

Dear Editor and Reviewers,

We sincerely thank the Editor and all reviewers for their careful evaluation of our manuscript and for the constructive and insightful comments. We greatly appreciate the recognition of the value of our cosmogenic ^{10}Be and ^7Be precipitation observations from the Tibetan Plateau, as well as the important concerns raised regarding the research design, interpretation of isotope signals, dynamical evidence, and statistical analysis. These comments have helped us critically reassess the scientific scope of our study and substantially improve the clarity, rigor, and coherence of the manuscript.

In response to these comments, we have made several important revisions. First, we have refined the scientific focus and revised the title to emphasize the exploration of possible links between stratospheric dynamics and precipitation during the observed 2022–2023 QBO phase transition, rather than claiming to establish a general causal mechanism. We have also clarified the complementary roles of the Lhasa observations and the Xi'an low-elevation reference site, while explicitly acknowledging differences in sampling coverage and atmospheric conditions.

Second, we have strengthened the interpretation of elevated $^{10}\text{Be}/^7\text{Be}$ events by considering the effects of atmospheric mixing, precipitation scavenging, and air-mass history. We have clarified the empirical nature of the event-selection criterion and distinguished the sensitivity of the flux–precipitation regressions from independent evidence of stratospheric influence. To provide additional dynamical constraints, we have incorporated ERA5 potential-vorticity cross-sections (Fig. S6) and integrated their interpretation with the HYSPLIT trajectories and isotope observations.

Third, we have clarified the distinct roles of the event-scale isotope measurements and the longer-term XGBoost–SHAP analysis. In particular, SHAP contributions are now interpreted as contributions to model predictions rather than physical or causal contributions of the QBO to precipitation. We have also expanded the description of AMS quality control, removed the speculative sulfate-related mechanism, and reorganized the Results and Discussion to establish a clearer progression from observations to transport diagnostics, circulation context, and synthesis.

Most importantly, we have carefully reconsidered the strength of the conclusions supported by the available evidence. The revised manuscript distinguishes direct observations, dynamical interpretations, and statistical associations, while acknowledging the limitations of the observational duration, spatial representativeness, and potential influences of other climate processes. We believe these changes provide a more balanced and scientifically defensible assessment of the possible relationships among QBO-associated circulation variability, atmospheric transport, and regional precipitation.

We are grateful for the reviewers' valuable suggestions, which have significantly improved the manuscript. Detailed point-by-point responses are provided below, together with the corresponding revised manuscript text and locations of the changes. We hope that the revised manuscript satisfactorily addresses the reviewers' principal concerns and is now more suitable for publication in *Atmospheric Chemistry and Physics*.

Sincerely,

The Authors

CC1: Liu et al. present daily observations of cosmogenic ^{10}Be and ^7Be in precipitation from Lhasa and Xi'an during the 2022–2023 rainy seasons. They propose using the $^{10}\text{Be}/^7\text{Be}$ ratio as a tracer for stratosphere-troposphere exchange processes modulated by the Quasi-Biennial Oscillation (QBO), thereby revealing the impact of these processes on summer precipitation over the southern Tibetan Plateau. The topic is interesting and combines isotope observations, reanalysis, trajectory analysis, and machine learning. The observational dataset itself is also valuable, particularly the measurements from the Tibetan Plateau. However, several issues need to be addressed before publication. I suggest making minor revisions based on the following concerns:

Q1: By relying on the $^{10}\text{Be}/^7\text{Be}$ ratio as a tracer for stratospheric tropospheric exchange, QBO circulation can be linked to plateau precipitation. But rainfall diluted the two isotopes, reducing their absolute concentrations. Besides the increase in the $^{10}\text{Be}/^7\text{Be}$ ratio caused by QBO driven stratospheric downdrafts, does local rainfall dilution also lead to an increase in the peak $^{10}\text{Be}/^7\text{Be}$ ratio?

A1: We thank the reviewer for raising this important point. Rainfall can affect the concentrations and wet-deposition fluxes of both radionuclides through scavenging and dilution. In the limiting case where both nuclides are diluted or scavenged proportionally from the same aerosol population, their ratio is not systematically increased by dilution alone. This assumption, however, need not hold for individual storms: differing aerosol populations, residence times and scavenging histories may influence the rainwater ratio. We therefore no longer assign elevated $^{10}\text{Be}/^7\text{Be}$ uniquely to a QBO-driven stratospheric downdraft. The revised Abstract and Sections 3.1–3.3 describe high-ratio events as consistent with enhanced upper-atmospheric influence, subject to independent circulation and PV diagnostics. This approach also preserves the distinction between transport effects on the isotope signal and processes producing precipitation.

Where revised: Abstract; Sections 3.1–3.3 (especially the final paragraph of 3.1 and discussion of event-specific scavenging in 3.2).

Revised manuscript — Section 3.1 (verbatim): Precipitation strongly affects the absolute concentrations of aerosol-bound ^{10}Be and ^7Be through wet scavenging and dilution. In contrast, the $^{10}\text{Be}/^7\text{Be}$ ratio is expected to be less sensitive to processes acting similarly on both radionuclides and has therefore been widely used as an STE-sensitive tracer (Zanis et al., 2003). Nevertheless, event-scale rainwater ratios may still be influenced by differences in aerosol populations and scavenging histories.

Revised manuscript — Section 3.3 (verbatim): Simple precipitation dilution acting proportionally on the same aerosol population is not expected to systematically increase their ratio. These changes coincided with the QBO phase transition and with upper-level circulation anomalies that are consistent with enhanced downward transport. However, mixtures of aerosol populations, their residence times and scavenging histories can also affect event-scale rainwater ratios. Therefore, we use trajectories and PV to evaluate the high ratio group, treating the $^{10}\text{Be}/^7\text{Be}$ ratio as an observation sensitive to transport during the QBO transition period, rather than a unique identifier for stratospheric air.

Q2: The manuscript attributes the lower beryllium flux rainfall correlation in Lhasa solely to

terrain vertical exchange, while there is a difference in tropospheric thickness between the two locations. This may overlook the influence of cosmogenic nuclides in the free troposphere, especially ^{10}Be with a long half-life. Therefore, it is recommended to clarify how to avoid local ^{10}Be noise in the troposphere.

A2: We agree with the reviewer that the original explanation was too restrictive. The weaker Be flux–precipitation relationship at Lhasa cannot be attributed solely to terrain-induced vertical exchange. Because Lhasa is located at substantially higher elevation than Xi'an, precipitation collected there is more directly influenced by the free troposphere and by variations in upper-tropospheric transport. In addition, ^{10}Be has a very long radioactive half-life, so background ^{10}Be transported within the free troposphere may contribute to individual precipitation events independently of immediate local rainfall intensity. We therefore cannot completely eliminate this free-tropospheric background using surface rainwater observations alone.

In the revised manuscript, we have changed our interpretation accordingly. We now attribute the weaker rainfall-Be relationship at Lhasa to the combined effects of high-elevation exposure to the free troposphere, orographic and synoptic vertical transport, variations in aerosol scavenging, and precipitation dilution, rather than to terrain-induced vertical exchange alone. We also clarify that the $^{10}\text{Be}/^7\text{Be}$ ratio is used to reduce, rather than completely eliminate, ambiguity associated with absolute ^{10}Be concentrations, because the ratio provides information on air-mass residence time and source history.

Furthermore, following the reviewer's Q3, we supplement the isotopic evidence with an independent dynamical diagnostic based on potential vorticity, thereby avoiding reliance on ^{10}Be concentration alone when interpreting possible stratospheric influence.

Where revised: Section 3.2 (flux–precipitation comparison); Sections 2.6 and 3.3 (transport diagnostics).

Revised manuscript — Section 3.2 (verbatim): Notably, the correlation between ^{10}Be and ^7Be fluxes and precipitation is substantially lower in Lhasa ($R^2 < 0.33$; Fig. 2c) than in Xi'an ($R^2 > 0.54$; Fig. 2d). The weaker flux-precipitation correlations at Lhasa relative to Xi'an likely reflect multiple interacting processes rather than orographic exchange alone. Owing to its high elevation, Lhasa is more directly exposed to the free troposphere, where variations in large-scale transport can alter the background abundance of aerosol-bound cosmogenic Be independently of local precipitation. Orographic lifting, event-specific wet scavenging, and dilution may further modulate the observed concentrations and fluxes. Thus, the difference between the two sites should be interpreted as the combined result of contrasting atmospheric structure, transport, and scavenging regimes.

Q3: HYSPLIT trajectories alone cannot prove a stratospheric origin. While back-trajectories are useful, they cannot determine whether an air mass originated in the lower stratosphere; the majority of the presented trajectory paths lie within the troposphere. Given that potential vorticity ($\text{PV} > 1.5\text{--}2 \text{ PVU}$) is a robust tracer for stratospheric air in the troposphere, I strongly recommend adding a quantitative analysis of PV along the HYSPLIT trajectories or using ERA5 PV fields. This would provide much stronger dynamical evidence for the inferred stratospheric origin of the observed high $^{10}\text{Be}/^7\text{Be}$ events. At present, the attribution to STE relies primarily on isotope ratios and backward trajectories, which is suggestive but not yet conclusive.

A3: We appreciate the reviewers' comments and agree with their views. The original manuscript placed excessive weight on the HYSPLIT trajectories when inferring a stratospheric contribution. Backward trajectories identify the transport history of sampled air masses but, without an independent dynamical tracer, do not by themselves establish that the air originated in the stratosphere.

Following the reviewer's suggestion, we have added an analysis of ERA5 potential vorticity (PV) for the high $^{10}\text{Be}/^{7}\text{Be}$ events. PV provides an independent dynamical diagnostic of stratospheric influence because the transition from low tropospheric PV to substantially higher stratospheric PV forms the basis of the dynamical tropopause.

Where revised: Section 2.6; Section 3.3; Fig. S6 and caption in the Supplement.

Revised manuscript — Section 2.6 (verbatim): The trajectories are used here to characterize transport pathways and do not, by themselves, establish a stratospheric origin of the sampled air. Independent dynamical diagnostics, such as potential-vorticity fields near the dynamical tropopause, are required to further evaluate stratospheric influence. The trajectories are therefore evaluated alongside event-period vertical distributions of PV over the two study regions.

Revised manuscript — Section 2.6 (verbatim): Daily mean ERA5 pressure-level PV fields were used to construct meridional latitude–pressure sections along 91.5°E near Lhasa and 109°E near Xi'an for the selected elevated-ratio events in 2023 (Fig. S6). The dates correspond to the event groups in Fig. 2a and 2b. PV is expressed in potential vorticity units ($1 \text{ PVU} = 10^{-6} \cdot \text{K} \cdot \text{m}^2 \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$), and 2 PVU is used as a conventional dynamical-tropopause reference (Millán et al., 2021). These regional sections describe the event-period PV distribution and complement the trajectories; they do not provide PV histories along individual trajectories.

Revised manuscript — Section 3.3 (verbatim): The HYSPLIT calculations characterize transport pathways connecting the sampled air masses with the upper troposphere (Fig. 3c, 3d). Complementing these trajectories, the event-period PV sections show values exceeding 2 PVU below 200 hPa over both study regions (Fig. S6). Together, the isotope, trajectory and PV evidence is consistent with stratospheric influence aloft during the selected events.

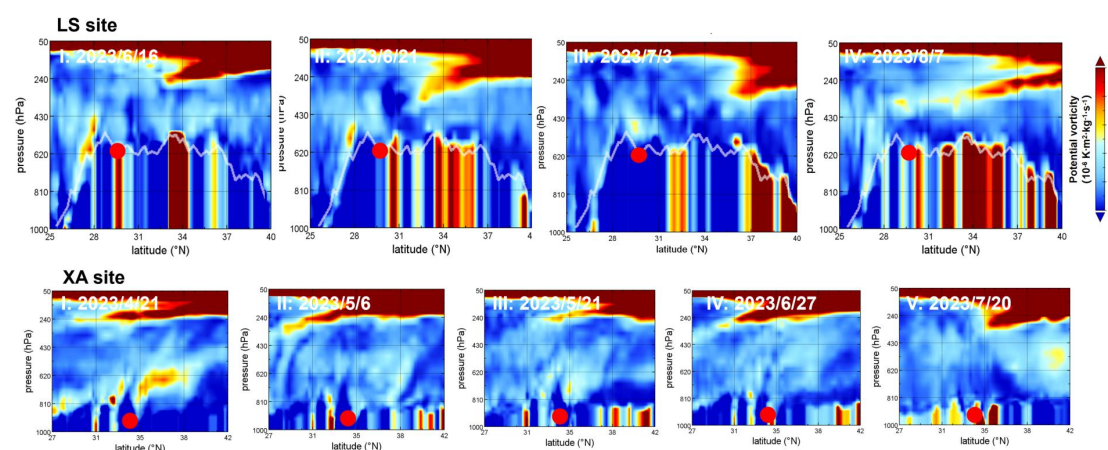


Fig. S6 Meridional latitude–pressure cross-sections of potential vorticity (PV) derived from daily mean ERA5 data along 91.5°E near Lhasa on the Tibetan Plateau (LS; upper row) and 109°E near Xi'an on the Loess Plateau (XA; lower row) during selected elevated $^{10}\text{Be}/^{7}\text{Be}$ events in 2023. The dates shown in the panels correspond to the event periods identified in Fig. 2a and b, respectively. Colour shading indicates PV in PVU ($1 \text{ PVU} = 10^{-6} \cdot \text{K} \cdot \text{m}^2 \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$). Red dots mark the

sampling-site latitudes and approximate surface pressures on the respective cross-sections.

Q4: AMS measurement is a major strength of this study. More information regarding quality control (blank correction, inter-comparison, and reproducibility) should be moved from the supplementary material to the main text. Furthermore, the text repeatedly claims to provide "first-time direct evidence" or to "reveal the mechanism." In reality, the study presents observational evidence rather than definitive proof of the mechanism. Therefore, the wording in the abstract, discussion, and conclusion sections should be adjusted.

A4: We thank the reviewer for recognizing the value of the AMS measurements and agree with both suggestions. First, we have expanded Section 2.4 to provide the principal quality-control information directly in the main manuscript. Each analytical batch included three reference samples and one procedural blank; the procedural blank signal was approximately three orders of magnitude lower than that of the rainwater samples. Replicate measurements were also used to evaluate reproducibility, with the replicate results remaining within the reported 2σ analytical uncertainty. Additional quality-control information and replicate data remain available in the Supplementary Information. Second, we fully agree that the original wording occasionally exceeded what can be demonstrated from the available observations. We have therefore systematically replaced expressions such as "reveal the mechanism," "directly demonstrate," and "first-time direct evidence" with more evidence-based formulations such as "provide observational evidence for," "are consistent with," and "suggest a possible dynamical linkage." These changes have been implemented throughout the Abstract, Discussion, and Conclusions.

Where revised: Section 2.4 (AMS measurements and quality control; cite Liu et al., 2024b), Fig. S3; Abstract; Sections 3.3–3.6; Section 4 (Conclusions).

Revised manuscript — Section 2.4 (verbatim): 7Be and 10Be analyses were carried out at the Xi'an Accelerator Mass Spectrometry Center using a 3 MV multi-isotope AMS system. Both 7Be and 10Be were measured concurrently on a single target in a +4 charge state, with analytical conditions based on previously published parameters (Liu et al., 2024b). Quality control was performed for each analytical batch using three reference measurements and one procedural blank. The blank signal was approximately three orders of magnitude lower than that of the precipitation samples. Replicate analyses showed agreement within the reported 2σ analytical uncertainties (Fig. S3).

Revised manuscript — Section 3.3 (verbatim): Within this framework, elevated $10\text{Be}/7\text{Be}$ ratios are used as complementary tracer evidence for enhanced upper-atmospheric influence during selected events, rather than as proof that a specific QBO circulation directly generated the observed rainfall. The combined isotope, reanalysis, PV, and trajectory evidence therefore supports a possible dynamical linkage involving vertical transport, moisture flux, and circulation anomalies, while the magnitude and causality of the QBO precipitation response remain to be quantified with longer observations and additional dynamical diagnostics.

Q5: In Section 4.4, SHAP values are interpreted as physical contributions. However, SHAP measures predictive importance rather than causal contribution. The manuscript should clearly state this distinction; otherwise, such an interpretation is misleading.

A5: We agree with the reviewer. The original manuscript overinterpreted SHAP attribution as a physical or causal contribution, which is not justified by the method. SHAP values quantify how individual predictors contribute to the output of the trained XGBoost model; they therefore

describe model-based predictive attribution, not causal effects of atmospheric variables on precipitation. Furthermore, correlations among meteorological predictors can redistribute feature attribution and complicate the physical interpretation of individual SHAP values.

We have consequently revised Section 4.4 and the Conclusions to clearly distinguish statistical model interpretation from physical attribution. In particular, we no longer describe the SHAP-derived quantity as the percentage of precipitation “caused” or “contributed” by the QBO. Instead, SHAP is used to identify which meteorological predictors are most influential for the model predictions and to examine whether their dependence patterns are dynamically consistent with the circulation interpretation derived independently from reanalysis and isotope observations. The previous statement that the QBO-related circulation “contributes 31.3% to annual precipitation” has therefore been removed from the causal interpretation. Any quantitative SHAP summary retained in the revised manuscript will be explicitly described as a normalized model-attribution metric rather than a physical precipitation contribution.

Where revised: Abstract; Sections 2.5 and 3.5; Conclusions. The term “contribution” is deliberately retained for contributions to model output, with its non-causal meaning explicitly explained.

Revised manuscript — Section 3.5 (verbatim): Mean absolute SHAP values summarize model importance, and the sign of each SHAP value indicates whether a predictor increases or decreases the model output relative to its baseline. Because the isotope observations were not used to train the model, the results complement rather than quantitatively validate the isotope-based transport interpretation.

Revised manuscript — Section 3.5 (verbatim): This model association is consistent with examining the observed events in a QBO-related circulation context, but SHAP does not yield a physical percentage of rainfall caused by the QBO. Correlated predictors and other climate variability remain relevant to the interpretation.

Q6: The manuscript attributes the enhancement in sulfate production to STE. This discussion (Section 4.5) is purely speculative and unrelated to the isotopic observations. Please provide supporting evidence or significantly shorten this section.

A6: We agree with the reviewer. Because sulfate was not measured in the precipitation samples, the proposed pathway involving stratospheric transport, sulfate aerosol formation, cloud condensation nuclei, and precipitation cannot be directly evaluated using the present dataset.

