

# Sub-cloud rain evaporation obscures water-cycle intensification

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## Article

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# Sub-cloud rain evaporation obscures water-cycle intensification

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## Abstract

Understanding how rainfall responds to global warming is central to the hydrological cycle, yet processes shaping rainfall before it reaches the surface remain poorly understood. A substantial portion of rain can evaporate below cloud, altering lower-atmospheric heat and moisture budgets and surface rainfall, but this process is difficult to measure and poorly constrained in simulations. Here, we combine satellite and reanalysis datasets to analyze rain evaporation from 2006-2020. We show that rain evaporated percent (REP) and evaporation flux (Flux) have distinct spatial patterns: REP is largest in weak-rain regimes, whereas Flux is largest in rain-rich tropical regimes. Flux is controlled by rain amount and drop size, while REP is shaped by thermodynamic state. Water vapor isotopes provide a novel metric differentiating top-heavy from bottom-heavy evaporation profiles. Over the 15-year record, weakening evaporation partly masks declines in cloud-base rain in weak-rain regimes, whereas strengthening evaporation damps increasing cloud-base rain in intense-rain regimes. These effects obscure dry-gets-drier and wet-gets-wetter signals. Our analyses distinguish two regimes: one where sub-cloud evaporation efficiently reduces surface rainfall and water availability, and another where evaporation is energetically important for atmospheric circulation. Constraining both is critical for evaluating whether models reproduce water-cycle changes in a warming climate.

Sub-cloud rain evaporation is the partial or complete evaporation of falling hydrometeors in the unsaturated layer between cloud-base and the surface. It controls how much condensed water reaches the surface as rain and modifies boundary-layer heat and moisture budgets, with potential effects on cloud cover and albedo<sup>1;2</sup>. Limited direct observations leave its contributions to water cycle processes poorly constrained. In marine low-cloud regimes, rain sedimentation and below-cloud evaporation are central to the stratocumulus water budget and cloud-layer decoupling, but process-level understanding remains elusive<sup>3-6</sup>. Sub-cloud evaporation of drizzle generated in penetrative cumulus can accelerate the stratocumulus-to-cumulus transition<sup>7</sup>, while rain evaporation can either maintain cloud by moistening the sub-cloud layer or erode it via warming and drying, depending on environmental conditions<sup>1</sup>. Evaporation-driven cooling also strengthens downdrafts and cold pools that modulate convective organization and cloud evolution, key targets for advancing numerical models<sup>3;5;8-18</sup>.

Despite its role in lower-atmospheric heat and moisture redistribution and surface precipitation, rain evaporation remains poorly constrained in simulations, and GCM representation of rain evaporation produces persistent biases in surface rain amount. Department of Energy Atmospheric Radiation Measurement (ARM) observations show that the ECMWF model produces precipitation too frequently and too little sub-cloud evaporation, leading to excessive surface rain and compensating errors in low-cloud water<sup>19</sup>. Similarly, E3SMv1 exhibits unrealistically small rain-evaporation fractions and near-surface evaporation, despite realistic cloud evolution<sup>20</sup>. These results suggest that misrepresented sub-cloud evaporation contributes to energy and moisture budget errors and requires stronger observational constraints.

Most observational studies are also limited in space and time. Aircraft observations showed strong evaporation below marine stratocumulus off southern California, with frequent complete drop evaporation except in deeper sub-cloud layers<sup>21</sup>. More recent profiling and scanning radar studies confirm frequent sub-cloud evaporation in tropical and subtropical shallow-cloud environments<sup>12;22-26</sup>. Yet, little is known outside these geographically limited regions.

Satellite platforms offer global, long-term measurements. Their value for global precipitation is well established<sup>27-29</sup>, and their value for evaluating hydrometeor evaporation is emerging. Three spaceborne radars showed that completely evaporating shallow rain occurs in over 30-50% of precipitating profiles in arid regions, demonstrating that evaporation can strongly limit surface rain<sup>30</sup>. Over southeastern Pacific marine stratocumulus, CloudSat retrievals indicate that 50-80% of shallow low-cloud rain evaporates before reaching the surface, where more than 70% of rain occurs as evaporation-prone weak drizzle<sup>31</sup>. Together, these studies show that sub-cloud evaporation is widespread and can remove a substantial fraction of falling rain.

Rain evaporation can be characterized by the percent of falling rain removed, or rain evaporated percent (REP), and the latent flux associated with the amount evaporated (Flux). REP measures how efficiently evaporation reduces rain reaching the surface, whereas Flux measures associated latent cooling and moistening. No study has mapped this distinction globally. Here, we analyze rain rate, REP, and Flux using CloudSat, AIRS and ERA5 products for 2006-2020. We organize observations into low-, mid-, and high-Flux regimes to distinguish weak-rain efficient evaporation from rain-rich, energetically important evaporation. We then examine how evaporation modifies 15-year cloud-base and surface-rain trends and whether it masks expected hydrologic intensification<sup>32;33</sup>. Finally, we use stable water isotope ratios to evaluate the vertical structure of evaporation and distinguish top-heavy from bottom-heavy profiles. These analyses constrain how rain evaporation redistributes water and energy in the lower troposphere and affects hydrological cycle change.

## Results

### Rain evaporation percent efficiency and energetics are distinct

Evaluating 15 years (2006-2020) of CloudSat rain retrievals with AIRS and ERA5 environmental fields (see Methods), we compare rain near cloud-base ( $R_{cb}$ ), surface rain ( $R_{sf}$ ), REP, and Flux.  $R_{cb}$  is largest along the tropical rain belts, the tropical warm pool, the tropical Indian Ocean, and midlatitude storm-track regions (Figure 1a).  $R_{sf}$  follows the same broad pattern but with smaller magnitudes (Figure 1b).

REP has a different spatial structure from either  $R_{cb}$  or  $R_{sf}$ . High REP occurs mainly in weak-rain subtropical ocean regions, including the eastern subtropical basins where small amounts of falling rain can be efficiently evaporated before reaching the surface (Figure 1c). These high-REP regions are associated with drier sub-cloud air, small cloud-base raindrops, and deeper sub-cloud layers, indicated by lower  $RH_{sf}$ , smaller  $D_g$ , and higher cloud-base height (CBH) (Figure 1e,f,h). In contrast, REP is lower across much of the deep tropics, where rain rates are larger and the sub-cloud layer is more humid.

Flux shows a different geography from REP (Figure 1d). The largest Flux occur where falling rain is abundant, especially in tropical rain belts, warm-pool regions, and storm-track zones. These regions do not always have the largest evaporated fraction, but produce strong latent cooling because more rain is available to evaporate. The weakest Flux occur in subtropical low-cloud regions, even where REP is large, showing that high fractional loss does not necessarily imply a large energetic impact. REP measures evaporation efficiency, whereas Flux measures the associated latent cooling.

