NUMERICAL SIMULATIONS OF PLUME CRYOVOLCANISM: IMPLICATION FOR METHANE OUTGASSING ON TITAN G. Tobie[1], G. Choblet[1], C. Sotin[1], G. Mitri[2], J. I. Lunine[2] and A. P. Showman[2]. [1]LPG (UMR CNRS-6112) Univ. Nantes, , 2, rue de la Houssiniere, BP 92208, 44322 Nantes cedex 03, France, [2]LPL, University of Arizona, 1629 E University, Tucson, AZ 85721, USA.(corresp. author: gabriel.tobie@univ-nantes.fr)

Introduction: Photochemistry in the stratosphere of Saturn's moon would remove the present-day atmospheric inventory of methane there in a time span of a few tens of millions of years [1]. Before the Cassini-Huygens mission arrived at Saturn, widespread liquid methane or mixed hydrocarbon seas hundred of meters in thickness were proposed as reservoirs from which methane might be resupplied to the dominantly molecular nitrogen atmosphere in a continuous fashion over geologic time [2]. Cassini-Huygens observations [3,4,5,6] and ground-based observations [7] ruled out the presence of extensive bodies of liquid hydrocarbons at present, which means that methane must be derived from another source over Titan's history. Alternatively, evolution models [8] as well as infrared and radar observations [3,9] suggest that recent releases of methane occurred on Titan's surface through cryovolcanic processes. Methane would have been stored in the form of clathrate hydrate in the solid outer layer above an ammonia-water ocean subsequent to early interior differentiation (~4 Gyr ago), and would be dissociated by thermal instabilities within the outer layer at present time [8]. Here we perform numerical simulations of thermal convection to quantify how thermal icy plumes can destabilize the clathrate reservoir and thus induce methane outgassing.

2D simulations of thermo-compositional convection for a mixture of clathrate and ice: For the simulations, we consider a Cartesian domain with reflecting side boundaries. A free-slip condition is assumed for the upper and lower boundaries. We adopt the 2D numerical program used and described in Tobie et al. [10]. Methane clathrate has a low thermal conductivity and high viscosity as compared with water ice [10,11]. This is expected to strongly influence the thermal state and dynamics of the outer icy layer on Titan. Accordingly, the model has been modified to take into account the composition dependence of thermal conductivity and of viscosity. Methane clathrate is transported with the same advective scheme as temperature and melt fraction [10]. Temperature-dependent viscosity of the mixture of ice Ih and methane clathrate is evaluated with an exponential formulation of the temperature dependence as in ref. 10 and assuming that the viscosity of methane clathrate is 50 times higher than water ice at the same temperature [11]:

$$\eta(T, x_{MH}) = \left[1 - x_{MH} + x_{MH}/50\right]^{-1} \eta_{m,0} \exp\left(-\gamma_T \left[T - T_m^0\right]/\Delta T\right),$$

where T is the temperature, T_m is the melting temperature of ice Ih, x_{MH} is the mass fraction of methane clathrate, $\eta_{m,0}$ is the viscosity of ice Ih near the melting point, γ_T=14, and ΔT is the temperature variation across the layer. The thermal conductivity $k_{I/MH}$ and heat capacity $c_{I/MH}$ of the mixture are expressed as:

$$k_{I/MH} = x_{MH} k_{MH} + (1 - x_{MH}) \times k_I,$$
$$c_{I/MH} = x_{MH} c_{MH} + (1 - x_{MH}) \times c_I,$$

with k_I=2.5W.m^{-1}.K^{-1}, k_{MH}=0.5W.m^{-1}.K^{-1}, c_I=2000J.kg^{-1}.K^{-1}, c_{MH}=1600 J.kg^{-1}.K^{-1}.

Preliminary results: Figure 1 shows a snapshot of clathrate mixing ratio and temperature field for a simulation performed with a thickness of 24 km, a reference viscosity $\eta_{m,0}$ of 10^{14} Pa.s, a surface temperature of 94 K, a bottom temperature of 260 K, corresponding to the equilibrium temperature with a water ocean containing 8.5 %wt. of ammonia.The simulation is initiated with a conductive layer divided into an upper sublayer composed of pure clathrate (4km) and a lower ice layer (20km). For this simulation, no density contrast between ice and methane clathrate has been assumed. As the ice layer is unstable against thermal convection, a central thermal plume and two downwellings progressively form and erode the above clathrate layer. Part of the methane clathrate is mixed in the convective sublayer, while the other part remains in the conductive lid. The clathrate layer is thinner above the hot plume.