We have therefore removed this speculative discussion from Section 4.5. The revised discussion focuses on the processes that are directly supported by our observations and analyses: variations in $^{10}\text{Be}/^{7}\text{Be}$, upper-level circulation, possible STE, moisture transport, and precipitation. This revision also shortens the proposed mechanism chain and more clearly separates observations from hypotheses that cannot be tested with the present dataset.

Where revised: Section 3.6 (Synthesis and implications); no sulfate-mechanism subsection remains.

Revised manuscript — Section 3.6 (verbatim): The combined evidence separates two related aspects of the circulation–precipitation system (Fig. 4b). Atmospheric transport changes the sources and histories of aerosol-bound Be that can subsequently be scavenged by precipitation. Circulation also affects the moisture supply and ascent involved in rainfall. The isotope observations primarily constrain the first aspect, while the reanalysis and predictive model

describe elements of the second and their large-scale background. A common circulation setting can connect the two, but high-ratio deposition does not itself demonstrate that downward-transported air generated the precipitation.

Revised manuscript — Section 3.6 (verbatim): The study consequently provides observational constraints on a possible linkage among QBO-associated circulation, atmospheric transport and precipitation during the sampled period. It does not resolve the independent QBO contribution relative to ENSO, Indian Ocean variability or other meteorological influences. Longer isotope records, comparisons within common sampling seasons, sensitivity to event-grouping criteria, and higher-frequency transport diagnostics would help assess the persistence and specificity of the inferred relationships.

Others:

Q7: Abstract: The Abstract contains several strong statements such as "reveal the modulation mechanism" and "direct implications for evaluating climate model performance." These claims appear stronger than the evidence presented. I recommend using more cautious wording, such as "provide observational evidence" or "suggest a possible dynamical linkage."

A7: We agree and have revised the Abstract throughout to avoid implying definitive causal identification. Expressions such as "reveal the modulation mechanism," "demonstrate," and "direct implications for evaluating climate model performance" have been replaced by more cautious formulations emphasizing observational evidence and a possible dynamical linkage.

Q8: HYSPLIT settings, Please specify: the meteorological dataset version, vertical motion option, arrival height definition.

A8: Thank you for requesting clarification of the trajectory setup. Section 2.6 now specifies the 72–96 h backward-integration duration, 6 h initialization interval, and arrival heights (above ground level, a.g.l.): 10, 500, and 1000 m at Xi'an, and 10, 2000, and 6000 m at Lhasa. The coordinates of both sampling sites are also stated. For the previously established HYSPLIT methodology and associated model configuration, including the settings not repeated here, we refer the reviewer to Liu et al. (2024a). We have further clarified that the trajectories describe air-mass transport pathways; a stratospheric origin cannot be established from backward trajectories alone and is assessed alongside the regional ERA5 PV diagnostics (Fig. S6).

Where revised: Section 2.6 (backward trajectories and PV); methodological reference Liu et al. (2024a).

Revised manuscript — Section 2.6 (verbatim): Backward trajectories were calculated for 72-96 h. Arrival heights were defined relative to ground level: 10, 500, and 1000 m above ground level (a.g.l.) for Xi'an, and 10, 2000, and 6000 m a.g.l. for Lhasa. Trajectory calculations were initiated at 6 h intervals during periods of anomalous $^{10}\text{Be}/^{7}\text{Be}$ ratios and traced backward from the two sampling locations (Lhasa: $29^{\circ}38'49''\text{N}$, $91^{\circ}4'37''\text{E}$; Xi'an: $34^{\circ}13'20''\text{N}$, $109^{\circ}00'18''\text{E}$).

Q9: Line 377, "The results show (Fig. 3), Tibetan Plateau precipitation....." suggest changing to: The results show that precipitation over the Tibetan Plateau..

A9: Thank you. We have corrected the sentence as suggested: "The results show (Fig. 3) that precipitation over the Tibetan Plateau is associated in the XGBoost model with a range of ..."

Q10: Conclusion: "...provide new facts and evidence..." In English, "facts and evidence" are rarely used together. It is recommended to change it to: provides new observational evidence or provides new evidence.

A10: We agree and have replaced "provides new facts and evidence" with "provides new observational evidence."

CC2: General comments:

This study employs an interdisciplinary approach, combining accelerator mass spectrometry measurements of ^{10}Be and ^7Be in wet deposition with multi-decadal reanalysis data and an XGBoost-SHAP machine learning framework, to assess whether stratospheric Quasi-Biennial Oscillation dynamics modulate precipitation over the Tibetan Plateau through stratosphere-troposphere exchange. The continuous observation of ^{10}Be and ^7Be in precipitation over the Plateau constitutes a valuable dataset, and the attempt to integrate machine learning with atmospheric tracers is a commendable effort. The research topic falls within the scope of the journal.

However, the current version of the manuscript suffers from fundamental weaknesses in scientific logic, cross-scale reasoning, and methodological execution. The core weakness lies in the attempt to answer a long-term regional climate question using short-term site-specific observational data, an approach that is logically untenable. Furthermore, key quantitative conclusions, notably the 31.3% QBO contribution derived from SHAP values, appear unreliable because they are affected by multicollinearity and confounding of causal direction.

The manuscript requires major revision or even rewriting. The authors need to fundamentally restructure their research framework, scale back their attribution claims, and correct core methodological errors.

Major Concerns:

Q1. The role of the $^{10}\text{Be}/^7\text{Be}$ ratio is not clearly defined

The manuscript presents inconsistent descriptions of the $^{10}\text{Be}/^7\text{Be}$ ratio across different sections. The abstract and introduction describe it as a newly constructed indicator for revealing the modulation mechanism of the QBO on precipitation. In practice, however, the ratio is primarily used to identify stratosphere-troposphere exchange events and to filter data accordingly by excluding high-ratio points. In the subsequent mechanistic discussion, the isotope ratio is mentioned only qualitatively, lacking systematic quantitative analysis and playing no direct role in the calculation or validation of the 31.3% contribution. This leaves the reader uncertain whether the isotope ratio is a core analytical tool or merely an auxiliary data filtering parameter.

Moreover, high $^{10}\text{Be}/^7\text{Be}$ ratios are interpreted throughout the text as indicators of stratosphere-troposphere exchange, which is precisely the key process through which the QBO is hypothesized to influence precipitation. Excluding these points before analyzing the relationship between flux and rainfall therefore deviates from the research objective, since the excluded signal is exactly the phenomenon of interest. Similarly, the 31.3% contribution mentioned in the conclusions is derived independently from reanalysis data and the machine learning model, with no direct quantitative link to the $^{10}\text{Be}/^7\text{Be}$ ratio. Yet the abstract and conclusions frame this contribution in a way that could lead readers to believe it was directly revealed by the tracer data.

A1: We thank the reviewer for identifying an ambiguity in the role assigned to the $^{10}\text{Be}/^{7}\text{Be}$ ratio. In the revised manuscript, the ratio serves as an event-scale, transport-sensitive observational indicator, not as a newly developed quantitative measure of the QBO contribution to rainfall. It is used to identify and discuss unusual wet-deposition events, which are then compared with trajectories, potential-vorticity fields, and circulation patterns. We agree that isotope anomalies alone cannot identify the unique origin or cause of precipitation. The high-ratio observations were retained in the full-sample analyses; a separate, conditional regression excluding preidentified event groups is shown only to examine how background flux–precipitation associations differ when those events are set aside. We do not use the improvement in regression fit as proof of STE or precipitation causation. Importantly, isotope measurements were not inputs to XGBoost, so the SHAP analysis does not quantify or validate an isotope-derived QBO contribution. This separation is now explicit in the abstract and Sections 2.7, 3.2, and 3.5.

Revised manuscript text (verbatim)

Abstract:

Here, we use the ratio of the cosmogenic tracers ^{10}Be ($t_{1/2} = 1.39 \text{ Ma}$) and ^{7}Be ($t_{1/2} = 53.29 \text{ d}$) as a sensitive indicator of stratosphere–troposphere exchange to explore possible links between stratospheric dynamics and precipitation during the 2022–2023 QBO phase transition. We analyze synchronous wet-deposition observations from Lhasa (Tibetan Plateau) and Xi'an (Loess Plateau, as a low-elevation plain reference site within the precipitation response region influenced by the QBO) together with atmospheric reanalysis, HYSPLIT backward trajectories, and an XGBoost-SHAP machine learning framework. Elevated $^{10}\text{Be}/^{7}\text{Be}$ events are interpreted as signals consistent with enhanced upper-atmospheric or stratospheric influence. During the observation period, isotope anomalies coincided with QBO-related changes in upper-level circulation and with circulation patterns favorable for downward transport and regional moisture convergence. Further analysis of the 2001–2020 long-term climate reanalysis record using XGBoost-SHAP identifies upper-level zonal wind and circulation-related variables as predictive factors for precipitation; these SHAP attributions are interpreted as model-based predictive importance rather than causal contributions. Together, the observations provide evidence for a possible dynamical linkage between QBO-associated stratospheric variability and precipitation over the study region and demonstrate the practicality of the joint ^{10}Be – ^{7}Be analysis to constrain the impact of stratosphere–troposphere coupled motion on precipitation in a high-altitude monsoon environment.

Section 3.1

At the regional scale, precipitation is strongly modulated by atmospheric circulation patterns. Vertical atmospheric motions, especially under climate change, reinforce the established causal link between precipitation and circulation regimes. Cosmogenic ^{10}Be and ^{7}Be are recognized as sensitive tracers of atmospheric circulation dynamics (Raisbeck et al., 1981; Terzi and Kalinowski, 2017), with their distribution and deposition fluxes governed by circulation dynamics. Observational evidence (Fig. 1) shows elevated $^{10}\text{Be}/^{7}\text{Be}$ ratios in Lhasa and Xi'an, suggesting tropopause instability at the time, reflecting enhanced stratosphere-to-troposphere exchange, which elevated the relative input of ^{10}Be and consequently modified the $^{10}\text{Be}/^{7}\text{Be}$ ratio in precipitation. Precipitation strongly affects the absolute concentrations of aerosol-bound ^{10}Be and ^{7}Be through wet scavenging and dilution. In contrast, the $^{10}\text{Be}/^{7}\text{Be}$ ratio is expected to be less sensitive to processes acting similarly on both radionuclides and has therefore been widely used as

an STE-sensitive tracer (Zanis et al., 2003). Nevertheless, event-scale rainwater ratios may still be influenced by differences in aerosol populations and scavenging histories.

Section 3.6 synthesis

The combined evidence separates two related aspects of the circulation–precipitation system (Fig. 4b). Atmospheric transport changes the sources and histories of aerosol-bound Be that can subsequently be scavenged by precipitation. Circulation also affects the moisture supply and ascent involved in rainfall. The isotope observations primarily constrain the first aspect, while the reanalysis and predictive model describe elements of the second and their large-scale background. A common circulation setting can connect the two, but high-ratio deposition does not itself demonstrate that downward-transported air generated the precipitation.

Section 3.6 limitation

The study consequently provides observational constraints on a possible linkage among QBO-associated circulation, atmospheric transport and precipitation during the sampled period. It does not resolve the independent QBO contribution relative to ENSO, Indian Ocean variability or other meteorological influences. Longer isotope records, comparisons within common sampling seasons, sensitivity to event-grouping criteria, and higher-frequency transport diagnostics would help assess the persistence and specificity of the inferred relationships.

Q2. Temporal and spatial scales of the observational data do not match the research question

A fundamental problem with the study design is that the QBO is a slowly varying signal with a period of approximately 28 months, yet the authors' observations cover only 2022 to 2023, not even a single complete QBO cycle. To properly characterize the modulation mechanism of the QBO on precipitation, at least three complete QBO cycles, corresponding to roughly seven years, would be needed to observe the reproducibility of QBO effects and to exclude the contingency of a single event. For statistically reliable attribution analysis, each phase, whether easterly or westerly, would require at least 10 to 15 years of samples, totaling 20 to 30 years of continuous observations. This is because precipitation itself has strong interannual variability; data from a single year contain too much noise, and sufficient years are needed for averaging to extract a clean signal. Furthermore, the QBO period is not constant, ranging from 22 to 34 months, and both the amplitude and phase transition speed vary from cycle to cycle. Observing only one transition cannot represent the general behavior of the QBO. More importantly, the influence of the QBO on precipitation is not a direct causal effect but is transmitted through a long chain spanning stratospheric circulation, tropospheric circulation, the monsoon, and finally precipitation. Each step in this chain is subject to interference from other factors, especially ENSO.

With only two years of data, it is impossible to separate the QBO signal from stronger and more rapidly varying interannual signals such as ENSO and the Indian Ocean Dipole. This observation length fundamentally limits the scientific contribution of this study to a case observation report, documenting how isotope compositions in Lhasa and Xi'an behaved during a single QBO phase transition. Any conclusion about the mechanism of QBO modulation of precipitation far exceeds what two years of data can support. This is not a minor fix but a fundamental scale mismatch in the research design.

Spatially, the study uses a single site in Lhasa to represent the entire southern Tibetan Plateau and a single site in Xi'an to represent the entire Loess Plateau. Yet the southern Tibetan Plateau has extremely complex topography, with Himalayan mountains and valleys running through it,

meaning that precipitation at a single point in Lhasa cannot represent the entire region. The authors need to reframe the narrative. Rather than claiming that the QBO drives summer precipitation, they should state that during a QBO phase transition, they observed isotopic signals that may be associated with enhanced stratosphere-troposphere exchange, making it clear that this is a case observation that is suggestive rather than a statistical demonstration of the QBO summer impact. All references to southern Tibetan Plateau precipitation should be revised to Lhasa site precipitation, including in the title, unless additional data from a broader network of stations across the region are available to support regional claims.

A2: We agree that a two-rainy-season record at Lhasa (2022–2023), a one-season record at Xi'an (2023), and a QBO oscillation of roughly 28 months cannot establish a repeatable phase-dependent response across several QBO cycles. We re-examined the scope of inference and changed the title to “Exploring Links Between Stratospheric Dynamics and Precipitation During a QBO Phase Transition: Evidence from Stratospheric $^{10}\text{Be}/^{7}\text{Be}$ Isotope Characteristics at Lhasa, Tibetan Plateau.” “Exploring Links” and “During a QBO Phase Transition” deliberately limit the claim to associations during the observed transition rather than a general mechanistic demonstration. We also sharpened the study objectives: the event-level rainwater measurements constrain isotope variability and transport-sensitive events; ERA5 and potential-vorticity analyses characterize the concurrent dynamical environment; the longer reanalysis period provides contextual statistical patterns, not replication of the isotope record. Other influences, including monsoon circulation and local scavenging, cannot be independently excluded using the present temporal coverage. This limitation is acknowledged in the synthesis rather than concealed by the new title.

Introduction, final paragraph

This study aims to constrain possible links among QBO-related stratospheric dynamics, atmospheric transport, and precipitation during 2022–2023 using cosmogenic ^7Be and ^{10}Be measurements. The Tibetan Plateau provides a setting in which monsoon convection and high-altitude topography influence atmospheric exchange (Bian et al., 2020). Lhasa (3650 m a.s.l.) represents the high-altitude site, whereas Xi'an (420 m a.s.l.) provides a low-elevation reference in the same broad QBO-related rainfall-response sector. We first characterize isotope concentrations, wet-deposition fluxes, and ratios at the two sites and examine their relationships with precipitation. We then evaluate elevated-ratio events using backward trajectories and potential vorticity (PV), before placing the events in the context of the QBO transition and longer-term circulation–precipitation associations. This sequence connects the event-scale tracer evidence with the regional dynamical setting while distinguishing observations from the proposed physical interpretation.

Section 3.6, limits

The main observational contribution is the event-resolved joint record from the high-altitude Lhasa site, interpreted with the Xi'an low-elevation reference site and independent transport diagnostics. Similar high-ratio behavior in the two settings can be examined within the same broad QBO-related rainfall-response sector, while differences help identify the importance of local transport and scavenging conditions. Neither urban rooftop site represents the full range of environments across its surrounding region, and their contrasting observation coverage limits direct full-record comparisons.

The study consequently provides observational constraints on a possible linkage among QBO-associated circulation, atmospheric transport and precipitation during the sampled period. It does not resolve the independent QBO contribution relative to ENSO, Indian Ocean variability or other meteorological influences. Longer isotope records, comparisons within common sampling seasons, sensitivity to event-grouping criteria, and higher-frequency transport diagnostics would help assess the persistence and specificity of the inferred relationships.

Q3. Treating Xi'an as a control site is not justified

Section 2.1 defines Xi'an, with an elevation of 420 meters, as a control site for Lhasa, with an elevation of 3650 meters. The elevation difference of more than 3000 meters means the meteorological conditions are fundamentally different, making a control comparison invalid. Lhasa lies in the free atmosphere, strongly influenced by solar radiation and stratospheric processes, while Xi'an sits in the Guanzhong Basin, governed by local urban boundary layer dynamics and aerosol scavenging mechanisms. The starting height of the back trajectories differs by a factor of six, with 6000 meters for Lhasa versus 1000 meters for Xi'an, indicating that the air masses sampled at the two sites originate from entirely different altitudes. I strongly recommend that Xi'an not be referred to as a control site. Instead, it should be called a low-elevation reference point within the same monsoon corridor. The authors should directly discuss the influence of elevation differences on isotope deposition rather than attempting to compare two sites with completely different conditions. The more radical solution would be to remove the Xi'an site entirely, since the two sites are separated by more than 1500 kilometers, have different topography, different elevations, and different meteorological conditions, making any comparison of limited value, unless the authors deliberately compare the differences between the two sites throughout the paper, in which case the title would need to be revised to highlight this comparison.

A3: We agree that the elevation separation (Lhasa approximately 3650 m a.s.l.; Xi'an approximately 420 m a.s.l.) makes "control site" misleading. These locations differ in pressure, boundary-layer/free-tropospheric exposure, precipitation regime, and potential aerosol and scavenging histories. Therefore, a direct site-to-site difference cannot be interpreted as the isolated causal effect of elevation or QBO. We replaced "control site" and "plain-site control" with "low-elevation reference site" wherever Xi'an's observational role is described. Xi'an provides a second, geographically distinct record in the broad regional circulation sector, allowing qualitative examination of whether some anomalous isotope/precipitation behavior is observed in both settings. Its role is contextual rather than experimental. The revised discussion explicitly recognizes the combined influence of atmospheric structure, transport, and wet scavenging when comparing the two sites; the comparison does not assume meteorological equivalence.

