THE EFFECT OF A CLATHRATE LAYER ON THE EVOLUTION AND DYNAMICS OF TITAN'S CRUST.
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Introduction: Titan was observed by the Cassini mission during the period 2004-2017. The many intriguing features of Saturn's largest moon include its dense atmosphere and the presence of a deep ocean. The presence of large amounts of methane in Titan's atmosphere [1], the hydrocarbon lakes at its surface [2], Titan's climate with rains of methane and ethane [3], and the formation of clathrates from the reaction of liquid hydrocarbons with water ice [4] suggest that its icy crust can be covered by a layer of methane clathrates [5]. The thermal properties of clathrates are very different from those of water ice - the thermal conductivity in particular is more than an order of magnitude lower than that of water ice at Titan's surface temperature [6]. The clathrate cap is thus acting as a powerful insulator. In this paper, we study the dynamics and heat transfer through Titan's clathrate capped ice crust. We show that the vigor of convection is limited by the presence of the clathrate layer. For reasonable values of radioactive heat flux, convection processes would not be efficient enough to extract internal heating thus providing an alternative explanation for the presence of a deep ocean inside Titan

Model: We solve thermal convection of viscous fluid (ice) in a 2d Cartesian box assuming the incompressible Boussinesq approximation of the governing equations. We include the strongly nonlinear viscosity of ice which depends on temperature, grain size and stress using the composite law [7]. The temperature dependence of thermal conductivity [8] with values of 2.3 and 5.7 W m^{-1} K^{-1} at the ocean interface and surface, respectively, is taken into account. Finally, we also include the insulating effect of methane clatrates by prescribing a constant clathrate conductivity of 0.5 W m^{-1} K^{-1} in a layer of thickness hc. The governing equations are supplemented with the following boundary conditions: free-slip on all boundaries, fixed temperature at the bottom and top boundary, and thermally insulating side boundaries. The whole system is implemented in the open source Finite Element Method library FEniCS [9].

Results: We conducted 23 numerical simulations for different grain sizes (viscosities) and different thicknesses of the clathrate layer. We also investigated the effect of tidal dissipation in the icy crust.

The effect of the presence of a clathrate cap on the convection pattern can be assessed by comparing the results of simulations with a clathrate layer thickness (h_c) of 9 km with the case with no clathrates. In both cases, the grain size is 1 mm. Figure 1 shows the obtained average temperature profiles. For a pure ice layer (h_c=0 km, left), convection occurs in a stagnant lid regime with the thickness of the stagnant lid (h_{sl}) being equal to 42 km (cyan box). The inclusion of a 9 km thick layer of low conductivity clathrates (right) reduces the thickness of the stagnant lid to 15 km and thus brings warmer material much closer to Titan's surface. The presence of clathrates also increases the temperature of the convective interior (T_c) therefore reducing the temperature contrast at the hot thermal boundary layer (ΔT is smaller by ~3 K when a 9 km clathrate cap is included). As a result, the buoyancy of warm ice at the ocean interface decreases, the efficiency of convection diminishes, and significantly less heat is extracted from the ocean - the heat flux (red dashed lines) decreases from 13.1 mW m^{-2} without clathrates to 7.8 mW m^{-2} with 9 km of clathrates.

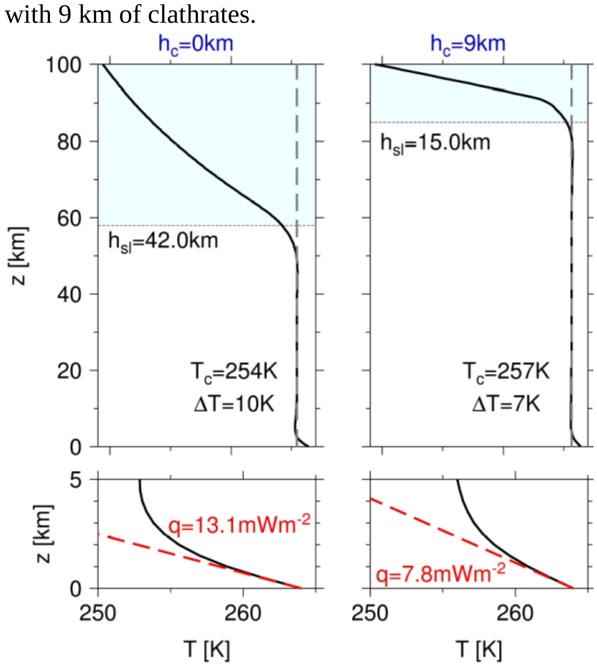

Figure 1: Horizontally averaged temperature profiles (black) for clathrate layer thickness of 0 (left) and 9 km (right). The grain size is 1 mm in both cases. The bottom panels give the detail of the bottom 5 km. The dashed lines show the temperature of the convective interior (Tc, gray) and the basal heat flux (red). The cyan box shows the stagnant lid of thickness h_{sl}.

