Response to reviewers

We would like to express our gratitude to the reviewer for the detailed assessment and constructive comments. We provide below detailed answers (in blue) to the remarks made by the reviewer (in black). Line numbers refer to those from the submitted paper.

This manuscript attempts to quantify snow mass balance components over the Tibetan and Pamir Plateaus using a combined modeling and machine learning framework, and to assess the relative contributions of snow to water resources and atmospheric moisture. The topic is relevant, and the integration of modeling with parameter regionalization is of some interest.

However, the manuscript has several fundamental issues. The central conclusion—that snow contributes more to atmospheric moisture than to water resources—is not robust. It relies heavily on simulated sublimation, which is highly uncertain, lacks proper validation, and is not accompanied by any uncertainty analysis.

More broadly, the credibility of the modeling framework is insufficient. The evaluation relies largely on model-derived SWE rather than independent observations, and key processes such as sublimation and snowmelt are not rigorously assessed. This weak observational constraint substantially limits confidence in the results. A critical concern lies in snowfall, which is the fundamental input to the entire snow mass balance. As acknowledged by the authors, there are no direct snowfall observations, and precipitation data themselves carry considerable uncertainties over the TPP. These uncertainties are further amplified by the rain–snow partitioning parameterizations. Given the compounded uncertainties in this key input, it is difficult to see how the study can robustly constrain snow mass balance partitioning or support quantitative conclusions.

Furthermore, this study addresses a large and important scientific question, and the conclusion is potentially far-reaching. However, relying primarily on limited regional observations and a complex modeling chain is insufficient to support such a strong claim. The applicability of model parameterization schemes over the TPP requires careful, component-wise validation. Parameterizations developed and tested in other regions cannot be assumed to be directly transferable, and thus the reported partitioning results cannot be considered reliable.

We thank the reviewer for these important comments. First, we would like to clarify that the ΔSNOW-derived SWE dataset is not an unvalidated model product. The ΔSNOW framework was evaluated against direct SWE measurements in its original study (Fontrodona-Bach et al., 2023). Because the original validation was conducted mainly outside the TPP, we further evaluated the reconstructed SWE using the available discontinuous observations from 66 stations across the study region and a continuous SWE record from one station (Fig. S3). These evaluations assess both the reconstructed product's spatial applicability across the available station network and its ability to reproduce the temporally continuous seasonal SWE evolution. Evaluation results support the use of the reconstructed SWE as an observation-informed reference for regional snow-storage variability.

Second, we agree with the reviewer that the original manuscript stated the regional snow-mass partition and its broader implications too strongly relative to the available observational constraints. Also, uncertainties in precipitation (snowfall) forcing and rain–snow partitioning propagate through all simulated snow components, while agreement in snow depth or SWE between the observations and model data does not by itself validate the individual snowfall, sublimation, refreezing, and snowmelt fluxes. We further agree that the regional transferability of the parameterization schemes cannot be assumed solely from an integrated snow-state evaluation, particularly because spatially representative observations of plateau-wide sublimation remain extremely limited.

To strengthen the evaluation, we added further analyses after extensively reviewing the literature and talking to experts in snow and snow sublimation: 1) an independent Yakou site experiment evaluating snowfall, SWE, and surface–atmosphere water-vapour exchange (E); 2) an event-scale comparison with near-surface water-vapour isotopes; 3) a comparison with the atmospheric moisture-budget diagnostic variable Q_2 (the apparent moisture sink diagnosed from the atmospheric moisture budget) across the TPP; and 4) an ERA5-based analysis of near-surface specific-humidity changes around snowfall events over the TPP. The Yakou experiment provides a direct point-scale test of the snowfall calculation, rain–snow partitioning, and resulting snow-storage evolution, whereas the isotope, Q_2 and ERA5 specific humidity change analyses provide complementary process-consistency evidence for the simulated sublimation–atmosphere relationship. These analyses constrain different parts of the evidence chain and are not presented as eliminating the remaining forcing, parameter, and structural uncertainties.

Evidence 1. Independent evaluation at the Yakou Snow Observation Station

Principle and method. The recently available Yakou observations provide a rare opportunity to evaluate the snow simulation using direct, co-located measurements at a high-elevation Tibetan Plateau site (Figure 1). The station includes corrected solid-precipitation measurements, independent SWE observations, meteorological forcing, blowing-snow measurements, and eddy-covariance measurements of surface–atmosphere water-vapour exchange (Li et al., 2025). Rather than comparing a regional grid-cell value directly with a point observation, we drove the model with the observed Yakou meteorological data and applied the same snow-process parameterization used in the regional framework. We then compared the simulated snowfall, SWE, and snow-related vapour loss with the corresponding station records.