To identify factors associated with REP or Flux, we investigate their spatial correlations with thermodynamic and microphysical variables. Flux is largest in rain-rich tropical and storm-track regions, where larger  $R_{cb}$  provides more rain to evaporate and larger  $D_g$  is consistent with stronger rain production (Figure 1f). In contrast, REP is organized primarily by  $RH_{sf}$  and CBH, which regulate evaporation potential and raindrop fall distance. Thus, Flux is associated mainly with rain amount, whereas REP reflects how efficiently rain is removed under prevailing microphysical and thermodynamic conditions.

To identify where sub-cloud evaporation may have the most influence on surface rain and lower-atmospheric latent cooling, we classify each grid-month into low-, mid-, or high-Flux regimes (see Methods). Mapping their frequency identifies where weak or strong evaporation persists and provides spatial context for evaluating its effects in climatologically wet and dry regions. At each grid point, we compute the fraction of months assigned to each regime over 2006-2020 (Figure 2). The low-Flux regime occurs most frequently over broad subtropical and high-latitude ocean regions, including eastern subtropical basins and coastal low-cloud regions (Figure 2a). Here, Flux is weak even though fractional rain loss can be large. The high-Flux regime is concentrated in tropical rain belts, the tropical Indian Ocean, and warm-pool regions (Figure 2c), where frequent rain supports strong sub-cloud latent cooling. The mid-Flux regime occupies the transition between these states (Figure 2b). Using this three-regime framework, we next examine whether sub-cloud evaporation modifies cloud-base and surface rain trends differently across regions where Flux is persistently weak or strong.

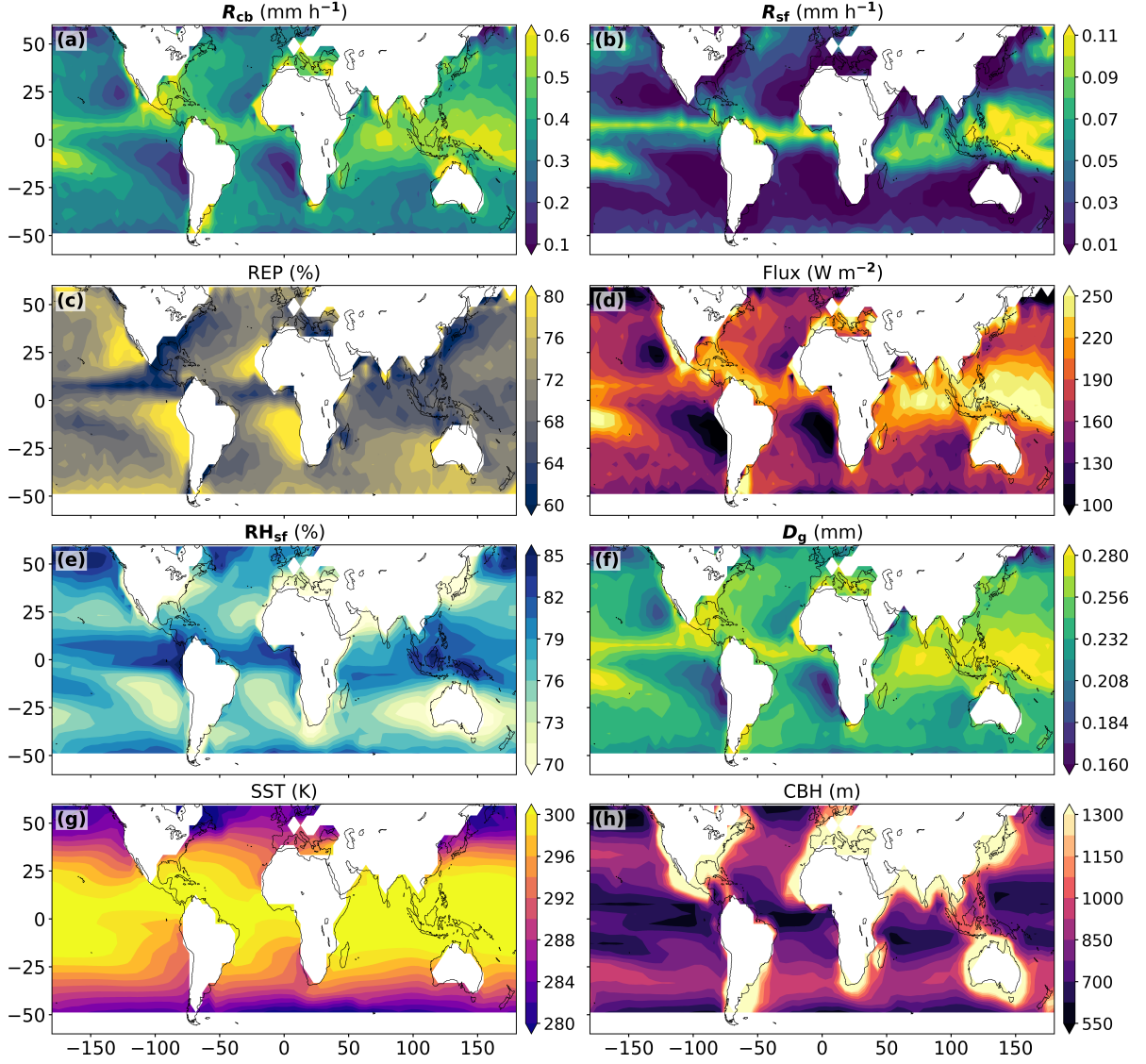


Figure 1: Global 2006-2020 mean fields of (a) Cloud-base rain rate  $R_{cb}$  (mm hr<sup>-1</sup>), (b) surface rain rate  $R_{sf}$  (mm hr<sup>-1</sup>), (c) relative evaporation percentage REP (%), (d) sub-cloud evaporation flux (Flux) (W m<sup>-2</sup>), (e) surface relative humidity  $RH_{sf}$  (%), (f) geometric mean drop diameter,  $D_g$  (mm), (g) sea-surface temperature (K), and (h) cloud-base height, CBH (m).