The numerical simulations show that the amount of heat that can be extracted by convection not only depends on the reference viscosity (grain size) but also on the thickness of the clathrate layer (Fig. 2): the thicker the clathrate layer, the less heat can be extracted. For comparison, we plotted the conductive heat flux (dashed line in Figure 2) that takes into account the temperature-dependent thermal conductivity of water ice and the very low thermal conductivity of the clathrates. For a 100 km thick crust, the conductive heat flux varies from 7 $mW.m^{-2}$ without clathrates down to 3.5 $mW.m^{-2}$ with a 10 km thick clathrate layer. For the range of viscosities and clathrates thicknesses investigated in the present study, the convective heat flux is larger than the conductive heat flux. However, for a modest tidal dissipation of 5.10^{-8} Wm^{-3}, the convective heat flux is just slightly larger than the conductive heat flux for a clathrate layer thickness of 9 km (orange squares in Figure 2), suggesting that conductive solutions are not impossible. The basal heat flux can be compared with the amount of heat produced by the decay of long-lived radioactive elements assuming either CV or CI composition of the silicate fraction [10] (brown box in Figure 2). Comparing the heat fluxes obtained from the numerical simulations with the estimated range of heat fluxes coming from Titan's silicate core suggests that the presence of a clathrate layer ~10 to 20 km thick ensures the long term stability of Titan's deep water ocean without the necessity of additional dissipation or composition effects. Adding tidal dissipation reduces the thickness of the clathrate layer necessary to obtain equilibrium between the internal heat and the extracted heat.

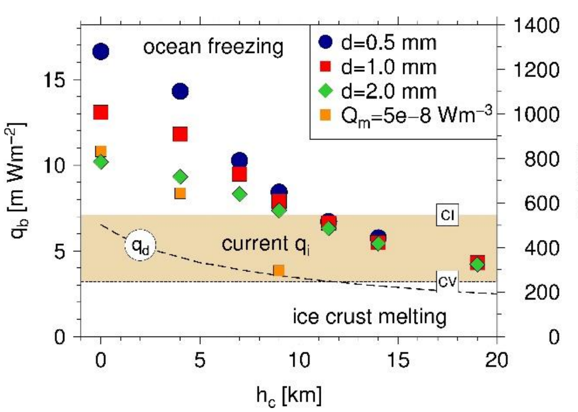

Figure 2: Effect of grain size (d, symbols) and clathrate layer thickness (h_c, x-axis) on the heat flux extracted from the ocean (q_b). The brown rectangle gives the range of current heat flux from Titan's silicate core. The dashed line indicates the conductive heat flux through the crust (q_d).

Conclusions: The presence of clathrates has an insulating effect for both the conduction and convection model. For the convection model, this result cannot be predicted by scaling laws developed in the stagnant lid convection regime without clathrates. The presence of the clathrate layer reduces the thickness of the stagnant lid, which leads to stagnant lid scaling laws predicting a higher value of heat flux. As explained in the previous section, the presence of the clathrate layer also limits the buoyancy of hot plumes, which leads to smaller value of heat flux. This result is important for understanding the evolution of Titan's crust and ocean.

The presence of a clathrate layer allows warmer material to get closer to the surface. This would facilitate cryovolcanism. It would also modify the morphology of the impact craters, allowing faster relaxation for craters forming where the clathrate layer is thick. This could be an explanation for the apparent dearth of impact craters at high latitudes [11].

Such a clathrate layer would be a major reservoir of hydrocarbons on Titan. Their destabilization by impacts and cryovolcanism could provide the replenishment required to explain the presence of methane in Titan's atmosphere. Global models describing the fate of hydrocarbons on Titan should include the role of such a reservoir. The future Dragonfly mission to Titan with its geophysical package may be able to determine the thickness of a clathrate layer on Titan.

Finally, the calculations performed for Titan could also be applied to Ceres, Europa, or Pluto where the presence of clathrates has been suggested.

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