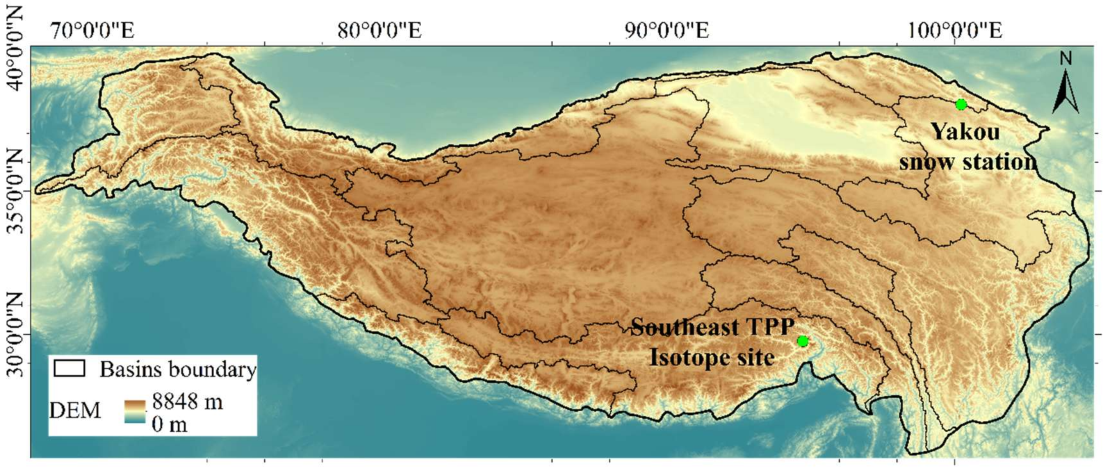

Figure 1. Spatial distribution of the station data used in Evidence 1 and Evidence 2.

Result and interpretation. Simulated snowfall agrees reasonably well with the observed solid precipitation (r = 0.819, RMSE = 2.589 mm), indicating that the forcing treatment and rain–snow partitioning applied in this work reproduces the timing and relative magnitude of the principal snowfall events at this site. The SWE comparison shows moderate agreement (r = 0.476, RMSE = 16.355 mm), demonstrating skill in representing part of the observed snow accumulation and depletion cycle, though discrepancies are also noted.

Observed SWE increases during approximately October 2015–January 2016 and September 2016–January 2017 are not accompanied by comparable increases in local snowfall (Figure 2). Wind-driven snow redistribution from surrounding areas is a possible explanation, but we present this only as a hypothesis rather than a confirmed attribution.

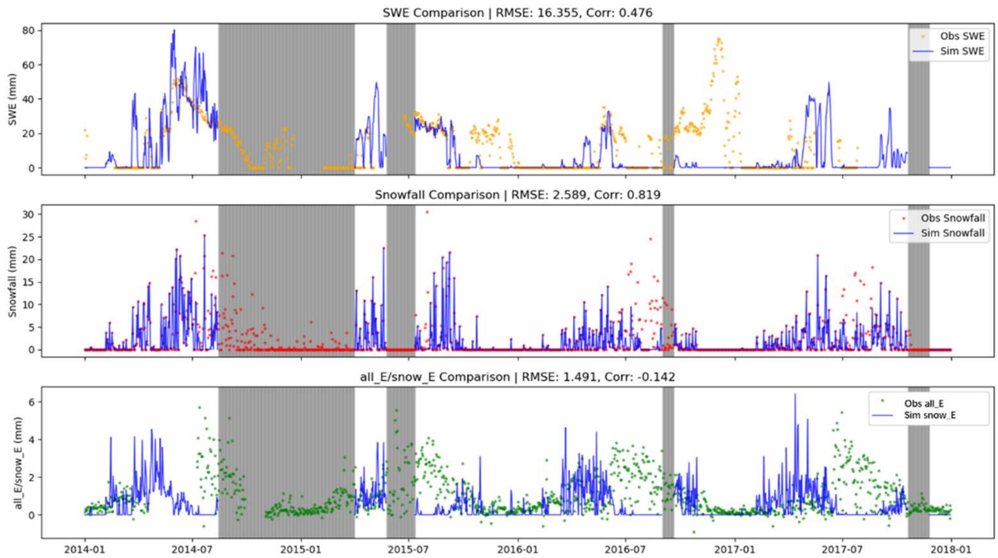

Figure 2. Independent site-scale comparison at the Yakou Snow Observation Station (see Figure 1). The gray-shaded periods indicate intervals with missing meteorological forcing data, during which the model could not be reliably driven and the corresponding results were excluded. Here, all_E represents the total evaporation and sublimation measured by the eddy-covariance system across all seasons, whereas snow_E represents the model-simulated sublimation from the snow surface and blowing snow. Therefore, all_E and snow_E are not directly equivalent, particularly during the snow-free season when evaporation from soil and vegetation contributes substantially to all_E. The snowfall comparison provides the strongest direct test. The SWE comparison shows moderate skill and distinct periods of discrepancy. The observed total water-vapour flux and simulated snow-related flux are not physically identical and are shown as a diagnostic comparison rather than direct sublimation validation.

