Response to Referee #1
Manuscript: Galewsky and Los (2025)

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We thank the reviewer for the careful second review. We agree that the previous response was too brief and did not provide enough detail to evaluate the revisions. Below we provide a point-by-point response and describe the corresponding manuscript changes. The most important revision is that the earlier isotope-only liquid–vapor exchange term has been removed. The model now treats below-cloud rain evaporation as an explicit mass flux that enters both the water-vapor mass budget and the deuterium mass budget.

General Comment

I was disappointed by the brevity of the response to reviewers. For my comments there is just one page (twice shorter than my initial comments!) with just a few selected points and vague responses of a few lines. I would have expected a more detailed point-by-point review to better assess the improvement on the manuscript and better understand the choices made by the authors.

Response: We agree. The revised response is now organized point by point and explicitly states which changes were made, which choices were retained, and why. We have also revised the manuscript itself so that the model assumptions, equations, parameter choices, and limitations are visible in the main text rather than left implicit.

The article has been improved with the inclusion of an enriching effect of liquid-vapor exchanges as an increasing function of mesoscale ascent. Now the analytical model is able to reproduce the larger sensitivity to mesoscale ascent of δD relative to q. However, from a physical point of view, considering liquid-vapor exchanges with no moistening rather than rain evaporation brings some inconsistencies. In addition, the theoretical model deserved to be better explained and justified.

Response: We agree with this criticism. The revised model no longer contains a term that changes isotopic composition without changing water-vapor mass. Instead, below-cloud rain evaporation is represented as a vapor mass source F_{rain} and a corresponding deuterium mass source $F_{\text{rain},D} = F_{\text{rain}} R_{\text{ev}}$. The subcloud layer is advanced using conserved variables, $Q = \rho h q$ and $M_D = \rho h q R$, so every isotope tendency is tied to a corresponding moisture tendency. We also moved the model equations into the main text, added a parameter table, and expanded the Discussion to explain what the model does and does not imply.

1 Major Comments

1.1 Better highlight the role of rain evaporation

The addition of rain evaporation in the model is a key component of the model and of the interpretation. It should be explained in the abstract.

Response: Done. The abstract now explicitly states that modest below-cloud rain evaporation is a mechanism tested by the model. It also states the central model result: a W-dependent drizzle source rotates the fitted δD contours relative to humidity, whereas a no-rain control collapses this separation. We frame this as a physically consistent mechanism rather than as a unique causal proof.

l 36: add the key role of rain evaporation.

Response: Done. The Introduction now introduces below-cloud evaporation of falling hydrometeors as a distinct process that can return condensate-derived water to the subcloud layer. We also revised the final paragraph of the Introduction to state that the paper tests how entrainment, mesoscale ascent, and below-cloud rain evaporation jointly shape lower-tropospheric moisture.

I don't understand how diffusive exchanges can enrich the water vapor. Hydrometeors come from the cloud layer, so they come from the condensation of a vapor that is more depleted than the SCL. So diffusive exchanges alone would deplete the vapor. The only process that can enrich the water vapor is total or near-total evaporation of rain drops, e.g. [Tremoy et al., 2014; Graf et al., 2019]. So the process to incorporate in the model is not just diffusive exchange, it is rain evaporation. This could easily be incorporated as an input of water with the isotopic composition of hydrometeors.

Response: We agree. We removed the earlier isotope-only "diffusive exchange" interpretation and replaced it with explicit rain evaporation. The revised model assumes that raindrops form at cloud base by equilibrium condensation from cloudy-layer vapor, then partially evaporate through the unsaturated subcloud layer. The isotopic ratio of the vapor released by evaporation, R_{ev}, is calculated with the Stewart (1975) below-cloud evaporation formulation and then enters the vapor budget through $F_{\mathrm{rain},D} = F_{\mathrm{rain}} R_{\mathrm{ev}}$. In the manuscript we now give the baseline magnitude explicitly: the cloud-base liquid has $\delta D_{r,\mathrm{cb}} \approx +2.6‰$ and the mass-weighted evaporated vapor has $\delta D_{\mathrm{ev}} \approx -10‰$, enriched by about 60‰ relative to ambient subcloud vapor. We added Tremoy et al. (2014) and Graf et al. (2019) to the manuscript to motivate this physical interpretation.

It's awkward to argue that rain evaporation impacts more δD than q using a model in which the impact of rain evaporation on q is neglected. It is a circular rationale. So I recommend to explicitly account for the role of rain evaporation on both q and δD.