Introduction, site roles

This study aims to constrain possible links among QBO-related stratospheric dynamics, atmospheric transport, and precipitation during 2022-2023 using cosmogenic ^7Be and ^{10}Be measurements. The Tibetan Plateau provides a setting in which monsoon convection and high-altitude topography influence atmospheric exchange (Bian et al., 2020). Lhasa (3650 m a.s.l.) represents the high-altitude site, whereas Xi'an (420 m a.s.l.) provides a low-elevation reference site in the same broad QBO-related rainfall-response sector. We first characterize isotope concentrations, wet-deposition fluxes, and ratios at the two sites and examine their relationships

with precipitation. We then evaluate elevated-ratio events using backward trajectories and potential vorticity (PV), before placing the events in the context of the QBO transition and longer-term circulation–precipitation associations. This sequence connects the event-scale tracer evidence with the regional dynamical setting while distinguishing observations from the proposed physical interpretation.

Section 2.1 study area

The Loess Plateau is adjacent to the Tibetan Plateau and is influenced by the same large-scale atmospheric circulation patterns. Furthermore, it is located on the same side of the dipole rainfall pattern as the Tibetan Plateau, and is therefore used as a reference observation site in this work. Rainfall also exerts a significant impact on the vulnerable ecosystems of the Loess Plateau: too much can intensify soil erosion and geomorphic degradation, while too little may lead to reduced vegetation cover and weakened ecosystem functions (Cai et al., 2022). According to Chinese Loess ^{10}Be sedimentary records, climate change has historically caused variations in the intensity of rainfall events on the Loess Plateau (Zhou et al., 2023). Xi'an, where sampling was conducted, lies in the southern Loess Plateau of China and receives approximately 500–750 mm of rainfall annually. Their urban sampling settings and different observation coverage are considered when interpreting the comparison.

Section 3.2 site comparison

Notably, the correlation between ^{10}Be and ^7Be fluxes and precipitation is substantially lower in Lhasa ($R^2 < 0.33$; Fig. 2c) than in Xi'an ($R^2 > 0.54$; Fig. 2d). The weaker flux-precipitation correlations at Lhasa relative to Xi'an likely reflect multiple interacting processes rather than orographic exchange alone. Owing to its high elevation, Lhasa is more directly exposed to the free troposphere, where variations in large-scale transport can alter the background abundance of aerosol-bound cosmogenic Be independently of local precipitation. Orographic lifting, event-specific wet scavenging, and dilution may further modulate the observed concentrations and fluxes. Thus, the difference between the two sites should be interpreted as the combined result of contrasting atmospheric structure, transport, and scavenging regimes. As highlighted by red-circled data in Fig. 2a and 2b, steeper slopes-indicative of elevated $^{10}\text{Be}/^7\text{Be}$ ratios: coincide with seasonal peaks in stratosphere-troposphere exchange. These elevated $^{10}\text{Be}/^7\text{Be}$ ratios reflect intensified stratosphere-troposphere exchange events (Zanis et al., 2003; Liu et al., 2024a). These findings imply that downward-transported stratospheric air masses, enriched in beryllium isotopes, intrude into the lower atmosphere and modulate rainfall and deposition patterns (Graham et al., 2003; Heikkilä et al., 2008). However, it should be noted that this phenomenon is not the only diagnostic evidence of stratospheric invasion. Simple dilution acting similarly on both aerosol-bound radionuclides is not expected by itself to systematically increase the ratio, but differences in aerosol populations and scavenging histories may still contribute to event-scale variability. Accordingly, interpretation of high-ratio events requires comparison with independent circulation and transport diagnostics.

Section 3.4 regional reference

At Lhasa, Be fluxes and $^{10}\text{Be}/^7\text{Be}$ ratios increased during parts of 2023 relative to 2022. Annual precipitation increased from 273 mm in 2022 to 439 mm in 2023, while Xi'an experienced an increase of approximately 34%. Within the broad QBO-related rainfall-response sector considered here, Xi'an supplies a low-elevation reference site for examining the corresponding regional

precipitation change and isotope-event behavior. These concurrent changes provide context for the transport-sensitive observations, but the annual rainfall differences cannot be assigned uniquely to the QBO. Other circulation variability and local precipitation processes can contribute to the changes at both sites.

Q4. Logical problems arising from subjective data filtering

In Section 4.2, the authors set a threshold of $^{10}\text{Be}/^7\text{Be} > 1.8$ and exclude these data points before running the regression again, which substantially improves the correlation, with R^2 rising from 0.33 to 0.92. This practice raises two problems. First, the threshold lacks physical justification because the authors provide no independent evidence that ratios above 1.8 indeed represent stratospheric intrusion, leading readers to reasonably suspect that this threshold was chosen to make the statistical results look better. Second, the manuscript falls into a logical conflict between data processing and causal inference. On one hand, the authors subjectively remove high isotope ratio points to improve linear correlation. On the other hand, they use these very points as the core evidence for stratospheric material downward transport and its modulation of precipitation. According to the authors' own theoretical premise, stratospheric intrusion with elevated isotope ratios should act as an additive component superimposed on wet deposition, not disrupting the positive correlation between total flux and precipitation. If anything, adding these points should strengthen the positive correlation. Yet the fact that R^2 jumps from below 0.33 to 0.85 to 0.92 after excluding them proves that these data points do not follow the conventional precipitation scavenging mechanism, as their dynamics are more consistent with dry deposition or non-precipitation processes. By treating these points as noise and removing them, the authors are methodologically acknowledging that these signals have no direct causal relationship with precipitation. However, they then go on to use these same precipitation-independent signals to explain precipitation variability and attribute it to QBO-modulated stratospheric forcing.

This constitutes a classic circular argument where the authors presuppose that a high ratio equals stratospheric intrusion as a filtering criterion, then use the strong correlation in the filtered residual data to argue for the existence of stratospheric influence, and finally use the unvalidated stratospheric intrusion to explain precipitation genesis. If QBO-modulated stratosphere-troposphere exchange is precisely the core mechanism the paper aims to reveal, then these high-ratio points carrying strong stratospheric characteristics are precisely the most critical carriers of the process signal. Removing them as interference not only deprives the core mechanism of data support but also completely breaks the causal chain linking stratospheric signals to surface precipitation. These logical issues ultimately reduce to a single question: what exactly does the isotope ratio indicate about precipitation?

A4: We thank the reviewer for their comments and suggestions. We revisited both the operational definition of the plotted groups and the inference drawn from the re-fitted regressions. For the comparisons in Fig. 2, we group observations with $^{10}\text{Be}/^7\text{Be} > 1.8$ and relatively high concentrations of both radionuclides by their proximity in sampling date. The value 1.8 is a study-specific event-selection criterion, NOT a universal dividing line between stratospheric and tropospheric air or an independently calibrated STE threshold. We first retain the regression using the complete record, then compare it with fits excluding those predefined event groups. The higher correlations of the reduced sample describe how those selected observations influence the precipitation–flux relationship. This statistical change cannot independently prove that the removed points represent stratospheric intrusions, because the points were selected partly using

the isotope behavior under discussion. Their atmospheric interpretation instead depends on separate information from circulation anomalies, backward trajectories, and regional PV sections, and remains phrased as being consistent with possible stratospheric influence. We have stated this separation explicitly in Methods and Discussion. No alternative-threshold sensitivity experiment is provided in the current materials, and we do not claim one.

Section 2.7 event group definitions

The Zonal (east–west) wind and geopotential datasets were obtained from ERA5 monthly averaged data on pressure levels, and PV was obtained from ERA5 daily average data on pressure levels (Hersbach et al., 2023), both visualized using Panoply. PV is expressed in potential vorticity units ($1 \text{ PVU} = 10^{-6} \cdot \text{K} \cdot \text{m}^2 \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$). The 2 PVU threshold is used as a conventional dynamical-tropopause reference (Millán et al. 2021). The meteorological data used for machine learning came from ERA5 (2001-2020, 25°N - 40°N , 80°E - 100°E). Origin 2020 was used to process and graph the raw data. Rainfall data were retrieved from the China Meteorological Data Network (<http://data.cma.cn/>). Annual fluxes were estimated using average concentrations during the sampling period and annual precipitation totals. For the event-group comparisons in Fig. 2, the threshold of $^{10}\text{Be}/^{7}\text{Be} > 1.8$ was adopted as an empirical criterion for identifying relatively high-ratio events in the observational dataset. This selection is physically motivated by previous studies showing that enhanced $^{10}\text{Be}/^{7}\text{Be}$ ratios can be associated with stratospheric influence (Jordan et al., 2003; Zanis et al., 2003). Notably, ratios of approximately 1.71-1.90 have been reported during an independently identified stratospheric intrusion event over Europe (Zanis et al., 2003). Nevertheless, because the ratio varies with atmospheric transport, mixing, and air-mass history, the value of 1.8 is not considered a universal boundary between stratospheric and tropospheric air. The threshold is used solely to define the event groups examined in Fig. 2, and the potential stratospheric influence associated with these events is evaluated using independent atmospheric transport and dynamical diagnostics.

Section 3.2 event description

In Lhasa (two-year record) and Xi'an (one-year record), we fitted ^{10}Be and ^{7}Be concentrations and fluxes in precipitation against daily rainfall amounts (Fig. 2). The results reveal that ^{10}Be and ^{7}Be levels are closely tied to rainfall intensity (~ 0.5 - $100 \text{ mm} \cdot \text{h}^{-1}$) during daily precipitation events, suggesting a concurrent variation between rainfall intensity and the deposition behavior of beryllium isotopes. This phenomenon indicates that in modern environments, precipitation intensity will simultaneously regulate the deposition processes of both ^{7}Be and ^{10}Be .

Section 3.2 regression interpretation

To isolate the contribution of stratosphere-to-troposphere vertical motion on ^{7}Be and ^{10}Be , we excluded data points with high $^{10}\text{Be}/^{7}\text{Be}$ ratios and conducted a re-analysis. This resulted in a significant improvement in the linear relationship between daily ^{7}Be and ^{10}Be wet deposition fluxes and rainfall amounts (Fig. 2c, 2d, $R^2 = 0.85$ - 0.92 , $p < 0.05$) in both Lhasa and Xi'an. This implies that, under regional tropospheric control, the deposition of ^{7}Be and ^{10}Be is predominantly governed by precipitation. The slopes of these linear regression models provide a means to trace environmental process variations over short-term (daily to seasonal) and long-term (103-105 years) timescales. This provides further insight into the mechanisms through which factors such as precipitation, climate change, and stratosphere-troposphere exchange influence ^{7}Be and ^{10}Be concentrations (Juri Ayub et al., 2012; Deng et al., 2020). It should be clarified that this result

supports precipitation scavenging as an important control on routine ^7Be and ^{10}Be wet deposition, while the anomalous high-ratio events require additional consideration of transport, air-mass history, and event-specific scavenging.

Section 3.3 independent dynamical context

The HYSPLIT calculations characterize transport pathways connecting the sampled air masses with the upper troposphere (Fig. 3c, 3d). Complementing these trajectories, the event-period PV sections show values exceeding 2 PVU below 200 hPa over both study regions (Fig. S6). Together, the isotope, trajectory and PV evidence is consistent with stratospheric influence aloft during the selected events. Annual precipitation increased from 273 mm in 2022 to 439 mm in 2023 at Lhasa, with an increase of approximately 34% at Xi'an. While the exact contribution of the QBO to these precipitation anomalies cannot yet be quantified, the temporal synchronicity of these changes suggests the potential influence of large-scale circulation.

Q5. Clear temporal mismatch between two years of observations and twenty years of model data

The isotope observations are limited to the 2022 to 2023 summer seasons, while the XGBoost machine learning attribution model is based on long-term ERA5 reanalysis data from 2001 to 2020. The 2022 to 2023 observations are not even within the training or validation period of the machine learning model, which ends in 2020. This means that the core new observational data, which the authors spent considerable effort collecting and analyzing, were logically not used to train, calibrate, or test the machine learning model that produced the 31.3% contribution figure.

Furthermore, the paper's stated motivation is to use new isotope observations to reveal stratospheric dynamic mechanisms, yet the actual structure is that the first half discusses isotopes for 2022 to 2023, and the second half abruptly shifts to two decades of large-scale meteorological reanalysis and machine learning from 2001 to 2020. The authors do not establish a clear mathematical or physical link to explain which specific features or events in the 2001 to 2020 model correspond to the high-ratio anomalies measured in Lhasa during 2022 to 2023. As a result, the isotope observations and the machine learning attribution analysis operate independently of each other. This disjointed structure makes the logical chain less coherent, rendering the isotope observations a relatively isolated component that lacks substantive connection to the subsequent machine learning attribution. The spatiotemporal context on which the machine learning model is based has no direct overlap with the isotope observation data, meaning the resulting 31.3% contribution is entirely computed from long-term reanalysis data and lacks direct cross-validation or linkage with the isotope observations that the paper emphasizes as its innovative contribution.

A5: We agree that two distinct timescales must not be conflated. The 2022–2023 isotope observations address event-scale changes during an observed QBO phase transition; the separate XGBoost–SHAP analysis draws on a longer ERA5 series to describe predictive relationships among meteorological variables and precipitation in the broader region. Crucially, the rainwater isotope measurements were not used to train the model, and a long-term SHAP attribution is not an event-specific quantification or independent validation of the observed $^{10}\text{Be}/^7\text{Be}$ peaks. We rewrote Section 3.5 and the synthesis to show how the two analyses complement one another without treating statistical consistency as mechanistic proof. The proposed dynamical link consequently remains a hypothesis supported by convergent but not definitive evidence.

Introduction, objectives

This study aims to constrain possible links among QBO-related stratospheric dynamics, atmospheric transport, and precipitation during 2022-2023 using cosmogenic ^7Be and ^{10}Be measurements. The Tibetan Plateau provides a setting in which monsoon convection and high-altitude topography influence atmospheric exchange (Bian et al., 2020). Lhasa (3650 m a.s.l.) represents the high-altitude site, whereas Xi'an (420 m a.s.l.) provides a low-elevation reference site in the same broad QBO-related rainfall-response sector. We first characterize isotope concentrations, wet-deposition fluxes, and ratios at the two sites and examine their relationships with precipitation. We then evaluate elevated-ratio events using backward trajectories and potential vorticity (PV), before placing the events in the context of the QBO transition and longer-term circulation–precipitation associations. This sequence connects the event-scale tracer evidence with the regional dynamical setting while distinguishing observations from the proposed physical interpretation.

Section 2.5 statistical period

Employing the XGBoost machine-learning model (Chen and Guestrin, 2016), we examined 20 years (2001-2020) of ERA5 reanalysis for the Tibetan Plateau region (25°N - 40°N , 80°E - 100°E), and used interpretable SHapley Additive exPlanations (SHAP) analysis to disentangle and quantify the influence of each meteorological parameter on rainfall (Lundberg et al., 2020) (Fig. S5). The predictors include: R1000 (relative humidity at 1000 hPa, %), CAPE (convective available potential energy, J/kg), Q1000 (specific humidity at 1000 hPa, g/kg), MSL (mean sea-level pressure, hPa), BLH (boundary-layer height, m), T2M (2-m air temperature, K), U50 (zonal wind at 50 hPa, m/s), Z200 (200-hPa geopotential height, m), U100 (100-m zonal wind, m/s), and V100 (100-m meridional wind, m/s). It should be noted that when applying SHAP analysis, interdependencies among features can lead to additive contribution effects, which may potentially affect the quantitative interpretation of the importance of individual features.

Section 3.5 statistical context

The XGBoost analysis provides a longer-term statistical perspective on precipitation over the Tibetan Plateau during 2001-2020 (Fig. 5). Unlike the event diagnostics, this analysis evaluates how equatorial QBO wind and regional meteorological predictors are associated with precipitation across the longer record. Mean absolute SHAP values summarize model importance, and the sign of each SHAP value indicates whether a predictor increases or decreases the model output relative to its baseline. Because the isotope observations were not used to train the model, the results complement rather than quantitatively validate the isotope-based transport interpretation.

Section 3.6 synthesis

The combined evidence separates two related aspects of the circulation–precipitation system (Fig. 4b). Atmospheric transport changes the sources and histories of aerosol-bound Be that can subsequently be scavenged by precipitation. Circulation also affects the moisture supply and ascent involved in rainfall. The isotope observations primarily constrain the first aspect, while the reanalysis and predictive model describe elements of the second and their large-scale background. A common circulation setting can connect the two, but high-ratio deposition does not itself demonstrate that downward-transported air generated the precipitation.

Section 3.6 limitations

The study consequently provides observational constraints on a possible linkage among QBO-associated circulation, atmospheric transport and precipitation during the sampled period. It

does not resolve the independent QBO contribution relative to ENSO, Indian Ocean variability or other meteorological influences. Longer isotope records, comparisons within common sampling seasons, sensitivity to event-grouping criteria, and higher-frequency transport diagnostics would help assess the persistence and specificity of the inferred relationships.

Q6. Methodological problems in the machine learning approach

The authors acknowledge in Section 2.5 that correlations among variables affect SHAP analysis results, yet in Section 4.4 they present a precise 31.3% contribution, creating an internal inconsistency. More seriously, the model uses concurrent near-surface relative humidity and specific humidity as predictors of precipitation. Because precipitation and humidity co-occur, using humidity measured at the same time as precipitation to predict precipitation reverses the causal direction.

Additionally, translating SHAP values into percentages lacks a mathematical basis. SHAP values represent the marginal contribution of features to model output, with units matching those of precipitation itself. Dividing a feature SHAP value by total precipitation and claiming that this feature contributed 31.3% has no mathematical justification, especially since SHAP values can be positive or negative, and feature interactions mean that individual SHAP values do not strictly sum to the prediction value. I strongly recommend that the authors conduct variance inflation factor tests and remove variables with VIF greater than 10, replace concurrent humidity with humidity from prior time steps such as previous day values, and use SHAP only for relative importance ranking while refraining from presenting an absolute percentage like 31.3%.

A6: We agree that the earlier interpretation of a precise “31.3% contribution” to actual precipitation was not methodologically warranted. We have retained the term “contribution” where it means contribution to the trained XGBoost model output, as requested, but now differentiate it explicitly from a physical or causal contribution of the QBO to rainfall. A SHAP value describes the change in a model prediction relative to its baseline attributable under the specified explanation framework; mean absolute SHAP values summarize predictor importance within that fitted model. They cannot isolate QBO forcing from correlated humidity, circulation, stability, and other climate variables. Accordingly, Section 3.5 reports model-based associations and avoids attributing a fraction of observed rainfall to QBO. We have also noted the methodological limitation of interdependent features in Section 2.5.

