Comparative Analysis of Tropospheric Water Isotope Distributions on Mars and Earth: Insights into Ice Cloud Microphysical Processes and Storm Dynamics

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Introduction:

Stable water isotopes are powerful tracers for studying planetary water cycles and quantifying the influence of key atmospheric processes [1,2]. In particular, the HDO/H_2O ratio (commonly expressed as D/H) records the history of phase changes, transport, and atmospheric escape. It is therefore essential for interpreting both present-day and ancient water cycles.

On Mars, the atmospheric D/H ratio is approximately 5–7 times higher than on Earth, a signature commonly attributed to preferential escape of lighter hydrogen following photodissociation of water in the upper atmosphere. This enrichment has been used to infer the cumulative loss of water over geological time[3]. However, recent studies suggest that tropospheric fractionation—prior to vapor reaching the upper atmosphere—may alter D/H ratios and introduce uncertainty into such reconstructions[4,5].

To address this, we focus on the isotopic behavior of water vapor within the Martian troposphere and compare it with that on Earth. Specifically, we ask:

What are the similarities and differences in isotopic processes between Mars and Earth?

Can a unified theoretical framework explain the isotopic distributions on both planets?

By comparing the spatio-temporal patterns and fractionation controls of D/H in the tropospheres of Mars and Earth, this study seeks to identify the key drivers of isotopic variation on each planet and evaluate their implications for the atmospheric evolution and water budgets.

Evolution during storms

We use the MPCM and LMDZ general circulation models to simulate D/H evolution on Mars and Earth. On Mars, the global dust storm in MY34 begins around solar longitude (Ls)≈ 185° [6], during which D/H increases and gradually extends to higher altitudes. The enrichment weakens as the storm decays around Ls ≈ 210° (Fig.1a). The comparison with the calmer MY35 confirms that D/H is consistently elevated during the storm period (Fig.1b and Fig.2a).

This enrichment arises from key Mars-specific atmospheric conditions: increased dust and higher temperatures suppress condensation, allowing heavier isotopologues (HDO) to remain in the vapor phase [4]. In addition, because there is no liquid water, neither rainout nor raindrop evaporation occurs.

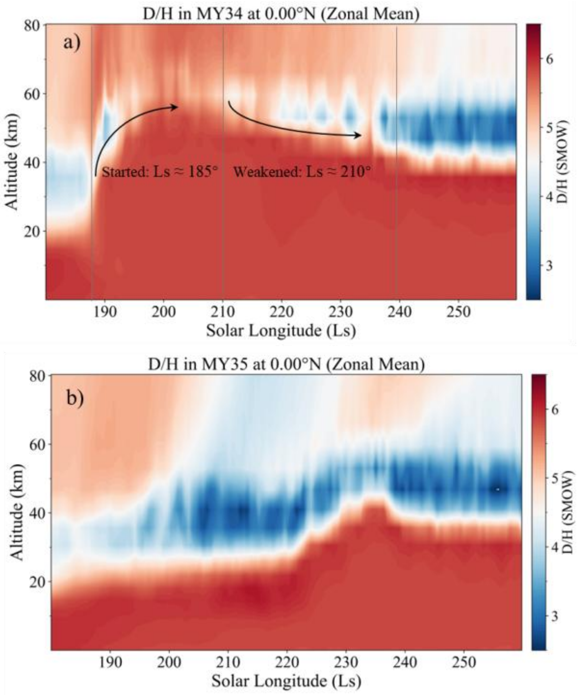

Fig.1 Zonal-mean D/H profiles at 0°N in (a) MY34 (global storm) and (b) MY35 (no global storm).

