Formation of CO_2 Glaciers on Mars during Low Obliquity Periods L.Lange[1,*], F.Forget[1], A.Grau Galfore[2], R.-Vandemeulebrouck[1] and E.Millour[1], [1]Laboratoire de Météorologie Dynamique,Institut Pierre-Simon Laplace (LMD/IPSL), Sorbonne Université, CNRS, Paris, France; [2]Laboratoire de Planétologie et Géosciences, CNRS UMR 6112, Nantes, France. *lucas.lange@lmd.ipsl.fr.

Introduction: Some high latitude craters expose intriguing moraines that are interpreted to be formed by CO_2 ice glacier flows [1]. These glaciers might have formed when Mars's obliquity was low and the local climate was colder [1, 2]. The obliquity of Mars reached values ~ 15° nearly 800,000 years ago, and probably less than a few degrees during the Amazonian era [3]. Using radiative equilibrium models, [2, 4, 5] suggested that the atmosphere could collapse into massive CO_2 glaciers, leaving behind a residual atmosphere 20 times less dense than today, mainly composed of only Ar and N_2. We investigate the possibility of an atmospheric collapse and the formation of massive CO_2 glaciers using a complete 3D global climate model (the Mars Planetary Climate Model (Mars PCM, [6])), coupled with the Planetary Evolution Model (PEM, [7]) in the context of the « Mars Trough Time » ERC project.

Methods:
The Mars PCM The current Mars PCM cannot be used directly to study the formation and evolution of CO_2 glaciers: the typical resolution is about hundreds of km, while moraines suspected to be deposited by CO_2 glaciers in [1] are rather of the order of km. We introduced in the Mars PCM a parametrization to simulate sub-grid scale slope microclimates. In short, for each PCM mesh, we decompose the cell as a distribution of sloped terrains (defined by characteristic slopes) and a flat terrain. On each sub-grid terrain, we let the microclimates evolve so that slope-specific phenomena (e.g., condensation of volatiles, formation of glaciers, migration of subsurface ice, etc.) can be simulated. This parametrization has been tested and validated using the current observations of CO_2 ice deposits on pole-facing slopes [8].

The PEM To accurately simulate the climate and the fate of volatiles for thousands to millions of years we must couple physical processes with very different timescales, ranging from clouds microphysics and atmospheric dynamics (represented in the PCM) to the evolution of glacier accumulation, and subsurface ice evolution. To do so, we use a new model called PEM [7]. At each timestep, the inputs from the atmosphere (e.g. mean precipitation, sublimation, evaporation, temperatures, dust deposition) are extracted from multi-annual runs of the Mars PCM. Tendencies obtained from this model are then extrapolated in the PEM over tens/hundreds of years. The PEM also models glaciers and subsurface evolution as detailed below.

Glacier Flow For the sake of computation time efficiency , we decided to use a simplified glacier flow model, and not yet an ice sheet model. Here, we assume that a glacier on a Mars PCM subgrid-slope cannot exceed a critical thickness, in which case the excess ice is transferred into the adjacent sub-slope. To provide an estimate of this critical thickness, we derive the characteristic driving stress of CO_2 ice with parameters taken from [9,10] by adapting a well-established scaling balance from terrestrial glaciology to the flow of CO_2 ice [11,12]. Using the flow law parameters given by [9,10] (noting the discrepancy between values in [9,13]), we derive a characteristic driving stress of about $\sim 10^3$ Pa (compared to $\sim 10^5$ for water ice), which translate to critical ice thicknesses on the order of ~10 m to start ice flow on a 0.1º slope.

Subsurface Evolution Because of its high thermal inertia, subsurface ice has been shown to have a significant impact on the amount of CO_2 ice that condenses each winter for present-day climate [14]. This ground ice can move as the obliquity changes [15] and thus impact the amount of the atmosphere that should condense during the collapse. We model the subsurface ice evolution on flat and slopped terrains using the method from [16]. Details about this implementation are given in another abstract in this issue. CO_2 and H_2O adsorption is simulated using the computational methods presented in [21,22].

Results:
We present here preliminary results based on a simulation that does not consider the subsurface evolution (warming, ground ice, and adsorption). Updated results considering all of the contributors detailed here will be presented at the conference. In this simulation, the opacity of the atmosphere is fixed, and we only consider two tracers in the atmosphere: CO_2 and Ar/N_2. Water is not modeled here. Values of albedo, emissivity for CO_2, as well as ice tables, are set to the current values used in the Mars PCM. The obliquity of the simulations is set to 5°. Other orbital parameters than the obliquity are kept at their current value. The resolution is 3.75° latitude, 5.625° longitude, with 26 levels for vertical resolution. The initial state is the current martian climate at Ls = 0°. Results obtained with the PEM have been compared and validated against a 400-year run of the Mars PCM.
A significant collapse first occurs within the first fifty years (Fig. 1A), as a consequence of the violent shift of obliquity. Massive (> 10 m thick) deposits form at the