The comparison between observed E (evaporation) and simulated snow-related vapour loss is weak. This is partly because the eddy-covariance observation represents integrated surface–atmosphere water-vapour exchange, whereas the simulated quantity includes only the snow-related component. The two quantities are especially non-comparable during warm or snow-free periods when soil and vegetation evaporation may contribute to the observed flux. We therefore use the E comparison to identify the current observational limitation, not as direct validation of the separate blowing snow sublimation and snowpack-surface sublimation components. This experiment provides an independent point-scale test of snowfall and snow-storage evolution, but one station cannot constitute plateau-wide validation.

Evidence 2. Water-vapour isotope response during simulated sublimation events

Principle and method. Stable water-vapour isotopes provide process information about changes in atmospheric moisture sources. Under dry conditions, snow–atmosphere exchange and kinetic fractionation may produce coordinated changes in vapour $\delta^{18}O$ and d-excess, two important isotopic metrics. Under dry atmospheric conditions, snow sublimation preferentially transfers the lighter isotopologue ($H_2{}^{16}O$) from the snowpack to the vapor phase, leaving the residual snow enriched in heavy isotopes and thus exhibiting higher $\delta^{18}O$ values. Consequently, the sublimated vapor is depleted in ^{18}O and has more negative $\delta^{18}O$ values than the source snow. Because sublimation under dry conditions is dominated by kinetic, diffusion-controlled fractionation, $H_2{}^{18}O$ diffuses slightly faster than HDO (semi-heavy water), altering the relationship between δ^2H and $\delta^{18}O$, expressed as ($d = \delta^2H - 8\ \delta^{18}O$). As a result, the sublimated vapor typically exhibits higher (more positive) d-excess values. Therefore, the simultaneous occurrence of lower vapor $\delta^{18}O$ and higher vapor d-excess provides a characteristic isotopic signature of snow sublimation and can be used as evidence of active snow–atmosphere exchange. However, these variables are also affected by air-mass transport, relative humidity, precipitation, evaporation, and boundary-layer mixing. They must therefore be interpreted jointly and cautiously. We used the near-surface water-vapour isotope record reported by Cai et al. (2025) for the southeastern Tibetan Plateau (Figure 1). We extracted the simulated snow-sublimation series from the corresponding model grid, identified six major simulated sublimation events, and examined the accompanying changes in vapour $\delta^{18}O$ and d-excess.