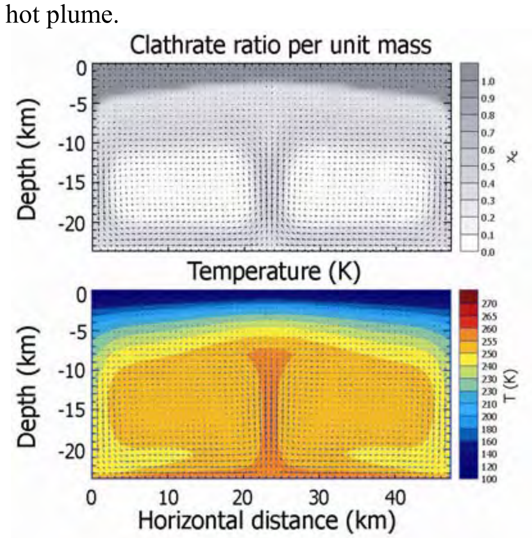

Figure 1: *Snapshot of clathrate ratio per unit mass and temperature fields.*

Figure 2 compares temperature profiles in the hot plume, in the cold downwelling as well as the horizontally averaged profile with dissociation curves of methane-nitrogen clathrates and the phase transition curve of NH_3-H_2O and CO_2, materials that could be potentially present in Titan's crust according to formation models [12]. This shows that melting of ammonia dihydrate or CO_2 ice can occur anywhere below 3 and 5 km under the surface, respectively. Dissociation of clathrate is more difficult; nitrogen-rich clathrate can dissociate at the top of the hot plume, but direct dissociation of pure methane clathrate hydrate is not possible, at least for plumes confined below a conductive lid as simulated here.

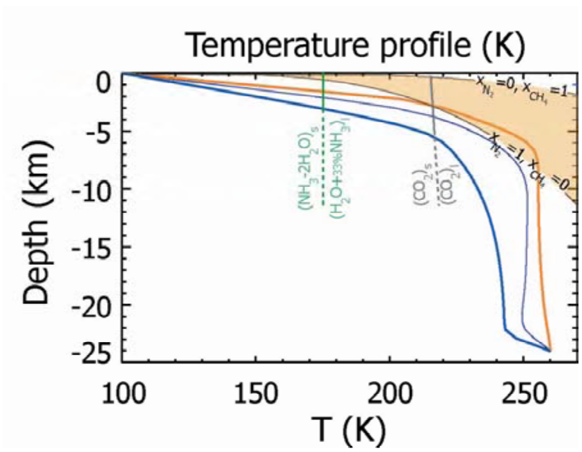

Figure 2: *Temperature profiles in the hot plume (red curve), in the cold downwelling (blue curve) and horizontally averaged (black curve). The pink-filled domain represents the domain where clathrate with a mixture of methane and nitrogen can dissociate, ranging from pure methane clathrate (x_{CH4}=1, x_{N2}=0) to pure nitrogen clathrate (x_{CH4}=0, x_{N2}=1). The two other curves represent the phase transition curve between ammonia dihydrate (NH_3-$2H_2O$) and ammonia-water solutions with 33% of NH_3 (green), and between solid and liquid CO_2.*

Implication for methane outgassing on Titan: On the basis of thermal-orbital coupled models, Tobie et al. [8] showed that methane could have been released during the early differentiation of the deep interior that formed a discrete rock core, and would be stored in the form of clathrate hydrate in the outer layer above an ammonia-water ocean. The remaining clahrate reservoir would have been dissociated since the outer layer became unstable against thermal convection about 0.5-1 billion years ago [8]. The simulation performed and displayed above would correspond to the state reached roughly 50-100 millions years after the onset of convection, and is expected to be the time of maximal surface heat flow, and hence maximal plume activity and outgassing. Even though direct destabilization of pure methane clathrate is not reached at the top of thermal plumes, two main processes should favor clathrate dissociation and hence release of methane:

- Breaking of the upper crust and intrusion of warm icy materials provided by hot thermal plumes.
- Infiltration of ammonia (or CO_2)-enriched cryomagmas, melted and/or transported by hot thermal plumes.

These two mechanisms would locally increase the temperature up to the dissociation point of methane clathrate, which in addition should be reduced by the presence of ammonia [13]. Indeed, ammonia is known to strongly reduce the melting point of ice and similarly is expected to help dissociation of methane clathrate [13]. Mitri *et al.* [14] recently proposed that thermal upwellings enriched in ammonia-water pockets could drive cryovolcanic processes and resurfacing on Titan. Moreover, the destabilization of methane clathrate reservoir would promote the eruption of cryomagma onto the surface [14]. As carbon dioxide may correspond to a bulk concentration potentially larger than ammonia [12], CO_2-bearing fluids may also be implicated.

In this first version of the code, the rupture of the upper crust, the phase transition and the effect of contaminants such as ammonia or carbon dioxide are not yet taken into account. We are currently incorporating the transport of ammonia-water pockets, the intrusion of warm diapirs through the brittle crust and the related eruption of methane and cryomagma, in order to properly simulate local cryovolcanic events related to thermal plumes.

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