Global Simulation of Shallow Subsurface Water Inventory on Mars with Adsorption Effects

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Introduction:

The regolith, which is loose, unconsolidated material consisting of fine dust, sand, and fragmented rock, is one of the main water reservoirs on Mars. Not only stable ice table in high latitudes, but also the regolith holds appreciable amounts of adsorbed water in the shallow subsurface. Adsorption isotherms determined by laboratory experiments demonstrated that the adsorbed water mass increases with decreasing temperature and increasing water vapor [1–4].

Global maps of Water Equivalent Hydrogen (WEH) have been provided by the Gamma-Ray Spectrometer (GRS) onboard the 2001 Mars Odyssey orbiter. The observations revealed 20–100 wt% WEH around the north pole, 20–50 wt% WEH around the south pole, and 2–10 wt% WEH in low and middle latitudes [5,6]. However, the substantial WEH up to 10 wt% around Arabia Terra and Medusae Fossae in low and middle latitudes remains unexplained. Water ice is unstable in the shallow subsurface equatorward of ±50° on present-day Mars [7–13], suggesting that adsorbed water is a potential factor influencing the high WEH at several locations in low and middle latitudes. Most previous global modeling studies of subsurface water distributions ignored adsorption effects by the regolith to reduce computational costs or assumed a globally homogeneous regolith [11,12, 14–17]. In addition, these studies focused on the water vapor exchange between the regolith and the atmosphere rather than the subsurface water inventory. Hence, this study estimates the water inventory in the shallow subsurface, using a regolith model that considers the adsorption effects with inhomogeneous regolith properties, extending the integration time compared to 500 Martian years of Kobayashi et al. (2025) to compute the converged water mass at deeper layers more than 1 m.

Methods:

Regolith model: The regolith model computes water vapor diffusion, adsorption, and condensation in the regolith [18]. Input parameters for the regolith model are obtained by a Mars Global Climate Model (MGCM), which considers the formation of seasonal water ice caps and surface frost, turbulent flux at the surface, and simple cloud formation based on the large-scale condensation [18–21]. The adsorbed water mass is determined by the adsorption isotherm of Jakosky et al. (1997), but the adsorption coefficient is considered a free parameter. We examine several adsorption coefficients, including zero and the inhomogeneous adsorption coefficients estimated by the regolith property model below.

Regolith property model: The regolith property model simulates inhomogeneous grain sizes, pore sizes, porosities, and adsorption coefficients, based on the laboratory experiments [22–26] and the retrieved nighttime thermal inertia [27].

Time integration: The subsurface water mass is calculated by integrating the regolith model over tens of thousands of years, considering the diurnal and seasonal variations of the water cycle obtained by MGCM. The water vapor and adsorbed water masses at 5 m converge in ten thousand Martian years.

Results and Implications:

Our results show that the regolith holds 0.2–2 kg m^{-2} of adsorbed water within 1 m, corresponding to 0.0133–0.133 wt%, in the case of a homogeneous adsorption coefficient of 46.20 kg m^{-3}. The adsorbed water mass increases with latitudes up to ±60°, where the annual mean surface temperature is 195 K, and rapidly decreases in higher latitudes. With inhomogeneous adsorption coefficients, the adsorbed water mass strongly depends on the adsorption coefficient. The equator regions around Arabia Terra, Alba Patera, and Amazonis Planitia hold 2–5 kg m^{-2} of adsorbed water within a depth of 1 m, corresponding to 0.133–0.332 wt%. In the other areas around the equator, there is 0.05–0.2 kg m^{-2} of adsorbed water within a depth of 1 m. The adsorption isotherm shows that the adsorbed water mass is proportional to the adsorption coefficient, and the adsorption coefficient ranges from 20 kg m^{-3} to 400 kg m^{-3}.

The regolith within 1 m contains 10^{-6}–10^{-5} kg m^{-2} of water vapor. There is more water in areas with low geopotential height, with plenty of atmospheric water vapor. High latitudes contain less water vapor because of less saturated water content. In the case of inhomogeneous adsorption coefficients, there is less water vapor in areas with high adsorption coefficients since the regolith with high adsorption coefficients reaches an equilibrium of less water vapor and more adsorbed water at the same temperature, based on the adsorption isotherm. This leads to smaller water vapor fluxes at the surface, because the water flux due to diffusion is determined by the diffusion coefficient and the gradient of the water vapor concentration between adjacent layers. In the context of long-term water retention on Mars, highly adsorptive regolith plays a role in retaining subsurface water, decelerating water transport in the regolith.

The pore ice mass increases towards high latitudes and deep layers. In high latitudes, pore ice can exist in the shallower layers, such as 0.15 m. The shallower layers polewards of ±45° hold a small amount of pore ice, suggesting that there is seasonal ice in the regolith. The regolith with higher adsorption coefficients holds more pore ice in the shallow layer, such as 0.01–0.2 kg m^{-3}, suggesting that the adsorbed water accumulated in summer turns into pore ice during winter before the adsorbed water diffuses into the atmosphere. Note that the adsorbed water mass decreases with ground temperature because the saturated water content exponentially decreases, although the adsorption isotherm shows an increase in adsorbed water with decreasing temperature.

Therefore, our results of the subsurface water mass indicate that the higher adsorptive regolith in low and middle latitudes is qualitatively consistent with the high concentration of WEH distribution. However, the computed adsorbed water mass is one order to two orders of magnitude less than the estimated WEH at the equator, suggesting that a large portion of the estimated WEH is stored as hydrous minerals rather than water molecules. Our results also indicate that the roles of the adsorbed water are 1) to substitute for pore ice during summer in the shallow layers in middle and high latitudes, and 2) to retain subsurface water by decelerating water transport due to less water vapor mass in equilibrium with highly adsorptive regolith.

References:

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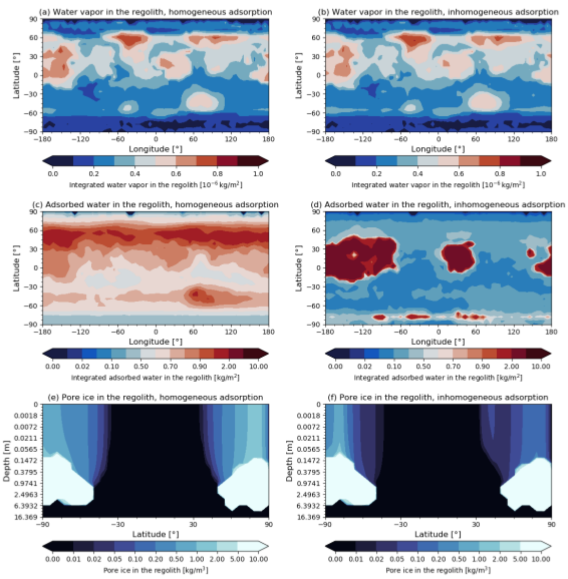

Figure. The annual mean subsurface water mass. The spatial distributions of the water vapor mass per unit volume of the regolith integrated down to 1 m (a, b), of the adsorbed water mass per unit volume of the regolith integrated down to 1 m (c, d), and the vertical distributions of the pore ice mass per unit volume of the regolith (e, f). The left column exhibits the case of a homogeneous adsorption coefficient of 46.20 kg m^{-3}, and the right column exhibits the case of inhomogeneous adsorption coefficients.