Response: Done. Rain evaporation now affects both q and δD through the conserved-variable budgets. The model solves for the column water-vapor inventory Q and the column heavy-isotopologue vapor inventory M_D, with rain evaporation included in both budget equations. The claim that rain evaporation affects δD more visibly than q is therefore no longer assumed. It emerges from the parameter regime in which the rain-evaporation mass flux is small relative to the total subcloud moisture budget but isotopically distinct from the ambient vapor.

l 394: "net vapor mass changes may be small": this deserves to be shown, otherwise the rationale showing small impact on q is circular.

Response: We have addressed this with the new model figure and discussion. The drizzle case shows that $|\partial \delta D/\partial W|/|\partial \delta D/\partial E| = 1.66$, while $|\partial q/\partial W|/|\partial q/\partial E| = 0.44$. Thus the same rain-evaporation source produces a nearly fourfold larger W-to-E sensitivity ratio for δD than for q. The no-rain control collapses both W sensitivities to zero because, in this process-test model, W enters through the rain-activity pathway rather than through a separate vertical-advection term. We now state this limitation explicitly in the manuscript. We also added a limitation noting that if the precipitation forcing is made much stronger, q becomes W-sensitive too and the observed contrast is no longer reproduced. This explicitly shows that the small humidity response is a constraint on the allowed rain-evaporation regime, not an assumption built into the model.

Be more explicit by correctly naming physical processes: l 260-263, l 271-273, l 284, l 313.

Response: Done. We revised the manuscript to name the physical processes directly. The relevant interpretation is now framed as a three-flux balance among surface evaporation, entrainment from the cloudy layer, and below-cloud rain evaporation. We removed or rewrote vague language such as "additional dynamical modulation" and "passive" behavior. The Discussion now states that surface evaporation plus cloudy-layer entrainment alone does not generate the observed non-parallel q–δD structure in this model, and that adding below-cloud rain evaporation provides one physically plausible route to this structure.

1.2 Clarify the model

The model equations should be in the main text. They are necessary to understand what are the key physical ingredients of the model. Otherwise, the model looks like something magical, and we discover only at the end that there were tricks that artificially made things work. Also, each model equation, hypotheses, approximations should be made explicit. The inclusion of arbitrary choices and tunable parameters should be highlighted, and whenever possible, justified by previous studies.

Response: Done. The model equations are now in the main text. The revised section presents: (1) the conserved-variable budgets for Q and M_D; (2) the surface evaporation flux and corresponding Craig–Gordon isotope flux; (3) the entrainment fluxes from the cloudy layer; (4) the rain-evaporation mass and isotope fluxes; (5) the W-dependent rain activity function; (6) the Stewart (1975) calculation of R_{ev}; (7) the integration procedure and equilibrium diagnostic; and (8) a parameter table. We also state explicitly which parameters are prescribed from campaign means or literature values and which are free rain-evaporation parameters, and we distinguish the surface-flux diffusivity ratio from the rain-evaporation diffusivity ratio used in the Stewart calculation.

A schematic illustrating the reservoirs, fluxes and processes taken into account in the model could be useful.

Response: We agree that a schematic would be useful. We chose not to add a separate schematic figure in order to keep the manuscript focused and avoid adding another figure late in revision. Instead, we rewrote the model text so that the reservoir structure is explicit: the subcloud layer exchanges water and deuterium mass with the ocean surface, the overlying cloudy layer, and a below-cloud rain-evaporation source. The new model figure then shows the equilibrium consequence of these fluxes in E–W space. If the editor or reviewer still prefers a schematic, we can add one in a subsequent revision.

Clarify the role of parameter tuning in the model: l 219-221; l 320 "without ad-hoc tuning".

Response: Done. We removed the phrase "without ad hoc tuning" from the Conclusions. The revised text explicitly acknowledges that P_{cb}, χ, and W_{width} are free rain-evaporation parameters, not independently retrieved observations. We now describe P_{cb} as a reference cloud-base precipitation-rate scale and state that the effective mean precipitation input is $P_{\mathrm{cb,eff}}(W) = f(W)P_{\mathrm{cb}}$. We justify the selected values as a weak-drizzle regime consistent with trade-cumulus precipitation rates and shallow, warm subcloud-layer conditions, while also noting that the fixed evaporated fraction is a bulk simplification rather than a resolved microphysical calculation. We also state the key constraint from sensitivity tests: if rain evaporation is made too strong, humidity becomes W-sensitive and the observed q–δD contrast degrades.

