CONVECTIVE HEAT TRANSFER IN TITAN'S OCEAN AND ITS ROLE IN THE EVOLUTION OF THE OUTER ICE SHELL. J. Kvorka[1] and O. Čadek[1], [1]Charles University, Faculty of Mathematics and Physics, Department of Geophysics, Prague, Czech Republic (jakub.kvorka@mff.cuni.cz).

Introduction: The large-scale topography of Titan [1,2] is dominated by zonal degree 2 and 4 components with pronounced (<-300 m) depressions in the polar regions and several elevated areas (>400 m) at mid-latitudes [3]. Three different mechanisms have been proposed to explain this pattern: the enhanced ethane precipitation at high latitudes [4], the temperature, porosity and compositional variations in the ice shell [3], and the latitudinal variations in the heat flux from the ocean [5]. Here we focus on the last mechanism and present a quantitative model of the convective heat transfer in Titans ocean, which is based on a large set of numerical simulations interpreted using a new scaling law.

Heat Transfer in a Subsurface Ocean: Most of the previous studies assumed that heat flowing into the ice shell is homogeneously distributed as a consequence of efficient thermal mixing in the ocean. This view has been questioned by recent studies of subsurface ocean dynamics [6,7] which have shown that the circulation of the subsurface ocean is modulated by the Coriolis force, resulting in a latitudinal gradient in heat flux at the base of the ice shell. Depending on the relative importance of rotation, the heat flux maximum is located either at the poles (polar cooling) or near the equator (equatorial cooling). Kvorka et al. [5] have argued that the polar depressions observed on Titan are a consequence of enhanced polar cooling, which causes the melting of ice and subsequent thinning of the ice shell at high latitudes. Although the studies of ocean dynamics mentioned above agree that the heat flux at the base of the ice shell can vary by tens of percent, they predict different distributions of heat flux anomalies at the upper boundary of Titan's ocean. While the models presented in [6] are consistent with weak equatorial cooling, the results presented in [7] suggest that the heat transfer in the ocean is dominated by polar cooling. In order to clarify this issue, we perform more than 100 numerical simulations of thermal convection in a rotating spherical shell, varying the mechanical boundary conditions and dimensionless input parameters (Rayleigh, Ekman and Prandtl numbers) by at least one order of magnitude. Based on this data set, we derive a scaling law that relates the heat flux pattern to the dimensionless characteristics of the ocean and estimate the distribution of the heat flux flowing into Titan's ice shell from its subsurface ocean.

Method: We investigate thermal convection in a subsurface ocean using the Navier-Stokes-Boussinesq model. The computational domain is a spherical shell with an inner to outer radius ratio of 0.8 and free-slip boundaries. Convection is driven by a fixed temperature contrast between the inner and outer boundary. The effect of salinity variations on the density of the ocean is neglected. This effect may be important [8,9] but it is difficult to implement due to the lack of knowledge about the composition of Titan's ocean.

Scaling Laws: The heat transfer in the ocean is controlled by three dimensionless parameters: the Rayleigh (Ra), Ekman (Ek) and Prandtl (Pr) numbers. The main drawback of the current models of ocean dynamics is that the dimensionless parameters that can be achieved in numerical simulations are orders of magnitude different from those controlling the real ocean. The simulations are performed for Ra which is usually 10 to 15 orders of magnitude smaller than its real value, while Ek is usually five to ten orders of magnitude larger than that expected in natural systems. In spite of this limitation, numerical simulations can provide valuable insight into the dynamics of rotating convective systems since the results obtained for unrealistic Ekman and Rayleigh numbers can be extrapolated using scaling laws. In practice it means that we must find a 'diagnostic' parameter, which is sensitive to changes in the heat flux pattern, insensitive to order-of-magnitude changes in control parameters Ra and Ek and which allows the cooling mode (polar or equatorial) to be unambiguously determined by the value of this parameter.

Results: Combining the results of our numerical simulations with the scaling laws obtained from numerical and laboratory experiments and asymptotic predictions, we find that the changes in the heat flux pattern can be characterized by the transitional number $R_G^* = RaEk^{12/7}Pr^{-1}$. The parameter was obtained from the transitional parameter derived in [10] by taking into account the effect of the Prandtl number.

The cooling pattern can be quantified by two parameters: the magnitude of the heat flux anomaly relative to the average heat flux, q^*, and the relative difference between the average heat flux at high latitudes and that at low latitudes, $q^{h/l}$ (see [7] for details). The value of $q^{h/l}$ is positive for polar cooling and negative for equatorial cooling. Our analysis suggests that the heat flux from the ocean is concentrated near the equator when $R_G^* < 1$ or $R_G^* > 10$ while polar cooling occurs when $1 \leq R_G^* \leq 10$ (Figure 1). The values of R_G^* for which $q^{h/l} = 0$ are the same for different values of Ek and Pr, suggesting that the transitions between equatorial and polar cooling depend only on the diagnostic parameter R_G^* and do not depend on the specific choice of the control parameters.