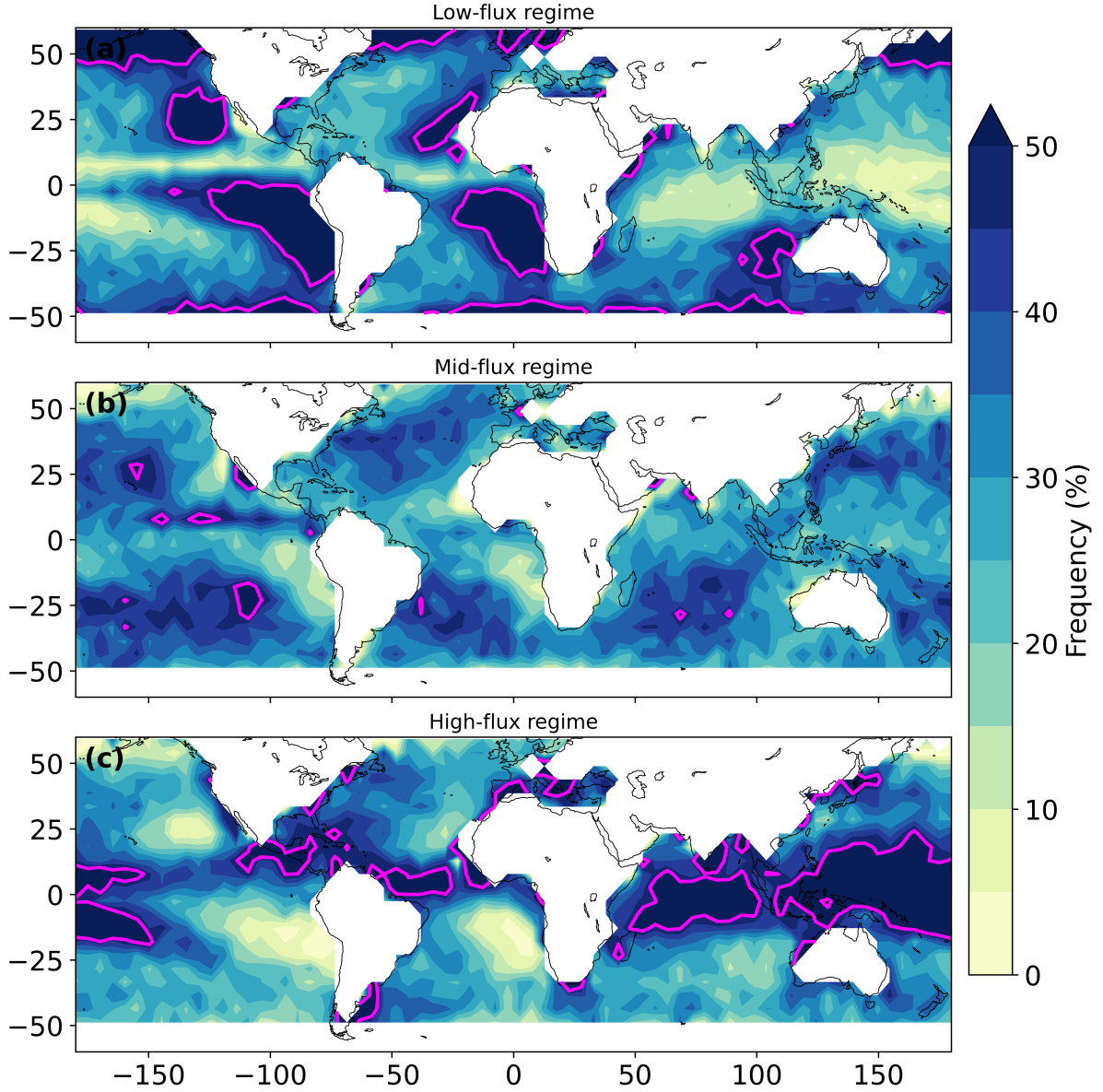


Figure 2: Temporal frequency of occurrence of the (a) low-, (b) mid-, and (c) high-Flux regimes, computed as the fraction of months from 2006-2020 assigned to each regime at every grid point. Regimes are defined from the Flux distribution using 1st-33rd (low), 33rd-66th (mid), and 66th-99th (high) percentile ranges. Thick magenta contours mark 50% occurrence, highlighting where each regime occurs persistently. The three frequencies sum to unity at each grid point.

## Rain evaporation obscures expected trends in surface precipitation

We also examine trends in  $R_{cb}$ ,  $R_{sf}$ , REP, and Flux. Because the Flux regimes occupy distinct climatological rain environments, they allow us to test whether evaporation masks or damps surface rain trends across weak- and intense-rain regions. These regimes reveal that surface rain trends do not directly reflect cloud-base rain changes over 2006-2020 (Figure 3), because sub-cloud evaporation causes cloud-base and surface rain to evolve differently.

In the low-Flux regime, found primarily in climatologically dry areas,  $R_{cb}$  decreases over time, consistent with dry-get-drier predictions. However, this decline is weakly observed at the surface (Panel 3b), due to weakening rain loss below cloud-base (Panel 3d), while fractional loss remains unchanged. As less rain is produced at cloud-base, less is available to evaporate,

121 partly compensating for the decline in  $R_{cb}$ . As a result, the  $R_{sf}$  trend is much weaker than  
 122 the  $R_{cb}$  trend. In this regime, weakening evaporation masks the surface expression of declining  
 123 cloud-base rain.