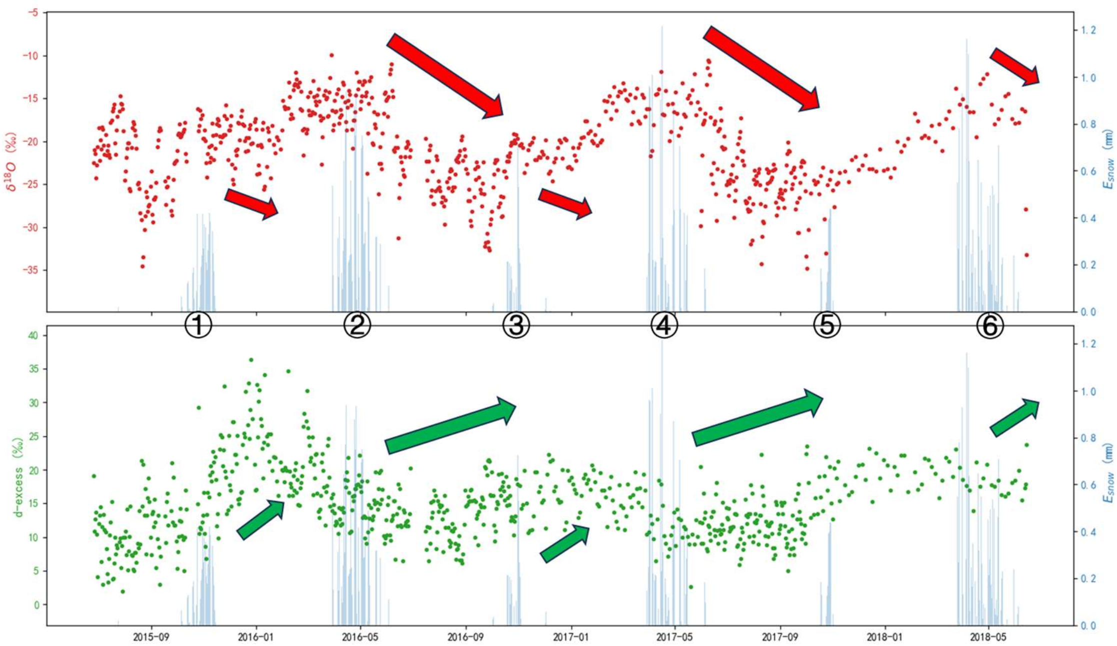

Figure 3. Near-surface water-vapour $\delta^{18}O$ and d-excess compared with simulated snow sublimation at the southeastern Tibetan Plateau isotope site (see Figure 1). The event correspondence is interpreted as exploratory process-consistency evidence, not as a unique isotopic fingerprint of local snow sublimation.

Result and interpretation. Five of the six simulated snow sublimation events during the simulation period were characterized by lower vapour $\delta^{18}O$ and higher d-excess following sublimation events (Figure 3). This response is consistent with kinetic fractionation and a local snow-related moisture contribution under dry conditions. Nevertheless, the isotope response is not unique to snow sublimation. Cold and dry air intrusion, changes in upstream moisture sources, rain evaporation, and transport history may produce similar variations. We therefore use this analysis as event-scale process-consistency evidence: it supports the physical plausibility and timing of the simulated sublimation events but does not directly validate their magnitude or uniquely attribute the observed vapour to local snow sublimation.

Evidence 3. Relationship between simulated snow sublimation and Q_2

Principle. Q_2 is the apparent atmospheric moisture sink diagnosed as a residual of the large-scale atmospheric moisture budget (Zhang et al., 2022).

We diagnose Q_2 following the apparent moisture-sink formulation. At pressure level p, the material tendency of specific humidity is

$$\frac{Dq}{Dt} = \frac{\partial q}{\partial t} + u\frac{\partial q}{\partial x} + v\frac{\partial q}{\partial y} + \omega\frac{\partial q}{\partial p} \qquad (1)$$

The pressure-level apparent moisture sink is then

$$Q_2(p) = -L_v[\frac{\partial q}{\partial t} + u\frac{\partial q}{\partial x} + v\frac{\partial q}{\partial y} + \omega\frac{\partial q}{\partial p}] \qquad (2)$$

and its vertically integrated value is

$$\langle Q_2 \rangle = -\frac{L_v}{g} \int_{p_{\mathrm{top}}}^{p_s} \left[\frac{\partial q}{\partial t} + u \frac{\partial q}{\partial x} + v \frac{\partial q}{\partial y} + \omega \frac{\partial q}{\partial p} \right] dp \qquad (3)$$

Equivalently, the moisture-equivalent form, without multiplication by latent heat, is

$$M_2 = \frac{\langle Q_2 \rangle}{L_v} = -\frac{1}{g} \int_{p_{\mathrm{top}}}^{p_s} \left(\frac{Dq}{Dt} \right) dp \qquad (4)$$

Symbol	Definition	Recommended unit
q	Specific humidity from ERA5 pressure levels	$kg\ kg^{-1}$
u, v	Zonal and meridional wind components	$m\ s^{-1}$
ω	Vertical velocity in pressure coordinates	$Pa\ s^{-1}$
p_s	Surface pressure	Pa
p_{top}	Upper boundary of integration	Pa
L_v	Latent heat of vaporization	$J\ kg^{-1}$
g	Gravitational acceleration	$9.80665\ m\ s^{-2}$
$\langle Q_2 \rangle$	Vertically integrated apparent moisture sink	$W\ m^{-2}$
M_2	Moisture-equivalent apparent sink	$kg\ m^{-2}\ s^{-1}$

It combines the local tendency of specific humidity with horizontal and vertical moisture transport and is then vertically integrated through the atmospheric column. Under the sign convention adopted here, positive Q_2 represents an apparent atmospheric moisture sink, whereas negative Q_2 represents an apparent atmospheric moisture source. Q_2 is derived from ERA5 (the fifth generation of global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts) atmospheric variables and is therefore independent of the VIC-simulated snow fluxes. If simulated snow sublimation is accompanied by a more negative Q_2 response over snow-covered regions, the two independently derived quantities are physically consistent with transfer of water vapour from the land surface to the atmosphere.

