THE INFLUENCE OF HETEROGENEOUS MANTLE HEATING ON OCEAN CONVECTION AT EUROPA.
K. M. Soderlund[1] , B. E. Schmidt[2], J. Wicht[3] and D. D. Blankenship[1], [1]University of Texas at Austin, John A. and Katherine G. Jackson School of Geosciences, Institute for Geophysics (UTIG), J.J. Pickle Research Campus, Bldg. 196; 10100 Burnet Road (R2200), Austin TX 78758-4445, USA. (krista@ig.utexas.edu). [2]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, 311 Ferst Drive, Atlanta, GA 30332-0340, USA. [3]Max Planck Institute for Solar System Research, 37191 Katlenburg-Lindau, Germany.

Introduction: Europa is fully differentiated with an iron core, silicate mantle, and outer H_2O layer that consists of a liquid water ocean beneath an icy outer crust [1-4]. An ocean is thermodynamically possible due to the satellite's proximity to Jupiter and the resulting tidal heating. The amplitude of tidal heating in the different internal structure layers is poorly constrained, but may play important roles in the ice shell [5-8], ocean [8-9, cf. 10], and/or mantle [6,8].

Here, we investigate whether the spatial distribution of heat flow from the mantle plays an important role in Europa's ocean dynamics and the transfer of heat to the overlying ice shell. Europa's mantle is heated by radiogenic and tidal dissipation [11,12]. While radiogenic sources may be uniformly distributed in the interior, tidal heating is spatially heterogeneous. Figure 1 shows the spatial distribution of heating due to eccentricity (left panels) and obliquity tides (right panels) for synchronous rotation from [8]. Obliquity tides are likely small, however, *if* estimates of Europa's obliquity are correct. Europa's mantle heating is predicted to consist primarily of Pattern C (bottom row) with secondary contributions from Patterns A (top row) and B (middle row). Eccentricity-induced tidal heating in the mantle will then peak at high latitudes. It is, therefore, important to understand the sensitivity of ocean circulations and heat transfer to variations in mantle heat flow.

Global Ocean Convection Model with an Isothermal Seafloor: Our team has recently developed a global model of Europa's ocean dynamics [13]. We simulate thermal convection of a Boussinesq fluid in a thin rotating spherical shell using the numerical model MagIC [14]. Both boundaries are impenetrable, and stress free flow conditions are chosen to exclude the effects of Ekman boundary layers, which are too thick at the large Ekman numbers assumed in the simulations due to computational limitations [15]. An isothermal top boundary condition reflects the fact that ice is at the freezing point here while allowing for horizontal heat flux variations. Isothermal bottom boundary conditions are considered for simplicity following a common practice in planetary dynamo models [16]. Fluid motions and heat sources in the ocean derived from orbital dynamics such as tides and libration are also neglected [8-10, 17].

