EUROPA'S OCEAN TRANSLATES INTERIOR TIDAL HEATING PATTERNS TO THE ICE-OCEAN BOUNDARY. K. M. Soderlund[1], D. Lemasquerier[1,2] and C. J. Bierson[3], [1]University of Texas at Austin, Jackson School of Geosciences, Institute for Geophysics (krista@ig.utexas.edu), [2]University of St Andrews, School of Mathematics and Statistics, [3]Arizona State University, School of Earth and Space Exploration.

Introduction: Several icy moons of Jupiter and Saturn, including Europa and Enceladus, host liquid water oceans buried beneath their icy crusts that make them compelling targets in the search for life beyond Earth[1,2]. Geological features of the ice crusts as well as large-scale variations of the ice thickness are often attributed to endogenic processes within the ice. However, the crust is also coupled to the rocky interior via the convective ocean which controls heat and material exchanges[3]. In particular, because of tidal dissipation in the silicate interior, heat flux at the seafloor is expected to be strongly inhomogeneous: significantly greater at the poles than at the equator, with longitudinal variations at low latitudes as well. How such tidal heating impacts the ocean convection is currently unknown, and whether thermal anomalies from the seafloor can be transposed up to the ice-ocean boundary is not yet understood. Europa Clipper will provide a wealth of new constraints on the satellite's interior, but forward modeling of the ocean dynamics is necessary to help interpret upcoming observations.

Towards this end, we focus here on Europa and three key questions: 1) How does an inhomogeneous basal forcing affect the thermally-driven circulation in the ocean? 2) Is the tidal heating pattern translated from the seafloor to the ice-ocean boundary, or is it erased by the vigorous convection? and 3) If heat anomalies are preserved, would they be significant enough to affect the ice shell equilibrium?

Methods: We numerically model the ocean circulation by solving for turbulent thermal convection in rotating spherical shells using the open-source code MagIC[4,5]. Heat flux at the bottom boundary is either homogeneous (i.e. radiogenic heating) or heterogeneous following the pattern of tidal heating[6], and temperature is imposed at the top boundary. For vertically-forced convection, the degree of rotational influence depends on the relative strengths of buoyancy versus Coriolis effects. Icy satellite oceans may fall in different convective regimes, and Europa's ocean was proposed to be less rotationally-constrained than moons like Enceladus[7,8]. To take into account this uncertainty, we consider two convective regimes called *weakly-rotating* (emphasized here) and *rapidly-rotating*.

Results: Figure 1 shows results obtained with no-slip mechanical boundary conditions. In the weakly-rotating regime, we observe a transition between two drastically different circulations. In the homogeneous mantle heating case (q^*=0), there are eastward zonal flows at the equator and high latitudes, westward flows at mid-latitudes, and radial motions concentrated near the equator. When the heterogeneity of basal heating is increased (i.e. increasing the relative contribution of tidal heating), the system progressively exhibits a circulation controlled by the horizontal temperature gradients ($q^*\gtrsim 1$). Here, baroclinic flows similar to so-called "thermal winds" develop and two narrow zones of downwelling appear at the equator, whereas the upwelling remains spread.

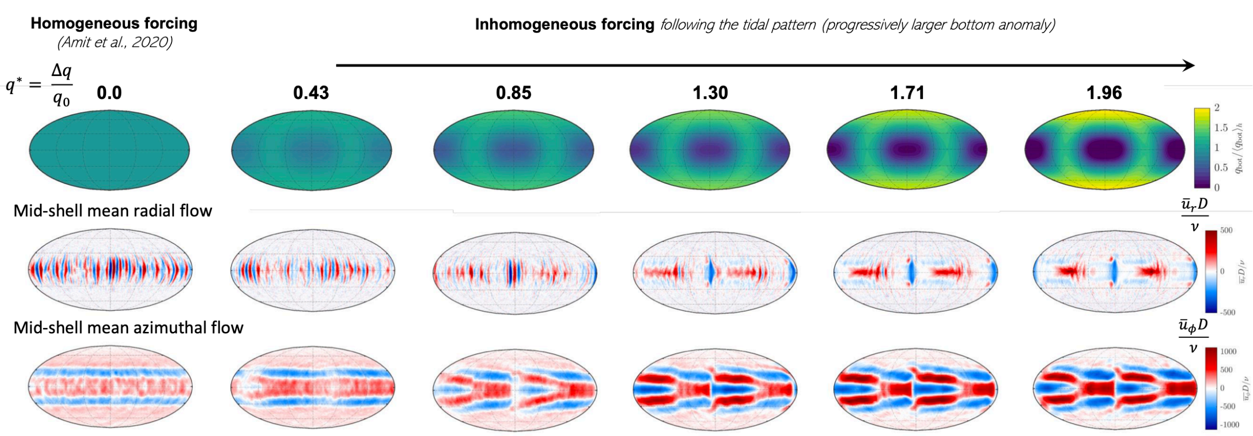

Figure 1: *Mean circulation in the weakly-rotating convective regime. Top: Heat flux pattern imposed along the bottom boundary. q* is the ratio of maximum heat flux contrast to mean basal heat flux. q*=0 corresponds to pure radiogenic heating; q*~1 corresponds to pure tidal heating. Middle: Radial velocity field at mid-ocean depths averaged over time; red (blue) denote upwelling (downwelling) fluid. Bottom: Azimuthal velocity field at mid-ocean depths averaged over time; red (blue) denote eastward (westward) fluid flow. All units are dimensionless.*

We next investigate whether the ocean effectively transfers the tidal heating pattern from the seafloor to the ice-ocean boundary. In Figure 2, we plot the mean heat flux as a function of latitude at the top and bottom boundaries, which shows that the heterogeneities are indeed mapped efficiently up to the top of the ocean. In the homogeneous case (black line), oceanic heat flux at the outer boundary has a peak at the equator because of the mean upwelling. As the relative contribution of tidal heating is increased, heat flux at the poles becomes dominant even if the mean upwelling persists (yellower lines).

