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2D dynamic model of convection dynamics in a complex ice mantle.

Effect of solid/solid phase transition on the chemical exchanges and the habitability of ocean planets.

B. Journaux (1) and L. Noack (2)
(1) Laboratoire de Glaciologie et Géophysique de l'Environnement, Grenoble, France (Baptiste.Journaux@lgge.obs.ujf-grenoble.fr), (2) Royal Observatory of Belgium, Belgium

Abstract

We model the possible material transport through high-pressure ice layers in water-rich planets. The model focusses on the influence of phase transitions on the convective patterns, where we apply physical properties of high pressure ice. We investigate if (or under which circumstances) the transport path through the ice may be blocked by phase-transition-induced multi-layer convection in the high-pressure ice layer.

1. Introduction

H_2O is one of the most abundant molecules in our galaxy and is present in a large variety of planetary environments [1,2]. In the last few years an increasing number of exoplanet discoveries suggested the existence of a new kind of planetary bodies very rich in H_2O that explain the low density of some relatively small planets [3].

They may contain a large H_2O-based icy mantle, up to thousands of kilometers thick, possibly overlaid by a liquid ocean. With such thermodynamic conditions the solid mantle would be dominated by dense high pressure ice polymorph, stable beyond the gigapascal (i.e. ice VI, ice VII or ice X) [2,4,5]. This thick ice mantle may represent a physical barrier for chemical exchange between the rocky core and the uppermost ocean. This is why the ocean of such planets are regarded as bad candidates for hosting habitable environment that would require inputs of nutrients.

Recent experimental results have suggested that a very different scenario might occur as some chemical species (e.g. NaCl, LiCl, RbI, CH_3OH) are soluble up to several mol% inside high pressure ice [6,7,8]. This would permit to bring nutrients to the ocean through solid-state convection [3,8]. A major limitation for such scenario is possible phase transitions inside the ice mantle that would imply viscosity, thermal physical properties and chemical solubility contrasts. This could alter convective currents and limit the possibility of upwarding solute flux and therefore the potential habitability of the uppermost ocean.

In the present work we study the influence of the presence of a phase transition on the convective patterns in a convective layer.

2. Modeling

We apply a Fortran convection codes (CHIC [9]) to investigate the convective behavior in a high-pressure ice layer including phase transitions. The density, the thermal expansion coefficient and the heat capacity at local conditions are obtained from equations of states of the relevant materials [9].

In our first simulations, we simulate a 200km deep high-pressure ice layer, where we apply a surface pressure of 1 GPa and a surface temperature of 280 K, leading to high-pressure ice phases VI and VII. The initial temperature profile is either constant or adiabatic. At the bottom, a temperature jump of 30 K acts as a heating source from below.

The density is determined self-consistently with local pressure and temperature after [10], heat capacity and thermal expansivity of ice phases VI and VII are taken from [10,11].
For our preliminary investigations, we apply a Newtonian viscosity law and ice VI rheology for the entire investigated high-pressure ice layer. Note that we use an increased reference viscosity (by a factor of 100) and neglect a possible pressure influence. The parameters for the rheology and for the phase transitions are listed in Table 1. The phase density jump is determined locally from the density profiles.

Table 1: Rheology and phase transition parameters

Parameter	Ice VI/VII
Activation energy [kJ/mol]	136
Reference viscosity [Pas]	$1 \cdot 10^{14}$
Reference temperature [K]	330
Phase transition pressure [GPa]	2.14
Phase transition temperature [K]	300
Clapeyron slope [MPa/K]	1.25

3. Results

Figure 1 shows the temperature field for a constant initial temperature profile in the ice layer. A two-layer convection pattern evolves, which strongly reduces material transport between the two layers.

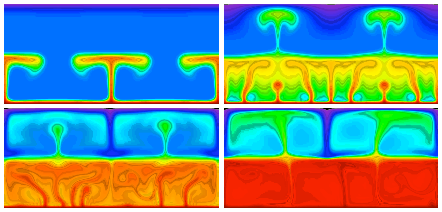

Figure 1: Temperature field at 1, 3, 6 and 13 Myr

For an initial adiabatic temperature profile, results are similar. With time, the ice VII layer heats up, as material transport through the phase boundary is again reduced due to the large density jump, see Fig. 2. At the start of the simulation, we put black and red tracers at the top and bottom of the investigated domain, to see if material exchange between the two high-pressure ice layers is possible.

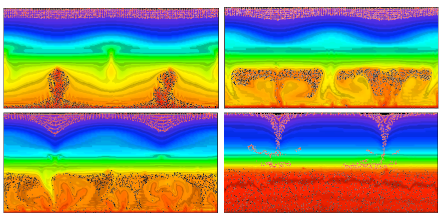

Figure 2: Temperature field including material tracers 0.05, 0.4, 1.3 and 11 Myr

In the lower half of the domain, strong convection leads to a homogeneous mixing in the ice VII layer. In the ice VI layer, convection acts on a longer time scale due to the colder temperatures, dominated by two downwellings, that are stopped at the ice VI-VII phase boundary. After 11 Myr, a small number of red particles can be found in the lithosphere of the ice VII layer, but no black tracers are in the ice VI layer.

4. Summary and Conclusions

Our first results show that the temperature profile, especially a possible temperature contrast at the bottom due to heating from the mantle below, has a major influence on the evolving convection pattern. More investigations including self-consistent thermodynamic profiles and inclusion of chemical species as well as melting processes will add to the picture.

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