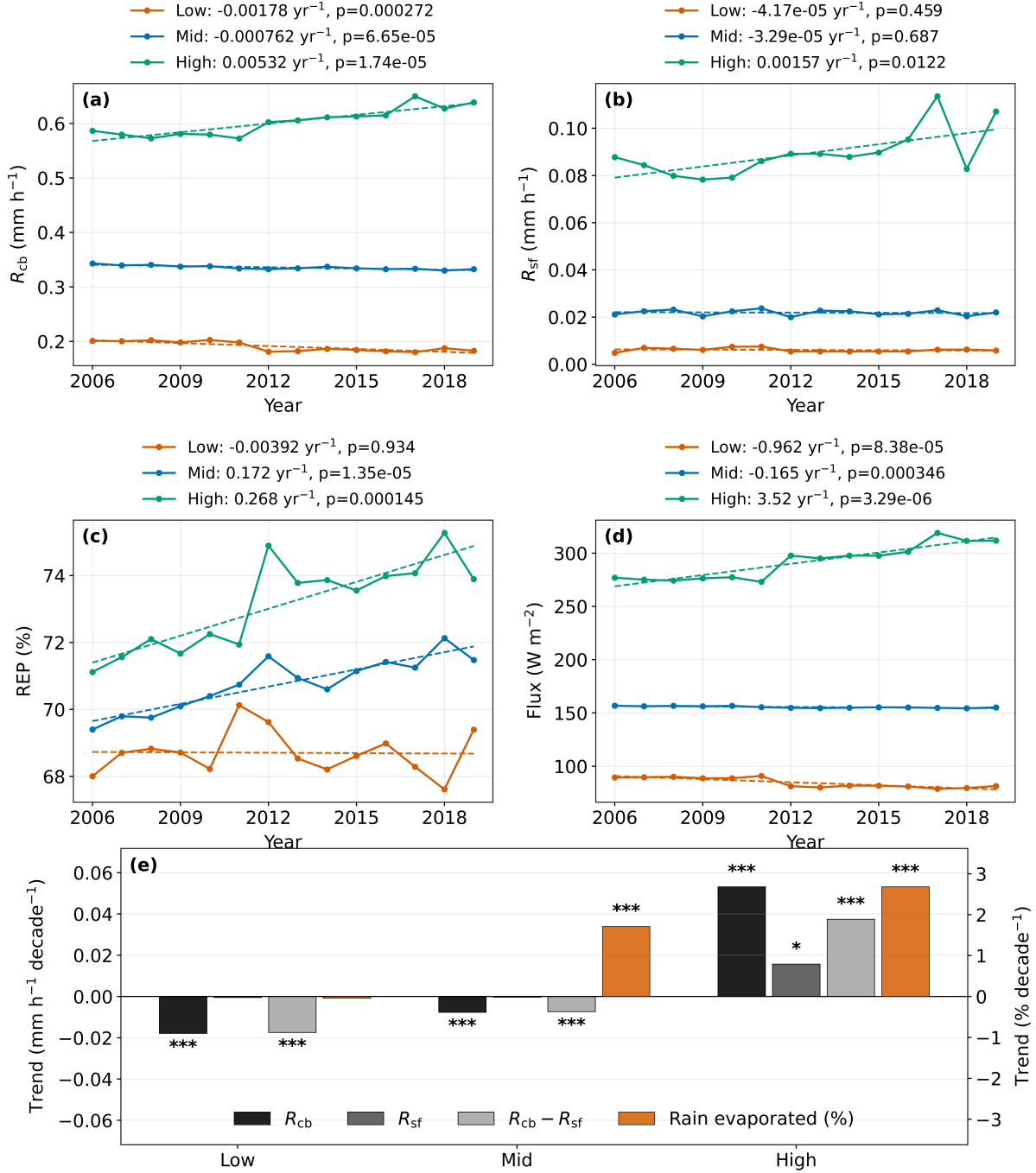


Figure 3: Interannual variability during 2006-2020 in the low-, mid-, and high-Flux regimes for (a) cloud-base rain rate ( $R_{cb}$ ), (b) surface rain rate ( $R_{sf}$ ), (c) rain evaporated %, (d) Flux. Red, blue, and green lines represent the low-, mid-, and high-Flux regimes, respectively. Dashed lines show linear trends, with slopes and p-values reported in the legends. Panel (e) summarizes the decadal trends. The left y-axis shows trends in  $R_{cb}$ ,  $R_{sf}$ , and  $R_{cb} - R_{sf}$ , while the right axis shows trends in percentage of rain evaporated. One, two, and three asterisks indicate statistical significance at  $p \leq 0.05$ ,  $p \leq 0.01$ , and  $p \leq 0.001$ , respectively.

124 The high-Flux regime shows the opposite behavior, with evidence of  $R_{cb}$  increasing over

time.  $R_{sf}$  also increases, but not as strongly as  $R_{cb}$ . Both mass loss (Flux) and fractional loss increase, showing that more rain is removed before reaching the surface and producing greater latent cooling. Thus in high-Flux regions, which manifest primarily in climatologically wet regions, rain evaporation damps the expected wet-get-wetter response in surface rain.

The mid-Flux regime forms a transition between these two responses.  $R_{cb}$  weakens, and  $R_{sf}$  changes less strongly. Fractional rain loss thus increases even when the absolute Flux weakens. This behavior reinforces the distinction between evaporation efficiency and energetic impact.

Together, these trends show that evaporation modifies how changes in cloud rain production appear at the surface. Weakening evaporation in the low-Flux regime allows more  $R_{cb}$  to survive, masking reduced precipitation formation, whereas strengthening evaporation in the high-Flux regime removes more additional rain, damping surface wetting. Observed surface rain trends may therefore understate the magnitude of changes in rain production associated with hydrological intensification as the planet warms.

