

1 **Disentangling controls of multi-scale variability in Precipitation Stable Isotopes**
2 **at Yadong and Ali on the Tibetan Plateau**

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10 **Abstract:**

11 Understanding precipitation stable isotope variability over the Tibetan Plateau (TP) is
12 essential for identifying moisture sources and assessing climatic responses. However,
13 drivers of daily and synoptic-scale variability beyond the westerlies and Indian
14 Summer Monsoon (ISM) remain poorly constrained in the southern and western TP.
15 Using event-based precipitation isotope data ($\delta^{18}\text{O}$ and δD) from Yadong and Ali
16 (May 2021–September 2023), we investigate multi-scale variability drivers. Both sites
17 exhibit nearly identical $\delta^{18}\text{O}$ and δD magnitudes during the monsoon
18 (June–September), while the westerly-dominated season (November–February) shows
19 maximum differences of 12.2 ‰ in $\delta^{18}\text{O}$ and 118.8 ‰ in δD . Meteorological controls
20 vary seasonally: amount effects dominate during the monsoon ($R = -0.28$ to -0.32 , p
21 < 0.05), while temperature effects prevail in the westerly season ($R = 0.51$ – 0.79 , $p <$
22 0.001). ISM dominates during isotopic convergence, while westerlies drive
23 divergence via distinct transport pathways. Local Meteoric Water Line analysis
24 indicates stronger moisture recycling and sub-cloud evaporation variability at Yadong.
25 On synoptic scales, simultaneous precipitation events reflect coherent ISM influence.
26 Interannual variability is significantly modulated by ENSO, with $\delta^{18}\text{O}$ enrichment of
27 2.8–5.1 ‰ (δD of 39.3–255.9 ‰) from La Niña to El Niño. During El Niño,
28 weakened Walker circulation reduces ISM transport and enhances the relative
29 contribution of local evapotranspiration. These results offer new constraints on

30 seasonal moisture source transitions and reveal ENSO sensitivity exceeding previous
31 estimates, advancing understanding of atmospheric moisture transport and regional
32 climate sensitivity over the TP.

33 **short summary**

34 This study characterized event-based precipitation stable isotopes ($\delta^{18}\text{O}$, δD) at
35 Yadong and Ali from May 2021 to September 2023 to investigate climate controls of
36 variability in precipitation stable isotopes on the Tibetan Plateau across daily, synoptic,
37 seasonal, and interannual scales. We characterize the influence of shifting moisture
38 sources under westerly and Indian Summer Monsoon transport regimes, and the
39 differential impact of El Niño and La Niña events on precipitation isotopes.

40 **1 Introduction**

41 Stable oxygen and hydrogen isotopes ($\delta^{18}\text{O}$ and δD) in water are ^{16}O , ^{17}O , and ^{18}O
42 for oxygen, and ^1H and ^2H (D) for hydrogen. During water phase change, such as
43 evaporation and condensation, isotopic fractionation leads to the change of isotopic
44 ratios (Gat, 1996; Frankenberg et al., 2009; Yoshimura et al., 2008). Stable isotopes in
45 ice cores serve as paleothermometers (Tian et al., 2021), when interpreted through
46 knowledge of precipitation isotope variability. Precipitation stable isotopes offer
47 insight into moisture sources and hydrological processes and form the theoretical
48 foundation for paleoclimate reconstruction and interpretation (Yoshimura, 2015).

49 Numerous studies have shown that precipitation isotopes are influenced by
50 temperature, precipitation amount, and altitude (Jasechko, 2019). Additional
51 influences include local recycling via evapotranspiration (Risi et al., 2010),
52 convective activity (Gao et al., 2013; Risi et al., 2008), sub-cloud evaporation (Ye et
53 al., 2024), topographic gradients (Zhang et al., 2023), atmospheric circulation (Wang
54 et al., 2024), moisture sources (Yang and Wang, 2024), and ENSO. The linear
55 relationship between δD and $\delta^{18}\text{O}$ in precipitation, known as the Global Meteoric
56 Water Line (GMWL; $\delta\text{D} = 8 \times \delta^{18}\text{O} + 10$), was first proposed by Craig (1961). The
57 slope reflects the fractionation ratio of δD and $\delta^{18}\text{O}$, and the intercept represents the
58 mean d-excess, which signals kinetic fractionation during ocean evaporation and

59 serves as a tracer of moisture source conditions (Merlivat and Jouzel, 1979). At
60 regional scales, this is referred to as the Local Meteoric Water Line (LMWL), which
61 varies according to local climatic conditions (e.g., temperature, precipitation amount,
62 humidity, wind) (Gao et al., 2011), large-scale convective activity (Dansgaard, 1964),
63 geographic factors (e.g., latitude, elevation, water recycling), and atmospheric
64 circulation patterns (e.g., source regions and transport pathways) (Chakraborty et al.,
65 2016). Deviations from equilibrium fractionation—such as sub-cloud
66 evaporation—can lower both the slope and intercept of the LMWL due to the
67 differing non-equilibrium fractionation of oxygen and hydrogen isotopes (Brunello et
68 al., 2024). Conversely, vapor recycling tends to increase both values (Adhikari et al.,
69 2020).

70 Deuterium excess ($d\text{-excess} = \delta D - 8 \times \delta^{18}O$), introduced by Dansgaard (1964), is
71 commonly used to assess kinetic fractionation and infer moisture source
72 characteristics (Zhang et al., 2021). Globally, average $d\text{-excess}$ in precipitation is
73 around 10 ‰. Lower oceanic relative humidity during winter enhances kinetic
74 fractionation, producing water vapor with elevated $d\text{-excess}$ (Natali et al., 2022).

75 Isotope monitoring on the TP began in 1991 with the establishment of the Tibetan
76 Plateau Network of Isotopes in Precipitation (TNIP) by the Chinese Academy of
77 Sciences (Yao et al., 1991). Precipitation $\delta^{18}O$ in the northern TP generally shows
78 positive correlation with temperature (i.e., enriched $\delta^{18}O$ in summer, depleted in
79 winter), while precipitation $\delta^{18}O$ in the southern TP exhibits a negative correlation
80 with precipitation amount, showing depletion in summer and enrichment in winter
81 (Tian et al., 2007). Spatial precipitation $\delta^{18}O$ patterns during summer reflect regional
82 circulation regimes: Indian summer monsoon (ISM) dominance in the south, westerly
83 influence in the north, and a transitional zone in central TP. In winter, westerlies
84 dominate across the entire TP (Yao et al., 2013; Gao et al., 2009).

85 Previous studies also demonstrated that moisture origins influence precipitation
86 isotopes (Dai et al., 2021). During monsoon seasons, convection transports marine
87 vapor from the Bay of Bengal (BOB), Arabian Sea (AS), and Indian Ocean northward,

88 yielding low d-excess precipitation over the Himalayas and beyond, reflecting marine
89 vapor origins. In contrast, wintertime westerlies carry moisture from remote sources
90 such as the Mediterranean Sea, producing precipitation with lower $\delta^{18}\text{O}$ and elevated
91 d-excess. Local evapotranspiration contributes isotopically distinct vapor, typically
92 enriched in both $\delta^{18}\text{O}$ and d-excess (Noone et al., 2011; Gao et al., 2019). Local
93 processes such as evaporation, convection, and sub-cloud evaporation also modulate
94 isotope values seasonally: high temperatures enhance evapotranspiration and
95 sub-cloud evaporation through unsaturated air during summer, enriching $\delta^{18}\text{O}$; as
96 sub-cloud evaporation decreases, d-excess rises (Ren et al., 2013). Vapor recycling
97 also contributes to elevated d-excess values (Wang et al., 2016).

