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**A NEW LONG-TERM PLANETARY EVOLUTION MODEL TO SIMULATE THE FORMATION OF POLAR LAYERED DEPOSITS ON MARS.** J.-B. Clément<sup>1</sup>, F. Forget<sup>1</sup>, L. Lange<sup>1</sup>, E. Vos<sup>1</sup>, E. Millour<sup>1</sup>, J. Naar<sup>1,2</sup> and R. Vandemeulebrouck<sup>1</sup>, <sup>1</sup>Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace, Sorbonne Université, CNRS, Paris, France ([jean-baptiste.clement@lmd.ipsl.fr](mailto:jean-baptiste.clement@lmd.ipsl.fr)), <sup>2</sup>Laboratoire Atmosphères, Observations Spatiales, Institut Pierre-Simon Laplace, Sorbonne Université, CNRS, Paris, France.

**Introduction:** The exploration of Mars has revealed a planet with a complex geological history, which underwent diverse climatic conditions. Variations of orbital parameters, in particular obliquity, are known to drive the planet climate. Compared to Earth, Mars shows large changes of obliquity [1], between 0° and 60°, which suggest deep impact on its climate. Understanding the evolution of Mars climate is crucial to determine its past habitability and to explain the mechanisms behind the geomorphological features we observe today. In particular, we focus on reservoirs related to Mars climate change between humid/hot and arid/cold periods such as the polar deposits.

To address this issue, we aim to simulate with a time marching model the climates that characterized Mars throughout its history. Up to now, Mars climate simulations in 3D based on Global Climate Models (GCM) are able to simulate many processes convincingly but are so time-consuming that it is impossible to consider simulating thousands of years. Moreover, they rely on prescribed reservoirs (glaciers, sub-surface ice) whose initialization may lead to unrealistic outcomes. GCM are also often unable to follow a change of obliquity smoothly. We propose a novel numerical climate evolution model, called the Planetary Evolution Model (PEM). Its core idea is to extrapolate climate tendencies over extended periods.

Our particular interest is focused on the polar layered deposits which archive Mars climate changes for the last millions years [2]. The layers differ in composition which can give clues about the climatic conditions of their formation [3,4]. The PEM aims to provide a comprehensive model able to reproduce the layering processes and to simulate the deposits observed on Mars.

**The Planetary Evolution Model (PEM):** The GCM we use is the Mars Planetary Climate Model (PCM) [5]. Long-term simulations of Mars past climates with the PCM are difficult and costly since it models precisely various processes from short timescale, like cloud microphysics, to long timescale, like evolution of glaciers. The PEM focuses on long variations of Mars reservoirs while bypassing their sub-year variability. This is an asynchronous model based on two principles. First, the algorithm makes the reservoirs evolve according to tendencies computed from two years simulated by a Global Climate Model

(GCM). It also makes subsequent adaptations for some climatic variables. Second, the evolution algorithm ends when one of the stopping criteria is met. Then, based on the state provided by the PEM, two GCM years are computed to update the tendencies on which the PEM can get going again.

The PEM algorithm can be used in two ways. First, it can provide a steady state for given conditions such as specific orbital configuration or reservoir initialization. Second, it can perform transient Mars climate simulations following an external forcing like orbital configurations.

The PEM takes into account several kind of surface and sub-surface reservoirs and makes them evolve according to physical processes.

*Condensation/sublimation of CO<sub>2</sub>/H<sub>2</sub>O glaciers.* The tendency for evolution of surface ice is computed locally from the difference between the minima of two successive PCM years which accounts only for inter-annual perennial ice. Moreover, it is assumed that water coming from sublimating reservoirs goes directly into condensing reservoirs. At the PEM timescale, the atmosphere is not considered as a water reservoir and thus humidity is assumed to be constant.

*Flow of CO<sub>2</sub> and H<sub>2</sub>O glaciers.* A statistical sub-grid slope parametrization [6] allows to represent the physical difference induced by the North-South orientation of the different possible slopes. It also enables the accumulating ice to flow between sub-slopes if a critical thickness is exceeded.

*Evolution of subsurface H<sub>2</sub>O ice.* The ice table depth is set according to a criterion computed from yearly-averaged PCM results. Its position is updated each year to reach its equilibrium depth.

*Evolution of soil properties.* The PEM bare subsurface is divided into three soils: a 10 m-thick regolith, a 1 km-thick breccia and then rock. The thermal properties of the two first soils are adapted according to pressure changes and the presence of pore-filling ice. Only the yearly-averaged part of the subsurface temperature profile is updated by the PEM.

*Adsorption/desorption of CO<sub>2</sub>/H<sub>2</sub>O.* The amount of adsorbed CO<sub>2</sub>/H<sub>2</sub>O [7] is in equilibrium with the atmosphere.