### Distinct factors control evaporative efficiency vs evaporative mass loss

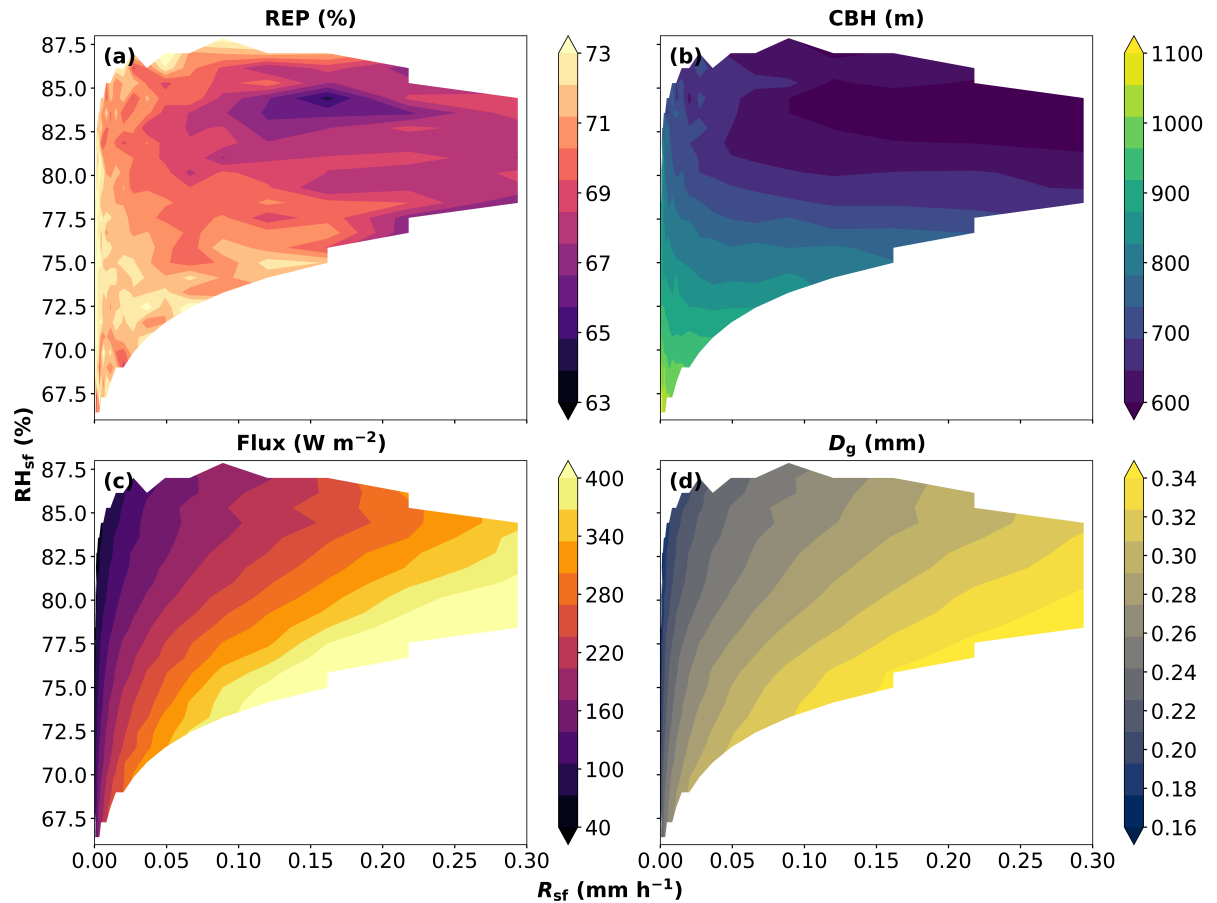


Figure 4: Binned relationships as a function of  $R_{sf}$  and  $RH_{sf}$  for (a) rain evaporated %, (b) cloud-base height (CBH), (c) Flux, and (d) geometric mean raindrop diameter ( $D_g$ ). Values are grid-month means over 2006-2020, and only sufficiently sampled bins with at least 100 samples are shown.

The distinction between REP and Flux reflects distinct controls by rain amount, humidity, CBH, and  $D_g$ . To examine these controls, we bin all months by  $R_{sf}$  and  $RH_{sf}$ , and then evaluate the mean REP, CBH, Flux, and  $D_g$  within each bin (Figure 4). This  $R_{sf}$ - $RH_{sf}$  space separates the rain supply from thermodynamic conditions favoring evaporation. This separation is relevant

to hydrological frameworks that interpret rain changes in terms of climatologically wet and dry regimes, moisture availability, and energetic constraints<sup>32;34</sup>.

REP is largest where  $R_{sf}$  is weak and the sub-cloud layer is comparatively dry. In these conditions, modest absolute rain loss can remove a large fraction of falling rain before it reaches the surface. A drier sub-cloud layer favors evaporation during descent, while small  $R_{sf}$  allows the evaporation amount to represent a large fraction of initial  $R_{cb}$ . REP decreases as  $R_{sf}$  increases, especially in humid environments where more rain survives to the surface.

CBH further reinforces this pattern: higher cloud-bases occur preferentially under weak-rain, dry conditions and provide a deeper sub-cloud layer through which drops can evaporate. Stronger rain, in contrast, is generally associated with lower cloud-bases and more humid air. This combination helps explain why weak-rain regions can have large REP even when their Flux is small.

Flux follows a different structure. It increases mainly with  $R_{sf}$ , because Flux depends on the absolute amount of rain available to evaporate. Dry conditions favor evaporation, but cannot produce large Flux when little rain is falling. Large Flux therefore occurs where rain supply is sufficient, even if the REP is not large. This explains why rain-intense tropical and storm-track regions can have large latent cooling while maintaining only small-to-moderate REP.

Drop size also matters for Flux: larger drops evaporate less fractionally because of smaller surface-area-to-volume ratios and faster fall speeds. This is consistent with lower REP at high rain rates. Yet, these rain-intense regimes produce large Flux because abundant rain is available to evaporate. Thus, raindrop size helps limit fractional rain removal, while rain supply controls where evaporation produces the largest latent cooling.

## Isotopes constrain the vertical distribution of rain evaporation

Stable water isotope ratios provide an additional constraint because they respond to both rain mass loss and rain-vapor exchange. During evaporation, lighter water isotopologues ( $H_2O$ ) evaporate more readily, causing the remaining liquid to become more concentrated in heavy isotopes<sup>35;36</sup>. At the same time, falling raindrops exchange isotopically with the surrounding vapor. Surface rain isotopic composition therefore depends on evaporation amount, relative humidity, ambient vapor isotopes, and fall distance. Based on this, we test whether rain-vapor isotopic differences diagnose where evaporation is strongest within the sub-cloud layer.

We use the one-dimensional rain evaporation model of Sarkar et al.<sup>37</sup>, applied here to the global satellite framework described in Methods. The model is initialized at cloud-base using CBH,  $R_{cb}$ , together with a sub-cloud relative humidity profile that increases linearly from  $RH_{sf}$  at the surface to 100% at cloud-base. The initial cloud-base rain isotope value is inferred from AIRS vapor  $\delta D$  by assuming rain-vapor equilibrium at cloud-base. It then simulates both the vertical evolution of rain rate and  $\delta D$  evolution of falling rain through the sub-cloud layer. This model provides vertical evaporation profiles and surface rain isotope ratios.

From the modeled rain-rate sub-cloud profile, we define  $Z_{max}$  as the height where rain loss is strongest, or where the vertical gradient of rain rate is largest.  $Z_{max}$  identifies whether evaporation peaks higher in the sub-cloud layer or near the surface, describing its vertical pathway rather than fractional or energetic magnitude.

From the modeled surface rain isotope value, we calculate the isotope composition of vapor that would be in equilibrium with the rain ( $\delta D_{rain,vapor,eqm}$ ) and compare it with the AIRS-derived environmental vapor isotope composition near cloud-base ( $\delta D_{env,cb}$ ). We normalize this difference by CBH:  $I_{vap} = \frac{\delta D_{rain,vapor,eqm} - \delta D_{env,cb}}{CBH}$ .  $I_{vap}$  represents this isotopic difference per unit fall distance with larger absolute values indicating a stronger sub-cloud isotopic contrast.

$I_{vap}$  is strongly associated with the modeled height of maximum evaporation (Figure 5). When  $I_{vap}$  is small, the evaporation maximum tends to occur higher in the sub-cloud layer and  $RH_{sf}$  tends to be lower. Under these circumstances, dry air promotes rapid, kinetically

192 influenced evaporation soon after rain enters the sub-cloud layer. As  $I_{vap}$  increases,  $Z_{max}$  shifts  
 193 downward, and the evaporation maximum occurs closer to the surface. Large  $I_{vap}$  cases tend  
 194 to occur at higher  $RH_{sf}$ . Under these moister sub-cloud layer conditions, evaporation is slower  
 195 and isotope exchange is closer to equilibrium, allowing drops to survive farther downward even  
 196 while continuing to exchange isotopically with the surrounding vapor.

197 Overall,  $I_{vap}$  diagnoses whether modeled rain loss is concentrated higher in the sub-cloud  
 198 layer or near the surface. This information cannot be obtained from surface rain, REP, or Flux  
 199 alone, which describe integrated rain loss or latent cooling rather than its vertical location.