Section 2.5 SHAP method

Employing the XGBoost machine-learning model (Chen and Guestrin, 2016), we examined 20 years (2001-2020) of ERA5 reanalysis for the Tibetan Plateau region (25°N-40°N, 80°E-100°E), and used interpretable SHapley Additive exPlanations (SHAP) analysis to disentangle and quantify the influence of each meteorological parameter on rainfall (Lundberg et al., 2020) (Fig. S5). The predictors include: R1000 (relative humidity at 1000 hPa, %), CAPE (convective available potential energy, J/kg), Q1000 (specific humidity at 1000 hPa, g/kg), MSL (mean sea-level pressure, hPa), BLH (boundary-layer height, m), T2M (2-m air temperature, K), U50 (zonal wind at 50 hPa, m/s), Z200 (200-hPa geopotential height, m), U100 (100-m zonal wind, m/s), and V100 (100-m meridional wind, m/s). It should be noted that when applying SHAP analysis, interdependencies among features can lead to additive contribution effects, which may potentially affect the quantitative interpretation of the importance of individual features.

Section 3.5 SHAP scope

The XGBoost analysis provides a longer-term statistical perspective on precipitation over the Tibetan Plateau during 2001-2020 (Fig. 5). Unlike the event diagnostics, this analysis evaluates how equatorial QBO wind and regional meteorological predictors are associated with precipitation across the longer record. Mean absolute SHAP values summarize model importance, and the sign of each SHAP value indicates whether a predictor increases or decreases the model output relative to its baseline. Because the isotope observations were not used to train the model, the results complement rather than quantitatively validate the isotope-based transport interpretation.

Section 3.5 predictor associations

The results show (Fig. 5) that precipitation over the Tibetan Plateau is associated in the XGBoost model with a range of meteorological predictors, including 1000 hPa relative humidity (R1000), convective available potential energy (CAPE), 1000 hPa specific humidity (Q1000), mean sea-level pressure (MSL), boundary-layer height (BLH), 2 m air temperature (T2M), zonal wind at 50 hPa (U50), 200 hPa geopotential height (Z200), and 100 m zonal and meridional winds (U100, V100). The SHAP dependence patterns for R1000 and Q1000 are nonlinear (Fig. 5b), with values above approximately 75% for R1000 and 10 g/kg for Q1000 associated with higher model-predicted rainfall, particularly over the southern Plateau (Fig. 5c). Considering U100 and V100, enhanced southeast winds primarily drive the increase in southern Tibetan Plateau rainfall, while dominant westerlies inhibit precipitation (Fig. 5b). A similar pattern is observed in the northern Plateau. Moisture influx from the Indian Ocean elevates relative humidity in the southern Tibetan Plateau, thereby significantly promoting precipitation along the southern flank. In addition, rising temperatures (T2M) intensify atmospheric convection, further augmenting rainfall. These statistical relationships are physically consistent with enhanced moisture supply and convection, but they are not interpreted as independent causal estimates.

Section 3.5 interpretation

For the EQBO phase (Fig. 5b, U50 negative), negative values corresponding to upper-level easterly flow are associated in the model with higher predicted precipitation over parts of the southern Tibetan Plateau, whereas the opposite wind regime is associated with lower predicted precipitation. CAPE and Z200 also show substantial predictive importance and are related to atmospheric stability and upper-level circulation structure. This model association is consistent with examining the observed events in a QBO-related circulation context, but SHAP does not yield a physical percentage of rainfall caused by the QBO. Correlated predictors and other climate variability remain relevant to the interpretation.

Q7. Back trajectory starting heights do not reach the stratosphere

The Lhasa back trajectories start at 6000 meters above sea level. Since the Lhasa site itself is at 3650 meters, the effective starting height is approximately 9650 meters or about 300 hPa, which is still in the upper troposphere. Because the QBO signal resides near 30 hPa at approximately 24 kilometers, a vertical gap of about 14 kilometers remains unbridged. This altitude is far from reaching the stratosphere, meaning the trajectories track upper tropospheric local circulation rather than stratospheric air masses. The authors should either raise the trajectory starting heights to reach stratospheric levels or explicitly acknowledge this limitation in the text.

A7: We appreciate this clarification request. The trajectory arrival heights are defined above ground level (a.g.l.), not above sea level: Xi'an uses 10, 500 and 1000 m a.g.l.; Lhasa uses 10, 2000 and 6000 m a.g.l. These are levels at which HYSPLIT trajectories are initiated backward in

time; they do not by themselves demonstrate that sampled rainwater came from the stratosphere, regardless of the maximum arrival level. We therefore use HYSPLIT to characterize possible transport pathways rather than independently assign source regions. To provide a separate diagnostic, we added daily ERA5 latitude–pressure PV sections for high-ratio event periods, along 91.5°E near Lhasa and 109°E near Xi'an (Fig. S6), and discuss features exceeding the conventional 2-PVU dynamical-tropopause reference. Importantly, these are regional/event-period sections, not PV values calculated along the individual HYSPLIT parcels. Their value is to contextualize the observed events with possible stratospheric influence aloft; they do not establish parcel-by-parcel descent or directly prove the origin of the precipitation samples. Both the methods and interpretation now state these limits.

Section 2.6 trajectory settings

The Hybrid Single-Particle Lagrangian Integrated Trajectory model (NOAA HYSPLIT. <https://www.ready.noaa.gov/HYSPLIT.php>) is a commonly used tool for tracking atmospheric transport and identifying air mass sources (Stein et al., 2015). The calculations employed 1°-resolution gridded meteorological data from the Global Data Assimilation System, with settings otherwise consistent with our previous study (Liu et al., 2024a). Backward trajectories were calculated for 72-96 h. Arrival heights were defined relative to ground level: 10, 500, and 1000 m above ground level (a.g.l.) for Xi'an, and 10, 2000, and 6000 m a.g.l. for Lhasa. Trajectory calculations were initiated at 6 h intervals during periods of anomalous 10Be/7Be ratios and traced backward from the two sampling locations (Lhasa: 29°38'49"N, 91°4'37"E; Xi'an: 34°13'20"N, 109°00'18"E). The trajectories are used here to characterize transport pathways and do not, by themselves, establish a stratospheric origin of the sampled air. Independent dynamical diagnostics, such as potential-vorticity fields near the dynamical tropopause, are required to further evaluate stratospheric influence. The trajectories are therefore evaluated alongside event-period vertical distributions of PV over the two study regions.

Section 2.6 PV sections

Daily mean ERA5 pressure-level PV fields were used to construct meridional latitude–pressure sections along 91.5°E near Lhasa and 109°E near Xi'an for the selected elevated-ratio events in 2023 (Fig. S6). The dates correspond to the event groups in Fig. 2a and 2b. PV is expressed in potential vorticity units ($1 \text{ PVU} = 10^{-6} \cdot \text{K} \cdot \text{m}^2 \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$), and 2 PVU is used as a conventional dynamical-tropopause reference (Millán et al., 2021). These regional sections describe the event-period PV distribution and complement the trajectories; they do not provide PV histories along individual trajectories.

Section 3.3 trajectories + PV

The HYSPLIT calculations characterize transport pathways connecting the sampled air masses with the upper troposphere (Fig. 3c, 3d). Complementing these trajectories, the event-period PV sections show values exceeding 2 PVU below 200 hPa over both study regions (Fig. S6). Together, the isotope, trajectory and PV evidence is consistent with stratospheric influence aloft during the selected events. Annual precipitation increased from 273 mm in 2022 to 439 mm in 2023 at Lhasa, with an increase of approximately 34% at Xi'an. While the exact contribution of the QBO to these precipitation anomalies cannot yet be quantified, the temporal synchronicity of these changes suggests the potential influence of large-scale circulation.

Section 3.6 limitations

The study consequently provides observational constraints on a possible linkage among QBO-associated circulation, atmospheric transport and precipitation during the sampled period. It does not resolve the independent QBO contribution relative to ENSO, Indian Ocean variability or other meteorological influences. Longer isotope records, comparisons within common sampling seasons, sensitivity to event-grouping criteria, and higher-frequency transport diagnostics would help assess the persistence and specificity of the inferred relationships.

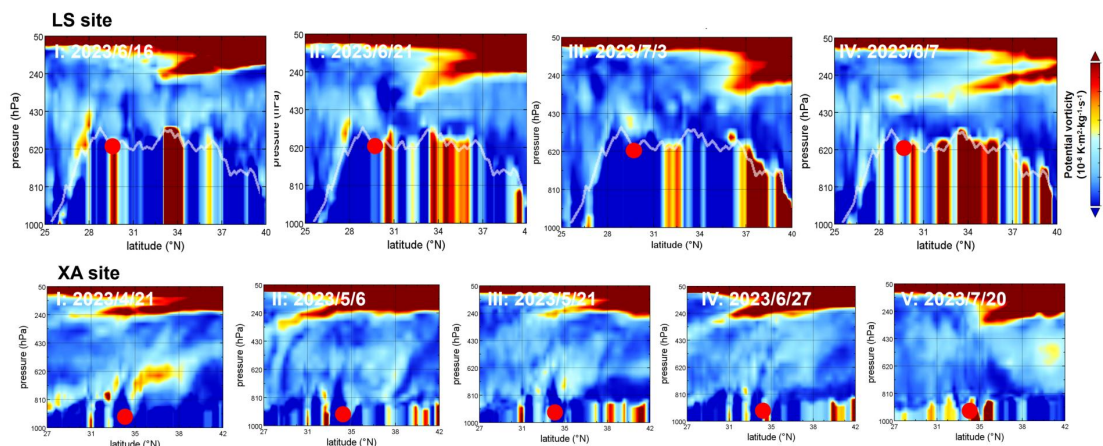


Fig. S6 Meridional latitude–pressure cross-sections of potential vorticity (PV) derived from daily mean ERA5 data along 91.5° E near Lhasa on the Tibetan Plateau (LS; upper row) and 109° E near Xi'an on the Loess Plateau (XA; lower row) during selected elevated $^{10}\text{Be}/^7\text{Be}$ events in 2023. The dates shown in the panels correspond to the event periods identified in Fig. 2a and b, respectively. Colour shading indicates PV in PVU ($1 \text{ PVU} = 10^{-6} \text{ K} \cdot \text{m}^2 \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$). Red dots mark the sampling-site latitudes and approximate surface pressures on the respective cross-sections.

Q8. Structural disorganization of paragraphs

The manuscript suffers from structural disorganization, with multiple paragraphs belonging in the Results section placed in the Discussion, and material appropriate for the Introduction appearing in later sections. For example, the regression analysis of isotope fluxes against precipitation amounts is presented in the Discussion rather than in Results, while the extended discussion of QBO background characteristics in the Results section would be more appropriately placed in the Introduction. A systematic reorganization of the text is needed to establish a logical progression from empirical observations to numerical modeling and synthesis.

A8: We agree that the original order made it difficult to see which statements were observations, which were diagnostic interpretation, and which were broader implications. The revised manuscript now follows a staged evidentiary sequence within “Results and Discussion”: (3.1) observed isotope concentrations, ratios and wet-deposition fluxes; (3.2) rainfall dependence and the explicitly defined high-ratio event groups; (3.3) QBO-period circulation, backward trajectories and PV diagnostics; (3.4) regional circulation and precipitation context; (3.5) longer-term XGBoost–SHAP associations; and (3.6) synthesis and limitations. This sequence helps avoid using an interpretation from later sections as if it were an initial measured fact. We have also tempered the Abstract and concluding claims to reflect this hierarchy. Some contextual material necessarily remains in integrated Results and Discussion; the aim of the reorganization is a transparent inference chain rather than formal separation of all results from discussion.

3. Results and Discussion

Section 3.1 observations

Fig. 1a illustrates the time series of ^{10}Be and ^7Be concentrations and their daily deposition fluxes in Lhasa precipitation during the 2022-2023 rainy seasons (June to September). The concentrations of ^{10}Be and ^7Be varied from $(0.94 \pm 0.08) \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1}$ to $(29.70 \pm 0.44) \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1}$ rain, and from $(0.63 \pm 0.32) \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1}$ rain to $(10.29 \pm 0.22) \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1}$ rain, respectively. Their median concentrations were $2.10 \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1}$ rain for ^{10}Be and $1.42 \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1}$ rain for ^7Be . The $^{10}\text{Be}/^7\text{Be}$ ratios varied between 0.97 ± 0.26 and 3.64 ± 0.32 . The daily wet deposition fluxes of ^{10}Be and ^7Be in Lhasa, estimated using daily rainfall, ranged from $(0.41 \pm 0.02) \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ to $(43.07 \pm 0.64) \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ and from $(0.29 \pm 0.05) \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ to $(14.92 \pm 0.31) \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, respectively. Median fluxes were $1.93 \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ for ^{10}Be and $0.98 \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ for ^7Be

Section 3.2 observations + groups

In Lhasa (two-year record) and Xi'an (one-year record), we fitted ^{10}Be and ^7Be concentrations and fluxes in precipitation against daily rainfall amounts (Fig. 2). The results reveal that ^{10}Be and ^7Be levels are closely tied to rainfall intensity ($\sim 0.5\text{-}100 \text{ mm} \cdot \text{h}^{-1}$) during daily precipitation events, suggesting a concurrent variation between rainfall intensity and the deposition behavior of beryllium isotopes. This phenomenon indicates that in modern environments, precipitation intensity will simultaneously regulate the deposition processes of both ^7Be and ^{10}Be

Section 3.3 circulation analysis

Reanalysis data for the 2022-2023 observation period (Fig. 3a) indicate that the upper-level zonal wind shifted from a westerly to an easterly phase, unlike the QBO disruption events during the 2015/16 and 2019/20 periods, which also featured zonal wind reversals, the QBO during 2022/23 underwent a stable and well-defined transition from WQBO to EQBO. The summer season is commonly when QBO wind direction transitions occur. During early summer (June), the geopotential height differences from 50 hPa to 850 hPa over East Asia generally shifted from negative to positive (Fig. 3b). In central and northern China, negative anomalies in geopotential height between 50 hPa and 200 hPa caused upper-level warm air to sink. During the EQBO phase, the subtropical high-pressure anomalies at 500 hPa and 850 hPa were more pronounced, strengthening the North Pacific High Center. Notably, the two high-pressure centers at approximately 850 hPa over the Tibetan Plateau and the Loess Plateau moved closer together, leading to abnormal near-surface uplift of air masses and increased moisture convergence in the region, thereby raising the probability of rainfall over these regions.....

Section 3.4 context

At Lhasa, Be fluxes and $^{10}\text{Be}/^7\text{Be}$ ratios increased during parts of 2023 relative to 2022. Annual precipitation increased from 273 mm in 2022 to 439 mm in 2023, while Xi'an experienced an increase of approximately 34%. Within the broad QBO-related rainfall-response sector considered here, Xi'an supplies a low-elevation reference site for examining the corresponding regional precipitation change and isotope-event behavior. These concurrent changes provide context for the transport-sensitive observations, but the annual rainfall differences cannot be assigned uniquely to the QBO. Other circulation variability and local precipitation processes can contribute to the changes at both sites.....

Section 3.5 model

The XGBoost analysis provides a longer-term statistical perspective on precipitation over the Tibetan Plateau during 2001-2020 (Fig. 5). Unlike the event diagnostics, this analysis evaluates how equatorial QBO wind and regional meteorological predictors are associated with precipitation across the longer record. Mean absolute SHAP values summarize model importance, and the sign of each SHAP value indicates whether a predictor increases or decreases the model output relative to its baseline. Because the isotope observations were not used to train the model, the results complement rather than quantitatively validate the isotope-based transport interpretation.....

Section 3.6 synthesis

The combined evidence separates two related aspects of the circulation–precipitation system (Fig. 4b). Atmospheric transport changes the sources and histories of aerosol-bound Be that can subsequently be scavenged by precipitation. Circulation also affects the moisture supply and ascent involved in rainfall. The isotope observations primarily constrain the first aspect, while the reanalysis and predictive model describe elements of the second and their large-scale background. A common circulation setting can connect the two, but high-ratio deposition does not itself demonstrate that downward-transported air generated the precipitation.....

Q9: Specific comments:

Line 26: analyzes → analyze, Line 33: linking → link, Line 49: 370 billion yuan → 370 billion CNY, Line 412: V200 → V100, Line 452: Hugh Coe, 2024 → Coe, 2024

A9: We thank the reviewer for their comments; we have made all the suggested revisions and further checked the relevant wording for grammatical issues.

We appreciate the close reading. We checked the reviewer’s specific textual and variable-label corrections against the latest available manuscript. The currency appears as “370 billion CNY”; the meridional wind variable is identified as V100, including in the model definitions and Fig. 5 caption. The revised Abstract uses plural-subject syntax appropriate to “we” and describes possible links rather than demonstrated causality. We also reviewed the requested author-name correction, while recognizing that author metadata must follow the cited paper’s verified bibliographic entry. Rather than claim every original line number still applies after extensive reorganization, we point to the corresponding current locations below.

RC1: This manuscript presents an interesting and novel approach by using cosmogenic ^{10}Be and ^7Be isotopes as tracers to link QBO-modulated stratospheric dynamics with precipitation over the southern Tibetan Plateau. The topic is timely and the dataset is valuable. However, several methodological and logical issues require further revision before the manuscript can be considered for publication.

Q1: Section 3: The authors compare the wet deposition data of ^{10}Be and ^7Be between Lhasa (the 2022–2023 rainy season, June–September) and Xi’an (March–September 2023). However, the observation time windows are asymmetric: the Lhasa data only cover summer, whereas the Xi’an data cover both spring and summer. Spring and summer differ in atmospheric circulation characteristics (e.g., the position of the westerlies and tropopause height), precipitation types (e.g., spring rain vs. summer convective rain), and aerosol sources. Directly comparing Lhasa’s 4-month dataset with Xi’an’s 7-month dataset (especially comparing the medians) may introduce a considerable seasonal bias, thereby exaggerating Xi’an’s deposition fluxes.

A1: We thank the referee for highlighting the asymmetric temporal coverage of the two observational records and its potential implications for the site comparison. We agree that differences in seasonal sampling may affect the measured ^{10}Be and ^7Be concentrations, their wet-deposition fluxes, and their ratio, independently of the differences in altitude and atmospheric circulation between the two locations. The sampling windows were determined by actual precipitation and the minimum amount of rainwater required for reliable beryllium-isotope analysis, rather than by a deliberate selection of particular atmospheric conditions. In Lhasa, precipitation is scarce in spring, and individual events often produce insufficient water for the analytical procedure. Consequently, suitable samples were obtained principally during the summer rainy season. By contrast, adequate precipitation samples could be collected over a longer spring–summer period at Xi'an. We have clarified this practical constraint in the sampling description. Importantly, the different sampling windows do not justify assuming that the two datasets are directly seasonally comparable. Seasonal changes in transport pathways, aerosol sources, wet scavenging and background radionuclide concentrations may contribute to their differences. We therefore interpret Xi'an as a lower-elevation reference site, not a strict climatological or experimental control. In the revised discussion, we explicitly limit full-record comparisons to descriptive observations within the respective sampling periods. Any inference about site contrasts independent of seasonality would require a matched-season comparison, for example using the overlapping June–September 2023 observations. We do not claim that seasonality has been removed from the present comparison.