More comments on the model formulation in the detailed comments.

Response: The detailed formulation comments are addressed below. Several became obsolete because the previous isotope-only exchange formulation has been replaced by explicit rain evaporation.

1.3 Deepen the discussion

Here the model assumes a relationship between W and rain-vapor exchanges. Is this relationship expected to be universal or case-specific? Should it depend on cloud organization? On aerosols? On thermodynamical conditions? To what extent could these results be generalized to other regions or cloud organizations? What could be done to address these questions?

Response: We added this limitation to the Discussion. The revised text states that the W–rain relationship is not universal and likely depends on cloud organization, aerosol conditions, precipitation efficiency, subcloud relative humidity, and the depth over which falling drops evaporate. We now present the model as an equilibrium process test for EUREC^{4}A-like trade-cumulus conditions, not as a universal precipitation parameterization. We also state explicitly that W enters this model through the rain-activity function and that the model does not separately represent direct W-driven vertical advection of the SCL moisture budget. Generalization would require direct rain-rate observations, cold-pool diagnostics, and model tests across different cloud organizations.

l 253-254: what mechanisms are responsible for the localization of the correlation maximum? Is it due to the shape of the W profile? Does it correspond to the rain evaporation maximum just below cloud base?

Response: We revised the Discussion to be more cautious. The manuscript now states that the correlation maximum just below the subcloud-layer top is consistent with the layer where mesoscale vertical motion, cloud-base exchange, and evaporation of shallow precipitation are expected to interact most strongly. We also state that the current observations cannot uniquely separate these mechanisms. This avoids over-interpreting the vertical localization while still connecting it to the model physics.

Better discuss and more precisely name physical processes. In absence of a deeper discussion on physical mechanisms, the sentence "... sharpens the physical picture ..." seems exaggerated. What are the physical mechanisms revealed by your study?

Response: Done. We removed the overgeneralized phrasing and now name the physical mechanisms explicitly: surface evaporation, entrainment from the cloudy layer, and below-cloud rain evaporation. The proposed mechanism is that mesoscale ascent changes the relative contribution of these fluxes. Rain evaporation can substantially alter δD because its isotopic composition differs from ambient subcloud vapor, while its moisture contribution remains modest in the weak-drizzle regime.

2 Minor and Detailed Comments

l 5: it is hard to compare a response of δD with a response of q. Reword.

Response: Done. The abstract now states that δD shows strong sensitivity to mesoscale vertical velocity relative to humidity, rather than implying a direct dimensional comparison between unlike quantities. The quantitative comparison is made later using standardized coefficients and W-to-E sensitivity ratios.

l 5: does this conclusion hold only if the regression slopes are unstandardized? Or is it robust?

Response: We clarified this in the Results. The standardized and unstandardized metrics answer different questions: standardized coefficients compare relative statistical influence, whereas unstandardized slopes quantify physical compensation in mm s^{-1}. The revised Results give both. For δD, about 0.7 mm s^{-1} of ascent offsets the isotope effect of 1 mm s^{-1} of entrainment. For humidity, the corresponding value is about 4.4 mm s^{-1}. However, we now state explicitly that the confidence interval on the δD counteraction-efficiency ratio is broad, so the data do not tightly constrain the magnitude of the humidity–isotope efficiency contrast or rule out a smaller, statistically indistinct difference. We therefore interpret the efficiency contrast as suggestive rather than precisely resolved.

l 36: "mixing with unsaturated air from below": clarify.

Response: Done. We removed this wording. The Introduction now distinguishes vapor added by ocean evaporation from below-cloud evaporation of falling hydrometeors.

I would put Fig 4 before Fig 3.

Response: Done. In the revised manuscript, the time series of E, W, δD, and humidity is presented as Fig. 3 and appears before the vertical correlation profile, which is presented as Fig. 4. Thus the reader first sees the time-varying predictors and responses before the altitude-dependent correlation analysis.

Fig 4c: at what altitude are these measurements made?

Response: Done. The figure caption now states that the Picarro inlet was at approximately 20.3 m above sea level and that the matched humidity values are at the same inlet height.

l 144: "()A)" → "(A)"

Response: Done.

l 174-188: What is the role of the standardisation? Is the result robust whatever the kind of slopes we calculate?

Response: We expanded the explanation. Standardization is used only to compare the relative statistical influence of E and W after accounting for their covariance and different natural variability. The physical compensation calculation is now made separately using the unstandardized regression slopes. Both approaches give point estimates in which δD is more sensitive to W than humidity is, but we now state that the magnitude of the corresponding efficiency contrast remains uncertainty-limited.

l 174-175: Are there no units?