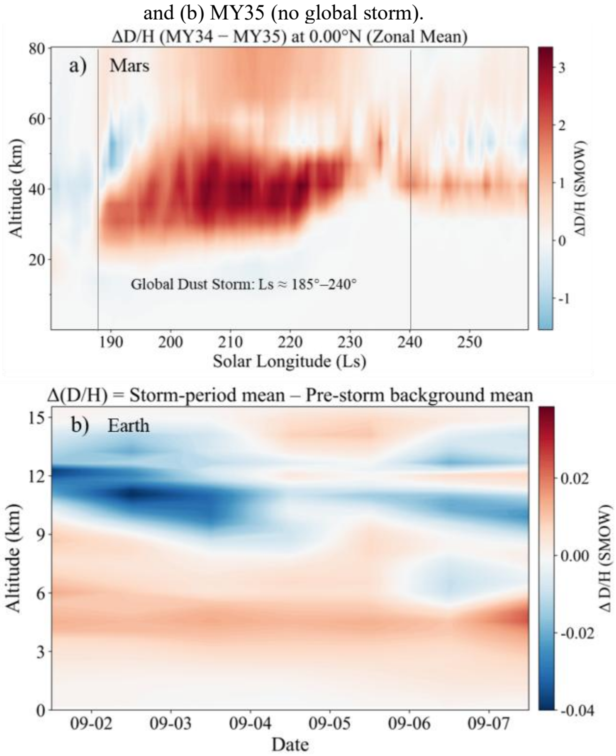

Fig.2 ΔD/H: (a) Mars (MY34 − MY35) shows D/H enhancement during the global dust storm; (b) Earth shows D/H depletion during the storm period relative to the pre-storm mean.