poles. The polar night at high latitudes regions tend to be depleted with CO_2, and enriched with non-condensable gases (Fig. 1B). This depletion is however not observed at such magnitude in equatorial regions. After a fast condensation of the atmosphere, a slower regime appears: ice at high latitudes is transferred to the poles. Finally, the ice from the South Pole is transferred to the North Pole. This is expected as the Northern hemisphere has a lower altitude: ice will be thus more stable. After 650 martian years of simulations, we reach equilibrium, i.e., the Northern massif ice deposit (> 65m thick) is in equilibrium with the atmosphere. Ongoing efforts are done to simulate a real descent of obliquity based on [3] rather than just setting the obliquity to 5°.

Our model also suggests that Northern pole-facing slopes at high latitudes are candidates for CO_2 flows (Fig. 1C). Thick ice deposits are predicted by the model where CO_2 moraines have been observed.

Yet, we still find that some moraines are not well correlated with a significant amount of ice. This is possibly due to the coarse resolution of the Mars PCM used here. Updated results with a finer resolution will be presented at the conference.

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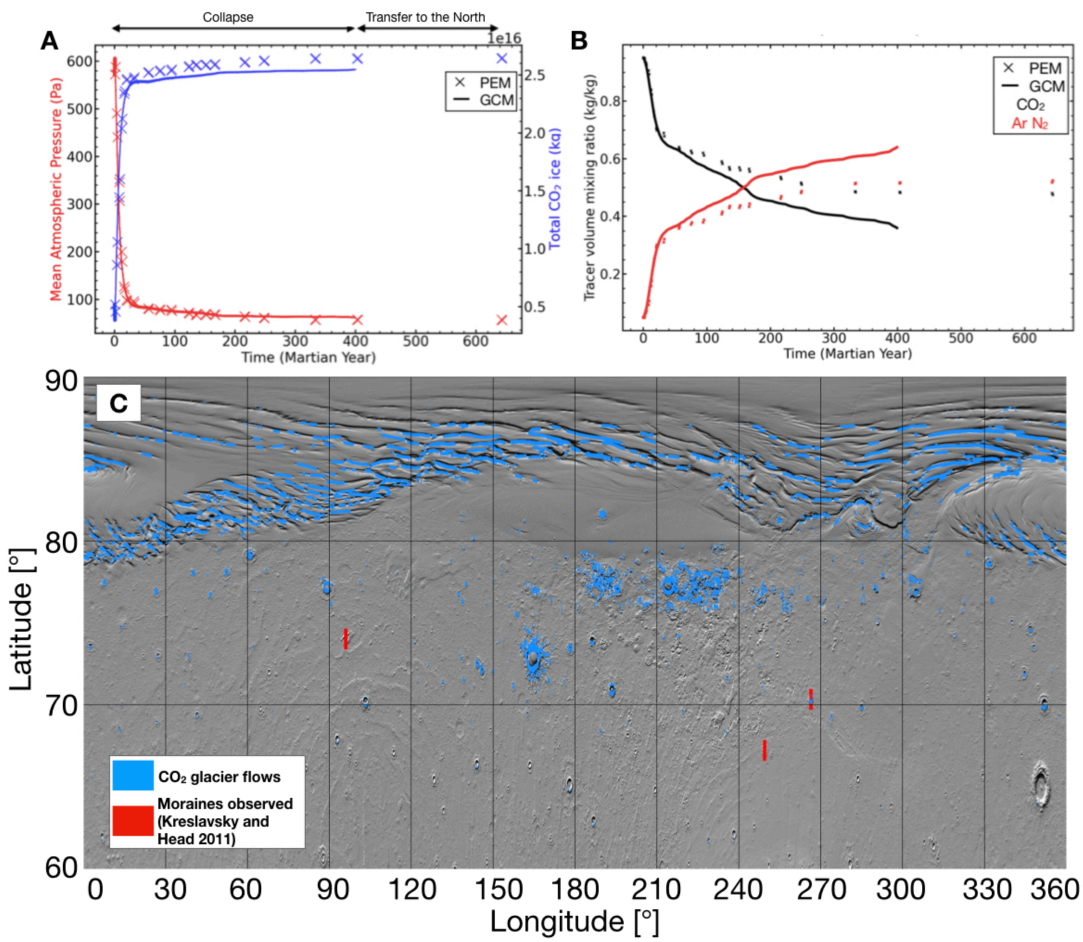

Figure 1: *a)* Evolution of the global averaged atmospheric surface pressure (red) and the total amount of surface CO_2 ice (blue). Plain curves are the outputs of the PCM, whereas crosses are for the PEM.
b) Same but for the volume mixing ratio of CO_2 (red) and Ar/N2 (black).
c) Representation of the sloped terrains where thick CO_2 deposits are predicted (blue) and where CO_2 moraines are observed (red).