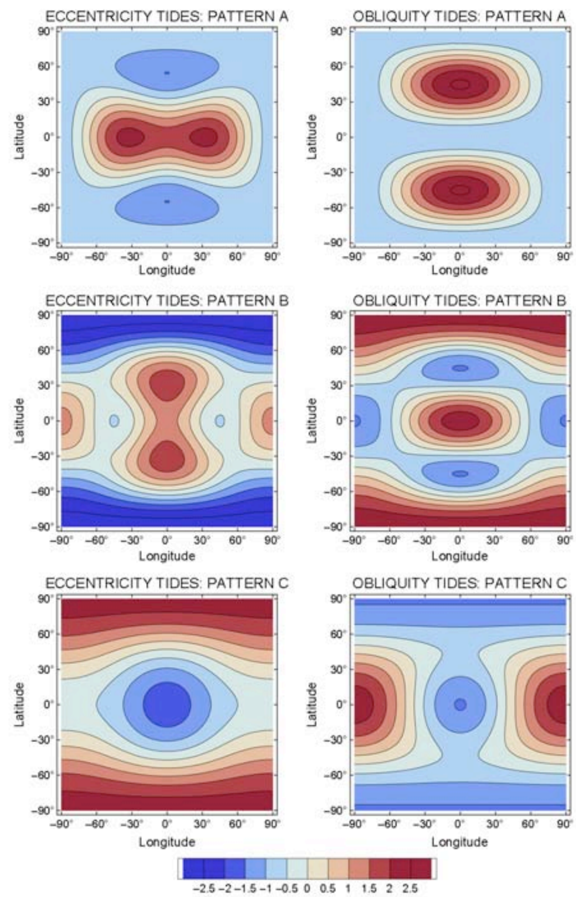

Figure 1: Distribution of tidal heating due to eccentricity and obliquity tides from [8]. Pattern A represents contributions from radial dissipation, pattern B represents contributions from radial-tangential shear dissipateon, and pattern C represents tangential dissipation. These patterns may also be expressed analytically as linear combinations of spherical harmonic components of degree zero, two and four. Reprinted from Icarus, 223, M. Beuthe, Spatial patterns of tidal heating, 208-329, Copyright (2013), with permission from Elsevier.

We argue in [13] that the Coriolis force is not sufficiently strong to organize the flow into rotationally aligned Taylor columns [cf. 18-19]. Small-scale convection instead adopts a quasi-three-dimensional structure that is more vigorous at low latitude. Global-scale currents are organized into three east-west jets and two equatorial Hadley-like circulation cells. The zonal jets have westward flow near the equator and prograde flow at higher latitudes with typical current speeds of ~250 cm/s. The meridional circulations have upwelling fluid near the equator that sinks at mid-latitudes; mean radial current speeds are ~3 cm/s. We find that the combination of stronger equatorial turbulence and Hadley-like cells causes heat from the mantle to be transmitted across the ocean to the ice shell most effectively at low latitudes (Figure 2). When averaged in time, the outer boundary heat flux is enhanced at the equator by a factor of 1.4 compared to higher latidues.

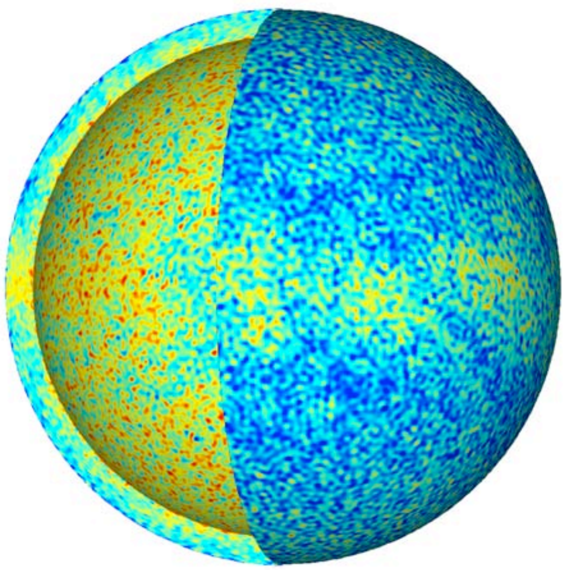

Figure 2: Instantaneous temperature field in a simulation of Europa's global ocean dynamics with isothermal boundary conditions. Hot plumes (red) rise from the seafloor, while cool fluid (blue) sinks downward from the ice-ocean interface. More heat is delivered to the ice shell near the equator where convection is more vigorous.

Influence of Mantle Heat Flow Heterogeneities on Ocean Convection: We will determine the sensitivity of Europa-like ocean dynamics to mantle heat flow variations by modifying the thermal boundary condition at the ocean-mantle interface of our model. Towards this end, we will first contrast the preceding isothermal case against an otherwise identical simulation where the seafloor instead has a fixed, homogeneous heat flux. We will then superimpose the predicted mantle tidal heating pattern using the analytical expressions of [8]. Our analysis will focus on convective heat transfer because of the competing nature of ocean circulations (equatorial heat flux maximum) versus tidal heating in the mantle (polar heat flux maxima). The heat flux pattern along the ice-ocean interface is of particular importance because it can directly impact the ice shell and the potential for geologic activity within it [13].

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