Supporting Information for ”Rain evaporation, snow melt and entrainment at the heart of water vapor isotopic variations in the tropical troposphere, according to large-eddy simulations and a two-column model”

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Introduction

This supporting information assess the robustness of the results with respect to the definition for clouds and the environment (Text S1) and details how the simple equation for rain evaporation is derived (Text S2).

Text S1: Robustness of the results with respect to the definition for clouds and the environment

In our simple two-column framework, we decide to separate cloudy regions from their environment based on a threshold on cloud water content (e.g. Thayer-Calder and Randall (2015)): we define parcels as "cloudy" when the cloud water content exceeds 10^{-6} g/kg. In the previous studies, alternative definitions have been based on vertical velocity (e.g. Hohenegger and Bretherton (2011)) and/or buoyancy (e.g. Siebesma and Cuijpers (1995)), or position in altitude-equilvalent potential temperature diagrams (Pauluis & Mrowiec, 2013). We thus test here the robustness of our results to different definitions, by defining "very cloudy regions" with cloud water content larger than 10^{-3} g/kg, "cloudy updrafts" with cloud water content larger than 10^{-6} g/kg and ascending vertical velocity, "saturated drafts" with relative humidity larger than 99%, "nearly-saturated drafts" with relative humidity larger than 95%, and (7) "moist static energy updrafts" including all parcels falling into bins of frozen moist static energy in which the vertical velocity is positive (Pauluis & Mrowiec, 2013).

"Cloudy updrafts" and "nearly-saturated regions" are the most and least restrictive definitions respectively (Figure S1a,f). In all definitions, the cloudy region fraction remains below 10% except in the free lower and middle troposphere. In stricter definitions, the cloudy regions are characterized by a larger vertical velocity (Figure S1b) and a larger cloud water content (not shown). The entrainment is not strongly sensitive to the definition in the free troposphere (Figure S1c).

The ratio of the isotopic ratio in the rain evaporation over that in the environment vapor ($\phi = R_{ev}/R_v$) is not very sensitive to the definition for the ctrl (Figure S1e), but its value near the melting level is quite sensitive (Figure S1g). In all definitions, we can see the negative anomaly near the melting level, but it is much more negative in the loosest definitions. This is because in stricter definitions, the non-fractionating evaporation of cloud water droplets takes place in the environment. Since droplet evaporation takes place in shells around convective updrafts, and does not directly affect the environment, we chose a loose definition for the "cloudy regions".

The ratio of the large-scale mass flux over the cloudy mass flux, η, for HighPrec is larger in loose definitions (Figure S1h). This is because the cloudy regions incorporates cloudy downdrafts that compensate for the upward mass flux in cloudy updrafts. This large η in the loose definition may contribute to the overestimate of the direct effect of large-scale forcing on δD by the two-column model, and ultimately to the underestimate of the "vapor amount efect".

Text S2: Simple equation for rain evaporation

The quick equilibration between the rain and vapor motivates us to use a simple equation in which some mass q_{l0} of rain, with isotopic ratio R_{l0}, partially evaporates and isotopically equilibrates with some mass q_{e0} of vapor (subscript e for environment), with isotopic ratio R_{e0}. After the evaporation and equilibration process, the masses of rain and vapor are noted q_l and q_v:

$$q_l = q_{l0} - q_{ev}$$

$$q_e = q_{e0} + q_{ev}$$

where q_{ev} is the mass of evaporated rain water. The corresponding isotopic budget writes:

$$R_l \cdot q_l = R_{l0} \cdot q_{l0} - R_{ev} \cdot q_{ev}$$

$$R_e \cdot q_e = R_{v0} \cdot q_{v0} + R_{ev} \cdot q_{ev}$$

where R_l, R_e and R_{ev} are isotopic ratios in the final rain, final vapor and evaporation flux. Isotopic equilibrium writes:

$$R_l = \alpha_{eq} \cdot R_e$$

where α_{eq} is the equilibrium fractionation coefficient.