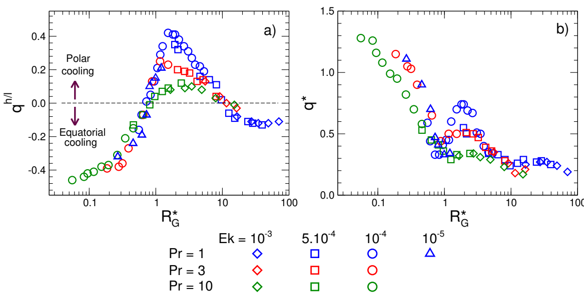

Figure 1: Heat flux characteristics $q^{h/l}$ and q^* plotted as a function of the diagnostic parameters R_G^*. The dashed line in panel a marks the transition from equatorial ($q^{h/l} < 0$) to polar ($q^{h/l} > 0$) cooling. The symbols represent the numerical simulations.

Implications for Titan: The cooling style of Titan's ocean depends on whether $R_G^* = RaEk^{12/7}Pr^{-1}$ is inside the interval $\langle 1, 10 \rangle$ or outside of it, where Ra, Ek and Pr now denote the parameters controlling the thermal evolution of the real ocean. Taking into account the uncertainties in current estimates of the ocean thickness and its material parameters, we get $Ra \in (4 \cdot 10^{19}, 9 \cdot 10^{21})$, $Ek \in (10^{-12}, 4 \cdot 10^{-11})$ and $Pr \approx 10$, corresponding to R_G^* between 3.3 and 9.8 (Figure 2). Based on this result, we predict that the heat flux on Titan peaks near the poles and is dominated by zonal degree 2 and 4 terms (Figure 3).

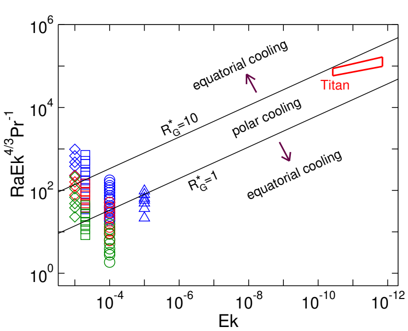

Figure 2: Boundaries between the areas of polar and equatorial cooling plotted as a function of parameter Ek (decreasing from left to right) and $RaEk^{4/3}/Pr$, characterizing the supercriticality of the system. The parameters relevant to Titan's ocean (the red area in the graph on the right) lie between the lines $R_G^* = 1$ and $R_G^* = 10$, suggesting that Titan's ocean is in the polar cooling mode. The symbols on the left side of the graph represent the numerical simulation (see Figure 1 for the legend).

Comparison of the panels in Figure 3 shows that the predicted heat flux distribution is negatively correlated with the axisymmetric part of Titan's long-wavelength topography, suggesting a coupling between ocean dynamics and the evolution of the ice shell. Although our model provides a plausible explanation of degree 2 and 4 zonal topography, it cannot account for the longitude dependent part of the topographic signal or the fact that the topography is more pronounced in the southern than in the northern hemisphere. It is therefore likely that other effects, such as ethane precipitation, climatically controlled erosion and others, can also contribute to the development of the long-wavelength topography, or that some of the topographic features are of ancient origin.

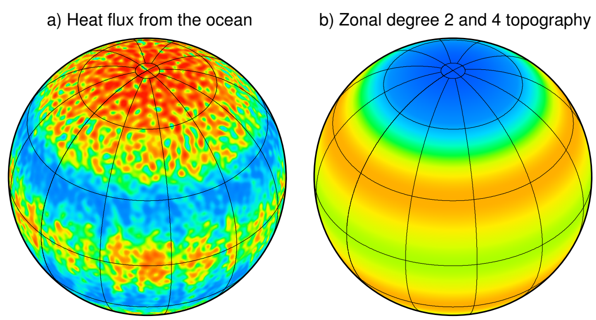

Figure 3: a) Variations in heat flux from the ocean computed for $Pr = 10$, $Ek = 10^{-3}$ and $Ra = 6.8 \cdot 10^6$ ($R_G^* = 4.9$) and averaged over 0.02 viscous diffusion time. b) Titan's zonal degree 2 and 4 topography (height above an equipotential surface). Red (blue) denotes positive (negative) values.

Concluding Remark: It is likely that variations in the heat flux from the ocean also influence the evolution of other icy moons, as suggested in several recent studies [e.g., 11,12]. The scaling law presented in this work is applicable to icy moons where the role of salinity is limited [9] and the ocean is underlain by a layer of high-pressure ice, which guarantees that the temperature at the bottom boundary of the ocean is constant.

References: [1] Corlies P. et al. (2017) *GRL, 44,* 11,754–11,761. [2] Durante D. et al. (2019) *Icarus, 326,* 123–132. [3] Čadek O. et al. (2021) *Icarus, 364,* 114466. [4] Choukroun M. and Sotin C. (2012) *GRL, 39,* L04201. [5] Kvorka J. et al. (2018) *Icarus, 310,* 149–164. [6] Soderlund K. (2019) *GRL, 46,* 87008710. [7] Amit H. et al. (2020) *Icarus, 338,* 113509. [8] Lobo A. H. et al. (2021) *Nat. Geosci., 14,* 185–189. [9] Zeng Y. and Jansen M. F. (2021) *Planet. Sci. J., 2,* 151. [10] Gastine T. et al. (2016) *J. Fluid Mech., 808,* 690732. [11] Soderlund K. et al. (2014) *Nat. Geosci., 7,* 16–19. [12] Čadek O. et al. (2019) *Icarus, 319,* 476–484.