98 ENSO modulates precipitation across the TP by altering the Walker Circulation
99 and associated convective and large-scale moisture transport patterns (Mason and
100 Goddard, 2001). Central Pacific El Niño events typically increase spring precipitation
101 in the western TP and reduce it in the east, while La Niña events have the opposite
102 effect (Wang et al., 2024). In summer, eastern Pacific El Niño events suppress rainfall
103 in the southwest TP, while Central Pacific La Niña conditions enhance it (Liu et al.,
104 2023). ENSO-driven changes in precipitation modify isotope signals through the
105 amount effect, as well as upstream convective activity along vapor transport pathways.
106 For example, $\delta^{18}\text{O}$ values at Lhasa are significantly correlated with convective activity
107 both in moisture source regions and along the transport path (Cai et al., 2017). ENSO
108 also alters $\delta^{18}\text{O}$ in the northwestern TP by affecting regional circulation patterns and
109 the availability of water vapor (Yang et al., 2018). Therefore, the precipitation stable
110 isotopes across the TP serve as effective tracers of ENSO-related climate variability
111 (Murray et al., 2025).

112 The Yadong Valley, located in the southern TP within the monsoon domain,
113 receives abundant ISM precipitation. Moisture supply linked to evaporation over
114 northeastern India and losses associated with convection over the BoB and
115 Bangladesh significantly impact $\delta^{18}\text{O}$ and d-excess (Axelsson et al., 2023). In contrast,
116 the Ali region in the arid western TP remains under-studied due to sparse

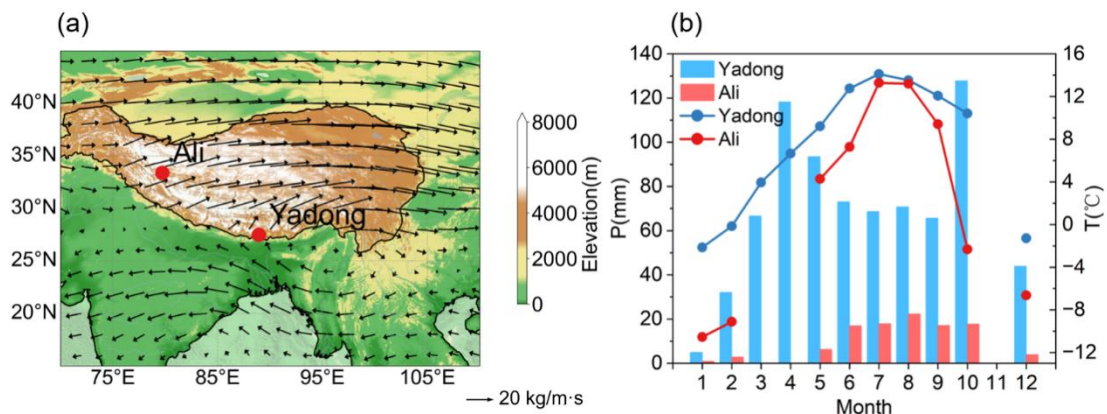
117 observational data. Prior work has linked sharp mid-summer drops in $\delta^{18}\text{O}$ to ISM
 118 intrusions, while $\delta^{18}\text{O}$ –temperature correlations dominate during the non-monsoon
 119 season, reflecting westerly and local circulation influences (Yu et al., 2009).

120 Despite these insights, a systematic understanding of drivers on daily and
 121 synoptic-scale variability of precipitation isotopes and their response to large-scale
 122 systems such as the westerlies, ISM, and ENSO, between the southern and western TP
 123 is still lacking. Therefore, here we analyze event-based $\delta^{18}\text{O}$ and δD data from Yadong
 124 and Ali (May 2021–September 2023), in conjunction with *in-situ* meteorological data,
 125 HYSPLIT backward trajectories, ERA5 reanalysis, and the Niño 3.4 index. We
 126 characterize isotope variability across daily to interannual timescales, evaluate the
 127 role of synoptic-scale moisture transport in modulating moisture sources, and assess
 128 ENSO’s impact on the TP. Our results offer new insights into precipitation isotope
 129 response to climate variations on the TP. Section 2 outlines the study sites, datasets,
 130 sampling and analysis methods. Section 3 presents the variability of precipitation
 131 isotopes and meteorological parameters, explores local controls, moisture transport
 132 process and ENSO influences on precipitation stable isotopes; and analyzes drivers of
 133 simultaneous events at Yadong and Ali.

134

135 2 Study Site, Data, and Methods

136 2.1 Study Site and Data



137

138 **Figure 1. Map showing the geographical locations of Yadong and Ali, the mean**
 139 **integrated water vapor flux (500-200 hPa) during the 1994 to 2023 monsoon**
 140 **seasons, and the monthly mean temperature and precipitation at both sites from**

141 **May 2021 to September 2023. (a) The location of the Yadong and Ali study sites**
142 **with arrows indicating the integrated water vapor flux from 500hPa to 200hPa**
143 **during the 1994 to 2023 monsoon seasons. (b) Monthly mean temperature (lines)**
144 **and precipitation (bars) at both sites from May 2021 to September 2023. Note the**
145 **absence of precipitation events at Yadong in November and at Ali in March,**
146 **April, and November during the study period.**

147

148 Precipitation samples were collected at Yadong and Ali sites. Yadong (88.92 °E,
149 27.49 °N, 2,990 m a.m.s.l.) is located within the Yadong Valley in the central
150 Himalayas, while Ali (79.70 °E, 33.39 °N, 4,270 m a.m.s.l.) lies in the western Tibet
151 at the intersection of the Himalayas, Karakoram, and Gangdise mountain ranges, with
152 an elevation difference of 1,280 m between these two sites (Fig. 1a). During the
153 monsoon season, Yadong is primarily influenced by the southwest monsoon and
154 receives an average annual precipitation of 764.8 mm. In contrast, Fig. 1 shows that
155 Ali is mainly influenced by the westerlies and has much lower annual precipitation of
156 105.6 mm, ~70% of which falls during the monsoon season. Temperature at both sites
157 follow a similar seasonal cycle, increasing in spring and summer and decreasing in
158 autumn and winter. However, due to its higher elevation, Ali is consistently colder
159 than Yadong, with an annual mean temperature of 2.1 °C compared to 7.2 °C at
160 Yadong (Fig. 1b).

161 Meteorological data used in this study include surface temperature, precipitation,
162 relative humidity, and wind speed, recorded at the beginning and end of each
163 precipitation event. Surface temperature, relative humidity, and wind speed were
164 averaged between the two measurements, while precipitation was calculated as the
165 total rainfall amount for each event. Meteorological data for Ali were obtained from a
166 Campbell ClimaVUE50 automatic weather station installed at the site (with
167 minute-level temporal resolution), whereas data for Yadong were provided with
168 hourly resolution. The observation period spans from May 2021 to September 2023 at
169 both sites. To account for the respective influences of the ISM and the mid-latitude