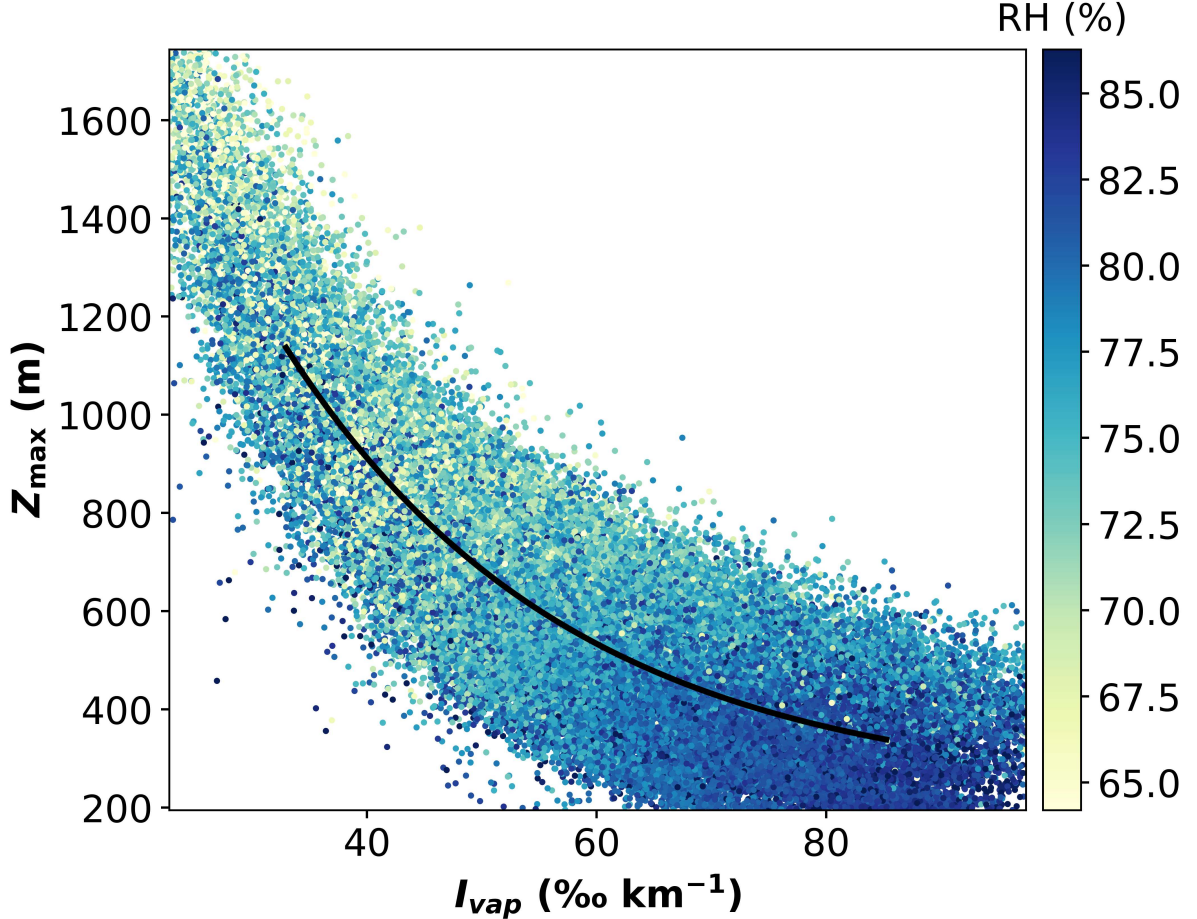


Figure 5: Relationship between the vapor-space isotope metric, ( $I_{vap} = (\delta D_{rain,vapor,eqm} - \delta D_{env,cb})/CBH$ ), and the height of maximum evaporation, ( $Z_{max}$ ). Points are grid-month samples colored by surface relative humidity. The black curve shows the fitted exponential relationship, ( $Z_{max} = Z_0 + A \exp[-k(I_{vap} - I_{min})]$ ), with ( $Z_0 = 227.58$  m), ( $A = 909.06$  m), ( $k = 0.0403$ ), and ( $I_{min} = 32.9405$  ‰  $km^{-1}$ ). Larger CBH-normalized isotope contrast corresponds to lower evaporation maxima, indicating more bottom-heavy evaporation.

## 200 Discussion

201 Previous studies have postulated that as global temperatures increase, wet regions will become  
 202 wetter and dry regions drier<sup>32;33</sup>, yet this prediction has been difficult to verify observation-  
 203 ally<sup>38</sup>. Our results suggest that sub-cloud evaporation partly obscures this response: weaken-  
 204 ing evaporation masks declining cloud-base rain in weak-rain regimes, whereas strengthening  
 205 evaporation damps increasing cloud-base rain in intense-rain regimes. Our findings also help  
 206 reconcile two views of rain evaporation in previous work: field and modeling studies empha-

size efficient below-cloud evaporation in shallow, dry, or weak-rain conditions<sup>6;7;12;25</sup>, whereas energy-budget studies emphasize evaporation as a latent cooling and moistening term in the lower atmosphere<sup>39–42</sup>. Both views are correct, but the relative importance of these roles differs depending on the environment in which precipitation occurs. REP is largest in weak-rain regimes, whereas Flux is largest in rain-rich regimes.

Future model evaluation efforts should treat REP and Flux as separate targets for model development, with REP relevant to precipitation biases and Flux to lower-atmospheric energy balance. GCMs often show biases in surface rain intensity and frequency, potentially reflecting compensating errors among rain formation, fallout, and evaporation<sup>19;27</sup>. A model can therefore match surface rain for the wrong physical reason: excessive cloud-base rain could be offset by excessive sub-cloud evaporation, producing a reasonable surface rain rate while misrepresenting both the cloud process and the sub-cloud energy budget. Evaluating cloud-base rain, surface rain, REP, and Flux together provides a more robust test of simulated precipitation processes.

Water vapor isotope ratios provide another useful diagnostic for model evaluation, since they are sensitive to the vertical pathway of evaporation and therefore to where rain modifies the lower atmosphere. Evaporation that peaks higher in the sub-cloud layer cools and moistens air closer to the cloud-base and may potentially destabilize the layer, whereas evaporation concentrated near the surface may be more stabilizing. Previous studies show that rain evaporation can influence cold pools, cloud organization, and low-cloud transitions<sup>1;7;23</sup>, though the importance of evaporation height remains unclear. Our results suggest that satellite-constrained rain-vapor isotopic differences, coupled with CBH, can diagnose whether evaporative cooling is top-heavy or bottom-heavy. This provides a potential path for evaluating when sub-cloud evaporation produces sufficient cooling to influence boundary-layer organization, mesoscale circulations, convective intensity, and cloud radiative effects.