Method. We calculated monthly vertically integrated Q_2 from ERA5 moisture-budget terms for 1979–2019. Monthly anomalies were obtained relative to the corresponding monthly climatology and standardized by their temporal standard deviations to reduce differences in magnitude among regions. At each model grid cell, we constructed a snow-sublimation index as the sum of simulated stationary snow-surface sublimation (SSSS) and blowing-snow sublimation (BSS) and calculated its temporal correlation with Q_2. To maintain correspondence with the physical process, the analysis was restricted to snow-active months in which the simulated sublimation index was greater than zero. Statistical significance was evaluated at each grid cell, and significant correlations are indicated by stippling in Figure 4. We also evaluated the relationship between the plateau-mean standardized series as a regional summary.

Result and interpretation. The spatial analysis shows predominantly negative correlations across large parts of the plateau, with extensive statistically significant areas in the western, northern, central, and eastern snow-covered regions. The correlation is spatially heterogeneous, and weak or positive correlations occur in several transition areas, indicating that the atmospheric response is not uniform. At the regional scale, the plateau-mean snow-sublimation index is negatively related to Q_2 (r =

−0.592, $p < 0.01$) (Figure 5). Under the adopted sign convention, these results indicate that periods of enhanced simulated snow-related vapour loss tend to coincide with lower (i.e. more negative) Q_2 values and thus a stronger apparent atmospheric moisture-source response. The broad spatial correspondence provides evidence beyond a single station or event for the contribution of snow-related processes to the atmosphere water vapour and supports the physical plausibility of a snow-sublimation influence on atmospheric moisture.

Nevertheless, Q_2 is a residual diagnostic rather than a direct measurement of snow sublimation. It integrates the effects of surface evapotranspiration, condensation and precipitation processes, horizontal and vertical transport, boundary-layer exchange, and reanalysis uncertainty. Moreover, restricting the analysis to snow-active months improves process correspondence but does not eliminate possible seasonality or temporal autocorrelation. We therefore interpret the spatial Q_2 relationship as independent atmospheric process-consistency evidence, not as direct validation of the simulated sublimation magnitude or as a quantitative attribution of atmospheric moisture solely to snow sublimation.

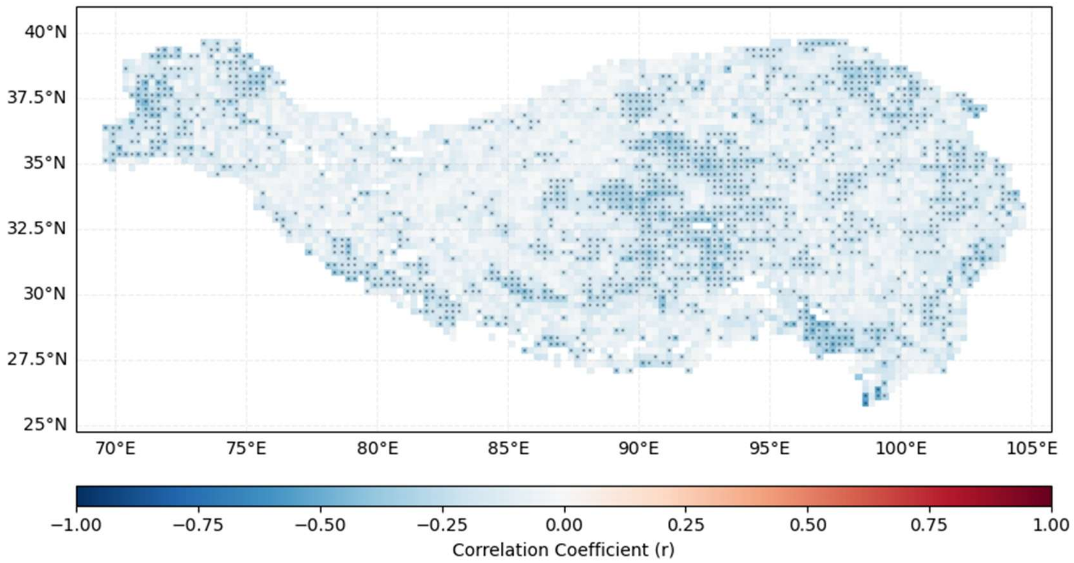

Figure 4. Spatial correlation between standardized monthly anomalies of the snow-sublimation index and Q_2 during snow-active months (1979–2019). Stippling marks statistically significant grid-cell ($p<0.05$) correlations under the current testing procedure. The map is interpreted as process-consistency evidence rather than direct flux validation.