170 westerlies on precipitation stable isotopes, the year is divided into a monsoon season
171 (June–September) and a non-monsoon season (October–May of the following year).
172 The non-monsoon season is further subdivided into the pre-monsoon (March–May),
173 post-monsoon (October), and westerlies (November–February) seasons, following
174 previous isotope-based studies over the Tibetan Plateau (Axelsson et al., 2023; Dai et
175 al., 2021). This seasonal classification is consistent with the typical progression of the
176 ISM as reported by the India Meteorological Department (IMD;
177 <https://mausam.imd.gov.in/>). During the study period, monsoon onset dates occurred
178 on 3 June 2021, 29 May 2022, and 8 June 2023, while monsoon withdrawal dates
179 were 25 October 2021, 23 October 2022, and 16 October 2023, respectively.
180 Meteorological conditions at both Yadong and Ali exhibited pronounced seasonal
181 cycles. Air temperature at both sites peaked during the monsoon season (July means
182 of 14.1°C at Yadong and 13.3°C at Ali) and reached minima during the westerlies
183 season (January means of –2.1 °C and –10.5 °C, respectively). Precipitation patterns
184 differed markedly between the two sites: Yadong experienced substantial rainfall with
185 maxima during both the pre-monsoon (118.2 mm) and post-monsoon (127.8 mm)
186 seasons, whereas approximately 70 % of Ali’s annual precipitation occurred during
187 the monsoon season (Fig. 1b). Relative humidity remained consistently high at
188 Yadong throughout the year (pre-monsoon: 93 %; monsoon: 94 %; post-monsoon:
189 95 %; westerlies: 92 %), while at Ali it was substantially lower overall and exhibited a
190 seasonal maximum during the post-monsoon period (pre-monsoon: 67 %; monsoon:
191 59 %; post-monsoon: 81 %; westerlies: 70 %). Wind speeds at Yadong were
192 persistently low with minimal seasonal variability (pre-monsoon: 1.6 m s⁻¹; monsoon:
193 2.2 m s⁻¹; post-monsoon: 1.5 m s⁻¹; westerlies: 1.7 m s⁻¹). In contrast, Ali experienced
194 generally stronger winds, with maxima during the pre-monsoon (2.7 m s⁻¹) and
195 monsoon (2.9 m s⁻¹) seasons (post-monsoon: 1.6 m s⁻¹; westerlies: 1.7 m s⁻¹)
196 To investigate the influence of ENSO events on precipitation stable isotopes at
197 Yadong and Ali, we used the monthly Oceanic Niño Index (ONI) provided by the

198 National Oceanic and Atmospheric Administration Climate Prediction Center (NOAA
199 CPC,
200 https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php,
201 last access: 3 May 2025), based on sea surface temperature (SST) anomalies in the
202 Niño 3.4 region (5° N-5° S, 120°-170° W).

203

204 **2.2 Sample Collection and Measurement**

205 In total, 359 precipitation samples from Yadong and 80 samples from Ali were
206 analyzed, all collected between May 2021 and September 2023. After each
207 precipitation event, samples were immediately transferred into 4 ml glass bottles,
208 sealed, and labeled with event-specific metadata including temperature, precipitation
209 amount, relative humidity, and wind speed at both the beginning and end of the event.
210 All samples were stored under refrigeration until isotope measurements were made.
211 Measurements of $\delta^{18}\text{O}$ and δD were conducted at the State Key Laboratory of Tibetan
212 Plateau Earth System, Environment and Resources, Institute of Tibetan Plateau
213 Research, Chinese Academy of Sciences (CAS), using a cavity ring-down
214 spectrometer (Picarro-2130i Liquid Water Isotope Analyzer) with an analytical
215 precision of ± 0.08 ‰ for $\delta^{18}\text{O}$ and ± 0.5 ‰ for δD . Stable isotope measurements were
216 calibrated and quality-controlled following a standardized analytical protocol. Each
217 analytical batch comprised 27 precipitation samples and 4 laboratory reference
218 standards, with each sample measured six consecutive times. To minimize instrument
219 memory effects, the first three injections were discarded. The remaining three
220 injections were required to meet strict precision criteria, with a standard deviation (SD)
221 of < 0.08 ‰ for $\delta^{18}\text{O}$ and < 0.5 ‰ for δD ; samples that did not meet these thresholds
222 were remeasured. For calibration, 4 laboratory reference standards calibrated against
223 Vienna Standard Mean Ocean Water (V-SMOW) ($\delta^{18}\text{O} = -0.9$ ‰ and $\delta\text{D} = -5.3$ ‰,
224 $\delta^{18}\text{O} = -10.9$ ‰ and $\delta\text{D} = -77.0$ ‰, $\delta^{18}\text{O} = -19.7$ ‰ and $\delta\text{D} = -147.0$ ‰, $\delta^{18}\text{O} =$
225 -29.4 ‰ and $\delta\text{D} = -224.6$ ‰) were used to cover the isotopic range of ambient
226 precipitation samples at both sites, with reference standard values spanning a similar

227 range to those used in recent precipitation isotope studies from the same TP region
 228 (Wang et al., 2023). For each analytical batch, a univariate linear regression was
 229 established between the measured isotope values and the assigned values of the
 230 reference standards. The resulting calibration equation was then applied to correct the
 231 raw isotope measurements of the co-analyzed precipitation samples, ensuring
 232 consistency and traceability of the final dataset. Isotope values are reported in
 233 delta-notation (δ) relative to Vienna Standard Mean Ocean Water (V-SMOW)
 234 (Dansgaard, 1964):

$$\delta^{18}\text{O} = \left(\frac{\left(\frac{^{18}\text{O}}{^{16}\text{O}} \right)_{\text{sample}}}{\left(\frac{^{18}\text{O}}{^{16}\text{O}} \right)_{\text{standard}}} - 1 \right) \times 1000\text{‰} \quad (1)$$

235 The daily, monthly, seasonal, and annual averages of $\delta^{18}\text{O}$ are calculated as
 236 precipitation amount-weighted averages:

$$\delta^{18}\text{O}_w = \frac{\sum P_i \delta^{18}\text{O}_i}{\sum P_i} \quad (2)$$

237 where P_i represents the precipitation amount during the i -th rainfall event. $\delta^{18}\text{O}_w$
 238 denotes the precipitation amount-weighted daily, monthly, seasonal, or annual average.
 239 The definition of δD follows a form analogous to Eq. (1), and its precipitation
 240 amount-weighted average is calculated identically using Eq. (2).

241

242 **2.3 Rayleigh Distillation and Mixing Model**

243 The Rayleigh distillation model describes the progressive depletion of heavy
 244 isotopes in an air mass as it cools along its trajectory. During this process,
 245 condensation and precipitation preferentially remove the heavier isotopes, leaving the
 246 residual vapor increasingly depleted (Gat, 1996):

$$R = R_0 f^{\alpha_v^l(T)-1} \quad (3)$$

247 where R and R_0 represent the isotopic ratios of residual and initial vapor,
 248 respectively. $\alpha_v^l(T)$ denotes the equilibrium fractionation factor, and f is the fraction

249 of residual water vapor.

250 By integrating Eq. (1), the Rayleigh distillation model can be expressed as
251 follows:

$$\delta = (\delta_0 + 1)f^{\alpha_v(T)-1} - 1 \quad (4)$$

252 where δ and δ_0 are the isotope ratios against V-SMOW in residual and initial vapor,
253 respectively.

254 To examine the isotopic characteristics after the mixing of two air masses we
255 employ the following mixing model (Galewsky and Hurley, 2010):

$$R_{\text{mix}} = \frac{f[\text{HDO}]_1 + (1 - f)[\text{HDO}]_2}{f[\text{H}_2\text{O}]_1 + (1 - f)[\text{H}_2\text{O}]_2} \quad (5)$$

256 where R_{mix} represents the isotopic ratio of the mixed air mass, while $[\text{HDO}]$ and
257 $[\text{H}_2\text{O}]$ denote isotopic water vapor volume mixing ratios. f is the mixing fraction.