Several uncertainties should be considered. CloudSat provides rare global vertical rain information, but its record is short for climate trend analysis, and sampling is limited by orbital coverage and retrieval assumptions. Further study is required to determine whether sub-cloud evaporation alone can obscure trends in surface hydrological intensification. AIRS isotope retrievals and ERA5 thermodynamic fields add additional uncertainties, especially near cloud-base, particularly because AIRS cannot retrieve water vapor isotopes in cloudy scenes. However, convective isotopic signatures can persist even after clouds dissipate and remain consistent with moist adiabatic processes<sup>43;44</sup>. The one-dimensional evaporation model also assumes vertical raindrop fall paths, linear temperature and humidity profiles, cloud-base rain-vapor equilibrium, and empirically derived  $D_g$ . These assumptions affect absolute values of REP, Flux,  $Z_{max}$ , and  $I_{vap}$ , but our conclusions rely mainly on contrasts among regimes, which are consistent with independent physical expectations from rain supply, humidity, drop size, and isotope exchange.

Future model evaluation should test cloud-base rain, surface rain, REP, Flux, and evaporation height together, rather than surface rain alone. This can reveal compensating errors where biases in cloud-base rain are offset by biases in sub-cloud evaporation. Surface rain and water vapor isotopes, together with CBH, can further assess the modeled vertical structure of evaporation.

Sub-cloud rain evaporation is not simply a loss term between cloud and surface. It is a vertically structured process that governs how cloud-base rain influences surface water resources, and where latent cooling occurs in the lower atmosphere. We find that evaporation fraction is largest in climatologically dry, weak-rain regions, where much of the rain that forms can evaporate before reaching the surface, making rain evaporation relevant for water resource forecasting. In climatologically wet regions, evaporation flux and thus latent cooling are high, while most rainfall still reaches the surface because the evaporated fraction is low. Thus, in heavy-rain-dominated environments, evaporation can strongly cool the atmosphere at key heights, potentially altering circulation, cloud formation, convective organization.

As climate change accelerates, the expected pattern of rainy regions getting rainier and

dry regions getting drier may be incompletely expressed using surface rainfall observations, masking the underlying rate of change. Measured changes in rainfall that we see globally can be systematically altered by rain evaporation processes, which dampen the effects we "should" expect based on both theory and changes in cloud-base rainfall. Accurately accounting for rain evaporation is therefore critical for interpreting surface rainfall trends, evaluating rain processes in numerical simulations, and understanding how the lower atmosphere redistributes water and energy in a changing climate.

## Methods

### Data

Monthly datasets from CloudSat, AIRS, and ERA5 over 2006-2020 on a common  $5^\circ \times 5^\circ$  horizontal grid resolution. The AIRS isotope product is obtained from WISO-SAT<sup>45</sup>, while CloudSat and ERA5 variables are regridded to the common analysis grid.

1. **CloudSat.** Rain properties are obtained from the CloudSat 2C-RAIN-PROFILE product and associated processing. The primary quantities used are surface rain rate  $R_{sf}$ , rain evaporation percentage (REP), and rain microphysical properties used to reconstruct the raindrop size distribution (RSD).

Because CloudSat does not directly provide total raindrop number concentration  $N_T$ , it is estimated from rain rate using the empirical relationship of Feingold and Levin (1986),

$$N_T = 172R^{0.22}, \quad (1)$$

where  $R$  is in  $\text{mm hr}^{-1}$  and  $N_T$  is in  $\text{m}^{-3}$ . This parameterization is based on observed lognormal raindrop spectra and provides a rain-rate-dependent estimate of total drop concentration.

The RSD is represented by a three-parameter lognormal distribution described by  $N_T$ , geometric mean diameter  $D_g$ , and geometric standard deviation  $\sigma$ . We assume  $\sigma = 1.4$ , following Feingold and Levin<sup>46</sup>, who parameterized  $\sigma$  as

$$\sigma = 1.43 - 3.0 \times 10^{-4}R, \quad (2)$$

where  $R$  is the rain rate in  $\text{mm hr}^{-1}$ . This parameterization gives  $\sigma = 1.43$  at  $R = 0.01 \text{ mm hr}^{-1}$  and  $\sigma = 1.40$  at  $R = 100 \text{ mm hr}^{-1}$ , indicating that  $\sigma$  varies only weakly over the broad range of rain rates considered here. This assumption is also supported by the aircraft observations analyzed in Sarkar et al.<sup>25</sup>, where  $\sigma$  is centered near 1.4 and exhibits substantially smaller relative variability than  $D_g$  and  $N_T$  across rain conditions, supporting its treatment as a fixed RSD parameter. The CloudSat-derived  $D_g$ , together with the rain-rate-derived  $N_T$  and assumed  $\sigma$ , is used to reconstruct the cloud-base RSD that initializes the evaporation model.

2. **AIRS.** Monthly AIRS water-vapor  $\delta D$  profiles at  $5^\circ \times 5^\circ$  horizontal resolution are obtained from WISO-SAT<sup>45</sup>. We use quality-controlled WISO-SAT AIRS product and retain retrievals with a degree of freedom of 1 or higher to reduce sensitivity to the retrieval a priori. For each grid-month, the vapor isotope composition near cloud-base,  $\delta D_{\text{env,cb}}$ , is obtained from the AIRS retrieval level closest to the ERA5 CBH. When the closest CBH equivalent pressure level is 975-1000 hPa, the sample is rejected. The cloud-base  $\delta D$  is assumed to represent the vapor from which cloud water forms and is used to initialize cloud-base rain under liquid-vapor isotopic equilibrium. The level AIRS vapor  $\delta D$  just one step below cloud-base level is used to represent the background vapor isotope composition of the sub-cloud layer in the evaporation model.

3. **ERA5.** ERA5 reanalysis provides  $RH_{sf}$ , CBH, SST, and cloud cover. These fields are averaged onto the common  $5^\circ \times 5^\circ$  grid. CBH determines the modeled sub-cloud fall distance, while  $RH_{sf}$  constrains the sub-cloud humidity profile. SST is used as the near-surface temperature for the equilibrium conversion of modeled surface-rain isotope composition to its vapor-equivalent isotope composition. The analysis is restricted to oceanic grid cells between  $60^\circ\text{S}$  and  $60^\circ\text{N}$ .

## Methods

1. **cloud-base rain rate.** CloudSat 2C-RAIN-PROFILE provides the surface rain rate ( $R_{sf}$ ) and the rain evaporated in the sub-cloud layer in percentage (REP). We derive cloud-base rain rate ( $R_{cb}$ ) by rearranging the REP definition:

$$R_{cb} = \frac{R_{sf}}{1 - \text{REP}/100}. \quad (3)$$

2. **Flux regimes.** We define low-, mid-, and high Flux regimes using the 33rd and 66th percentiles of evaporation Flux across all valid grid-months. Grids below the 33rd percentile are classified as low Flux, those between the 33rd-66th percentiles as mid Flux, and those above the 66th percentile as high Flux. At each grid point, the regime frequency is calculated as the number of valid months assigned to a given regime divided by the total number of valid months. For each regime and month, we calculate the spatial mean of all grid cells assigned to that regime. The resulting monthly series are smoothed using a 3-month moving mean, and temporal rates of change are estimated using ordinary least-squares linear regression against time, with slopes reported per year in Figure 3.