Section 3.1,

Because the Lhasa series principally represents the summer rainy season whereas the Xi'an series also includes spring, differences in isotope concentrations, ratios and wet-deposition fluxes may partly reflect seasonal variation in aerosol sources, circulation and precipitation scavenging. Xi'an is consequently used as a lower-elevation reference site to provide regional context, rather than as a seasonally matched control from which an altitude effect can be isolated.

Section 2.1, inter-site context

The Loess Plateau is adjacent to the Tibetan Plateau and is influenced by the same large-scale atmospheric circulation patterns. Furthermore, it is located on the same side of the dipole rainfall pattern as the Tibetan Plateau, and is therefore used as a reference observation site in this work. Rainfall also exerts a significant impact on the vulnerable ecosystems of the Loess Plateau: too much can intensify soil erosion and geomorphic degradation, while too little may lead to reduced vegetation cover and weakened ecosystem functions (Cai et al., 2022). According to Chinese Loess ^{10}Be sedimentary records, climate change has historically caused variations in the intensity of rainfall events on the Loess Plateau (Zhou et al., 2023). Xi'an, where sampling was conducted, lies in the southern Loess Plateau of China and receives approximately 500-750 mm of rainfall annually. Their urban sampling settings and different observation coverage are considered when interpreting the comparison.

Section 2.2 (sampling constraints): The duration and seasonal coverage of rainwater sampling were constrained by the occurrence of precipitation and the volume required for isotope analysis. In Lhasa, spring precipitation was sparse and individual rainfall events generally yielded insufficient sample volume for analysis; accordingly, suitable observations were mainly obtained during the summer rainy season. In Xi'an, precipitation events suitable for sampling occurred over

a longer period extending from spring into summer. The resulting temporal coverage is therefore asymmetric and reflects local precipitation conditions and analytical requirements rather than an intentionally season-matched design.

Section 3.1, interpretative paragraph

The full-record comparisons between Lhasa and Xi'an must be interpreted in light of their different sampling windows. Because the Lhasa series principally represents the summer rainy season whereas the Xi'an series also includes spring, differences in isotope concentrations, ratios and wet-deposition fluxes may partly reflect seasonal variation in aerosol sources, circulation and precipitation scavenging. Xi'an is consequently used as a lower-elevation reference site to provide regional context, rather than as a seasonally matched control from which an altitude effect can be isolated.

Q2: L274-275: The authors state that Lhasa and Xi'an have "similar annual mean precipitation," which serves as the foundation for concluding that the ^{10}Be flux signal mainly reflects changes in the production rate. However, this directly contradicts the data presented in L266-267, where annual precipitation is reported as 356.6 mm for Lhasa versus 550.9 mm for Xi'an, a difference of over 50%. Because the precipitation amounts are not similar, the subsequent conclusion regarding production-rate dominance may not be well supported.

A2: We thank the referee for identifying an inconsistency. The reported annual precipitation totals are 356.6 mm at Lhasa and 550.9 mm at Xi'an. Their difference is 194.3 mm, corresponding to approximately 54.5% of the Lhasa amount; describing the two totals as "similar" is inaccurate. We also agree that the stronger statement attributing interannual ^{10}Be flux variability mainly to cosmogenic production is not established by these data. Wet deposition depends on rainfall amount, aerosol scavenging, atmospheric transport, and source conditions, and the annual fluxes in this study were estimated by extrapolating measurements from sampling periods using annual precipitation totals. In the existing revision, we already caution that these extrapolations cannot disentangle production, transport, and deposition; however, a contradictory production-dominance sentence remains.

Section 3.1, stated annual totals

This represents the first long-term daily-resolution observational record of atmospheric ^{10}Be and ^7Be wet deposition in the high-altitude regions of China, specifically the Tibetan Plateau (Fig. 1a). In light of the strong utility of ^7Be for investigating aerosol deposition, the joint use of ^{10}Be and ^7Be in our observations helps circumvent the natural-process constraints inherent to single-isotope tracers, paving the way for more precise quantitative assessments of bulk aerosol deposition rates. The results reveal that the concentrations and ratios of ^{10}Be and ^7Be in precipitation from the Tibetan Plateau and Loess Plateau are broadly consistent with previous studies from other regions. Additionally, the $^{10}\text{Be}/^7\text{Be}$ ratio range in rainwater aligns with the dry deposition records of aerosols we previously collected from various locations across China (Liu et al., 2024b). According to the mean annual precipitation for the corresponding years in Lhasa (356.6 mm) and Xi'an (550.9 mm), the annual wet deposition fluxes of ^{10}Be and ^7Be in Lhasa (29°N) are $74.69 \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$ and $50.72 \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$, respectively. In contrast, for Xi'an (34°N), the respective fluxes are $460.10 \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$ for ^{10}Be and $229.31 \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$ for ^7Be . The production rate ratio of ^{10}Be to ^7Be remains consistent across latitudes (Masarik and Beer, 1999). Furthermore, our findings align with the modern trend of

increasing ^{10}Be deposition flux with latitude, typically ranging from $(40\text{--}530)\cdot 10^8$ atoms $\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$ between latitudes 10° and 47° (Deng et al., 2020). Annual precipitation amounted to 356.6 mm at Lhasa and 550.9 mm at Xi'an in the years considered, and the two sites therefore cannot be regarded as having similar annual precipitation. Differences in ^{10}Be and ^7Be wet-deposition fluxes may arise from precipitation amount and scavenging, aerosol loading, atmospheric transport, and radionuclide source conditions. Moreover, the estimated annual fluxes extrapolate sampled concentrations using annual precipitation totals. Consequently, these observations do not allow us to identify changes in cosmogenic production as the dominant cause of the inter-site or interannual flux differences. The isotope time series are instead interpreted jointly with precipitation and circulation diagnostics.

Section 3.1

From these data, it can be seen that for Lhasa and Xi'an, which have similar annual mean precipitation, the ^{10}Be flux signal on an interannual scale mainly reflects changes in the production rate of ^{10}Be . This is consistent with previous studies, which concluded that on a seasonal scale, the flux variations of ^7Be and ^{10}Be are related to environmental factors such as precipitation rate and the height of the tropopause (Terzi and Kalinowski, 2017; Heikkilä and Smith, 2013). Therefore, the seasonal data of ^{10}Be and ^7Be may contain information on rainfall induced by monsoon circulation changes, particularly the daily resolution ^{10}Be and ^7Be flux data, which have the potential to record rapid rainfall variations. The low-elevation reference site helps assess whether event behavior occurs in both environments within the same broad QBO-related rainfall-response sector. Differences in precipitation, local aerosol reservoirs, wet scavenging and transport must nevertheless be considered together. The annual flux estimates also depend on extrapolating sampled concentrations and cannot, by themselves, distinguish nuclide production from transport and deposition.

Q3: Section 4.2: By selectively excluding data points, the authors may inadvertently bias the remaining data toward a precipitation-dominated model and then use this optimized fit to argue that precipitation is the dominant factor. This approach may introduce circular reasoning. In addition, it would be helpful if the authors quantified the percentage of excluded data relative to the total dataset. Furthermore, the authors use a $^{10}\text{Be}/^7\text{Be}$ ratio threshold of 1.8 to exclude data points, but no justification is provided for this specific value. Why 1.8 and not 1.5 or 2.0? If this threshold is arbitrary, the reported high correlations ($R^2=0.85\text{--}0.92$) may simply be an artifact of data selection. The authors should clarify the basis for this threshold and perform a sensitivity analysis to show whether the main conclusions remain robust under different thresholds.

A3: We appreciate the referee's concern. We have reconsidered both the statistical purpose and the atmospheric interpretation of the event-selection criterion. The $^{10}\text{Be}/^7\text{Be}$ threshold of 1.8 was adopted as an exploratory, data-informed criterion in the analysis of the observed isotope relationships. Observations exceeding this value, accompanied by relatively high concentrations of both radionuclides, were grouped according to temporal proximity to examine selected elevated-ratio episodes. This criterion is broadly compatible with the established use of relatively high $^{10}\text{Be}/^7\text{Be}$ ratios as indicators of increased upper-atmospheric or stratospheric influence, including ratios around or above 2 discussed in the relevant literature. However, we do not treat

1.8—or 2—as a universal quantitative boundary separating stratospheric from tropospheric air. A precipitation sample integrates aerosol populations, transport and scavenging histories, and mixing, which can alter the measured ratio. Crucially, the criterion is used to define event groups for a conditional regression comparison, not to establish their atmospheric origin. The regression with all observations and the regression omitting the selected groups are both shown. The increase in R^2 after exclusion indicates that the selected observations exert a substantial influence on the fitted flux–precipitation relationship; it does not independently validate the threshold, establish a causal contribution from stratosphere–troposphere exchange, or demonstrate that precipitation is the sole control on the remaining observations. We therefore base the interpretation of the high-ratio episodes on their joint consistency with isotope characteristics, air-mass trajectories, upper-level circulation and event-period potential-vorticity fields, while acknowledging that these diagnostics remain suggestive rather than conclusive. We also recognize that the data-informed threshold introduces selection dependence.

Literature basis and interpretation: The use of an elevated ratio is consistent with published $^{10}\text{Be}/^{7}\text{Be}$ studies of stratosphere–troposphere exchange. In an independently assessed European stratospheric-intrusion episode, Zanis et al. (2003, Atmospheric Chemistry and Physics) reported ratios around 1.71–1.90 at Zugspitze. Jordan et al. (2003) examined isotope-ratio behavior in aircraft observations and demonstrated variability across atmospheric regimes. These aerosol/airborne studies support the plausibility of investigating ratios near 1.8, but they do not calibrate a universal threshold for rainwater at Lhasa. We therefore retain 1.8 as an exploratory, dataset-specific grouping criterion and do not regard the strengthened regression after exclusion as independent validation of stratospheric origin.

Section 2.7, event-selection protocol

For the event-group comparisons in Fig. 2, the threshold of $^{10}\text{Be}/^{7}\text{Be} > 1.8$ was adopted as an empirical criterion for identifying relatively high-ratio events in the observational dataset. This selection is physically motivated by previous studies showing that enhanced $^{10}\text{Be}/^{7}\text{Be}$ ratios can be associated with stratospheric influence (Jordan et al., 2003; Zanis et al., 2003). Notably, ratios of approximately 1.71–1.90 have been reported during an independently identified stratospheric intrusion event over Europe (Zanis et al., 2003). Nevertheless, because the ratio varies with atmospheric transport, mixing, and air-mass history, the value of 1.8 is not considered a universal boundary between stratospheric and tropospheric air. The threshold is used solely to define the event groups examined in Fig. 2, and the potential stratospheric influence associated with these events is evaluated using independent atmospheric transport and dynamical diagnostics.

Section 3.2, current regression interpretation

To isolate the contribution of stratosphere-to-troposphere vertical motion on ^{7}Be and ^{10}Be , we excluded data points with high $^{10}\text{Be}/^{7}\text{Be}$ ratios and conducted a re-analysis. This resulted in a significant improvement in the linear relationship between daily ^{7}Be and ^{10}Be wet deposition fluxes and rainfall amounts (Fig. 2c, 2d, $R^2 = 0.85\text{--}0.92$, $p < 0.05$) in both Lhasa and Xi'an. This implies that, under regional tropospheric control, the deposition of ^{7}Be and ^{10}Be is predominantly governed by precipitation. The slopes of these linear regression models provide a means to trace environmental process variations over short-term (daily to seasonal) and long-term (103–105 years) timescales. This provides further insight into the mechanisms through which factors such as precipitation, climate change, and stratosphere–troposphere exchange influence ^{7}Be and ^{10}Be

concentrations (Juri Ayub et al., 2012; Deng et al., 2020). It should be clarified that this result supports precipitation scavenging as an important control on routine ^7Be and ^{10}Be wet deposition, while the anomalous high-ratio events require additional consideration of transport, air-mass history, and event-specific scavenging.

Q4: Section 4.3: The authors acknowledge that the QBO descends at approximately 1 km per month (L351-352), which implies a time lag for the signal to propagate from the lower stratosphere to the surface. However, the manuscript appears to imply a synchronous link between the EQBO phase and surface precipitation isotope anomalies. Without a lag correlation analysis or direct dynamical evidence (e.g., potential vorticity or vertical velocity), the causal claim that QBO-driven stratosphere-troposphere exchange directly modulates surface precipitation may lack sufficient support.

A4: We agree with the referee that the downward phase progression of the QBO and the transport of a particular stratospheric air mass toward the surface are physically distinct phenomena. The commonly cited QBO descent rate describes the downward evolution of the equatorial stratospheric zonal-wind regime over months; it should not be interpreted as a parcel-descent velocity or as evidence for a simultaneous surface precipitation response. Our revised interpretation accordingly separates (i) the evolving QBO-related circulation background, (ii) the observed event-scale $^{10}\text{Be}/^7\text{Be}$ anomalies, and (iii) independent diagnostics of upper-atmospheric transport. The ERA5 potential-vorticity sections added as Fig. S6 show the regional latitude–pressure distribution of PV around the selected elevated-ratio events, including PV values above the conventional 2-PVU dynamical-tropopause reference aloft. These sections complement the HYSPLIT trajectories by providing dynamical context, but they are not PV histories evaluated along the trajectories; they therefore do not establish when or where the sampled air parcels crossed the tropopause. Likewise, temporal coincidence between isotope anomalies, circulation changes and precipitation is not sufficient to demonstrate a direct, instantaneous QBO-to-precipitation mechanism. We have therefore replaced deterministic language with formulations such as 'consistent with possible enhanced upper-atmospheric influence' and 'a plausible dynamical linkage'.

Section 3.3, dynamical interpretation

Previous studies suggest that QBO-associated secondary circulations and anomalous high-pressure systems can influence Rossby-wave propagation and the East Asian jet (Hu et al., 2022). Such circulation changes provide a plausible pathway through which stratospheric variability may affect upper-tropospheric transport, moisture convergence, and regional precipitation. Within this framework, elevated $^{10}\text{Be}/^7\text{Be}$ ratios are used as complementary tracer evidence for enhanced upper-atmospheric influence during selected events, rather than as proof that a specific QBO circulation directly generated the observed rainfall. The combined isotope, reanalysis, PV, and trajectory evidence therefore supports a possible dynamical linkage involving vertical transport, moisture flux, and circulation anomalies, while the magnitude and causality of the QBO precipitation response remain to be quantified with longer observations and additional dynamical diagnostics.

Section 3.3, PV and trajectories

The HYSPLIT calculations characterize transport pathways connecting the sampled air masses with the upper troposphere (Fig. 3c, 3d). Complementing these trajectories, the event-period PV

sections show values exceeding 2 PVU below 200 hPa over both study regions (Fig. S6). Together, the isotope, trajectory and PV evidence is consistent with stratospheric influence aloft during the selected events. Annual precipitation increased from 273 mm in 2022 to 439 mm in 2023 at Lhasa, with an increase of approximately 34% at Xi'an. While the exact contribution of the QBO to these precipitation anomalies cannot yet be quantified, the temporal synchronicity of these changes suggests the potential influence of large-scale circulation.

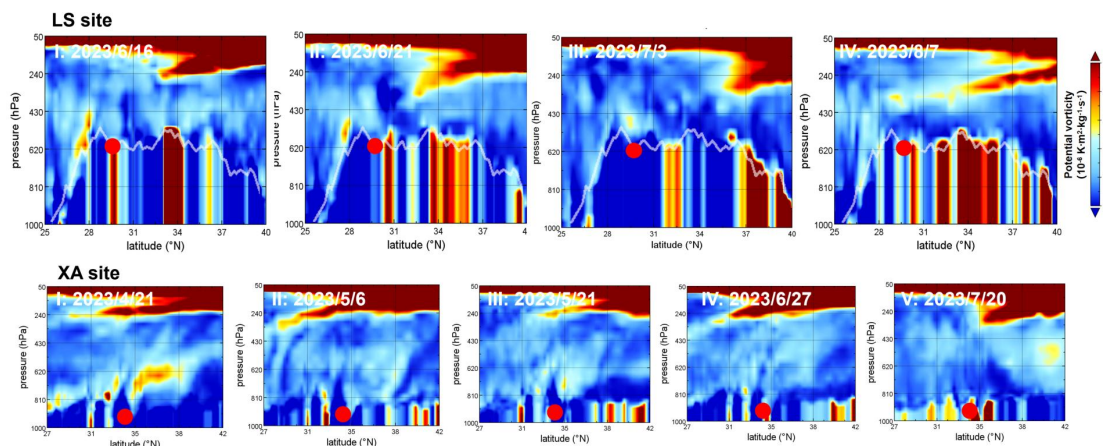


Fig. S6 Meridional latitude–pressure cross-sections of potential vorticity (PV) derived from daily mean ERA5 data along 91.5° E near Lhasa on the Tibetan Plateau (LS; upper row) and 109° E near Xi'an on the Loess Plateau (XA; lower row) during selected elevated $^{10}\text{Be}/^{7}\text{Be}$ events in 2023. The dates shown in the panels correspond to the event periods identified in Fig. 2a and b, respectively. Colour shading indicates PV in PVU ($1 \text{ PVU} = 10^{-6} \text{ K} \cdot \text{m}^2 \cdot \text{kg}^{-1} \cdot \text{s}^{-1}$). Red dots mark the sampling-site latitudes and approximate surface pressures on the respective cross-sections.