258

259 **2.4 Backward Trajectory Calculation and Integrated Water Vapor Flux**

260 To assess the influence of moisture sources on precipitation stable isotopes, we
261 employed the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT)
262 model developed by the US National Oceanic and Atmospheric Administration
263 (NOAA) to calculate 120 h backward trajectories for air masses arriving 200 m above
264 ground level at Yadong and Ali stations. Backward trajectories were calculated with a
265 duration of 120 h, which was selected because it sufficiently captures transport times
266 from the major moisture source regions to the TP, as demonstrated in previous studies
267 (Gao et al., 2013; Dai et al., 2021). Sensitivity tests using 140 h trajectories showed
268 no significant differences in transport pathways or moisture source attribution
269 compared to the 120 h case (Fig. S1). Therefore, 120 h was adopted as an optimal and
270 computationally efficient choice for this study. Trajectories were initialized four times
271 daily (00:00, 06:00, 12:00, and 18:00 UTC) on all rainy days between May 2021 and
272 September 2023, with one air parcel released at each start time. Specific humidity (q)
273 was tracked along each trajectory, and the magnitude of moisture change ($|\Delta q| = |q_{\text{end}} -$
274 $q_{\text{initial}}|$) ranged from 0.5 to 8.1 g kg⁻¹ at Yadong and from 0.1 to 16.9 g kg⁻¹ at Ali,
275 indicating substantial moisture uptake and loss along transport pathways.

276 Cluster analysis was performed using the HYSPLIT clustering algorithm, which
277 groups trajectories with similar spatial pathways. The optimal number of clusters was
278 determined by minimizing the Total Spatial Variance (TSV). For each cluster, a mean
279 trajectory represents the spatial average of all trajectories within that cluster. The
280 percentages shown in Figures 4 and 7 indicate the fraction of trajectories assigned to
281 each cluster relative to the total number of trajectories at each site. We have added
282 Table S1 to show Total Spatial Variance (TSV, units: $^{\circ}^2$) of trajectory clusters at
283 Yadong and Ali in different seasons of each year. The model uses Global Data
284 Assimilation System (GDAS) reanalysis data with a spatial resolution of $1^{\circ} \times 1^{\circ}$ and a
285 temporal resolution of 6 h, provided by the National Centers for Environmental
286 Prediction (NCEP, <ftp://arlftp.arlhq.noaa.gov/archives/gdas1/>, last access: 8 January
287 2025). To quantify the moisture contribution of each trajectory cluster, we combined
288 the relative frequency of clustered trajectories with the along-trajectory variations in q .
289 Increases in q were interpreted as moisture uptake from surface evaporation over the
290 ocean or evapotranspiration over land, whereas decreases in q were attributed to
291 moisture loss associated with precipitation processes (Dai et al., 2021; Adhikari et al.,
292 2020).

293 To assess the robustness of the moisture source identification and ensure
294 consistency with the water vapor flux analysis, trajectory analyses were conducted
295 using two distinct initialization levels to verify robustness (See supplementary file): (1)
296 Condensation level: Derived from event-specific in-situ temperature and relative
297 humidity, this level represents the altitude at which water vapor condensation likely
298 occurs and, therefore, corresponds closely to the effective cloud base. The mean
299 heights were 3143 m a.m.s.l. at Yadong (153 m AGL) and 5396 m a.m.s.l. at Ali (1126
300 m AGL). (2) 500 hPa: The second trajectory set was initiated at the 500 hPa pressure
301 level (mid-troposphere). This level was selected to ensure consistency with the
302 500-200 hPa used for calculation of vertically integrated water vapor fluxes,
303 minimizing potential discrepancies between trajectory-derived pathways and
304 flux-based transport diagnostics.

305 We also used ERA5 reanalysis data to calculate integrated water vapor flux from
306 500 hPa to 200 hPa above the Yadong and Ali sites on rainy days during the study
307 period. ERA5 data, provided by the European Centre for Medium-Range Weather
308 Forecasts (ECMWF, <https://cds.climate.copernicus.eu/eu/>, last access: 4 February
309 2025), include specific humidity (q), zonal wind (u), and meridional wind (v)
310 components, and have a spatial resolution of $0.25^\circ \times 0.25^\circ$ and temporal resolution of
311 1 h. These data were used to calculate the integrated water vapor flux (Q) using:

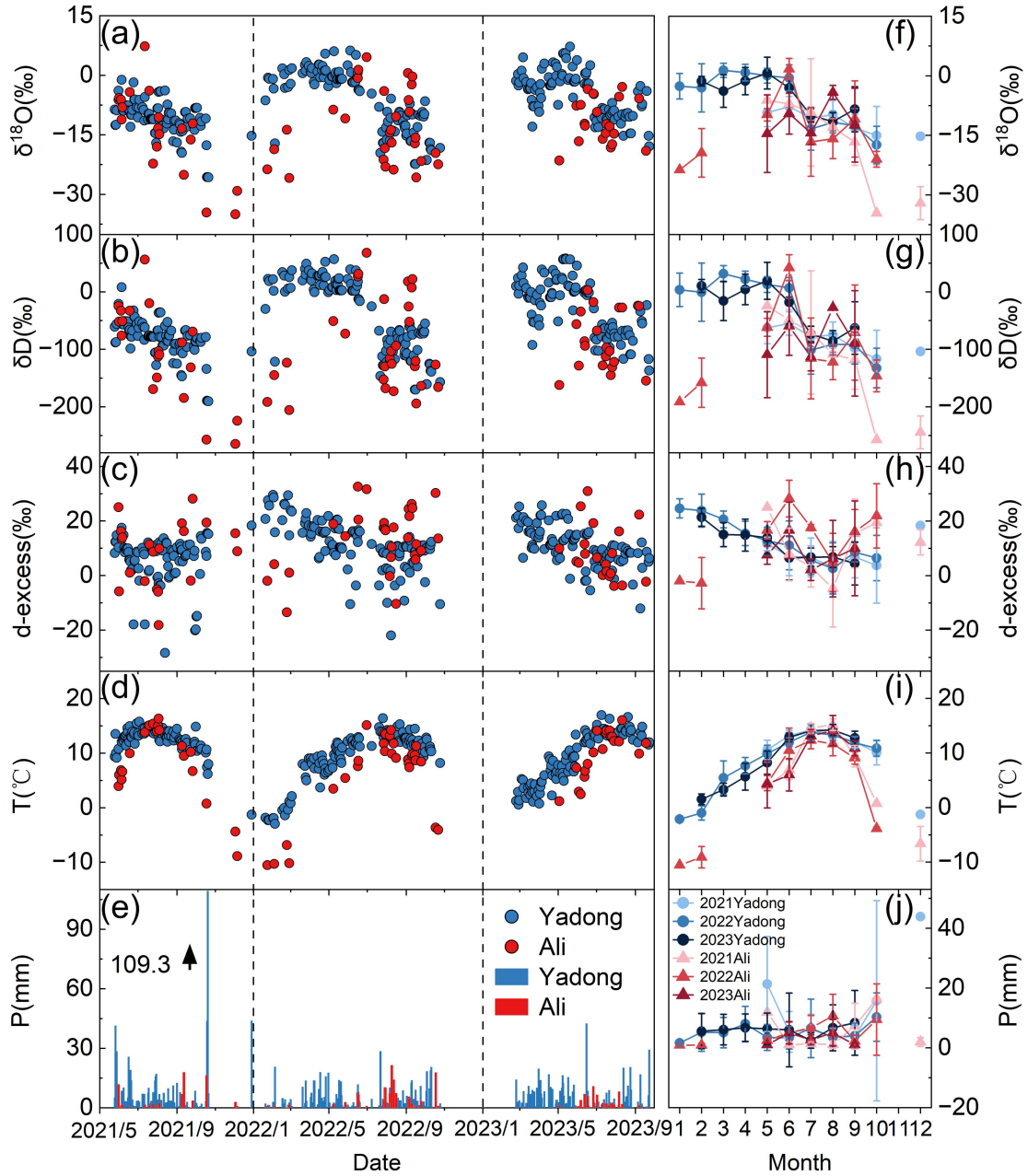
$$Q = \frac{1}{g} \int_{P_t}^{P_s} (u, v)qdp \quad (6)$$

312 where g is gravitational acceleration, while P_s and P_t are surface pressure and 200
313 hPa pressure, respectively.