Response: The standardized regression coefficients are dimensionless. We now state that the standardized metric compares influence in units of standard deviations. We also provide unstandardized regression equations with physical units in the text.

l 187: and for humidity, can you also give the regression lines and then deduce the unstandardized η values?

Response: Done. The text already gives the humidity regression line, and we now add the corresponding physical compensation estimate: approximately 4.4 mm s^{-1} of mesoscale ascent would be required to offset the drying associated with 1 mm s^{-1} of entrainment. This contrasts with the 0.7 mm s^{-1} value for δD.

l 201: "passive reservoir": unclear wording.

Response: Removed or rewritten. The model now treats reservoirs through explicit fluxes rather than describing them as passive.

l 211: no, it is not "orthogonal", just non-parallel. Same l 226.

Response: Done. We use "non-parallel" and contour-angle separation rather than "orthogonal."

Clarify "active processing", "dynamically modulated", etc.

Response: Done. We replaced this vague language with explicit process descriptions. The revised text describes a three-source balance among surface evaporation, entrainment, and below-cloud rain evaporation.

Fig 8: it would be easier to capture the model-observation agreement if adding (a) observations and (b) model, using same line styles and color codes.

Response: We considered this and agree it would be a useful alternative figure design. For the current revision we retained separate observational and model figures because they serve different purposes: the observational figure presents the fitted E–W dependence of measured q and δD, while the model figure isolates the mechanism through a drizzle/no-rain comparison. We revised the Discussion to explicitly connect the two figures and emphasize the quantitative agreement in the differing W-to-E sensitivities. This avoids overloading one figure while still making the comparison explicit.

l 219: clarify "enriched hydrometeor equilibrium".

Response: This wording is no longer used. The revised model defines the initial raindrop isotopic ratio as equilibrium condensation from cloudy-layer vapor at cloud-base temperature, then computes the isotopic ratio of the vapor released by partial evaporation with the Stewart (1975) formulation.

l 342: "F is the net entrainment flux": unclear sign convention.

Response: The revised model section defines $F_{\mathrm{ent}} = \rho E(q_{\mathrm{CL}} - q)$ and $F_{\mathrm{ent},D} = \rho E(q_{\mathrm{CL}} R_{\mathrm{CL}} - qR)$. We now describe these as entrainment tendency terms in the conserved-variable budgets. Because $q_{\mathrm{CL}} < q$ under the modeled trade-wind conditions, F_{ent} is negative and represents a moisture sink for the subcloud layer. This makes the sign convention explicit.

What is the rationale for formulating ϵ_{eff} this way? Are there any previous studies supporting such a formulation?

Response: This comment referred to the previous exchange formulation. That formulation has been removed. The revised model no longer uses ϵ_{eff}.

How are variables tuned? Cite previous studies or observations to justify orders of magnitudes?

Response: We added a parameter table and revised the parameter discussion. Campaign-mean environmental values are used for SST, subcloud-layer depth, and pressure; literature values are used for fractionation parameters; cloudy-layer end members are tied to dropsonde/isotope constraints; and the rain parameters are identified as free but physically constrained. We also clarify that P_{cb} is a reference precipitation-rate scale, while $f(W)P_{\mathrm{cb}}$ is the effective mean cloud-base precipitation input. We removed language implying that no tuning choices were present.

Comments on Appendix formulation (A12, k_{ex}, R_{rain}, etc.).

Response: These comments became obsolete because the Appendix-style exchange formulation has been replaced. The revised model no longer includes isotope-only re-equilibration, k_{ex}, or an imposed R_{rain} relaxation value. Instead, R_{ev} is calculated from the raindrop mass balance during below-cloud evaporation and enters the isotope budget only through the associated rain-evaporation mass flux.

References added in response to the review

Graf, P., Wernli, H., Pfahl, S., and Sodemann, H.: A new interpretative framework for below-cloud effects on stable water isotopes in vapour and rain, Atmospheric Chemistry and Physics, 19, 747–765, 2019.

Tremoy, G., Vimeux, F., Soumana, I., Souley, I., Risi, C., Cattani, O., Favreau, G., and Oï, M.: Clustering mesoscale convective systems with laser-based water vapor δ^{18}O monitoring in Niamey (Niger), Journal of Geophysical Research: Atmospheres, 119, 5079–5103, 2014.