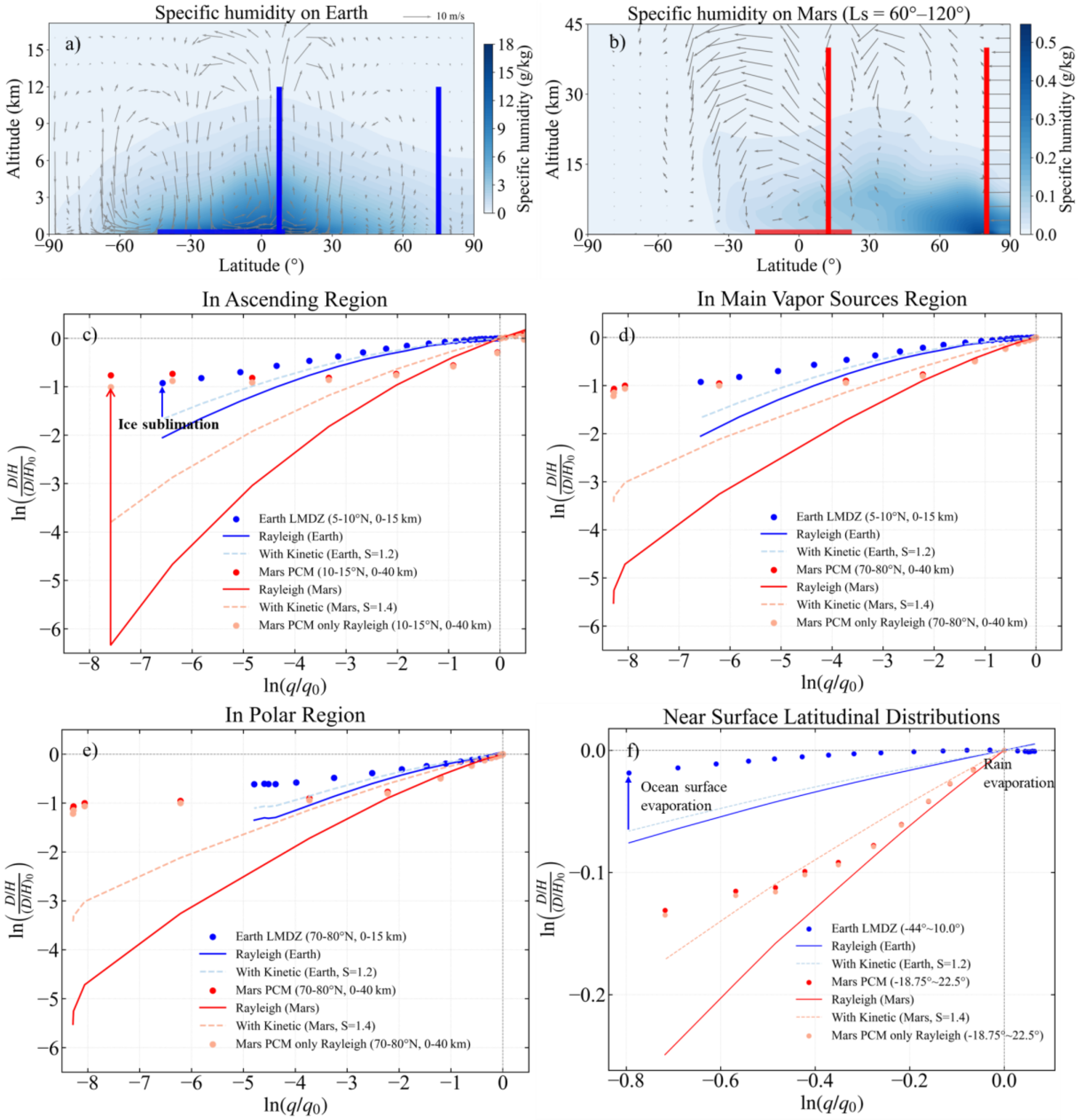

Fig.3 (a–b) Zonal-mean specific humidity and circulation on Earth (a) and Mars (b); (c-f) ln (R/R_0) vs. ln (q/q_0) relationship compared with Rayleigh and kinetic models in the ascending region (c), vapor source region (d), polar region (e), and near-surface latitudinal distributions (f).

In contrast, on Earth, during the Typhoon Haishen event, D/H ratios decrease relative to values observed two weeks prior (Fig.2b). The most pronounced depletion occurs between 6 and 12 km altitude and is primarily attributed to raindrop evaporation within convective clouds, which preferentially removes lighter isotopologues into vapor while retaining heavier isotopes in the liquid phase, thereby lowering the D/H ratio of the surrounding water vapor [7]. The degree of depletion varies across different periods and is related to storm intensity and type [8].

Ice cloud microphysical processes

On Earth, water vapor primarily originates from ocean surface evaporation in low latitudes and is transported poleward by the Hadley circulation (Fig.3a). In contrast, on Mars, atmospheric water vapor is mainly sourced from the sublimation of polar ice, particularly from the northern cap during spring and summer (Fig.3b).

To investigate isotopic fractionation during vertical transport, we analyzed isotopic profiles extracted from the ascending branches of the Hadley circulation, the main vapor source regions, and the polar regions on both planets (Fig. 3c–f). The relationship between humidity and isotopic composition represented using ln (R/R_0) vs. ln (q/q_0) serve to trace how isotopic fractionation evolves with progressive condensation, mixing, evaporation and sublimation [9]. R and q denote the D/H ratio and specific humidity, respectively, and subscript "0" indicates near-surface reference values. This normalization allows us to isolate the effects of atmospheric processes from initial boundary conditions.

Under ideal equilibrium conditions, condensation preferentially removes heavier isotopologues, causing vapor to become isotopically lighter with decreasing humidity. This process, known as Rayleigh distillation, is governed by equilibrium fractionation, which depends strongly on temperature [10]. However, in our simulations, data points from both Earth and Mars consistently lie above their respective Rayleigh curves (Fig. 3c–f), suggesting systematic enrichment in heavy isotopes due to non-equilibrium processes.

This isotopic anomaly is likely driven by the formation and persistence of ice clouds[9,11,12]. When ice particles sublimate in warmer or subsaturated atmospheric layers, they release previously retained heavy isotopologues back into the vapor phase, enriching the surrounding air in HDO. This effect is much more pronounced on Mars, where low atmospheric pressure, extremely low temperatures, strong vertical temperature gradients, and long residence times of ice particles enhance the impact of ice sublimation on vapor isotopic composition.

The latitudinal transect (Fig. 3f) further reveals the latitudinal signature of microphysical processes affecting vapor isotopes. On the Earth, deviations from Rayleigh predictions are buffered by ocean surface evaporation, which is itself enriched in heavy isotopes and moderates vapor depletion. Conversely, on Mars, the vapor D/H at low latitudes remains strongly enriched, consistent with sublimation-dominated moisture sources.

The systematic offset from Rayleigh expectations across diverse regions underscores the dominant influence of ice cloud microphysics on the isotopic structure of planetary tropospheres.