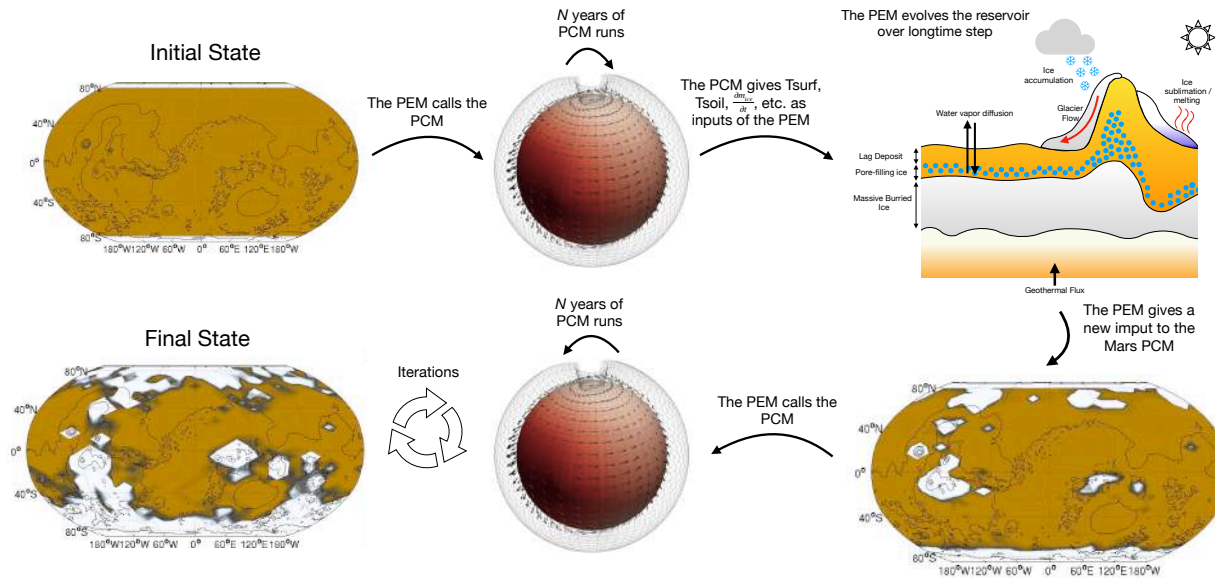


Figure 1: Diagram illustrating the asynchronous workflow between PCM and PEM calls. The PCM starts with an initial state and runs for N years. Then, the PEM takes the PCM climate variables and their tendencies as inputs. It evolves the reservoirs over long-term periods. Finally, it gives control back to the PCM. This cycle is repeated until a final state is reached.

In addition, the PEM performs several subsequent adaptations based on the above models and assumptions. Notably, as the Mars atmosphere is mainly composed of  $\text{CO}_2$ , the evolution of the different  $\text{CO}_2$  reservoirs is modifying the surface pressure by mass conservation. The volume mixing ratio of tracers is scaled accordingly. Thus, the  $\text{CO}_2$  tendencies obtained from the PCM are corrected. Moreover, surface temperature has to be adapted according to appearance/disappearance of ice on the surface.

The PEM algorithm holds several stopping criteria which account the magnitude of climate change with factors like surface ice sublimation, global average pressure and orbital variations. They ensure that the extrapolation remains within reasonable bounds. When it stops, the PEM new climate state is used to compute two new PCM years to calculate the new tendencies for the next PEM call. This cycle between PEM and PCM calls goes on until the targeted duration is met.

**Layered deposits:** The deposits are composed of layers formed at different climatic conditions spanning over extended periods of time. Ice can condensate and may include dust. Observations show that in the icy layers there is a dust fraction of up to 10%. When ice sublimates, it leaves behind the dust to create a lag layer. In addition, the interplay between  $\text{CO}_2$  and  $\text{H}_2\text{O}$  points of condensation/sublimation produce a various range of situations. For example,  $\text{H}_2\text{O}$  can act as a lag layer at the surface of  $\text{CO}_2$  glaciers as seen in observations in the South polar layered deposits and modeled by Buhler et al. [8].

The PEM tracks and stores the layers. This allows to manage easily and dynamically the formation/disappearance of a layer anywhere in the deposit. Changes of a layer composition are done easily by working with properties expressed in volume content. The structure is updated in the PEM according to the same input tendencies used for  $\text{CO}_2/\text{H}_2\text{O}$  glaciers.

**Perspectives:** By bridging the gap between short-term GCM simulations and long-term climate dynamics, the PEM represents a new tool to investigate Mars past climates and to understand the formation of today landforms like the polar layered deposits. Ongoing works aim at developing more realistic models for the PEM such as dynamic subsurface ice and simulation of climate evolution due to orbital parameters change such as a descent of obliquity. If the PEM is used for Amazonian studies, simulation of early Mars with focus on the hydrology (lakes, river systems) is also underway.

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