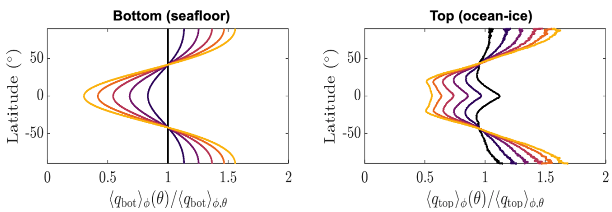

Figure 2: *Normalized heat flux profiles (averaged over all longitudes) as a function of latitude at the bottom (left) and top (right) of the ocean. The colors denote different q* values, with black corresponding to q*=0 and yellow to q*~2.*

These results show that inhomogeneous forcing of ocean convection due to tidal heating is likely to influence heat transfer between the silicate mantle and the ice shell significantly. Assuming a purely radially conducting ice shell, the ice thickness can be computed from the top ocean heat flux and temperatures at the base and surface of the ice. Figure 3 shows that if basal ocean heating is homogeneous (i.e. primarily radiogenic), the ice shell is expected to be thinner in the equatorial region, because of both the higher heat flux from the ocean and the higher surface temperature. If tidal heating from the mantle is considered, however, the polar ice becomes thinner and the equatorial ice is thicker on average. Longitudinal variations are also pronounced in the tidal heating cases, but these are found to be sensitive to the ocean model boundary conditions.

Conclusions: While our model simplifications for the ocean and neglected endogenic processes within the ice will add complexity to this simple picture, the key idea is that the ocean represents a "transfer function" between the rocky mantle and the ice shell. From a bottom-to-top perspective, quantifying this transfer could allow us to better constrain how the deep interior can affect the ice shell properties. Conversely, from a top-to-bottom perspective, this transfer function could help to better constrain tidal heating partitioning between the ice and the mantle.

Future observations from NASA's Europa Clipper mission should be able to disentangle between the different scenarios proposed here, by constraining for instance the depth of the ice-ocean interface using the ice-penetrating radar and magnetometer[9].

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References: [1] Khurana, K.K., et al. (1998) *Nature* 395, 777–780. [2] Schmidt, B.E. (2020) Planetary astrobiology, 185. [3] Soderlund, K.M., et al. (2020). *Space Sci Rev* 216, 1–57. [4] Wicht, J. (2002) *Phys Earth Planet Int* 132, 281–302. [5] Schaeffer, N. (2013) *Geochem Geophys Geosystems* 14, 751–758. [6] Roberts, J. & Nimmo, F. (2008) *Icarus* 194, 675–689. [7] Soderlund, K.M., et al. (2014) *Nature Geosci* 7, 16–19. [8] Soderlund, K.M. (2019) *Geophys Res Lett* 46, 8700–8710. [9] Howell, S.M. & Pappalardo, R.T. (2020) *Nature Comm* 11, 1–4.

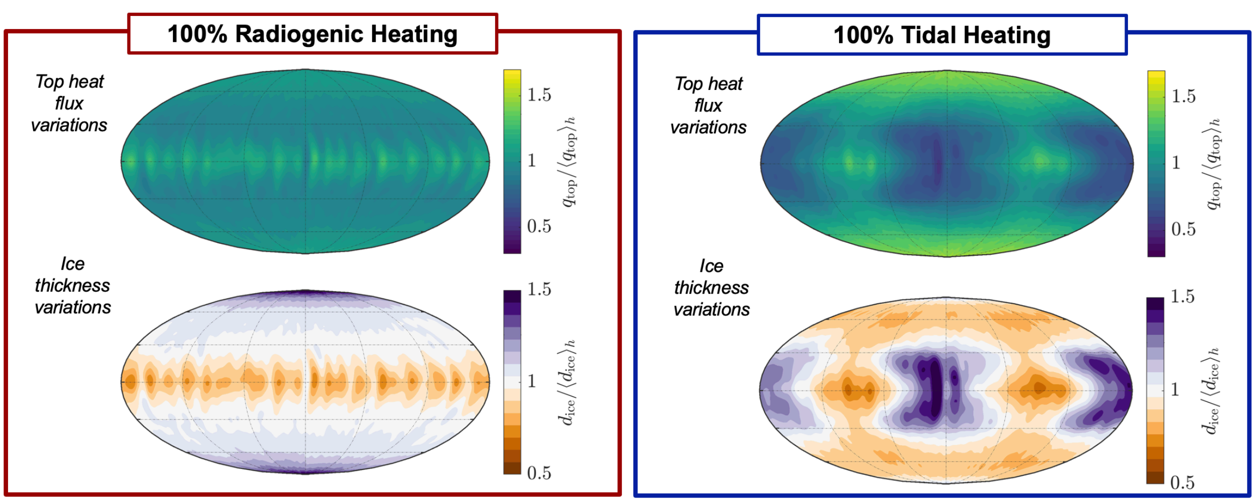

Figure 3: *Implications for ice-ocean heat flux (top) and ice shell thickness variations (bottom). Left: model with a homogeneous basal heat flux, q*=0. Right: model with a heterogeneous basal heat flux, q*=0.85.*