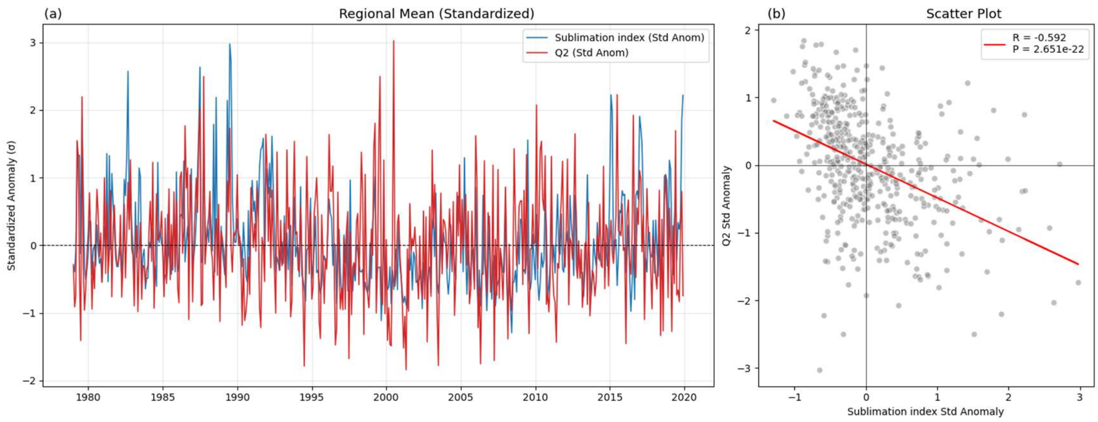

Figure 5. (a) Time series and (b) scatter regression analysis of the regional mean standardized anomalies of the snow-sublimation index and Q_2 during snow-active months from 1979 to 2019. The red solid line in (b) represents the linear regression fit, with the Pearson correlation coefficient (R) and its significance level (p) annotated in the panel, indicating a significant negative association under the current analysis.

Evidence 4. Interannual changes in near-surface specific humidity around snowfall events

Principle and method. To further examine whether snow sublimation could influence near-surface atmospheric moisture following snowfall, we analyzed ERA5 near-surface specific humidity (q; kg kg^{-1}), which represents the mass of water vapour per unit mass of air, over the Tibetan Plateau (TPP) during 1979–2019. For each snowfall event and grid cell, the specific humidity on the snowfall day (d0) was used as the reference, and its percentage change from 5 days before to 10 days after snowfall (d−5 to d+10) was calculated as

$$\Delta q_d = \frac{q_d - q_0}{q_0} \times 100\% \qquad (5)$$

where q_d denotes near-surface specific humidity on day d in period of d-5 and d+10, and q_0 denotes its value on the snowfall day. The event-scale grid-cell results were subsequently composited over the entire plateau to derive an annual mean sequence of percentage changes in specific humidity for each year.

Despite substantial interannual variability, the annual composites show a broadly consistent two-stage evolution of specific humidity change following snowfall (Figure. 6). The percentage change in specific humidity generally decreases rapidly from d0 to approximately d2–d3 and subsequently increases gradually from approximately d3 to d10. The first stage represents a period of net near-surface moisture loss, whereas the second stage represents a period of atmospheric moisture recovery. This common temporal pattern provides the basis for analyzing the decreasing and increasing stages separately, thereby preventing changes in opposite directions from cancelling each other in an overall post-snowfall trend.

For each year, we therefore calculated two conditional metrics: (1) the specific-humidity decrease rate using only the intervals during which q decreased in d0-d3, and (2) the specific-humidity increase rate using only the intervals (d4-d10) during which q increased. These rates were compared with the annual snow-sublimation index, defined as the sum of simulated blowing-snow sublimation and surface-snow sublimation (see Evidence 3), using all years jointly available in the specific-humidity and sublimation datasets (Figure. 7).

