at the bottom of very deep icy world oceans create or destroy topography there?

Topographic mixing at the seafloor: Whether atmosphere, global ocean, or planetary core, there are two possible circulation patterns for a spherical shell of fluid, heated from below, on a rotating planet. If rotation is rapid compared to the time it takes a convecting fluid parcel to rise, Coriolis forces constrain the flow and a series of counter-rotating banded jets form, similar to Jupiter's atmosphere. If rotation is slow, a single broad tropical jet emerges, as in Venus's atmosphere.

Computer simulations[2] of Europa's ocean place it in the slowly-rotating category, but these results depend on nondimensional scaling laws based on the behavior of thin thermal boundary layers in laboratory experiments. Do those scaling laws still apply when the boundary layer is being mechanically stirred by flow over rough topography? We are currently carrying out lab experiments to study rotating convection in the presence of topographic mixing, and to learn whether the scale of the topography matters.

Upper topography and the "ice pump": Because the melting point depends on pressure, liquid water in contact with ice at shallow depths will be above the melting point if carried to higher pressure. Thus, if water moves across a sloping ice-water interface, ice will melt where it is thick and freeze where it is thin, reducing the topography at the interface. This is the "ice pump" [3]. Along-slope flow can be driven either by buoyancy or by periodic tidal action. We have developed a simple theoretical model for the tidally-driven ice pump and incorporated it into a 2-d model of ice thermodynamics and flow. We find that the rate of topographic damping by the tidal ice pump scales like the cube of the tidal velocity: unless tides are very strong, the effect is less important than viscous flow of the base of the ice shell itself. However, in our model, ice flows rapidly enough to erase topography at the ice-water interface in centuries to millennia, confirming[4] that the ice-water interface is almost certainly very flat.

Basal topography in high-pressure icy worlds: Ice-water interfaces also exist at the bottom of large icy worlds like Titan or Ganymede, where pressures may reach the stability region of high-pressure ice (III, V, or VI) [5]. These layers cannot be solid ice: the thermal conductivity is not high enough to carry the required heat flow. Our simple 1-d model for shallow porous flow supplements other work on 2-phase convection [6], showing that in the upper part of the ice layer, geothermal heat is carried by liquid percolating upward through an ice slush. A positive feedback between percolation and permeability will focus the rising liquid into narrow channels like the "heat pipe" model for Io's crust [7] and early Earth. However, these "volcanic vents" will not form mountains, since the HP ice layer is covered in liquid water melt: surface topography should be controlled by the melting pressure-vs-temperature curve rather than local melt supply.

References: [1] Dombard, A. and Sessa, A. M. (2018) *49th LPSC*, Abstract #1593. [2] Soderlund, K. M. *et al*. (2014), *Nature Geosci.* **7,** 16-19. [3] Lewis, E. L. and Perkin, R. G. (1986), *JGR Oceans*, doi:10.1029/JC091iC10p11756. [4] Nimmo, F. (2004) *Icarus* **168**:205-208. [5] Vance, S. *et al.* (2014) *Planet. and Space Sci.* **96**:62-70. [6] Choblet, G. *et al.* (2017), *Icarus* **285:**252-262. [7] Moore, W. B. (2013) *Icarus* **154**: 548-550.