Part II
Inter-annual climate dynamics of Mars from thickness variation of the seasonal deposits at its polar regions.

Abstract

The seasonal deposition and sublimation of CO_2 snow and frost in the polar regions constitute a major element in the Martian volatile cycle. Although the lateral evolution of seasonal deposits has been extensively mapped using cameras and thermal emission spectrometers, their large-scale thickness evolution has only been examined by using height profiles acquired by the Mars Orbiter Laser altimeter (MOLA). Unfortunately, various factors could bias the MOLA-derived estimates. More importantly, the MOLA dataset is temporally limited to 1999 and 2001, a little more than one Mars year, preventing its use to examine inter-annual climate dynamics of Mars.

At the steep scarps of the North Polar Layered Deposits (NPLD; mainly composed of water ice), fractured fragments can detach and fall as ice blocks. For the first time, we propose to use variations in the shadows of these ice blocks, observed in orthorectified High Resolution Imaging Science Experiment (HiRISE) images of a spatial resolution up to 25 cm, to infer the thickness evolution of the seasonal deposits. The camera started to continuously acquire high-resolution pictures of targeted regions since September 2006, obtaining 5 to 20 observations per day, which has led to a high-cadence imagery of long temporal baseline. These ice blocks are located poleward of ∼80°N where the thickest seasonal deposits can be expected. Furthermore, by making reasonable assumptions about the distribution of the seasonal deposits around the ice blocks, we can separately measure the thickness of snow and frost. We have conducted a successful experiment at a steep scarp centered at (85.0°N, 151.5°E; Xiao et al., 2024 JGR-Planets).

Now, we plan to extend our analysis to all active scarps across the Martian north polar region. First, we devise an approach, built upon existing computer vision models and Convolutional Neural Networks (CNNs), to automatically identify the ice blocks and measure the length of their shadows. We benchmark our approach against existing tools for ice block and boulder detection on Mars. After that, for a specific image acquired during late winter and spring, we determine the ratio of ice blocks that have not been submerged compared to that during summer. Finally, we relate the detected ratio to the thickness of the seasonal ice layer at the image acquisition time, taking advantage of the distribution of the heights of the ice blocks. We expect that after applying this approach to all images at all sites with ice blocks, we can get a comprehensive picture of how the snow/frost spatially and temporally. We will investigate possible couplings with dust storms and water ice transport. Those enhanced understandings can place crucial constraints on the Martian volatile cycles. Moreover, we will examine the amount and volume of fallen ice blocks to quantify the retreat rate of all active scarps and mass waste of the NPLD. These would help determine the current mass balance of the upmost layer of the NPLD which has important implications for deciphering the stored Late Amazonian climate of Mars.

1 Antecedents

Carbon dioxide is a major constituent of the Martian atmosphere (∼95% by volume). Due to the present obliquity of its spin axis of approximately 25°, Mars has its own four seasons. During fall and winter, the temperature in its polar regions can plunge below the frost point of carbon dioxide (∼-125°C) and leads to its deposition on the surface as snow/frost. The Martian seasonal deposits can extend from the poles all the way to 50°S/N in latitude. Depleting up to one third of Martian atmosphere, this seasonal process constitutes as a major volatile cycle on Mars. Deciphering this volatile cycle with high temporal and spatial resolution helps to understand the dynamics of Martian climate and calibrate the existing General Circulation Models (GCMs).

Although the lateral evolution of seasonal snow / frost has been extensively mapped using satellite images and temperature measurements, its vertical evolution at high polar latitudes has only been investigated by using height profiles acquired by the Mars Orbiter Laser altimeter (MOLA) onboard NASA's Mars Global Surveyor (MGS). Previously, by reprocessing the MOLA profiles using updated ancillary information and self-registering them, we derived both spatial and temporal thickness variations of the seasonal polar caps with a maximum of about 2.5 m at the south and 1.3 m at the north (Xiao et al., 2022a, b, c). Unfortunately, there are various factors that could bias the MOLA-derived thickness estimates which are also hard to quantify. For example, there could be possible penetration of the laser pulses into the snow/frost when it becomes transparent due to densification and self-cleaning mechanisms (dust particles gradually burrowing down). MOLA can also only determine the combined thickness of seasonal snow/frost. In addition, MOLA dataset is temporally limited to 1999 and 2001, a little more than one Mars year, preventing its use to look into multi-year thickness variations of the seasonal deposits.

At steep scarps of the North Polar Layered Deposits (NPLD, mainly composed of water ice), fractured ice fragments can detach to form ice blocks at the bottom, which constitutes as an intensive mass wasting process. Su et al. (2023, 2024) quantified the detachment of ice fragments along the marginal scarps (the source of the fallen ice blocks) to monitor these activities, which holds a record of the planet's climate history. With AI-driven change detection applied to temporal HiRISE images, they created a comprehensive map of mass wasting throughout the NPLD. Su et al. (2024) also present a comparison between their estimated rates of erosion and retreat with those of Fanara et al. (2020) in the scarp studies by the latter. The detection of fallen ice blocks at the base of the scarps by Fanara et al. (2020) theoretically should yield comparable values to that of Su et al. (2024). Nevertheless, retreat rate by Su et al. (2024) surpasses that of Fanara et al. (2020) by an order of magnitude, suggesting a more active erosion process than previously thought. The discrepancy likely reflects the fact that ice fragments breaking into ice blocks also produce an additional, substantial quantity of fine and pulverized materials that are not visible at HiRISE scale and thus are undetectable by the method used by Fanara et al. (2020). However, biases and uncertainties in Su's estimates can also be responsible. For example, Su et al. assumed that the thickness of the ice fragments was homogeneous, which could possibly lead to large approximation errors.