314

315 **3 Results**

316 **3.1 Temporal Variability of Precipitation Stable Isotopes**



317

318 **Figure 2. Temporal variations of daily and monthly precipitation stable isotopes**

319 **($\delta^{18}\text{O}$, δD , d-excess) and local meteorological conditions (temperature,**

320 **precipitation amount) at Yadong and Ali from May 2021 to September 2023. (a)**

321 **and (f) Daily and monthly variations in $\delta^{18}\text{O}$. (b) and (g) same as (a) and (f), but**

322 **for δD . (c) and (h) same as (a) and (f), but for d-excess. (d) and (i) same as (a) and**

323 **(f), but for temperature. (e) and (j) same as (a) and (f), but for precipitation**

324 **amount.**

325

326 Both Yadong and Ali exhibit remarkable seasonal variations in temperature and
327 precipitation. Temperatures at both sites follow a unimodal pattern (Fig. 1b, 2d and 2i),
328 peaking in July during the monsoon season at 14.1 °C (Yadong) and 13.3 °C (Ali),
329 respectively, and reaching their lowest values in January during the non-monsoon
330 season at -2.1 °C (Yadong) and -10.5 °C (Ali). Also seasonal precipitation patterns
331 differ significantly between the two sites (Fig. 1b, 2e and 2j), with Yadong receiving
332 substantially higher annual precipitation than Ali (764.8 mm vs. 105.6 mm).
333 Precipitation at Ali exhibits a strong peak located within the monsoon season (August),
334 accounting for 70 % of its annual total. In contrast, the precipitation pattern at Yadong
335 is bimodal, with two peaks in April (pre-monsoon, 118.2 mm, 15.5 % of annual total)
336 and October (post-monsoon, 127.8 mm, 16.7 % of annual total).

337 Yadong exhibits a pronounced bimodal precipitation regime that exerts seasonally
338 distinct controls on the isotopic composition of precipitation ($\delta^{18}\text{O}$ and δD ; Figs. 1b
339 and 2e). During October, which corresponds to the primary precipitation maximum,
340 extreme rainfall events (e.g., 109.3 and 43.7 mm day⁻¹) dominate the monthly total
341 and induce a strong amount effect, reflected by a statistically significant negative
342 relationship between precipitation amount and isotopic composition ($R^2 = 0.36$). As a
343 result, October records the most depleted monthly mean isotope values ($\delta^{18}\text{O} =$
344 -16.0 ‰ ; $\delta\text{D} = -123.4 \text{ ‰}$), consistent with enhanced rainout and progressive isotopic
345 depletion during intense convective precipitation. In contrast, April represents a
346 secondary precipitation peak characterized by frequent but weak rainfall events
347 (0.4–18.0 mm day⁻¹). Despite relatively high cumulative precipitation, the monthly
348 mean isotope values are anomalously enriched ($\delta^{18}\text{O} = -0.2 \text{ ‰}$; $\delta\text{D} = 13.2 \text{ ‰}$). This
349 enrichment indicates that isotopic variability during April is not primarily governed
350 by the amount effect. Instead, it likely reflects the dominant influence of local surface
351 evaporation and sub-cloud kinetic fractionation, which preferentially enrich heavy
352 isotopes under warm and relatively dry pre-monsoonal conditions. These contrasting
353 isotopic responses highlight the seasonally varying balance between large-scale
354 moisture condensation and local evaporative processes in shaping precipitation

355 isotope signals over the southern TP.

356 Both Yadong and Ali exhibit a distinct three-stage isotopic cycle in response to
357 monsoon evolution: $\delta^{18}\text{O}$ and δD increase during the pre-monsoon, moderately
358 deplete during monsoon development, and reach their lowest values during the
359 post-monsoon season (Fig. 2a–b, Table S2). For instance, $\delta^{18}\text{O}$ at Yadong decreases
360 from -2.7‰ during the pre-monsoon to -10.7‰ during the mature monsoon,
361 reaching -22.9‰ at the end of the monsoon, before rising to -9.6‰ under westerly
362 influence. Ali follows a similar temporal variation, but with more pronounced
363 extremes (from -8.4‰ to -26.7‰).

364 Notably, a large number of positive values of $\delta^{18}\text{O}$ and δD are observed at both
365 sites, particularly at Yadong (Fig. 2a-b). These enriched values mainly occurred
366 during the pre-monsoon and westerly-dominated seasons. Such enrichment likely
367 results from local moisture recycling and the intrusion of dry continental westerly
368 winds. These positive $\delta^{18}\text{O}$ and δD values therefore indicate precipitation events
369 dominated by local recycling, westerly winds or evaporative continental moisture,
370 contrasting with the depleted signatures of ISM moisture (Adhikari et al., 2020; Wang
371 et al., 2019).

372 Both sites exhibit similar seasonal d-excess pattern (Fig. 2c, Table S2). At Yadong,
373 d-excess is elevated during the pre-monsoon (15.3‰), lowest during the peak
374 monsoon (6.7‰), and then increases again during the post-monsoon and westerly
375 periods (13.1‰ and 19.9‰ , respectively). Similarly, Ali shows high d-excess during
376 the pre-monsoon (20.9‰), a decline during the monsoon (14.0‰), a peak in the
377 post-monsoon (24.7‰), whereas the lowest values during the westerlies (-1.5‰)
378 may be attributed to sporadic precipitation events. These variations reflect shifts in
379 moisture sources and the humidity dependence of kinetic fractionation—higher
380 d-excess values are associated with low-humidity sources such as continental or
381 recycled vapor, whereas lower d-excess values correspond to humid or oceanic air
382 masses (Merlivat and Jouzel, 1979; Gat and Matsui, 1991). Ali shows greater
383 amplitude in d-excess changes, especially under westerly influence, indicating a

384 higher sensitivity to shifts between continental and maritime moisture regimes.

385 Interannual anomalies further highlight the influence of moisture origin and
 386 thermal regimes (Fig. 2f, 2h). At Yadong, pre-monsoon (May–June) $\delta^{18}\text{O}$ was more
 387 depleted in 2021 (-9.3‰ and -7.8‰) but shifted to more enriched values in 2022
 388 (0.0‰ and -0.5‰) and 2023 (0.7‰ and -3.1‰), despite only minor changes in
 389 d-excess. This indicates enhanced local recycling or warmer vapor source conditions
 390 in the latter years. At Ali, $\delta^{18}\text{O}$ peaked in June 2022 at 1.7‰ (compared to -7.1‰ in
 391 2021 and -9.5‰ in 2023), while in October 2021, $\delta^{18}\text{O}$ dropped to -34.6‰ (vs.
 392 -21.0‰ in 2022). These fluctuations correspond to d-excess maxima in mid-summer
 393 2022 (28.2‰ and 17.6‰) and a minimum in August 2021 (-4.8‰). These episodic
 394 enrichments and depletions probably result from variations in influence of large-scale
 395 mode (ENSO), which modulates the humid ISM and the drier westerly regimes,
 396 aligning with documented shifts in moisture transport over the TP (Yao et al., 2012).