Section 3.4

Long-term (multiannual) trends of ^{7}Be are significantly influenced by solar activity and large-scale teleconnection indices, including the Arctic Oscillation (AO), North Atlantic Oscillation (NAO), and QBO (Chham et al., 2019). In contrast, ^{7}Be seasonal variations are mainly controlled by local meteorology (Chham et al., 2019; Abdul et al., 2025). Our sampling occurred during the rising phase of the 25th solar cycle (2019–2030), when solar activity is not a major driver of ^{7}Be or ^{10}Be trends (Gerasopoulos et al., 2003; Chham et al., 2019). QBO modulates the phase evolution of AO and NAO, with EQBO winters characterized by stronger stratosphere-troposphere coupling and amplified NAO patterns, whereas the opposite holds during WQBO years (Cai et al., 2022). Furthermore, multiyear records show that surface ^{7}Be levels oscillate in phase with QBO (Terzi and Kalinowski, 2017; Chham et al., 2019), with a significant squared coherence (0.68, at the 90% confidence level) between the 20–30 month cycle of ^{7}Be and QBO (Gerasopoulos et al., 2003). The QBO descends at $\sim 1 \text{ km/month}$, promoting stratosphere-to-troposphere exchange, thus elevating surface ^{7}Be levels. Meanwhile, ^{7}Be and ^{10}Be in precipitation show strong correlations in both flux and concentration ($R^2 \geq 0.92$, $P < 0.05$; Fig. S4), suggesting shared controls over their wet scavenging processes, and that they follow comparable temporal cycles. These synchronized shifts in ^{10}Be and ^{7}Be are tightly connected to QBO-driven changes in East Asian circulation, driving enhanced upper-atmosphere-to-surface cosmogenic beryllium transport (Fig. 4b). Therefore, during the active period of the summer monsoon, it is essential to closely monitor changes in the $^{10}\text{Be}/^{7}\text{Be}$ ratio to track vertical

movements between the stratosphere and troposphere, which can trigger atmospheric circulation changes and lead to heavy rainfall.

Q5: L365: The authors state that the XGBoost model was trained using data from 2021-2020. This is likely a typo and should probably be "2001-2020" based on the context in Section 2.5. Please verify and correct.

A5: We thank the referee for pointing out the typographical inconsistency. The long-term XGBoost analysis is consistently described in Section 2.5, Section 3.5 and Fig. 5 as covering 2001–2020. The erroneous “2021–2020” span has been corrected in the relevant discussion.

Section 3.5, actual current description

The XGBoost analysis provides a longer-term statistical perspective on precipitation over the Tibetan Plateau during 2001-2020 (Fig. 5). Unlike the event diagnostics, this analysis evaluates how equatorial QBO wind and regional meteorological predictors are associated with precipitation across the longer record. Mean absolute SHAP values summarize model importance, and the sign of each SHAP value indicates whether a predictor increases or decreases the model output relative to its baseline. Because the isotope observations were not used to train the model, the results complement rather than quantitatively validate the isotope-based transport interpretation.

Q6: L395-397: The authors state that EQBO contributes as much as 31.3% to the Tibetan Plateau’s annual precipitation. Given that this quantitative estimate is a key result of the study, please clarify how this 31.3% contribution rate was calculated (e.g., based on SHAP values, variance decomposition, or another statistical method).

A6: We agree that the earlier statement assigning 31.3% of annual precipitation to the EQBO conflated statistical model attribution with a physical contribution to rainfall. The XGBoost–SHAP method decomposes predictions of the trained model relative to its baseline; a SHAP contribution therefore refers to the model output, not to a percentage of observed precipitation causally attributable to the QBO. We have removed the claim that the EQBO physically accounts for 31.3% of precipitation. We retain “contribution” when it clearly modifies “model output,” in line with the model-interpretation terminology. The revised Section 3.5 now distinguishes mean absolute SHAP predictor importance from signed SHAP effects on model predictions, and explicitly states that the results cannot yield the fraction of rainfall caused by the QBO. These results provide statistical context complementary to, rather than validation of, the isotope observations.

Section 3.5, SHAP interpretation

The XGBoost analysis provides a longer-term statistical perspective on precipitation over the Tibetan Plateau during 2001-2020 (Fig. 5). Unlike the event diagnostics, this analysis evaluates how equatorial QBO wind and regional meteorological predictors are associated with precipitation across the longer record. Mean absolute SHAP values summarize model importance, and the sign of each SHAP value indicates whether a predictor increases or decreases the model output relative to its baseline. Because the isotope observations were not used to train the model, the results complement rather than quantitatively validate the isotope-based transport interpretation.

Section 3.5, model-context and limitation

For the EQBO phase (Fig. 5b, U50 negative), negative values corresponding to upper-level easterly flow are associated in the model with higher predicted precipitation over parts of the

southern Tibetan Plateau, whereas the opposite wind regime is associated with lower predicted precipitation. CAPE and Z200 also show substantial predictive importance and are related to atmospheric stability and upper-level circulation structure. This model association is consistent with examining the observed events in a QBO-related circulation context, but SHAP does not yield a physical percentage of rainfall caused by the QBO. Correlated predictors and other climate variability remain relevant to the interpretation.

Q7: Section 4.5: The authors link the 2022–2023 EQBO transition to the observed ~60% increase in annual precipitation at Lhasa (from 273 mm to 439 mm) and ~34% at Xi'an, implying a direct causal relationship. However, this appears inconsistent with the 31.3% long-term statistical contribution of EQBO reported earlier in Section 4.4. While a statistical contribution rate and a single-event anomaly are not directly equivalent, this remains confusing.

A7: We agree that the 2022-to-2023 annual rainfall difference and SHAP-based model attribution are distinct quantities and should not be compared as though they measure the same effect. At Lhasa the reported annual totals increased from 273 to 439 mm, a change of 166 mm or approximately 60.8% relative to the 2022 baseline; Xi'an experienced a reported increase of approximately 34%. These are observed year-to-year changes, not estimates of precipitation induced by the QBO. The 31.3% statement was a model-interpretation error, and has been removed from the causal interpretation. The revised Sections 3.3 and 3.4 state that the precipitation anomalies cannot be uniquely assigned to the QBO because other large-scale circulation, moisture supply, convective conditions and local scavenging may contribute. We therefore use the rainfall changes as temporal context for the coincident circulation and isotope anomalies, not as quantitative measures of the QBO effect.

Section 3.3, year-to-year difference and limitation

The HYSPLIT calculations characterize transport pathways connecting the sampled air masses with the upper troposphere (Fig. 3c, 3d). Complementing these trajectories, the event-period PV sections show values exceeding 2 PVU below 200 hPa over both study regions (Fig. S6). Together, the isotope, trajectory and PV evidence is consistent with stratospheric influence aloft during the selected events. Annual precipitation increased from 273 mm in 2022 to 439 mm in 2023 at Lhasa, with an increase of approximately 34% at Xi'an. While the exact contribution of the QBO to these precipitation anomalies cannot yet be quantified, the temporal synchronicity of these changes suggests the potential influence of large-scale circulation.

Section 3.4, alternative contributors

At Lhasa, Be fluxes and $10\text{Be}/7\text{Be}$ ratios increased during parts of 2023 relative to 2022. Annual precipitation increased from 273 mm in 2022 to 439 mm in 2023, while Xi'an experienced an increase of approximately 34%. Within the broad QBO-related rainfall-response sector considered here, Xi'an supplies a low-elevation reference site for examining the corresponding regional precipitation change and isotope-event behavior. These concurrent changes provide context for the transport-sensitive observations, but the annual rainfall differences cannot be assigned uniquely to the QBO. Other circulation variability and local precipitation processes can contribute to the changes at both sites.

Section 3.5, separation from model output

The XGBoost analysis provides a longer-term statistical perspective on precipitation over the Tibetan Plateau during 2001-2020 (Fig. 5). Unlike the event diagnostics, this analysis evaluates

how equatorial QBO wind and regional meteorological predictors are associated with precipitation across the longer record. Mean absolute SHAP values summarize model importance, and the sign of each SHAP value indicates whether a predictor increases or decreases the model output relative to its baseline. Because the isotope observations were not used to train the model, the results complement rather than quantitatively validate the isotope-based transport interpretation.

RC2: This study combines precipitation ^{10}Be and ^7Be measurements with machine learning to examine how QBO-related stratospheric dynamics influence precipitation over the southern Tibetan Plateau. The manuscript presents ^{10}Be and ^7Be data from two sites, adding to the limited records of these isotopes in precipitation. The use of machine learning to explore the influence of the QBO on precipitation is also a novel aspect. However, the manuscript is difficult to follow, particularly for readers who do not work on stratospheric dynamics or Be isotopes. Substantial revision is needed to make it accessible to a broader readership. I would recommend authors to introduce fewer unnecessary concepts and more clearly discuss how the data support their conclusions.

Major comments

Q1: The Xi'an data receive little discussion, and the comparison between Lhasa and Xi'an is very limited. If the aim is to examine the mechanistic link between stratospheric dynamics and precipitation over the Tibetan Plateau, what is the purpose of including Xi'an?

A1: We thank the reviewer for asking why the Xi'an observations are necessary for a study focused on Lhasa. We have now made the complementary roles of the two sites explicit. Lhasa (3650 m a.s.l.) is the main high-elevation study site; Xi'an (420 m a.s.l.) is a lower-elevation reference with different boundary-layer exposure, aerosol backgrounds and wet-scavenging conditions. The comparison asks whether elevated-ratio episodes and their relationships with precipitation are also present outside the Lhasa high-altitude setting, rather than using Xi'an as a matched experimental control. The revised Introduction now states this comparative question explicitly, and Section 3.1 acknowledges that the two time series cover unequal seasons. Section 3.6 further explains how the second site provides regional context without implying that the stations share the same air masses or that their differences can be attributed solely to altitude. The current evidence supports this limited but scientifically useful observational role; no new common-season quantitative comparison is claimed.

Introduction — rationale and sequence

This study aims to constrain possible links among QBO-related stratospheric dynamics, atmospheric transport, and precipitation during 2022-2023 using cosmogenic ^7Be and ^{10}Be measurements. The Tibetan Plateau provides a setting in which monsoon convection and high-altitude topography influence atmospheric exchange (Bian et al., 2020). Lhasa (3650 m a.s.l.) represents the high-altitude site, whereas Xi'an (420 m a.s.l.) provides a low-elevation reference in the same broad QBO-related rainfall-response sector, and the comparison assesses whether elevated-ratio episodes also occur in a contrasting lower-elevation environment. We first characterize isotope concentrations, wet-deposition fluxes, and ratios at the two sites and examine their relationships with precipitation. We then evaluate elevated-ratio events using backward trajectories and potential vorticity (PV), before placing the events in the context of the QBO transition and longer-term circulation-precipitation associations. This sequence connects the

event-scale tracer evidence with the regional dynamical setting while distinguishing observations from the proposed physical interpretation.

Section 3.1 — inter-site comparability

Fig. 1b illustrates the time series of ^{10}Be and ^7Be concentrations and daily wet deposition fluxes in precipitation in Xi'an during the same period (March to September 2023). In Xi'an, the concentration ranges of ^{10}Be and ^7Be in precipitation were $(2.24 \pm 0.10) \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1} \text{ rain}$ to $(71.40 \pm 0.63) \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1} \text{ rain}$ and $(1.62 \pm 0.22) \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1} \text{ rain}$ to $(25.43 \pm 0.79) \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1} \text{ rain}$, respectively, with median values of $8.35 \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1} \text{ rain}$ and $4.16 \cdot 10^4 \text{ atoms} \cdot \text{g}^{-1} \text{ rain}$. The $^{10}\text{Be}/^7\text{Be}$ ratio ranged from 1.07 ± 0.09 to 2.81 ± 0.08 . The daily wet deposition fluxes of ^{10}Be and ^7Be in Xi'an ranged from $(1.28 \pm 0.07) \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ to $(86.22 \pm 1.83) \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ and $(0.68 \pm 0.06) \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ to $(55.60 \pm 3.08) \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$, respectively, with median values of $8.32 \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ for ^{10}Be and $5.89 \cdot 10^8 \text{ atoms} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ for ^7Be . The specific measurements for each rainfall event are listed in Tables S1 and S2. Because the Lhasa series principally represents the summer rainy season whereas the Xi'an series also includes spring, differences in isotope concentrations, ratios and wet-deposition fluxes may partly reflect seasonal variation in aerosol sources, circulation and precipitation scavenging. Xi'an is consequently used as a lower-elevation reference site to provide regional context, rather than as a seasonally matched control from which an altitude effect can be isolated.

Section 3.6 — scope and limitations

The main observational contribution is the event-resolved joint record from the high-altitude Lhasa site, interpreted with the Xi'an low-elevation reference site and independent transport diagnostics. Similar high-ratio behavior in the two settings can be examined within the same broad QBO-related rainfall-response sector, while differences help identify the importance of local transport and scavenging conditions. Neither urban rooftop site represents the full range of environments across its surrounding region, and their contrasting observation coverage limits direct full-record comparisons.

Q2: The links between the evidence and the conclusions are weak. Many conclusions lack direct support and appear speculative. The manuscript structure could also be improved. Sections 4.2 and 4.4 could potentially be combined, as could Sections 4.3 and 4.5. Please reconsider the organization of the Discussion.

A2: We appreciate the reviewer's criticism that the original manuscript brought together several analytical components without sufficiently specifying how the observations constrain the proposed interpretation. The latest revision has a more explicit evidential sequence: (i) measured ^{10}Be , ^7Be , isotope ratios and event precipitation (Figs. 1–2; Tables S1–S2); (ii) event-date HYSPLIT transport pathways and ERA5 regional PV cross-sections (Fig. 3 and Fig. S6); (iii) QBO-phase and upper-level circulation context (Figs. 3–4); and (iv) the distinct, longer-term statistical relationships provided by XGBoost–SHAP (Fig. 5). Most importantly, the new Section 3.6 separates what is constrained by aerosol-bound Be transport from what is inferred about circulation and moisture supply. Thus the study tests a physically plausible association; it does not assert that an isotope anomaly or PV feature proves QBO-caused rainfall. The regional PV fields are aligned by event date with the isotope and rainfall records and the numbered trajectories, but they are not PV histories following individual air parcels. We retain a combined Results and

Discussion chapter with topic-based subsections, rather than mechanically merging scientifically different analyses. This more explicit synthesis is now central to the answer to the reviewer.

Section 2.6 — event-to-figure correspondence and PV limitation

Daily mean ERA5 pressure-level PV fields were used to construct meridional latitude–pressure sections along 91.5°E near Lhasa and 109°E near Xi'an for the selected elevated-ratio events in 2023 (Fig. S6). The PV-section dates correspond to the isotope and rainfall records (Fig. 1; Tables S1-S2), the event groups (Fig. 2a-b), and the numbered backward trajectories (Fig. 3c-d). The dates correspond to the event groups in Fig. 2a and 2b. PV is expressed in potential vorticity units ($1 \text{ PVU} = 10^{-6} \text{ K} \cdot \text{m}^2 \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$), and 2 PVU is used as a conventional dynamical-tropopause reference (Millán et al., 2021). These regional sections describe the event-period PV distribution and complement the trajectories; they do not provide PV histories along individual trajectories.

Section 3.3 — event interpretation

The HYSPLIT calculations characterize transport pathways connecting the sampled air masses with the upper troposphere (Fig. 3c, 3d). Complementing these trajectories, the event-period PV sections show values exceeding 2 PVU below 200 hPa over both study regions (Fig. S6). Viewed alongside the associated rainfall and isotope observations, the event-date trajectories and regional PV fields are consistent with possible stratospheric influence aloft, without establishing the origin of individual sampled air parcels. Annual precipitation increased from 273 mm in 2022 to 439 mm in 2023 at Lhasa, with an increase of approximately 34% at Xi'an. While the exact contribution of the QBO to these precipitation anomalies cannot yet be quantified, the temporal synchronicity of these changes suggests the potential influence of large-scale circulation.

Section 3.6 — synthesis: two physical pathways

The combined evidence separates two related aspects of the circulation–precipitation system (Fig. 4b). Atmospheric transport changes the sources and histories of aerosol-bound Be that can subsequently be scavenged by precipitation. Circulation also affects the moisture supply and ascent involved in rainfall. The isotope observations primarily constrain the first aspect, while the reanalysis and predictive model describe elements of the second and their large-scale background. A common circulation setting can connect the two, but high-ratio deposition does not itself demonstrate that downward-transported air generated the precipitation.

Section 3.6 — attribution limits

The study consequently provides observational constraints on a possible linkage among QBO-associated circulation, atmospheric transport and precipitation during the sampled period. It does not resolve the independent QBO contribution relative to ENSO, Indian Ocean variability or other meteorological influences. Longer isotope records, comparisons within common sampling seasons, sensitivity to event-grouping criteria, and higher-frequency transport diagnostics would help assess the persistence and specificity of the inferred relationships.

Q3: As far as I understand, Lhasa and Xi'an are typical urban sites. How representative are they of the Tibetan Plateau and the Loess Plateau, respectively? The manuscript also places Xi'an in the Loess Plateau in some passages and in the Guanzhong Basin in others, which is confusing.

A3: We agree that observations from one urban valley and one urban basin cannot be extrapolated directly to entire plateaus. The revised Methods locates Lhasa in the southern Tibetan Plateau and Xi'an in the Guanzhong Basin adjacent to the southern Loess Plateau. These descriptions refer to local physiography and the broader geographic setting, respectively; Xi'an is not treated as a

representative sampling station for the entire Loess Plateau. Section 3.1 now explicitly identifies the unequal sampling-season coverage, and the new synthesis states that neither rooftop site represents the full environmental variability of its surrounding region. Consequently, the Be records are interpreted as site-scale observations placed within a larger circulation framework. We have avoided treating the site-to-site difference as a spatially resolved plateau-wide response.

Section 2.1 — Lhasa study setting

The Tibetan Plateau averages over 4000 meters in elevation and is characterized by limited precipitation, low pressure, and intense solar radiation. The region's natural setting is highly complex and distinctive, particularly in terms of precipitation patterns. Precipitation across the Tibetan Plateau is generally low, with most rainfall occurring in summer, especially during July and August. Under the combined effects of the East Asian and Indian monsoons, rainfall is unevenly distributed (higher in the eastern and southern regions), and lower in the western and northern areas. The plateau's precipitation is primarily shaped by its terrain, monsoon systems, and atmospheric circulation, influencing both regional ecosystems and the climate in adjacent areas. The sampling location, Lhasa, lies in the southern Tibetan Plateau, receiving roughly 400 mm of annual rainfall and sitting at an average altitude of 3600 m.

Section 2.1 — Xi'an and Guanzhong Basin

The Loess Plateau is adjacent to the Tibetan Plateau and is influenced by the same large-scale atmospheric circulation patterns. Furthermore, it is located on the same side of the dipole rainfall pattern as the Tibetan Plateau, and is therefore used as a reference observation site in this work. Rainfall also exerts a significant impact on the vulnerable ecosystems of the Loess Plateau: too much can intensify soil erosion and geomorphic degradation, while too little may lead to reduced vegetation cover and weakened ecosystem functions (Cai et al., 2022). According to Chinese Loess 10Be sedimentary records, climate change has historically caused variations in the intensity of rainfall events on the Loess Plateau (Zhou et al., 2023). Xi'an, where sampling was conducted, lies in the southern Loess Plateau of China and receives approximately 500-750 mm of rainfall annually. Their urban sampling settings and different observation coverage are considered when interpreting the comparison.

