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Dynamics of Titan's high-pressure ice layer

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Abstract

The abundance of methane and ^{40}Ar in Titan's atmosphere points to the exchange processes between the surface and the deep interior. Here, we study heat and water transport through Titan's high-pressure (HP) ice layer using a two-phase model of solid ice-liquid water mixture. Our results show that melting may occur at the interface with silicates and that the generated liquids then ascend through the layer before reaching the ocean. This process may facilitate the transport of volatiles from the core to the ocean. We also derive scaling laws to determine the occurrence of bottom melting. Using Cassini data and reasonable values of viscosity and heat flux, we predict that exchange processes through Titan's HP ice layer might be ongoing.

Introduction

Titan is likely differentiated into a hydrated silicates core [4] and a hydrosphere composed of a high-pressure (HP) ice layer, an ocean, and an ice I crust. The presence of an ocean was suggested based on the interpretation of (i) measurements of Schumann-like resonance [3], (ii) Cassini-inferred large value of k_2 [5], and (iii) the large measured value of obliquity [2].

Several observations and their interpretations also point to exchange processes between the deep interior and the atmosphere, such as the large amount of ^{40}Ar [9] and methane [1] and the observed ^{15}N/^{14}N isotope ratio [8]. Here, we study the dynamics of Titan's HP ice layer to investigate its permeability for volatiles transport between the silicate core and the ocean.

Numerical model

We solve the two-phase mixture equations [10] for the mixture of two coexisting phases - solid ice and liquid water. In this approach, the amount of water is described by porosity φ that is defined as a volume fraction of water in the mixture. We use the open source Finite Element Method library FEniCS [7]. For more details, see [6].

Results

Figure 1 shows the difference of temperature T from the melting temperature T_m (top) and the corresponding porosity φ (bottom) for the reference simulation. We observe that: (i) a layer of temperate ice ($T=T_m$, dark red) is established at the ocean interface, (ii) melt appears in the upwelling plumes and the top temperate layer from where it is extracted into the ocean, (iii) some melt may also be generated at the silicates interface, (iv) the amount of liquid water (porosity) is small (≤ few percent). Being less dense than the HP ice, the generated water provides additional buoyancy that promotes the ascent of hot temperate plumes and the extraction of most of the water produced at the silicates interface. The main model parameters (HP ice layer thickness H, HP ice viscosity μ, incoming silicates heat flux q_s) determine the convection and melt generation pattern.

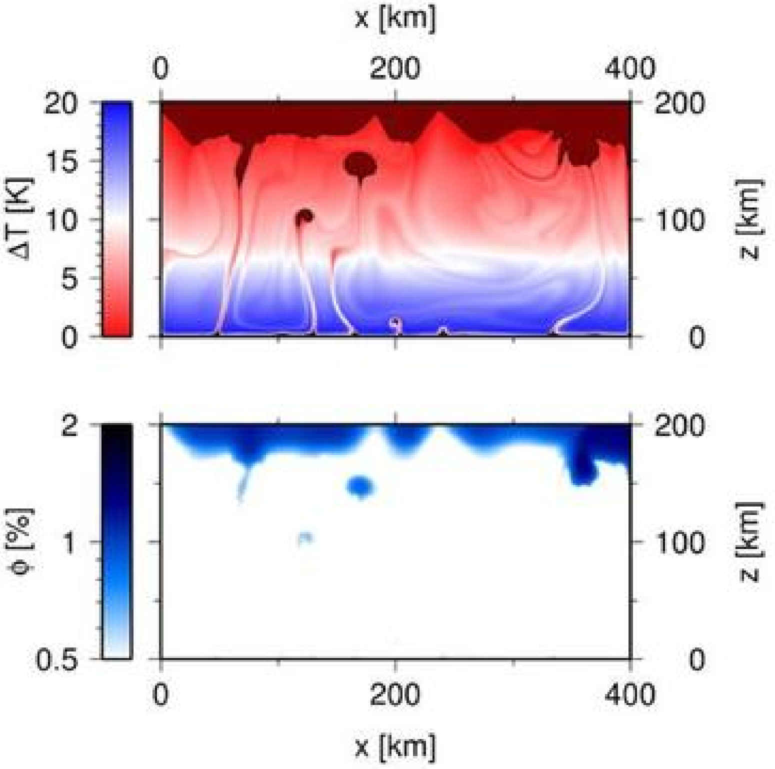

Figure 1: *Top*: Temperature difference from the melting temperature $\Delta T = T_m - T$. The dark red indicates the temperate (partially molten) ice. *Bottom*: Porosity (water volume fraction in the mixture).