397

398 3.2 The Local Meteoric Water Line

399 **Table 1. Local Meteoric Water Line (LMWL) for Yadong and Ali, including**
 400 **coefficient of determination (R^2) and p-value (H_0 : no linear relationship between**
 401 **$\delta^{18}\text{O}$ and δD).**

Station	Yadong	Ali
Full year	$\delta\text{D} = 8.43 \pm 0.07 \times \delta^{18}\text{O} + 12.70 \pm 0.70,$ $R^2 = 0.98, p < 0.001$	$\delta\text{D} = 8.38 \pm 0.16 \times \delta^{18}\text{O} + 15.41 \pm 2.46,$ $R^2 = 0.98, p < 0.001$
Pre-monsoon	$\delta\text{D} = 8.11 \pm 0.14 \times \delta^{18}\text{O} + 14.77 \pm 0.56,$ $R^2 = 0.97, p < 0.001$	$\delta\text{D} = 8.62 \pm 0.67 \times \delta^{18}\text{O} + 21.50 \pm 8.20,$ $R^2 = 0.98, p < 0.01$
Monsoon	$\delta\text{D} = 7.89 \pm 0.11 \times \delta^{18}\text{O} + 5.24 \pm 1.22,$ $R^2 = 0.96, p < 0.001$	$\delta\text{D} = 8.57 \pm 0.20 \times \delta^{18}\text{O} + 16.85 \pm 2.71,$ $R^2 = 0.97, p < 0.001$
Post-monsoon	$\delta\text{D} = 6.92 \pm 0.34 \times \delta^{18}\text{O} -$	$\delta\text{D} = 8.44 \pm 1.00 \times \delta^{18}\text{O} +$

	$12.41 \pm 5.76,$	$32.37 \pm 26.46,$
	$R^2 = 0.96, p < 0.001$	$R^2 = 0.99, p > 0.05$
Westerlies	$\delta D = 8.39 \pm 0.22 \times \delta^{18}O +$	$\delta D = 6.87 \pm 0.31 \times \delta^{18}O -$
	$24.31 \pm 1.39,$	$25.10 \pm 7.74,$
	$R^2 = 0.99, p < 0.001$	$R^2 = 0.99, p < 0.001$

402

403 We used total least squares (TLS) regression to calculate all LMWLs, accounting
404 for measurement precisions to estimate slope and intercept errors. As shown in Fig.
405 S2 and Table 1, the annual LMWL slope and intercept at Yadong (8.43 ± 0.07 and
406 12.70 ± 0.70 ‰, respectively) are higher than those of the GMWL (8 and 10 ‰),
407 which may reflect strong vapor recycling. During the pre-monsoon, the slope ($8.11 \pm$
408 0.14) approximates that of the GMWL, while the intercept is higher (14.77 ± 0.56 ‰),
409 suggesting a moisture source with relatively low humidity compared to the monsoon
410 and post-monsoon seasons. During the monsoon, the slope (7.89 ± 0.11) approximates
411 that of the GMWL, while the intercept is lower (5.24 ± 1.22 ‰), suggesting humid
412 moisture sources. During the post-monsoon, both the slope (6.92 ± 0.34) and intercept
413 (-12.41 ± 5.76 ‰) fall below the GMWL, indicating influence from sub-cloud
414 evaporation and humid moisture sources. In contrast, the LMWL slope and intercept
415 during the westerlies season (8.39 ± 0.22 and 24.31 ± 1.39 ‰) exceed those of the
416 GMWL, likely due to enhanced moisture recycling. These findings are consistent with
417 previous reports, such as an annual LMWL slope and intercept of 8.4 and 12.02 ‰ at
418 Yadong (Axelsson et al., 2023). Notably, the LMWL at Yadong during the monsoon
419 closely resembles that of Naqu (slope = 7.67, intercept = 1.3 ‰) in the central TP (Li
420 et al., 2023).

421 At Ali, the LMWL slopes (8.38 ± 0.16 , 8.62 ± 0.67 , 8.57 ± 0.20 , and 8.44 ± 1.00)
422 and intercepts (15.41 ± 2.46 ‰, 21.50 ± 8.20 ‰, 16.85 ± 2.71 ‰, and $32.37 \pm$
423 26.46 ‰) are consistently higher than the GMWL during the annual, pre-monsoon,
424 monsoon, and post-monsoon season, suggesting dominance of moisture recycling.
425 Although the linear fit is strong ($R^2 = 0.99$) during the post-monsoon season, the

426 result is not statistically significant ($p > 0.05$) due to the small sample size. However,
427 during the westerlies season, the slope (6.87 ± 0.31) and intercept ($-25.10 \pm 7.74 \text{ ‰}$)
428 are substantially lower, indicating strong sub-cloud evaporation and humid moisture
429 sources. This may result from synoptic transport from oceanic sources, which is
430 discussed in detail in section 3.4.

431

432 **3.3 The Influence of Local Meteorological Factors**

433 At Yadong, $\delta^{18}\text{O}$ exhibits a significant negative correlation with temperature
434 throughout the year (slope = -0.27 , $R = -0.42$, $p < 0.001$, H_0 : no linear correlation).
435 Seasonally, this relationship is negative from the late pre-monsoon to post-monsoon
436 ($R = -0.30$, $p < 0.001$), but shifts to a significant positive correlation from the
437 westerlies to the early pre-monsoon of the following year ($R = 0.51$, $p < 0.001$),
438 indicating a clear seasonal reversal in the temperature effect. At Ali, $\delta^{18}\text{O}$ is positively
439 correlated with temperature year-round (slope = 0.30 , $R = 0.39$, $p < 0.001$), with the
440 strongest correlation observed from the post-monsoon to the pre-monsoon season of
441 the following year ($R = 0.79$, $p < 0.001$).

442 In terms of precipitation, $\delta^{18}\text{O}$ at Yadong is significantly negatively correlated
443 year-round (slope = -0.35 , $R = -0.25$, $p < 0.001$), and particularly from the late
444 pre-monsoon to post-monsoon ($R = -0.28$, $p < 0.001$), reflecting a typical amount
445 effect. This correlation intensifies during the westerlies to early pre-monsoon season
446 ($R = -0.49$, $p < 0.001$). At Ali, a significant negative correlation between $\delta^{18}\text{O}$ and
447 precipitation is only observed during the monsoon season ($R = -0.32$, $p < 0.05$),
448 associated with the missing of temperature effect.