Section 3.6 — geographic generality

The main observational contribution is the event-resolved joint record from the high-altitude Lhasa site, interpreted with the Xi'an low-elevation reference site and independent transport diagnostics. Similar high-ratio behavior in the two settings can be examined within the same broad QBO-related rainfall-response sector, while differences help identify the importance of local transport and scavenging conditions. Neither urban rooftop site represents the full range of environments across its surrounding region, and their contrasting observation coverage limits direct full-record comparisons.

Q4: Urban effects may influence local precipitation at these sites. How do the authors distinguish these local influences from the effects of large-scale circulation? I understand that sampling in non-urban areas is very difficult. However, the authors should be more cautious when extrapolating urban observations to broader regions and discuss possible limitations.

A4: We appreciate this concern because the observation and circulation diagnostics operate at different spatial scales. Urban emissions, aerosol loading, building-related turbulence and local precipitation processes may influence the collected rainwater, whereas ERA5 circulation fields

and QBO composites describe much larger-scale dynamical conditions. The present dataset does not include a rural–urban station pair or other measurements that would permit a quantitative separation of those contributions. Rather than assuming such separation, Section 2.2 states the actual rooftop collection conditions; Section 3.1 specifies that Xi'an is a contextual reference rather than a seasonally matched control; and Section 3.6 explicitly limits regional representativeness. The interpretation now places the Be and rainfall observations alongside large-scale dynamics as complementary information, without presenting a unique attribution of individual urban precipitation events to the QBO.

Section 2.2 — site-specific rooftop sampling

In the rainy seasons of 2022–2023 (Mar.to Sep.), we obtained 60 precipitation samples from Lhasa, located in the southern Tibetan Plateau [29°38'49"N, 91°4'37"E, 3650 m above sea level (a.s.l.)], and Xi'an in the southern Loess Plateau (34°13'20"N, 109°00'18"E, 420 m a.s.l.). Outside of this period, either there was almost no rainfall or the precipitation volume was insufficient for effective sample collection. The Lhasa site is encircled by mountain ranges, whereas the Xi'an site lies in the Guanzhong Basin, north of the Qinling Mountains (geographical setting shown in Fig. S1). Samples were collected from rooftop locations at both sites (~18 m above ground in Lhasa and ~5 m in Xi'an). The volume of each sample ranged is 4–120 L, with the duration of collection determined by rainfall amount, not exceeding 24 h. Rainwater was collected over areas of (4·0.28) m² in Lhasa and (6·0.28) m² in Xi'an. Rainwater was collected and stored using acid-cleaned polyethylene trays and polyethylene containers. The acid pre-treatment of containers minimizes adsorption of ⁷Be and ¹⁰Be on container surfaces (Tiessen et al., 2019). The first ~0.5 hours of rainfall were excluded to eliminate contamination from re-suspended ¹⁰Be in dust, allowing for reliable measurements of wet ¹⁰Be deposition (Graham et al., 2003). The sampling times provided in this work are local time (UTC+8). The duration and seasonal coverage of rainwater sampling were constrained by the occurrence of precipitation and the volume required for isotope analysis. In Lhasa, spring precipitation was sparse and individual rainfall events generally yielded insufficient sample volume for analysis; accordingly, suitable observations were mainly obtained during the summer rainy season. In Xi'an, precipitation events suitable for sampling occurred over a longer period extending from spring into summer. The resulting temporal coverage is therefore asymmetric and reflects local precipitation conditions and analytical requirements rather than an intentionally season-matched design.

Section 3.1 — different sampling seasons

Fig. 1b illustrates the time series of ¹⁰Be and ⁷Be concentrations and daily wet deposition fluxes in precipitation in Xi'an during the same period (March to September 2023). In Xi'an, the concentration ranges of ¹⁰Be and ⁷Be in precipitation were $(2.24 \pm 0.10) \cdot 10^4$ atoms·g⁻¹ rain to $(71.40 \pm 0.63) \cdot 10^4$ atoms·g⁻¹ rain and $(1.62 \pm 0.22) \cdot 10^4$ atoms·g⁻¹ rain to $(25.43 \pm 0.79) \cdot 10^4$ atoms·g⁻¹ rain, respectively, with median values of $8.35 \cdot 10^4$ atoms·g⁻¹ rain and $4.16 \cdot 10^4$ atoms·g⁻¹ rain. The ¹⁰Be/⁷Be ratio ranged from 1.07 ± 0.09 to 2.81 ± 0.08 . The daily wet deposition fluxes of ¹⁰Be and ⁷Be in Xi'an ranged from $(1.28 \pm 0.07) \cdot 10^8$ atoms·m⁻²·d⁻¹ to $(86.22 \pm 1.83) \cdot 10^8$ atoms·m⁻²·d⁻¹ and $(0.68 \pm 0.06) \cdot 10^8$ atoms·m⁻²·d⁻¹ to $(55.60 \pm 3.08) \cdot 10^8$ atoms·m⁻²·d⁻¹, respectively, with median values of $8.32 \cdot 10^8$ atoms·m⁻²·d⁻¹ for ¹⁰Be and $5.89 \cdot 10^8$ atoms·m⁻²·d⁻¹ for ⁷Be. The specific measurements for each rainfall event are listed in Tables S1 and S2. Because the Lhasa series principally represents the summer rainy season whereas the Xi'an series also includes spring, differences in isotope concentrations, ratios and

wet-deposition fluxes may partly reflect seasonal variation in aerosol sources, circulation and precipitation scavenging. Xi'an is consequently used as a lower-elevation reference site to provide regional context, rather than as a seasonally matched control from which an altitude effect can be isolated.

Section 3.6 — explicit representativeness limit

The main observational contribution is the event-resolved joint record from the high-altitude Lhasa site, interpreted with the Xi'an low-elevation reference site and independent transport diagnostics. Similar high-ratio behavior in the two settings can be examined within the same broad QBO-related rainfall-response sector, while differences help identify the importance of local transport and scavenging conditions. Neither urban rooftop site represents the full range of environments across its surrounding region, and their contrasting observation coverage limits direct full-record comparisons.

Q5: The Results and Discussion are presented as separate sections. This seems unusual for ACP journal.

A5: Thank you for this presentation suggestion. The new manuscript combines Results and Discussion in Section 3, with subsections organized by the actual analytical sequence: deposition observations (3.1), precipitation and selected high-ratio events (3.2), event transport and PV (3.3), QBO/regional circulation (3.4), long-term meteorological associations (3.5), and a new integrative synthesis (3.6). The added synthesis makes the complementary roles of the evidence sources explicit and replaces the implication that a statistical model or circulation composite by itself validates the specific isotope events. We adopted this organization for scientific continuity rather than asserting that only one section structure is permitted by ACP.

Section 3 — combined Results and Discussion

3. Results and Discussion

Section 3.6 — integrative subsection

3.6 Synthesis and implications

Section 3.6 — relation between isotope and precipitation pathways

The combined evidence separates two related aspects of the circulation–precipitation system (Fig. 4b). Atmospheric transport changes the sources and histories of aerosol-bound Be that can subsequently be scavenged by precipitation. Circulation also affects the moisture supply and ascent involved in rainfall. The isotope observations primarily constrain the first aspect, while the reanalysis and predictive model describe elements of the second and their large-scale background. A common circulation setting can connect the two, but high-ratio deposition does not itself demonstrate that downward-transported air generated the precipitation.

Other comments

Q6: Lines 80–103: Please explain the physical meaning of the $^{10}\text{Be}/^7\text{Be}$ ratio more clearly, as most readers may not be familiar with this tracer.

A6: We agree that the physical interpretation must be accessible to readers unfamiliar with cosmogenic nuclides. Because ^7Be decays over a period of weeks whereas ^{10}Be is effectively stable over atmospheric transport timescales, their ratio contains information on differences in source history, atmospheric residence and mixing. A relatively high ratio can be consistent with a greater contribution of older upper-atmospheric aerosol populations, including possible

stratospheric influence. However, precipitation measurements reflect wet scavenging after transport and may also vary with aerosol size, mixing and event-specific scavenging histories. We therefore treat high-ratio events as an indicator requiring independent circulation, trajectory and PV diagnostics, not as an air-mass fingerprint or a universal stratospheric threshold. This qualified interpretation is described in the Introduction, Methods and Section 3.3 and is summarized in Section 3.6.

Introduction — origin, half-lives and tracer use

The distinct production locations and half-lives of ^7Be (half-life: 53.29 days) and ^{10}Be (half-life: 1.39 million years) allow us to distinguish air masses originating from the stratosphere and troposphere (Yamagata et al., 2010), while their deposition fluxes provide insights into moisture scavenging processes (Graham et al., 2003; Heikkilä and Smith, 2013). Cosmogenic ^7Be and ^{10}Be serve as robust tracers, enabling the quantification of Earth surface processes across timescales from daily to seasonal and on longer timescales of 103 to 105 years (Brown et al., 1989; Graham et al., 2003; Juri Ayub et al., 2012; Deng et al., 2020). In particular, the $^{10}\text{Be}/^7\text{Be}$ ratio has been widely used as a sensitive indicator of stratosphere-troposphere transport (Liu et al., 2022; Liu et al., 2024a), with the potential to capture the downward transport of air masses caused by stratospheric dynamic processes such as the QBO and their impact on surface precipitation dynamics. Therefore, these cosmogenic radionuclides are expected to become a key bridge connecting large-scale circulation changes with regional hydrological responses, providing a novel and powerful research tool for a deeper understanding of the formation mechanisms and variability patterns of monsoon precipitation. However, to the best of our knowledge—with the exception of our preliminary studies conducted in the Xi'an region of the Loess Plateau (Zhang and Fu, 2017; Liu et al., 2024a), long-term, simultaneous observational records of ^{10}Be and ^7Be in precipitation remain scarce. Currently, similar records exist only in regions such as the USA (Brown et al., 1989), New Zealand (Graham et al., 2003), and Switzerland (Heikkilä et al., 2008). Precipitation records from other regions demonstrate the value of this approach, while measurements from the Tibetan Plateau provide information from a high-altitude monsoon environment. Furthermore, a key prerequisite for the application of these nuclides is to adequately observe the fluxes of atmospheric ^7Be and ^{10}Be and to understand the processes governing their transport to the Earth's surface.

Section 2.7 — ratio criterion and physical limitations

The Zonal (east–west) wind and geopotential datasets were obtained from ERA5 monthly averaged data on pressure levels, and PV was obtained from ERA5 daily average data on pressure levels (Hersbach et al., 2023), both visualized using Panoply. PV is expressed in potential vorticity units ($1 \text{ PVU} = 10^{-6} \cdot \text{K} \cdot \text{m}^2 \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$). The 2 PVU threshold is used as a conventional dynamical-tropopause reference (Millán et al. 2021). The meteorological data used for machine learning came from ERA5 (2001–2020, 25°N–40°N, 80°E–100°E). Origin 2020 was used to process and graph the raw data. Rainfall data were retrieved from the China Meteorological Data Network (<http://data.cma.cn/>). Annual fluxes were estimated using average concentrations during the sampling period and annual precipitation totals. For the event-group comparisons in Fig. 2, the threshold of $^{10}\text{Be}/^7\text{Be} > 1.8$ was adopted as an empirical criterion for identifying relatively high-ratio events in the observational dataset. This selection is physically motivated by previous studies showing that enhanced $^{10}\text{Be}/^7\text{Be}$ ratios can be associated with stratospheric influence (Jordan et al., 2003; Zanis et al., 2003). Notably, ratios of approximately 1.71–1.90 have been

reported during an independently identified stratospheric intrusion event over Europe (Zanis et al., 2003). Nevertheless, because the ratio varies with atmospheric transport, mixing, and air-mass history, the value of 1.8 is not considered a universal boundary between stratospheric and tropospheric air. The threshold is used solely to define the event groups examined in Fig. 2, and the potential stratospheric influence associated with these events is evaluated using independent atmospheric transport and dynamical diagnostics.

Section 3.3 — alternatives to unique source attribution

Currently, East Asian precipitation follows a dipole oscillation centered around 30°N latitude (Zhang et al., 2024; Fu et al., 2024). The southern Tibetan Plateau and Loess Plateau lie on the same broad flank of this circulation pattern, although local meteorological conditions differ substantially. Compared with 2022, both the Be fluxes and 10Be/7Be ratio at Lhasa increased during parts of 2023. Elevated 10Be/7Be values provide information about atmospheric transport and air-mass history because the two radionuclides have different radioactive lifetimes (Raisbeck et al., 1981; Zanis et al., 2003). Simple precipitation dilution acting proportionally on the same aerosol population is not expected to systematically increase their ratio. These changes coincided with the QBO phase transition and with upper-level circulation anomalies that are consistent with enhanced downward transport. However, mixtures of aerosol populations, their residence times and scavenging histories can also affect event-scale rainwater ratios. Therefore, we use trajectories and PV to evaluate the high ratio group, treating the 10Be/7Be ratio as an observation sensitive to transport during the QBO transition period, rather than a unique identifier for stratospheric air.

Section 3.6 — interpretation in two pathways

The combined evidence separates two related aspects of the circulation–precipitation system (Fig. 4b). Atmospheric transport changes the sources and histories of aerosol-bound Be that can subsequently be scavenged by precipitation. Circulation also affects the moisture supply and ascent involved in rainfall. The isotope observations primarily constrain the first aspect, while the reanalysis and predictive model describe elements of the second and their large-scale background. A common circulation setting can connect the two, but high-ratio deposition does not itself demonstrate that downward-transported air generated the precipitation.

Q7: Lines 181–193: Please provide a more detailed description of the machine-learning methods in the Supplementary Information. Were all meteorological data mentioned here (including R1000, Q1000, BLH, wind speed etc.) obtained from the China Meteorological Data Network (<http://data.cma.cn/>)? Please provide specific data sources and links to ensure reproducibility.

A7: We thank the reviewer for requesting source provenance and enough detail to reproduce the XGBoost–SHAP analysis. The revised Methods states that the meteorological variables used for the regional model were taken from the ERA5 reanalysis over 25–40°N and 80–100°E for 2001–2020, and lists the individual predictors R1000, CAPE, Q1000, MSL, BLH, T2M, U50, Z200, U100 and V100. The manuscript separately reports precipitation retrieval from the China Meteorological Data Network; these two statements should not be conflated into a claim that all model inputs originated from that network. Section 3.5 explains that SHAP describes the model's prediction rather than the physical percentage of precipitation caused by QBO variability. We agree that the currently supplied Supplementary Information does not document sufficient training details to make this analysis fully reproducible: the exact ERA5 product identifiers, precipitation response-field definition, space/time matching, train–validation strategy, hyperparameters,

performance measures, and SHAP computation settings should be provided.

Section 2.5 — period, domain and predictors

Employing the XGBoost machine-learning model (Chen and Guestrin, 2016), we examined 20 years (2001-2020) of ERA5 reanalysis for the Tibetan Plateau region (25°N-40°N, 80°E-100°E), and used interpretable SHapley Additive exPlanations (SHAP) analysis to disentangle and quantify the influence of each meteorological parameter on rainfall (Lundberg et al., 2020) (Fig. S5). The predictors include: R1000 (relative humidity at 1000 hPa, %), CAPE (convective available potential energy, J/kg), Q1000 (specific humidity at 1000 hPa, g/kg), MSL (mean sea-level pressure, hPa), BLH (boundary-layer height, m), T2M (2-m air temperature, K), U50 (zonal wind at 50 hPa, m/s), Z200 (200-hPa geopotential height, m), U100 (100-m zonal wind, m/s), and V100 (100-m meridional wind, m/s). It should be noted that when applying SHAP analysis, interdependencies among features can lead to additive contribution effects, which may potentially affect the quantitative interpretation of the importance of individual features.

Section 2.7 — 2.6 Backward trajectories and potential vorticity

The Hybrid Single-Particle Lagrangian Integrated Trajectory model (NOAA HYSPLIT, <https://www.ready.noaa.gov/HYSPLIT.php>) is a commonly used tool for tracking atmospheric transport and identifying air mass sources (Stein et al., 2015). The calculations employed 1°-resolution gridded meteorological data from the Global Data Assimilation System, with settings otherwise consistent with our previous study (Liu et al., 2024a). Backward trajectories were calculated for 72-96 h. Arrival heights were defined relative to ground level: 10, 500, and 1000 m above ground level (a.g.l.) for Xi'an, and 10, 2000, and 6000 m a.g.l. for Lhasa. Trajectory calculations were initiated at 6 h intervals during periods of anomalous $^{10}\text{Be}/^7\text{Be}$ ratios and traced backward from the two sampling locations (Lhasa: 29°38'49"N, 91°4'37"E; Xi'an: 34°13'20"N, 109°00'18"E). The trajectories are used here to characterize transport pathways and do not, by themselves, establish a stratospheric origin of the sampled air. Independent dynamical diagnostics, such as potential-vorticity fields near the dynamical tropopause, are required to further evaluate stratospheric influence. The trajectories are therefore evaluated alongside event-period vertical distributions of PV over the two study regions.

Section 2.7 — stated data sources

The Zonal (east-west) wind and geopotential datasets were obtained from ERA5 monthly averaged data on pressure levels, and PV was obtained from ERA5 daily average data on pressure levels (Hersbach et al., 2023), both visualized using Panoply. PV is expressed in potential vorticity units ($1 \text{ PVU} = 10^{-6} \cdot \text{K} \cdot \text{m}^2 \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$). The 2 PVU threshold is used as a conventional dynamical-tropopause reference (Millán et al. 2021). The meteorological data used for machine learning came from ERA5 (2001-2020, 25°N-40°N, 80°E-100°E). Origin 2020 was used to process and graph the raw data. Rainfall data were retrieved from the China Meteorological Data Network (<http://data.cma.cn/>). Annual fluxes were estimated using average concentrations during the sampling period and annual precipitation totals. For the event-group comparisons in Fig. 2, the threshold of $^{10}\text{Be}/^7\text{Be} > 1.8$ was adopted as an empirical criterion for identifying relatively high-ratio events in the observational dataset. This selection is physically motivated by previous studies showing that enhanced $^{10}\text{Be}/^7\text{Be}$ ratios can be associated with stratospheric influence (Jordan et al., 2003; Zanis et al., 2003). Notably, ratios of approximately 1.71-1.90 have been

reported during an independently identified stratospheric intrusion event over Europe (Zanis et al., 2003). Nevertheless, because the ratio varies with atmospheric transport, mixing, and air-mass history, the value of 1.8 is not considered a universal boundary between stratospheric and tropospheric air. The threshold is used solely to define the event groups examined in Fig. 2, and the potential stratospheric influence associated with these events is evaluated using independent atmospheric transport and dynamical diagnostics.