The occurrence of melt at the silicates interface is determined by the efficiency of HP ice convection which is characterized by the Rayleigh number. To describe the thermal state of this interface when there is no melt ($T<T_m$), we perform thermal boundary layer (TBL) analysis that relates the hot TBL thickness with the Rayleigh number. We then derive an expression for the critical silicates heat flux for bottom melting which is shown in Figure 2. If, for given H and μ, the silicates heat flux q_s is smaller than the critical value q_s^c, temperature at the silicates interface is below the melting temperature and no melt is produced. On the other hand, if the silicates heat flux is larger than the critical value, melting occurs at the interface. Note that the smaller the viscosity (leading to more efficient heat transfer by solid state convection), the larger the heat flux that is necessary for bottom melting for a given HP ice layer thickness and vice versa.

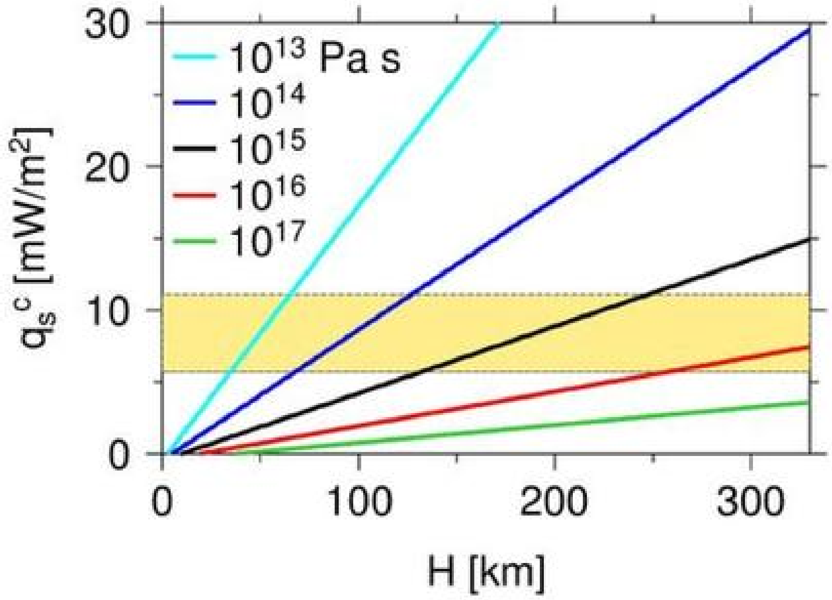

Figure 2: Scaling law for the critical heat flux q_s^c for bottom melting as a function of HP ice layer thickness H for different ice viscosities $\mu = 10^{13}$–10^{17} Pa s (colors). The light yellow rectangle represents the estimated present day values of silicates heat flux q_s.

The light yellow rectangle in Figure 2 shows the estimated present day value of the heat flux coming out of the silicate core [6]. Following [2] who predict the ice I crust thickness smaller than 100 km and assuming pure H_2O hydrosphere, the present day HP ice layer thickness is less than 140 km (determined by the ocean adiabat). For this value, melt is predicted at the silicates interface if the ice viscosity is 10^{15} Pa s or larger (Figure 2).

Conclusions

We investigated the dynamics of Titan's HP ice layer by solving the problem of two-phase thermal convection of solid ice and liquid water mixture. We showed that melting at the silicates interface depends on the ice viscosity, the HP ice layer thickness and the incoming heat flux and we found a corresponding scaling law for the critical silicates heat flux for bottom melting. If melting occurs at the silicates interface, argon, nitrogen and other volatiles coming out of the silicates could be dissolved in water, advected through the HP ice layer, and extracted into the ocean. Based on Cassini observations and reasonable values of HP ice viscosity, we predict that exchange processes through Titan's deep HP ice layer might be ongoing.

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