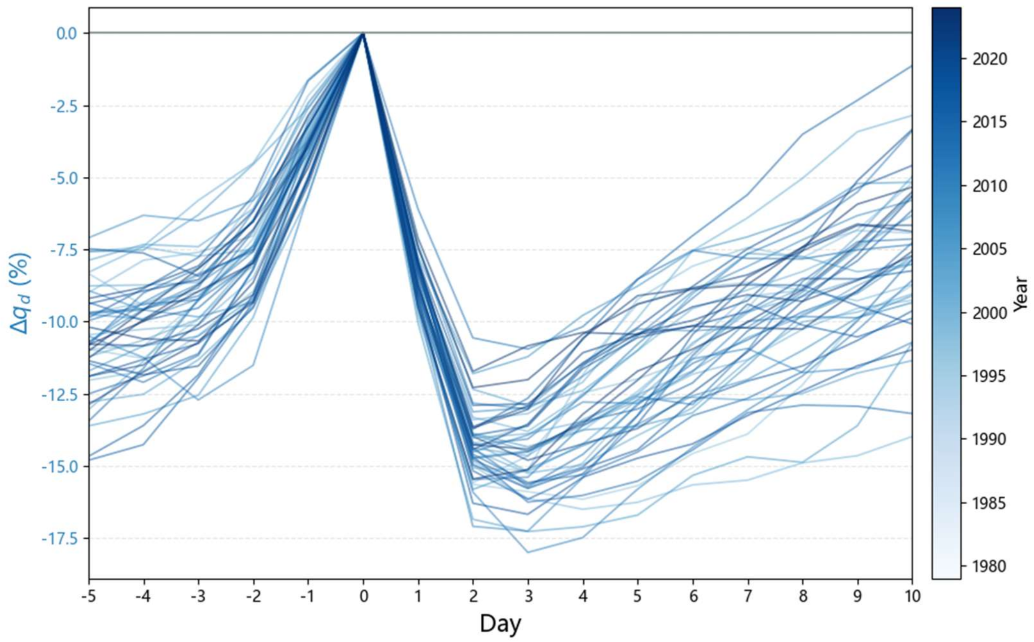

Figure 6. Interannual variation in near-surface specific humidity around snowfall events over the TPP during 1979–2019. For each snowfall event and grid cell, the percentage change in ERA5 near-surface specific humidity was calculated relative to its value on the snowfall day (d0) and subsequently composited over the entire plateau for each year. Individual curves represent annual mean composites from 5 days before to 10 days after snowfall. The composites generally exhibit two post-snowfall stages: a rapid decrease in specific humidity from d0 to approximately d2–d3, followed by a gradual recovery through d10.

Result and interpretation. The fitted relationships show that greater snow-sublimation indices were associated with a lower magnitude of specific-humidity decrease during the declining stage in d0-d3, and a higher specific-humidity increase rate during the recovery stage in d4-d10 (Figure. 7). In physical terms, these directional relationships suggest that enhanced snow sublimation may compensate for near-surface atmospheric moisture loss when specific humidity is decreasing and may enhance moisture recovery when specific humidity is increasing. However, neither fitted relationship was statistically significant ($p > 0.05$). Nevertheless, the analysis clearly demonstrates direct sublimation contribution to atmospheric water vapor by enhanced specific humidity after snowfall, providing validation of the atmospheric moisture contribution from snow sublimation. This analysis also serves as supplementary process-consistency evidence whose direction agrees with the expected influence of sublimated snow water on near-surface atmospheric moisture.

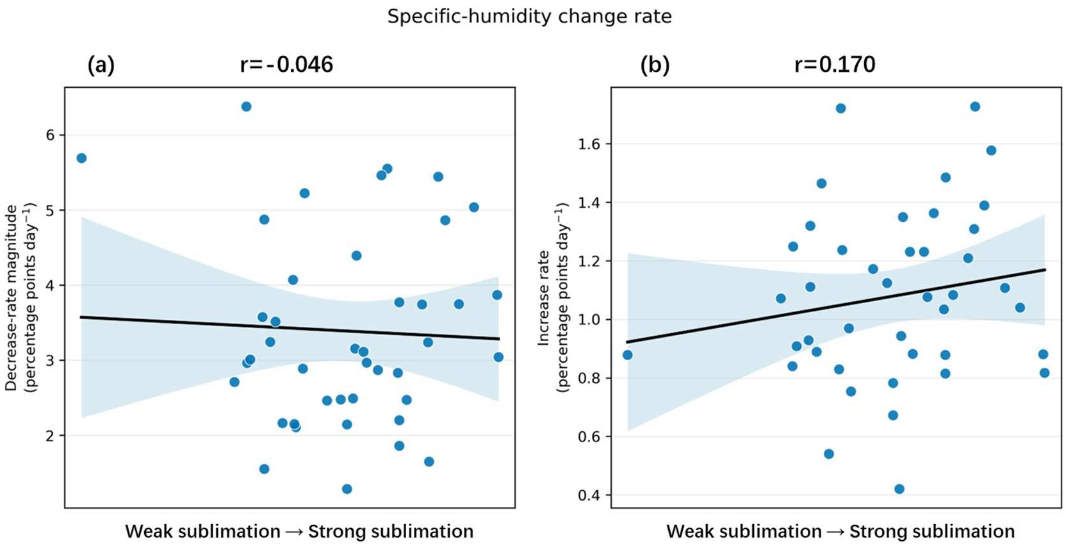

Figure 7. Relationships between the annual snow-sublimation index and conditional post-snowfall specific-humidity change rates over the TPP. The left panel (a) shows the magnitude of the specific-humidity decrease rate calculated only during period of decreasing specific humidity, whereas the right panel (b) shows the increase rate calculated only during period of increasing specific humidity. Each point represents one year, and the black lines

and shaded areas denote the linear fits and their 95% confidence intervals, respectively. The snow-sublimation index increases from left to right along the horizontal axis. Neither fitted relationship was statistically significant ($p > 0.05$).

