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J.-B Clément, F Forget, L Lange, E Vos, E Millour, Joseph Naar, R Vandemeulebrouck

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**INVESTIGATING LONG-TERM MARS CLIMATE EVOLUTION: THE PLANETARY EVOLUTION MODEL.** 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:** Exploration of Mars has unveiled a planet shaped by a complex geological history and a spectrum of climatic conditions. Compared to Earth, Mars exhibits significant variations in obliquity [1], ranging from 0° to 60°, which have profound implications for its climate dynamics. Understanding the evolution of Mars climate is crucial to determine its past habitability and to explain the mechanisms behind the present-day geomorphological features. Our focus lies particularly on reservoirs indicative of Mars' climate shifts between humid/hot and arid/cold periods, such as the polar deposits.

To tackle this challenge, we aim to simulate with a time marching model the climates that characterized Mars throughout its history. While existing 3D Global Climate Models (GCM) offer convincing simulations, they are computationally intensive, hindering long-term simulations spanning thousands of years. Moreover, they rely on prescribed reservoirs (glaciers, sub-surface ice) whose initialization may lead to unrealistic outcomes. GCM often struggle to smoothly track changes in obliquity. In contrast, 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 across timescales, from short cloud microphysics to long glacier evolution. In contrast, the PEM focuses on long-term variations of Mars reservoirs while bypassing sub-year variability, through an asynchronous modeling approach. The PEM algorithm operates on two principles. First, it extrapolates reservoir evolution based on tendencies computed from two years simulated by the PCM. 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 PCM 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 accounts for diverse kind of surface and sub-surface reservoirs, modeling their evolution according to physical processes.

*Condensation/sublimation of CO<sub>2</sub>/H<sub>2</sub>O glaciers.* Surface ice evolution is determined locally by comparing the minimum values of two consecutive PCM years, focusing solely on inter-annual perennial ice. Additionally, it is assumed that water from sublimating reservoirs is directed straight into condensing reservoirs. At the PEM timescale, the atmosphere is not considered as a water reservoir, hence 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 arising from the North-South orientation of various slopes. This framework allows 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 determined based on a criterion computed from yearly-averaged PCM results. Each year, its position is adjusted to achieve equilibrium depth.

*Evolution of soil properties.* The PEM bare subsurface is divided into three soil layers: a 10 m-thick regolith, a 1 km-thick breccia and underlying rock. Thermal properties of the two first soils are adjusted in response to pressure fluctuations and the presence of pore-filling ice. Only the yearly-averaged portion of the subsurface temperature profile is updated by the PEM.

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

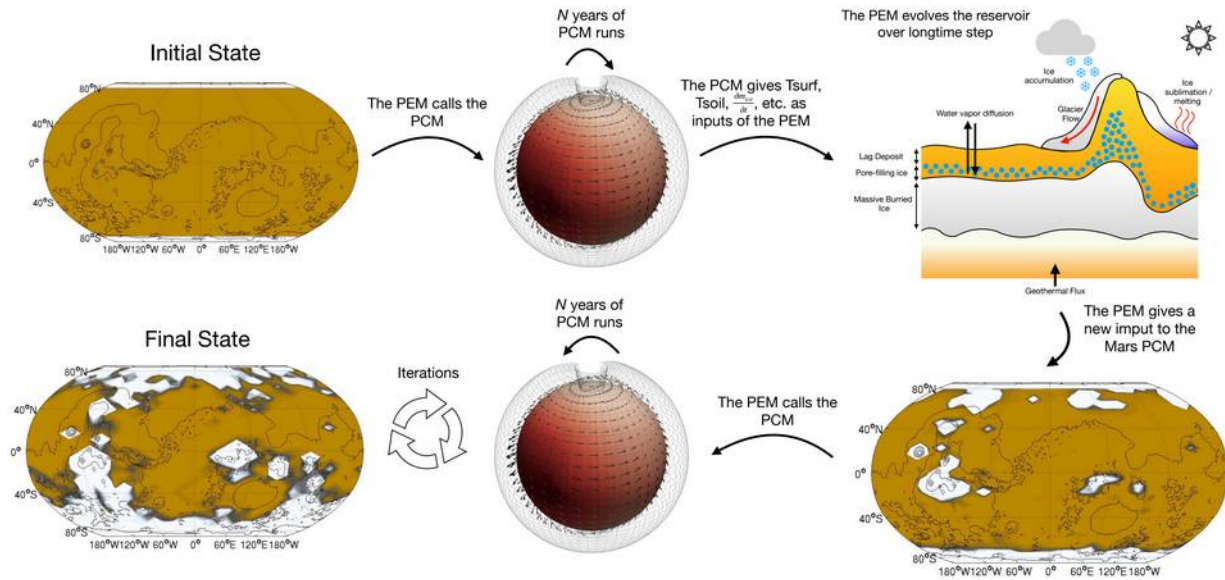


Figure 1: Diagram illustrating the asynchronous workflow between PCM and PEM calls. The PCM starts with an initial state and runs for  $N$  years. Then, the PEM takes the PCM climate variables and their tendencies as inputs. It evolves the reservoirs over long-term periods. Finally, it gives control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

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

The PEM algorithm employs to ensure that extrapolations remain within reasonable limits, considering factors such as surface ice sublimation, global average pressure and orbital variations. When it stops, the PEM new climate state is used to initiate the simulation of two new PCM years. Then, new tendencies are computed for the next PEM call. This cycle between PEM and PCM calls continues until it achieves the targeted duration.

**Layered deposits:** The deposits comprise layers formed under various 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 Bhuler et al. [8].

The PEM dynamically tracks and manages these layers, allowing for easy manipulation of their formation/disappearance 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 offers a new and promising tool to investigate Mars past climates and to understand the formation of today landforms like the polar layered deposits. Ongoing developments aim to enhance the PEM realism by incorporating dynamic subsurface ice and simulating climate evolution due to orbital parameter changes, such as obliquity descent. Additionally, we explore the application of the PEM to study early Mars, focusing on hydrological features (lakes, river systems) during the Amazonian period.

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