On both planets, the isotopic effects of ice sublimation are most prominent within ascending regions. This likely due to enhanced vertical transport, stronger temperature contrasts, and more frequent condensation–sublimation cycles in dynamically active zones.

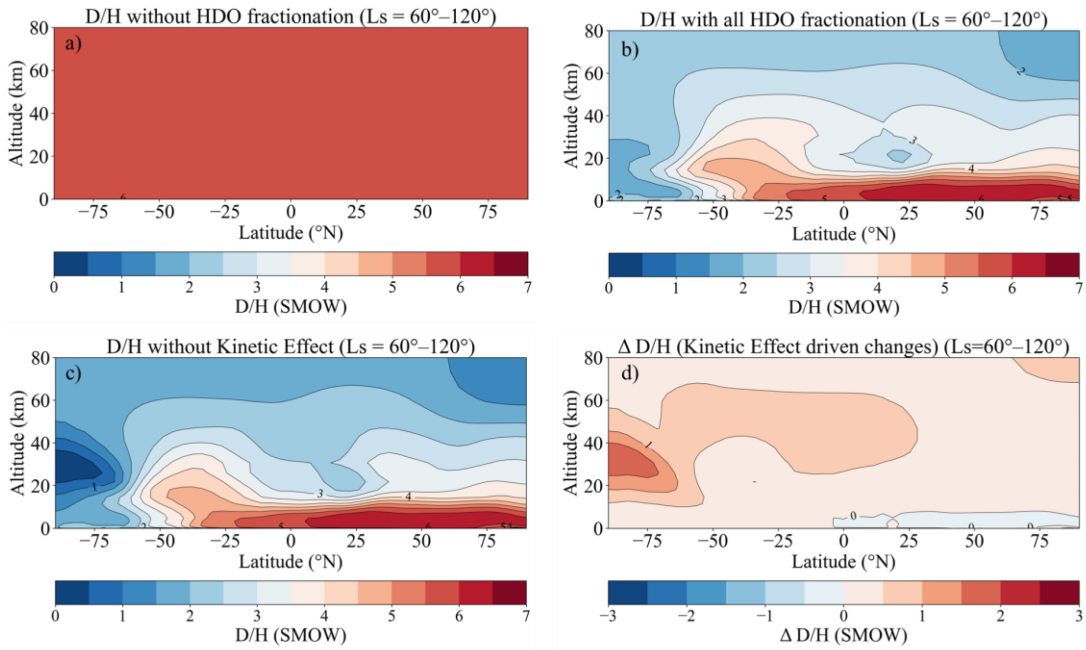

Fig.4 Latitudinal-altitudinal D/H distributions under different fractionation scenarios during Ls = 60°–120° on Mars: (a) No HDO fractionation; (b) Full HDO fractionation;(c) Without kinetic effect; (d) ΔD/H due to kinetic effect.

Kinetic effect

To assess the impact of kinetic fractionation, we conducted a set of simulations under three scenarios: without any isotopic fractionation (Fig. 4a), with all fractionation processes included (Fig. 4b), and with only equilibrium fractionation (Fig. 4c). The difference between the full and equilibrium-only cases (Fig. 4d) reveals that kinetic effects can enhance D/H ratios by up to ~2.5 SMOW units.

Conclusion

Our findings highlight two key processes—storm activity and ice particle sublimation—that contribute to elevated D/H ratios in Martian water vapor. These processes significantly modify the isotopic composition of water before it reaches the upper atmosphere, thereby altering the baseline for interpreting atmospheric escape. Accurate reconstructions of past water loss and ancient water inventories on Mars thus require careful consideration of these lower-atmosphere influences. Among them, isotopic enrichment caused by ice sublimation is particularly pronounced on Mars, markedly stronger than on Earth. While storms on Earth tend to lower tropospheric D/H ratios, Martian storms increase them. Despite this contrast, water isotopes on both planets effectively track storm onset and decay, suggesting their potential as sensitive tracers for reconstructing storm history and intensity across planetary environments. In addition, the kinetic isotope effect plays a critical role in modulating isotopic fractionation during these phase transitions and is also more influential under Martian atmospheric conditions.

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