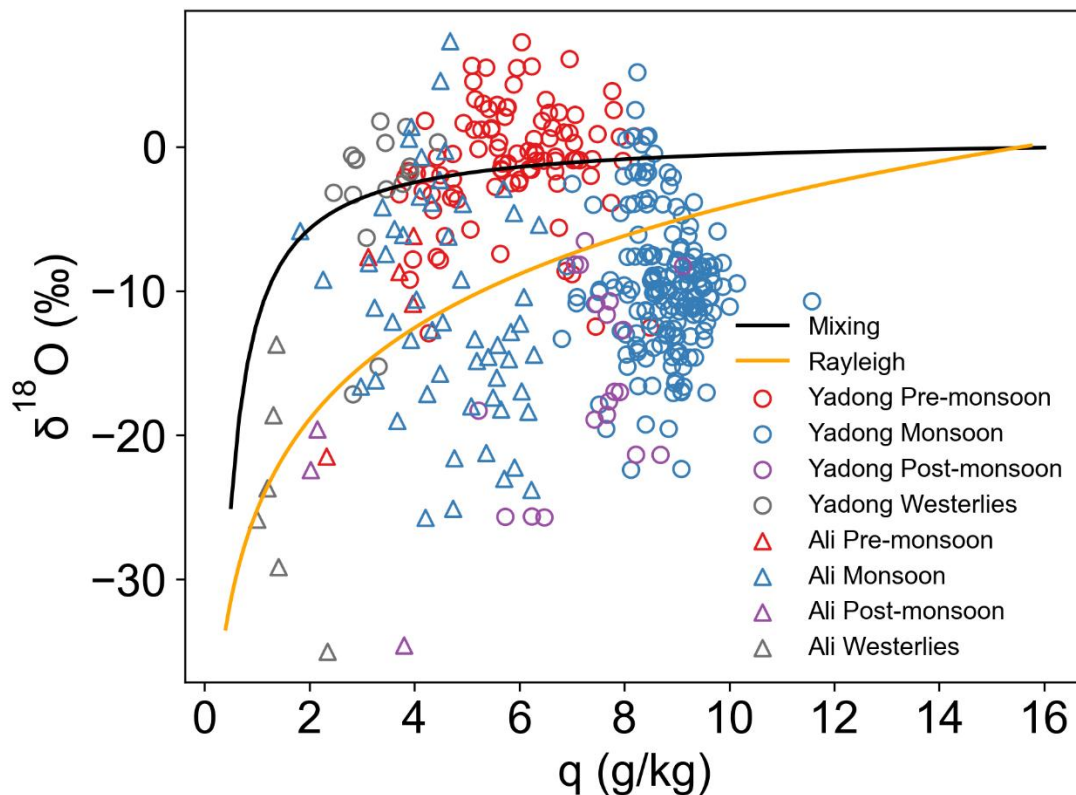
449 Regarding wind speed, $\delta^{18}\text{O}$ at Yadong shows a weak negative correlation over the
450 full year (slope = -0.02 , $R = -0.11$, $p < 0.05$), whereas at Ali, it is significantly
451 positively correlated year-round (slope = 0.04 , $R = 0.34$, $p < 0.01$), with the strongest
452 relationship during the post-monsoon to pre-monsoon ($R = 0.66$, $p < 0.001$),
453 associated with the strongest temperature effect (Fig. S3).

454 These results indicate that Yadong is predominantly influenced by the monsoon

455 from the late pre-monsoon to post-monsoon season, characterized by a strong amount
 456 effect. From the westerlies to early pre-monsoon, it is mainly affected by westerly
 457 winds and local moisture recycling, exhibiting a significant temperature effect. In
 458 contrast, Ali is primarily influenced by the monsoon during the monsoon season,
 459 showing a clear amount effect, and by westerlies and local vapor recycling from the
 460 post-monsoon to pre-monsoon, where the temperature effect becomes significant.
 461 These observations are consistent with previous studies reporting a significant amount
 462 effect in the southern TP, including at Bomi and Lhasa (Gao et al., 2011), and a
 463 dominant temperature effect in the northwestern TP, such as in the Bagrot Valley
 464 (Wang et al., 2019).

465

466 3.4 The Influence of Moisture Transport Processes



467

468 **Figure 3. Scatter plot of daily $\delta^{18}\text{O}$ versus q at Yadong and Ali, with mixing and**
 469 **Rayleigh fractionation curves. Black and orange lines represent the mixing and**
 470 **Rayleigh fractionation curves, respectively. The Rayleigh starting point is set at**
 471 **-0.07 ‰ and 16 g kg^{-1} at 25 °C , assuming equilibrium conditions for**

472 **precipitation from sea-level air with 80 % relative humidity. The mixing curve**
473 **uses the same wet end-member; the dry end-member is set at -25‰ and 0.5 g**
474 **kg^{-1} .**

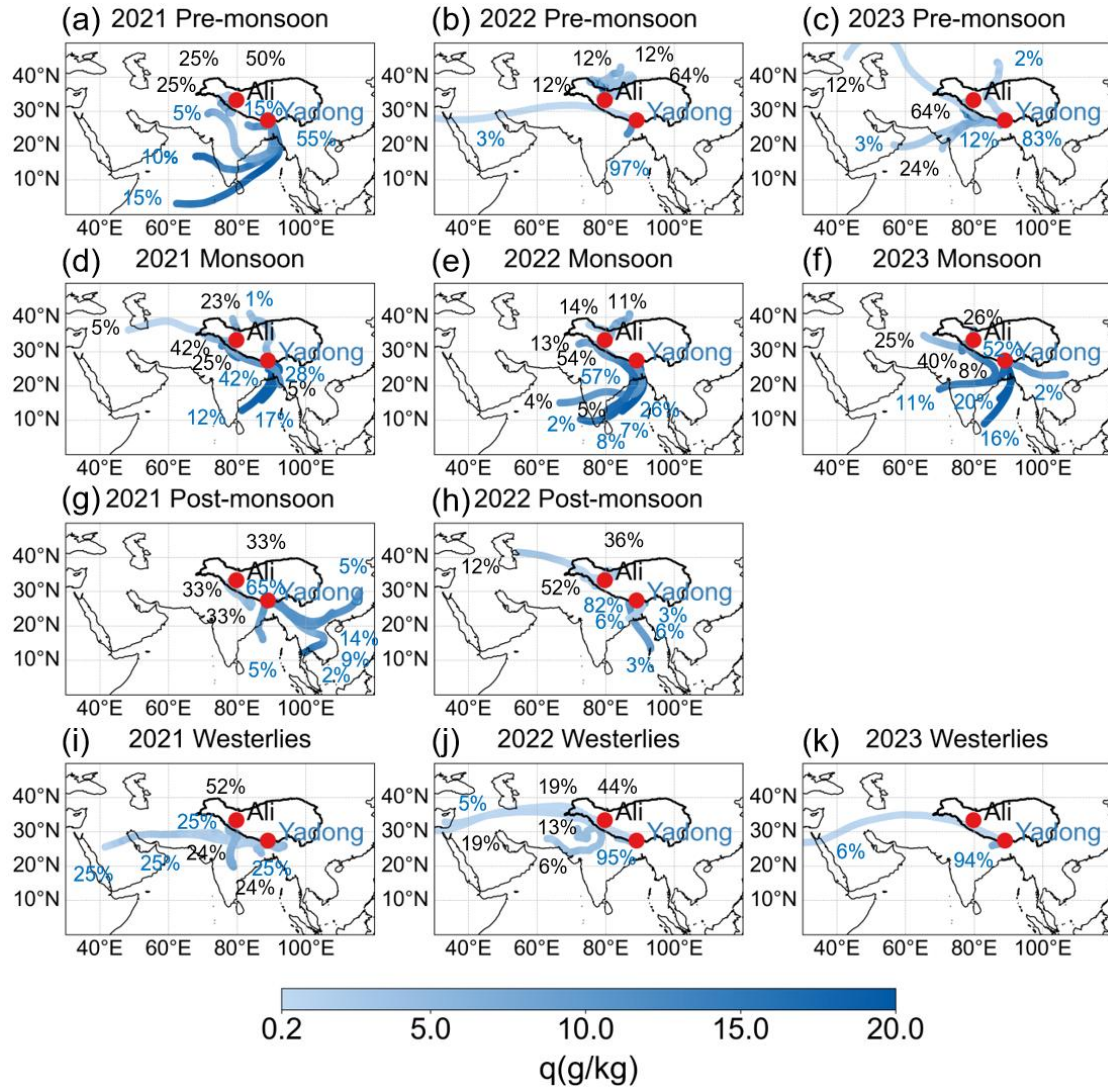
475

476 The q - $\delta^{18}\text{O}$ relationship effectively reflects seasonal controls on precipitation
477 isotopes at both sites (Fig. 3). At Yadong, during the pre-monsoon and westerlies
478 seasons, most $\delta^{18}\text{O}$ values lie above the mixing curve, indicating substantial influence
479 from local surface evaporation. In contrast, during the monsoon and post-monsoon,
480 most $\delta^{18}\text{O}$ values fall below the Rayleigh curve, suggesting dominant effects of
481 sub-cloud evaporation and rainout effect, consistent with prior LMWL-based
482 interpretations. Some monsoon-season values fall between the Rayleigh and mixing
483 curves, reflecting contributions from moisture mixing process.

