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Seasonal Water "Pump" in the Atmosphere of Mars: Vertical Transport to the Thermosphere

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Abstract

We present results of simulations with the Max Planck Institute general circulation model (MPI–MGCM) implementing a hydrological cycle scheme. The simulations reveal a seasonal water "pump" mechanism responsible for the upward transport of water vapor. This mechanism occurs in high latitudes above 60° of the southern hemisphere at perihelion, when the upward branch of the meridional circulation is particularly strong. A combination of the mean vertical flux with variations induced by solar tides facilitates penetration of water across the "bottleneck" at approximately 60 km. The meridional circulation then transports water across the globe to the northern hemisphere. Since the intensity of the meridional cell is tightly controlled by airborne dust, the water abundance in the thermosphere strongly increases during dust storms.

1. Introduction

Water is a minor component of the Martian atmosphere, which is largely confined within a few lower scale heights. Nevertheless, it is the main source of hydrogen in the upper atmosphere [13, 19, 14]. Escape of hydrogen atoms into space near the exobase varies by an order of magnitude seasonally, maximizing around southern summer solstice (solar longitude $L_s \approx 270^\circ$), according to MAVEN [10] and HST observations [2] during dust storms [1, 3, 6, 7]. Observed water in the lower atmosphere also experiences strong seasonal changes and depends on airborne dust load [25, 16, 26, 20]. This implies a link between water in the troposphere and thermosphere and a corresponding mechanism of transport between the layers.

The Martian middle atmosphere is too cold to sustain water vapor, especially around the mesopause, while ice particles are sufficiently heavy and prone to sedimentation. This water behavior is similar to that in the terrestrial middle atmosphere [21]. However, there are multiple observations showing a presence of water vapor in the middle atmosphere at certain locations and times [18, 9]. Heavens et al. [12] and Fedorova et al. [9] provided evidence of strong seasonal variations of the globally averaged water abundance and its vertical extension up to 70-80 km at perihelion during the Martian Year 28 (MY28) global dust storm. Hypotheses concerning the mechanism of vertical transport of water include mesoscale deep convection [12], turbulent mixing in the lower atmosphere and/or an unspecified dynamics in the upper atmosphere [8]. General circulation modeling underestimates the hygropause altitude at southern summer solstice to date [5, 20].

Our study addresses this gap in knowledge of processes that couple water in the lower and upper atmosphere. We present results of simulations with our recently developed hydrological scheme [22] implemented in the Max Planck Institute Martian general circulation model (MPI–MGCM). This is the first modeling study that considers in detail the transport of water from the surface to the thermosphere and explores its dependence on dust storms [24].

2. Main Results and Conclusions

Several mechanisms have been proposed to explain the observed presence of water in the middle atmosphere of Mars above 60 km. Maltagliati et al. [17] suggested supersaturation of water vapor due to purely microphysical reasons (lack of condensation nuclei). Clarke et al. [8] considered the dynamics and hypothesized that either turbulent mixing in the lower atmosphere raises water vapor upward, or the strengthened by solar UV circulation in the upper atmosphere facilitates this transport. Heavens et al. [12] attributed the appearance of water vapor and ice at upper levels to deep convection enhanced dust storms. Our simulations with the general circulation model revealed the full picture of water transport from the ground up to the thermosphere. The main findings are the following.

- Water is lifted up in high latitudes of the summer hemisphere by the upward branch of the pole-to-pole meridional circulation cell. It is then transported by the latter across latitudes in the mesosphere and thermosphere.

- Water can penetrate upper levels only during the perihelion season, when the meridional circulation cell is sufficiently strong.

- The influx of water to the middle and upper atmosphere increases, whenever the meridional cell intensifies, for instance, during dust storms. In addition, dust storm-induced heating increases the amount of water vapor in the lower atmosphere.

- Upward transport of water is significantly modulated by the solar tide. The latter acts as a "pump" by increasing the transport during certain local times and almost completely shutting it down during the others.

The described transport of water to the Martian upper atmosphere has some similarities and differences with that on Earth. In the terrestrial stratosphere and mesosphere, there is also a strong water upwelling in the summer hemisphere that even compensates for photochemical destruction [11]. Due to the circular orbit and unlike on Mars, it occurs during both solstices. However, water in the terrestrial atmosphere is rapidly destroyed by photolysis in the sun-lit summer hemisphere below 70 km, whereas on Mars its significant portion can be transported across the globe.

Photochemical calculations [4, 15] suggest that water abundances of $\sim$80 ppmv at 60–80 km can explain the observed magnitudes of hydrogen escape at the exobase. Our simulations show that, even at dustless seasons, the circulation can deliver these amounts of water over the southern high latitudes, at least during certain local times. Moreover, comparable abundances of vapor are distributed by the circulation over all latitudes above $\sim$120 km. During major dust storms (similar to that of MY28), the corresponding water abundances increase by a factor 2 and more. Overall, our simulations at least partly reconcile the existing observations and estimates, reveal the impact of planetary-scale circulations on the behavior of water in the middle and upper atmosphere, and provide testable predictions for evaluating alternative hypotheses against future observations.

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The data supporting the MPI-MGCM simulations can be found at https://mars.mipt.ru, https://zenodo.org/record/1553514 [23] or obtained from D. Shaposhnikov (shaposhnikov@phystech.edu).

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