3. **One-dimensional rain evaporation model.** We use the bin-resolved one-dimensional model of Sarkar et al.<sup>37</sup> to simulate the evolution of falling rain from cloud-base to the surface. The model follows individual raindrop size bins in a steady-state Lagrangian framework and calculates changes in drop diameter, drop temperature, terminal fall velocity, evaporation, and  $\delta D$  changes during descent. The treatment of drop evaporation, isotope exchange including equilibrium fractionation and kinetic rain-vapor exchanges is described in Sarkar et al.<sup>37</sup>, which follows established raindrop isotope framework<sup>47–49</sup>. At cloud-base, the RSD is represented by the lognormal distribution:

$$N(D) = \frac{N_T}{D\sqrt{2\pi}\ln\sigma} \exp\left[-\frac{(\ln D - \ln D_g)^2}{2(\ln\sigma)^2}\right], \quad (4)$$

where  $N(D)$  is the number concentration per unit diameter,  $N_T$  is total drop concentration,  $D_g$  is geometric mean diameter, and  $\sigma = 1.4$  is the geometric standard deviation. The distribution is discretized into 10 lognormally spaced diameter bins between 0.1 and 2.5 mm. The model cloud-base temperature is set to 290 K. Relative humidity varies linearly from 100% at cloud-base to ERA5  $RH_{sf}$  at the surface, while air temperature increases toward the surface according to a  $9.8 \text{ K km}^{-1}$  lapse rate. The background vapor  $\delta D$  is obtained from the AIRS pressure level immediately below the level corresponding to CBH and is assumed to remain vertically constant throughout the modeled sub-cloud layer. Cloud-base rain  $\delta D$  is initialized in isotopic equilibrium with AIRS cloud-base vapor:

$$\delta D_{\text{rain,cb}} = \alpha_D(T_{\text{cb}}) (\delta D_{\text{vapor,cb}} + 1000) - 1000, \quad (5)$$

where  $\alpha_D$  is the equilibrium liquid–vapor fractionation factor. As drops descend, the model calculates their evaporation and isotopic exchange with environmental vapor. The

evolving size bins are integrated to obtain the vertical rain-rate profile,  $R(z)$ , and rain isotope composition is mass-weighted across the surviving drop population to obtain  $\delta D_{\text{rain}}(z)$ . Model profiles are run through 100 normalized levels between cloud-base and the surface.

4. **Derived isotope metrics** Isotope process diagnostics are calculated from the modeled rain-isotope profiles together with AIRS vapor isotope measurements. The modeled surface-rain isotope composition,  $\delta D_{\text{rain,sf}}$ , is first converted to the isotope composition of vapor that would be in equilibrium with the surface rain. In isotope ratio space:

$$R_{\text{rain,vapor,eqm}} = \frac{R_{\text{rain,sf}}}{\alpha_D(T)}, \quad (6)$$

where  $R$  is the HDO/H<sub>2</sub>O isotope ratio. The equivalent vapor  $\delta D$  is then

$$\delta D_{\text{rain,vapor,eqm}} = 1000 \left( \frac{R_{\text{rain,vapor,eqm}}}{R_{\text{VSMOW}}} - 1 \right). \quad (7)$$

Equivalently,

$$\delta D_{\text{rain,vapor,eqm}} = \frac{\delta D_{\text{rain,sf}} + 1000}{\alpha_D(T)} - 1000. \quad (8)$$

where  $T$  is ERA5 SST. The equilibrium fractionation factor for HDO is calculated following Majoube<sup>47</sup>,

$$\alpha_D(T) = \exp \left( \frac{24844}{T^2} - \frac{76.248}{T} + 0.05261 \right). \quad (9)$$

We then define a vapor isotope metric as:

$$I_{\text{vap}} = \frac{\delta D_{\text{rain,vapor,eqm}} - \delta D_{\text{env,cb}}}{\text{CBH}_{\text{km}}}. \quad (10)$$

where CBH is expressed in km.  $I_{\text{vap}}$  therefore represents the isotope contrast between the vapor-equivalent composition of rain reaching the surface and the environmental vapor near cloud-base, normalized by the sub-cloud fall distance.

To characterize the vertical structure of evaporation, we calculate the height of maximum modeled rain loss,  $Z_{\text{max}}$ , defined as the altitude where the positive vertical rain-rate gradient,  $\partial R / \partial z$ , is largest.

5. **Derived rain evaporation metrics** The main rain-evaporation diagnostics are REP and the associated sub-cloud evaporation latent heat flux. REP represents the percentage of falling rain removed between cloud-base and the surface. The amount of rain evaporated is calculated as:

$$R_{\text{evap}} = R_{\text{cb}} \frac{\text{REP}}{100}, \quad (11)$$

where  $R_{\text{cb}}$  is the modeled cloud-base rain rate in mm hr<sup>-1</sup>. The corresponding latent evaporation flux is:

$$F_{\text{evap}} = L_v \rho_w R_{\text{evap}} \left( \frac{10^{-3}}{3600} \right), \quad (12)$$

where  $L_v \approx 2.45 \times 10^6 \text{ J kg}^{-1}$  is the latent heat of vaporization of water,  $\rho_w \approx 1000 \text{ kg m}^{-3}$  is the density of liquid water, and the factor  $10^{-3}/3600$  converts the rain rate from  $\text{mm hr}^{-1}$  to  $\text{m s}^{-1}$ .  $F_{\text{evap}}$  is expressed in  $\text{W m}^{-2}$  and represents the magnitude of latent cooling associated with sub-cloud rain evaporation.

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## Data Availability

All datasets used in this study are publicly available. ERA5 reanalysis data are available from the Copernicus Climate Data Store link. CloudSat 2C-RAIN-PROFILE data are available from the CloudSat Data Processing Center link. AIRS water vapor isotope data are obtained from the WISO-SAT dataset<sup>45</sup>.

## Code Availability

The MATLAB code for the one-dimensional rain evaporation model used in this study is publicly available as Supplementary Information to Sarkar et al.<sup>37</sup>.

## Author Contributions

M.S. conceived the study, developed the methodology, performed the analysis and visualization, and wrote the original manuscript. A.B. contributed to methodology, study conception and interpretation of results, and manuscript review and editing. S.D. contributed to interpretation of results, supervision, funding acquisition, and manuscript review and editing.

## Competing Interests

The authors declare no competing interests.

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