Taken together, these additional analyses lend credence to the observational and process basis of the modeling framework, although uncertainties associated with forcing data, parameterizations, and model structure inevitably remain. Based on the analyses and the reviewer's comments, we have rephased the title and also reworded the major conclusions to better reflect the modeling nature of this work, as well as the strength and uncertainties of the modeling framework and analyses.

Old title: Snow Mass Components Analysis: Greater Contribution to Atmospheric Water Vapor than to Water Resources on the Tibetan and Pamir Plateaus

New title: Modelled snow mass partitioning over the Tibetan and Pamir Plateaus

We would like to emphasize here that there have been very few observational studies on snow mass components and snow hydrology processes on the Tibetan and Pamir Plateaus, and elsewhere on the globe, due to the scarcity of observations and the harsh environment. It is our hope that this modelling study will motivate additional observational and modelling research to further improve our understanding of the snow mass components and snow hydrological processes not only in the Tibetan and Pamir Plateaus but also in other areas such as the Western U.S., Canada, the Alps, and the Andes where snow is an important water resource.

The overall presentation of the manuscript also requires substantial improvement. The figures and writing are difficult to follow, with redundant descriptions and unnecessary abbreviations (e.g., HAL). The introduction reads more like a literature summary than a clear formulation of the scientific question. In addition, several terms and expressions are unclear (e.g., "standstill snowpack" versus SWE, and "warming-up period"), which further reduces readability. If AI tools are used in the writing process, greater attention should be paid to clarity and precision.

That said, the study shows some technical progress in snow process representation. The work may be more suitable for a model-oriented journal if it is reframed to focus on methodological development rather than broad hydroclimatic conclusions.

We thank the reviewer for these constructive suggestions. We agree that the presentation of the manuscript can be substantially improved, and we will carefully revise the structure, terminology, figures, and language to make the scientific question and methodological contribution clearer.

Specifically, we will reorganize and shorten the Introduction so that it focuses more directly on the scientific question, the observational limitations over the Tibetan and Pamir Plateaus, the methodological approach adopted to address these limitations, and the specific objectives of the study. Redundant literature descriptions and background information that are not essential to the main question will be removed or condensed.

We will also revise the terminology and abbreviations throughout the manuscript. The unnecessary abbreviation "HAL" will be removed. "Warming-up period" will be replaced by the standard term "model spin-up period." The ambiguous expression "standstill snowpack" will be replaced by a clearer process-based term, such as "non-blowing snowpack" or "snowpack-surface sublimation," depending on the corresponding model variable. We will also clearly distinguish SWE, which is a snow-storage state variable, from snowfall, sublimation, and snowmelt, which are fluxes accumulated over a specified period.

The figures and captions will be simplified and standardized. We will use consistent terminology, units, panel ordering, abbreviations, and colour conventions in all the figures. Repetitive descriptions of patterns already visible in the figures will be reduced, and the Results section will focus more clearly on the principal findings and their physical interpretation. The modeling-framework figure will also be revised to distinguish direct observations, observation-constrained data, model calibration and evaluation data, parameter regionalization, and model outputs.

We appreciate the reviewer’s insightful assessment of the technical progress in snow-process representation and the suggestions to emphasize the methodological contribution. Without changing the principal scope of the study, we will revise the title, Abstract, Introduction, Discussion, and Conclusions to place greater emphasis on the development and evaluation of an observation-informed regional snow-modeling framework. At the same time, the broad hydroclimatic conclusions will be expressed more cautiously and explicitly linked to the limitations of the available observations and the model configuration.

We believe that this revision will retain the original scientific objective of investigating regional snow processes over the Tibetan and Pamir Plateaus while presenting the methodological contribution, supporting evidence, and inherent limitations more clearly and precisely.

Finally, we will conduct a comprehensive language review of the entire manuscript. Redundant expressions will be removed, long or ambiguous sentences will be rewritten, abbreviations will be minimized, and all terminology will be checked for consistency. The authors will take full responsibility for the clarity, accuracy, and precision of the revised manuscript.

References

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