Section 3.5 — what SHAP attributes

The XGBoost analysis provides a longer-term statistical perspective on precipitation over the Tibetan Plateau during 2001-2020 (Fig. 5). Unlike the event diagnostics, this analysis evaluates how equatorial QBO wind and regional meteorological predictors are associated with precipitation across the longer record. Mean absolute SHAP values summarize model importance, and the sign of each SHAP value indicates whether a predictor increases or decreases the model output relative to its baseline. Because the isotope observations were not used to train the model, the results complement rather than quantitatively validate the isotope-based transport interpretation.

Q8: Lines 311–320: Why does excluding high $^{10}\text{Be}/^{7}\text{Be}$ ratios help isolate the contribution of stratosphere-to-troposphere transport to ^{7}Be and ^{10}Be ? The authors previously state that high $^{10}\text{Be}/^{7}\text{Be}$ ratios indicate enhanced stratosphere–troposphere exchange. These statements appear contradictory. Please clarify.

A8: We agree that the original description confused a statistical comparison with a physical decomposition. Selected high-ratio events were excluded in order to assess how much they influence the fitted wet-deposition-flux versus precipitation relationships. Although the reduced-data fits have R^2 values of approximately 0.85–0.92, this is a conditional association after selecting observations, not an estimate of STE contribution or proof that the retained samples are exclusively tropospheric. The newer part of Section 3.2 expressly acknowledges this limitation and directs physical source interpretation to the separate trajectory, circulation and PV information.

Section 3.2 — current paragraph contains the original claim and its subsequent qualification

To isolate the contribution of stratosphere-to-troposphere vertical motion on ^{7}Be and ^{10}Be , we excluded data points with high $^{10}\text{Be}/^{7}\text{Be}$ ratios and conducted a re-analysis. This resulted in a significant improvement in the linear relationship between daily ^{7}Be and ^{10}Be wet deposition fluxes and rainfall amounts (Fig. 2c, 2d, $R^2 = 0.85\text{--}0.92$, $p < 0.05$) in both Lhasa and Xi'an. This implies that, under regional tropospheric control, the deposition of ^{7}Be and ^{10}Be is predominantly governed by precipitation. The slopes of these linear regression models provide a means to trace environmental process variations over short-term (daily to seasonal) and long-term (103-105 years) timescales. It should be clarified that this result supports precipitation scavenging as an important control on routine ^{7}Be and ^{10}Be wet deposition, while the anomalous high-ratio events require additional consideration of transport, air-mass history, and event-specific scavenging. To evaluate how the selected elevated-ratio episodes affect the empirical relationship between wet-deposition flux and precipitation, we compared the full-record regressions with fits excluding the event groups defined in Section 2.7. The higher R^2 values for the reduced datasets characterize the regression sensitivity to these selected observations. They do not, by themselves, identify the physical origin of the excluded samples or prove that precipitation alone controls the remaining deposition fluxes. Interpretations of possible enhanced upper-atmospheric or stratospheric

influence therefore also consider trajectory, circulation and PV evidence, as well as event-specific aerosol scavenging and mixing. This provides further insight into the mechanisms through which factors such as precipitation, climate change, and stratosphere-troposphere exchange influence ^7Be and ^{10}Be concentrations (Juri Ayub et al., 2012; Deng et al., 2020).

Section 3.6 — distinct mechanisms

The combined evidence separates two related aspects of the circulation–precipitation system (Fig. 4b). Atmospheric transport changes the sources and histories of aerosol-bound Be that can subsequently be scavenged by precipitation. Circulation also affects the moisture supply and ascent involved in rainfall. The isotope observations primarily constrain the first aspect, while the reanalysis and predictive model describe elements of the second and their large-scale background. A common circulation setting can connect the two, but high-ratio deposition does not itself demonstrate that downward-transported air generated the precipitation.

Q9: What criteria were used to exclude unusual $^{10}\text{Be}/^7\text{Be}$ data points, and why? A high $^{10}\text{Be}/^7\text{Be}$ ratio alone is not sufficient justification for exclusion.

A9: We appreciate the request for a transparent and defensible event-selection rule. The current Section 2.7 uses an exploratory observational threshold $^{10}\text{Be}/^7\text{Be} > 1.8$, together with relatively high concentrations of both radionuclides and temporal proximity of selected observations. The events are grouped by date for examination in Fig. 2. The rationale is consistent with prior STE-tracer research, including independently diagnosed transport events with isotope ratios near this range, but the value 1.8 is not a universal physical boundary. The complete-record flux–rainfall fits are compared with fits excluding the selected groups to show empirical sensitivity, not to prove that the excluded observations are stratospheric air. The latest manuscript records this distinction in Section 2.7 and the latter part of Section 3.2.

Section 2.7 — adopted threshold and caveat

The Zonal (east–west) wind and geopotential datasets were obtained from ERA5 monthly averaged data on pressure levels, and PV was obtained from ERA5 daily average data on pressure levels (Hersbach et al., 2023), both visualized using Panoply. PV is expressed in potential vorticity units ($1 \text{ PVU} = 10^{-6} \cdot \text{K} \cdot \text{m}^2 \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$). The 2 PVU threshold is used as a conventional dynamical-tropopause reference (Millán et al. 2021). The meteorological data used for machine learning came from ERA5 (2001-2020, 25°N - 40°N , 80°E - 100°E). Origin 2020 was used to process and graph the raw data. Rainfall data were retrieved from the China Meteorological Data Network (<http://data.cma.cn/>). Annual fluxes were estimated using average concentrations during the sampling period and annual precipitation totals. For the event-group comparisons in Fig. 2, the threshold of $^{10}\text{Be}/^7\text{Be} > 1.8$ was adopted as an empirical criterion for identifying relatively high-ratio events in the observational dataset. This selection is physically motivated by previous studies showing that enhanced $^{10}\text{Be}/^7\text{Be}$ ratios can be associated with stratospheric influence (Jordan et al., 2003; Zanis et al., 2003). Notably, ratios of approximately 1.71-1.90 have been reported during an independently identified stratospheric intrusion event over Europe (Zanis et al., 2003). Nevertheless, because the ratio varies with atmospheric transport, mixing, and air-mass history, the value of 1.8 is not considered a universal boundary between stratospheric and tropospheric air. The threshold is used solely to define the event groups examined in Fig. 2, and the potential stratospheric influence associated with these events is evaluated using independent atmospheric transport and dynamical diagnostics.

Fig. 2 caption — selected groups

Fig. 2 Linear fitting analysis of 10Be, 7Be, and daily precipitation. According to the observations from Lhasa (a) and Xi'an (b), data points with 10Be/7Be ratios above the 1.8 baseline and relatively high 10Be and 7Be concentrations are grouped into red circles based on their proximity in date and labeled in chronological order, while the other points are grouped into a black circle. For the data points in red circles (in Fig. 2a and 2b). Fig. 2c and 2d present linear fits of daily 10Be and 7Be deposition fluxes versus daily precipitation, both before and after removing these points.

Section 3.2 — effect on regression fits

To isolate the contribution of stratosphere-to-troposphere vertical motion on 7Be and 10Be, we excluded data points with high 10Be/7Be ratios and conducted a re-analysis. This resulted in a significant improvement in the linear relationship between daily 7Be and 10Be wet deposition fluxes and rainfall amounts (Fig. 2c, 2d, $R^2 = 0.85-0.92$, $p < 0.05$) in both Lhasa and Xi'an. This implies that, under regional tropospheric control, the deposition of 7Be and 10Be is predominantly governed by precipitation. The slopes of these linear regression models provide a means to trace environmental process variations over short-term (daily to seasonal) and long-term (103-105 years) timescales. It should be clarified that this result supports precipitation scavenging as an important control on routine 7Be and 10Be wet deposition, while the anomalous high-ratio events require additional consideration of transport, air-mass history, and event-specific scavenging. To evaluate how the selected elevated-ratio episodes affect the empirical relationship between wet-deposition flux and precipitation, we compared the full-record regressions with fits excluding the event groups defined in Section 2.7. The higher R^2 values for the reduced datasets characterize the regression sensitivity to these selected observations. They do not, by themselves, identify the physical origin of the excluded samples or prove that precipitation alone controls the remaining deposition fluxes. Interpretations of possible enhanced upper-atmospheric or stratospheric influence therefore also consider trajectory, circulation and PV evidence, as well as event-specific aerosol scavenging and mixing. This provides further insight into the mechanisms through which factors such as precipitation, climate change, and stratosphere-troposphere exchange influence 7Be and 10Be concentrations (Juri Ayub et al., 2012; Deng et al., 2020).

Q10: Section 4.3: Does this discussion refer to the Lhasa data, the Xi'an data, or both? Please specify.

A10: The event-based transport discussion involves both observational stations. Lhasa is the main high-elevation location, and Xi'an the low-elevation regional reference. Their backward trajectories are displayed separately in Fig. 3c and Fig. 3d, respectively, and the corresponding ERA5 regional PV latitude–pressure sections are plotted along 91.5°E for the Lhasa region and 109°E for the Xi'an region (Fig. S6). The sampling dates and isotope/precipitation information can be traced through Fig. 1, Fig. 2 and Tables S1–S2. Section 2.6 explicitly states that the PV information describes the event-period regional dynamical state, not PV followed along each trajectory or definitive origin of sampled air. Section 3.3 discusses both locations on that basis.

Section 2.6 — station-specific arrival heights and methods

The Hybrid Single-Particle Lagrangian Integrated Trajectory model (NOAA HYSPLIT. <https://www.ready.noaa.gov/HYSPLIT.php>) is a commonly used tool for tracking atmospheric transport and identifying air mass sources (Stein et al., 2015). The calculations employed

1°-resolution gridded meteorological data from the Global Data Assimilation System, with settings otherwise consistent with our previous study (Liu et al., 2024a). Backward trajectories were calculated for 72–96 h. Arrival heights were defined relative to ground level: 10, 500, and 1000 m above ground level (a.g.l.) for Xi'an, and 10, 2000, and 6000 m a.g.l. for Lhasa. Trajectory calculations were initiated at 6 h intervals during periods of anomalous $^{10}\text{Be}/^{7}\text{Be}$ ratios and traced backward from the two sampling locations (Lhasa: 29°38'49"N, 91°4'37"E; Xi'an: 34°13'20"N, 109°00'18"E). The trajectories are used here to characterize transport pathways and do not, by themselves, establish a stratospheric origin of the sampled air. Independent dynamical diagnostics, such as potential-vorticity fields near the dynamical tropopause, are required to further evaluate stratospheric influence. The trajectories are therefore evaluated alongside event-period vertical distributions of PV over the two study regions.

Section 2.6 — regional PV sections and dates

Daily mean ERA5 pressure-level PV fields were used to construct meridional latitude–pressure sections along 91.5°E near Lhasa and 109°E near Xi'an for the selected elevated-ratio events in 2023 (Fig. S6). The PV-section dates correspond to the isotope and rainfall records (Fig. 1; Tables S1–S2), the event groups (Fig. 2a–b), and the numbered backward trajectories (Fig. 3c–d). The dates correspond to the event groups in Fig. 2a and 2b. PV is expressed in potential vorticity units ($1 \text{ PVU} = 10^{-6} \text{ K} \cdot \text{m}^2 \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$), and 2 PVU is used as a conventional dynamical-tropopause reference (Millán et al., 2021). These regional sections describe the event-period PV distribution and complement the trajectories; they do not provide PV histories along individual trajectories.

Section 3.3 — both regions and PV limitation

The HYSPLIT calculations characterize transport pathways connecting the sampled air masses with the upper troposphere (Fig. 3c, 3d). Complementing these trajectories, the event-period PV sections show values exceeding 2 PVU below 200 hPa over both study regions (Fig. S6). Viewed alongside the associated rainfall and isotope observations, the event-date trajectories and regional PV fields are consistent with possible stratospheric influence aloft, without establishing the origin of individual sampled air parcels. Annual precipitation increased from 273 mm in 2022 to 439 mm in 2023 at Lhasa, with an increase of approximately 34% at Xi'an. While the exact contribution of the QBO to these precipitation anomalies cannot yet be quantified, the temporal synchronicity of these changes suggests the potential influence of large-scale circulation.

Q11: Section 4.4: Again, please specify which site's data this discussion refers to. The Xi'an results appear to receive little attention in either Section 4.3 or Section 4.4.

A11: We agree that earlier discussion did not distinguish site-specific observations from the regional statistical analysis clearly enough. The Lhasa/Xi'an isotope and rainfall comparisons concern the sampled events, and Section 3.4 describes the two sites as a main station and a lower-elevation reference. The XGBoost–SHAP analysis in Section 3.5 instead summarizes longer-term regional predictor–precipitation associations over the Tibetan Plateau for 2001–2020; it does not use the 2022–2023 Be isotope measurements as machine-learning predictors or separately model Xi'an isotopes. The new Section 3.6 reinforces that isotope observations mainly constrain aerosol transport, whereas the reanalysis and predictive model address the meteorological precipitation setting. This distinction explains why the Xi'an observations are discussed chiefly in the event-scale analyses, without treating them as missing input to the regional model. Model associations do not quantify a causal rainfall contribution of the QBO.

Section 3.4 — Lhasa and Xi'an observations

At Lhasa, Be fluxes and $10\text{Be}/7\text{Be}$ ratios increased during parts of 2023 relative to 2022. Annual precipitation increased from 273 mm in 2022 to 439 mm in 2023, while Xi'an experienced an increase of approximately 34%. Within the broad QBO-related rainfall-response sector considered here, Xi'an supplies a low-elevation reference site for examining the corresponding regional precipitation change and isotope-event behavior. These concurrent changes provide context for the transport-sensitive observations, but the annual rainfall differences cannot be assigned uniquely to the QBO. Other circulation variability and local precipitation processes can contribute to the changes at both sites.

Section 3.5 — regional model and non-causality

The XGBoost analysis provides a longer-term statistical perspective on precipitation over the Tibetan Plateau during 2001-2020 (Fig. 5). Unlike the event diagnostics, this analysis evaluates how equatorial QBO wind and regional meteorological predictors are associated with precipitation across the longer record. Mean absolute SHAP values summarize model importance, and the sign of each SHAP value indicates whether a predictor increases or decreases the model output relative to its baseline. Because the isotope observations were not used to train the model, the results complement rather than quantitatively validate the isotope-based transport interpretation.

Section 3.6 — evidence streams

The combined evidence separates two related aspects of the circulation-precipitation system (Fig. 4b). Atmospheric transport changes the sources and histories of aerosol-bound Be that can subsequently be scavenged by precipitation. Circulation also affects the moisture supply and ascent involved in rainfall. The isotope observations primarily constrain the first aspect, while the reanalysis and predictive model describe elements of the second and their large-scale background. A common circulation setting can connect the two, but high-ratio deposition does not itself demonstrate that downward-transported air generated the precipitation.

Q12: Line 451: Why is sulfate introduced here? If the authors wish to discuss its role, this should preferably be supported by sulfate measurements in rainwater.

A12: We agree that invoking a sulfate-specific deposition or cloud-chemistry mechanism would require sulfate measurements that are not part of the supplied observational dataset. The currently revised Results and Discussion does not retain a sulfate-specific causal claim; instead, it discusses aerosol mixtures, atmospheric transport and event-dependent wet scavenging as general sources of variability. This preserves the interpretive relevance of aerosol processes without inventing a chemical measurement. No sulfate concentrations or sulfate-controlled mechanism are asserted. The section-level scope and limitations are also reiterated in Section 3.6.

Section 3.2 — mixing, aerosol and wet scavenging

Notably, the correlation between 10Be and 7Be fluxes and precipitation is substantially lower in Lhasa ($R^2 < 0.33$; Fig. 2c) than in Xi'an ($R^2 > 0.54$; Fig. 2d). The weaker flux-precipitation correlations at Lhasa relative to Xi'an likely reflect multiple interacting processes rather than orographic exchange alone. Owing to its high elevation, Lhasa is more directly exposed to the free troposphere, where variations in large-scale transport can alter the background abundance of aerosol-bound cosmogenic Be independently of local precipitation. Orographic lifting, event-specific wet scavenging, and dilution may further modulate the observed concentrations and fluxes. Thus, the difference between the two sites should be interpreted as the combined result of

contrasting atmospheric structure, transport, and scavenging regimes. As highlighted by red-circled data in Fig. 2a and 2b, steeper slopes-indicative of elevated $^{10}\text{Be}/^{7}\text{Be}$ ratios: coincide with seasonal peaks in stratosphere-troposphere exchange. These elevated $^{10}\text{Be}/^{7}\text{Be}$ ratios reflect intensified stratosphere-troposphere exchange events (Zanis et al., 2003; Liu et al., 2024a). These findings imply that downward-transported stratospheric air masses, enriched in beryllium isotopes, intrude into the lower atmosphere and modulate rainfall and deposition patterns (Graham et al., 2003; Heikkilä et al., 2008). However, it should be noted that this phenomenon is not the only diagnostic evidence of stratospheric invasion. Simple dilution acting similarly on both aerosol-bound radionuclides is not expected by itself to systematically increase the ratio, but differences in aerosol populations and scavenging histories may still contribute to event-scale variability. Accordingly, interpretation of high-ratio events requires comparison with independent circulation and transport diagnostics.

Section 3.6 — aerosol transport and scavenging

The combined evidence separates two related aspects of the circulation–precipitation system (Fig. 4b). Atmospheric transport changes the sources and histories of aerosol-bound Be that can subsequently be scavenged by precipitation. Circulation also affects the moisture supply and ascent involved in rainfall. The isotope observations primarily constrain the first aspect, while the reanalysis and predictive model describe elements of the second and their large-scale background. A common circulation setting can connect the two, but high-ratio deposition does not itself demonstrate that downward-transported air generated the precipitation.

Q13: Please check the manuscript carefully for errors. For example, the period is given as “2021–2020” in line 365, and ^7Be appears twice in lines 340–343.

A13: We thank the reviewer for identifying textual errors. The latest manuscript consistently describes the long-term XGBoost analysis as 2001–2020 in the Abstract, Section 2.5, Section 2.7 and Section 3.5; the erroneous 2021–2020 range is not repeated in these descriptions. The analyses also refer to the distinct radionuclides ^7Be and ^{10}Be rather than a duplicated ^7Be label.