We define:

$$f_{ev} = \frac{q_{ev}}{q_{l0}}$$

$$g = \frac{q_{l0}}{q_{e0}}$$

$$\lambda = \frac{R_{l0}}{R_{e0}}$$

$$\phi = \frac{R_{ev}}{R_{e0}}$$

Re-arranging these equations, we get:

$$\phi = \frac{\lambda \cdot (1 + f \cdot g) - (1 - f) \cdot \alpha}{f \cdot (g \cdot (1 - f) \cdot \alpha + 1 + f \cdot g)}$$

If the mass of rain is much greater than than of vapor, i.e. $g \gg 1$, the equation becomes:

$$\phi = \frac{\lambda}{1 + (1 - f_{ev}) \cdot (\alpha_{eq} - 1)}$$

Therefore, ϕ scales with λ. In addition, ϕ increases with f_{ev} from $\phi = \lambda/\alpha_{eq}$ for $f_{ev} = 0$ (first order approximation) to $\phi = \lambda$ pour $f_{ev} = 1$ (total evaporation).

References

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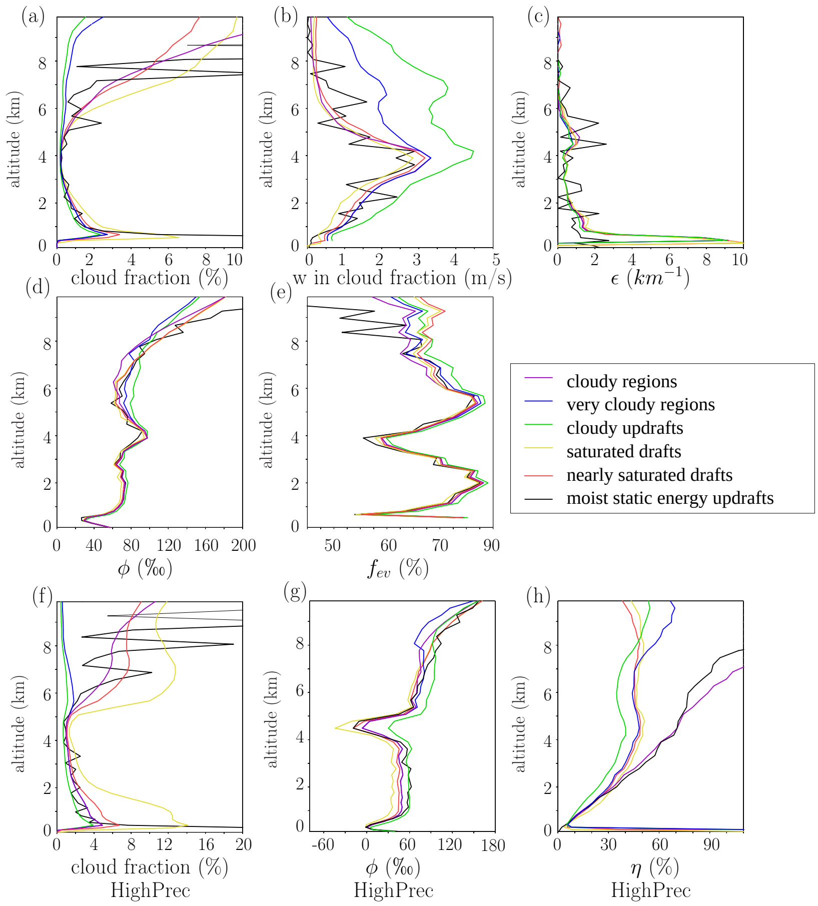

Figure S1. (a-e): Vertical profiles for the ctrl simulation. (a) fraction of the domain-area covered by cloudy regions. (b) Vertical velocity w in average over the cloudy regions. (c) Entrainement rate ϵ diagnosed from the frozen moist static energy budget as explained in the article. (d) $\phi = R_{ev}/R_e$, expressed in ‰; (e) rain evaporated fraction f_{ev}. The different colors show the different definitions for the cloudy regions: "cloudy regions" (purple), "very cloudy regions" (blue), "cloudy updrafts" (green), "saturated drafts" (yellow), "nearly saturated drafts" (red), and "moist static energy updrafts" (black). (f) Same as (a) but for HighPrec. (g) Same as (d) but for HighPrec. (h) Ratio of the large-scale mass flux over the cloudy mass flux, η, for HighPrec.