484 At Ali, $\delta^{18}\text{O}$ values during the pre-monsoon, monsoon, and westerlies seasons fall
485 between the Rayleigh and mixing curves, indicating joint control by moisture mixing
486 and precipitation processes. Notably, during the monsoon, post-monsoon, and
487 westerlies seasons, many $\delta^{18}\text{O}$ values fall below the Rayleigh curve, suggesting
488 sub-cloud evaporation is also influential, consistent with Ali's LMWL during these
489 seasons.

490 The isotope-humidity contrast between the two sites is clearest during the
491 westerlies season: $\delta^{18}\text{O}$ averages -9.6‰ at Yadong and -21.8‰ at Ali, with
492 corresponding q values of 3.3 g kg^{-1} and 1.4 g kg^{-1} . In contrast, during the monsoon
493 season, $\delta^{18}\text{O}$ averages converge (-10.7‰ at Yadong vs. -13.3‰ at Ali) with
494 consistent magnitudes, but q is nearly double at Yadong (8.8 g kg^{-1} vs. 4.7 g kg^{-1}).

495 In summary, monsoon-season $\delta^{18}\text{O}$ at both sites reflects combined influences of
496 sub-cloud evaporation, mixing, and rainout effect. Under westerly conditions, $\delta^{18}\text{O}$ at
497 Yadong is more influenced by local evaporation, while $\delta^{18}\text{O}$ at Ali is influenced by
498 Rayleigh-type fractionation and moisture mixing, leading to consistently lower $\delta^{18}\text{O}$
499 values.



500

501 **Figure 4. Clustered 120-hour backward trajectories for air masses arriving 200**
 502 **m above ground level at Yadong and Ali on rainy days across different seasons**
 503 **(pre-monsoon, monsoon, post-monsoon, westerlies season) from May 2021 to**
 504 **September 2023 based on the HYSPLIT model, with specific humidity value**
 505 **along trajectories and the proportion of each trajectory cluster. Red dots show**
 506 **the locations of both sites. Trajectory colors indicate the values of q , while**
 507 **numbers indicate the proportion of clustered trajectories to total trajectories at**
 508 **Yadong (blue) and Ali (black).**

509

510 $\delta^{18}\text{O}$ and d-excess in precipitation at Yadong and Ali during our observation
 511 periods reveal consistent distribution ranges and diurnal variability during the

512 monsoon season, implying consistent moisture origins. To delineate seasonal and
513 interannual insight into moisture sources and transport pathways variability, we
514 employed the HYSPLIT model to compute 120 h backward trajectories for rainy days
515 (Gao et al., 2013; Dai et al., 2021), covering four climatological intervals:
516 pre-monsoon, mature monsoon, post-monsoon, and westerly-dominated seasons.
517 During late May 2021 (pre-monsoon), moisture transport at Yadong exhibited atypical
518 characteristics for this season. The site experienced enhanced high-humidity
519 southwesterly moisture flux originating primarily from the BOB and the AS,
520 contributing approximately 55 % and 25 % of the total moisture supply, respectively
521 (Fig. 4a). This anomalous moisture transport was associated with relatively depleted
522 precipitation isotope values, with a mean $\delta^{18}\text{O}$ of -9.3 ‰. In contrast, in May
523 2022-2023, high-humidity local surface evapotranspiration (97 % and 83 % of total
524 contribution, respectively) combined with low - humidity westerly (both are 3 % of
525 total contribution) produced a bit enriched $\delta^{18}\text{O}$ average (Fig. 4b-c). During the
526 mature monsoon season, in 2021-2022 (Fig. 4d-e), high-humidity ISM (57 % and
527 43 % of total contribution, respectively) combined with high-humidity local surface
528 evapotranspiration (42 % and 57 % of total contribution, respectively) consistently
529 supplied moisture to Yadong, while in 2023 (Fig. 4f), moisture mainly contributed
530 from the high-humidity BOB (36 % of total contribution) and moist Indian
531 subcontinent as well as local recycling (63 % of total contribution) resulted in $\delta^{18}\text{O}$
532 average of -10.7 ‰ and d-excess of 6.7 ‰. During the post-monsoon season (Fig.
533 4g-h), the contribution from high-humidity ISM (7 % and 18 % of total contribution
534 in 2021 and 2022, respectively) and East Asian monsoon (28 % of total contribution
535 in 2021) resulted in depleted $\delta^{18}\text{O}$ to -22.9 ‰ and raised d-excess to 13.1 ‰. During
536 the westerlies season (Fig. 4i-k), the higher contribution from low-humidity westerly
537 (75 % of total contribution) in 2021 resulted in depleted $\delta^{18}\text{O}$ to -15.2 ‰ and
538 d-excess to 18.3 ‰, compared to those in 2022 and 2023.

539 Ali exhibited distinct seasonal patterns. During the pre-monsoon season, in
540 2021-2022 (Fig. 4a-b), moisture mainly contributed from high-humidity local

541 recycling, while in 2023 (Fig. 4c), Ali received additional moisture from the
542 low-humidity westerly (12 % of total contribution) and AS (24 % of total
543 contribution), resulting in $\delta^{18}\text{O}$ average of -8.4‰ and d-excess of 20.9‰ . During the
544 monsoon, in 2021-2022 (Fig. 4d-e), high-humidity ISM (5 % and 9 % of total
545 contribution, respectively) combined with high-humidity local surface
546 evapotranspiration and moist Indian subcontinent (67 % and 54 % of total
547 contribution, respectively) consistently supplied moisture to Ali, while in 2023 (Fig.
548 4f), moisture mainly contributed from the high-humidity eastern Indian subcontinent
549 and local circulation (74 % of total contribution), resulting in $\delta^{18}\text{O}$ averaged of
550 -13.3‰ and d-excess of 14.0‰ . In October 2021 (Fig. 4g), Ali was influenced by
551 dry northeastern Indian sources, producing extremely depleted $\delta^{18}\text{O}$ of -34.6‰ ,
552 compare to -21.0‰ in October 2022 (Fig. 4h), when moisture mainly contributed
553 from dry westerlies (12 % of total contribution) and western Tibet (88 % of total
554 contribution). During the westerlies season (Fig. 4i-j), Ali received both
555 high-humidity moisture from Indian sources and dry long-range continental moisture
556 via westerly winds, yielding a markedly depleted average $\delta^{18}\text{O}$ of -21.8‰ and
557 moderate d-excess of -1.5‰ .

558 Trajectories at the condensation level and at 500 hPa confirm that the dominant
559 large-scale moisture sources (ISM during the monsoon and the westerly during the
560 non-monsoon season) are consistently detected across arrival heights. However,
561 differences appear in the identification of secondary or weak signals, such as local
562 recycling and weak ISM intrusion, particularly during transitional periods. These
563 discrepancies likely reflect the combined influence of vertical moisture stratification,
564 atmospheric stability, and the complex topography surrounding Yadong and Ali.

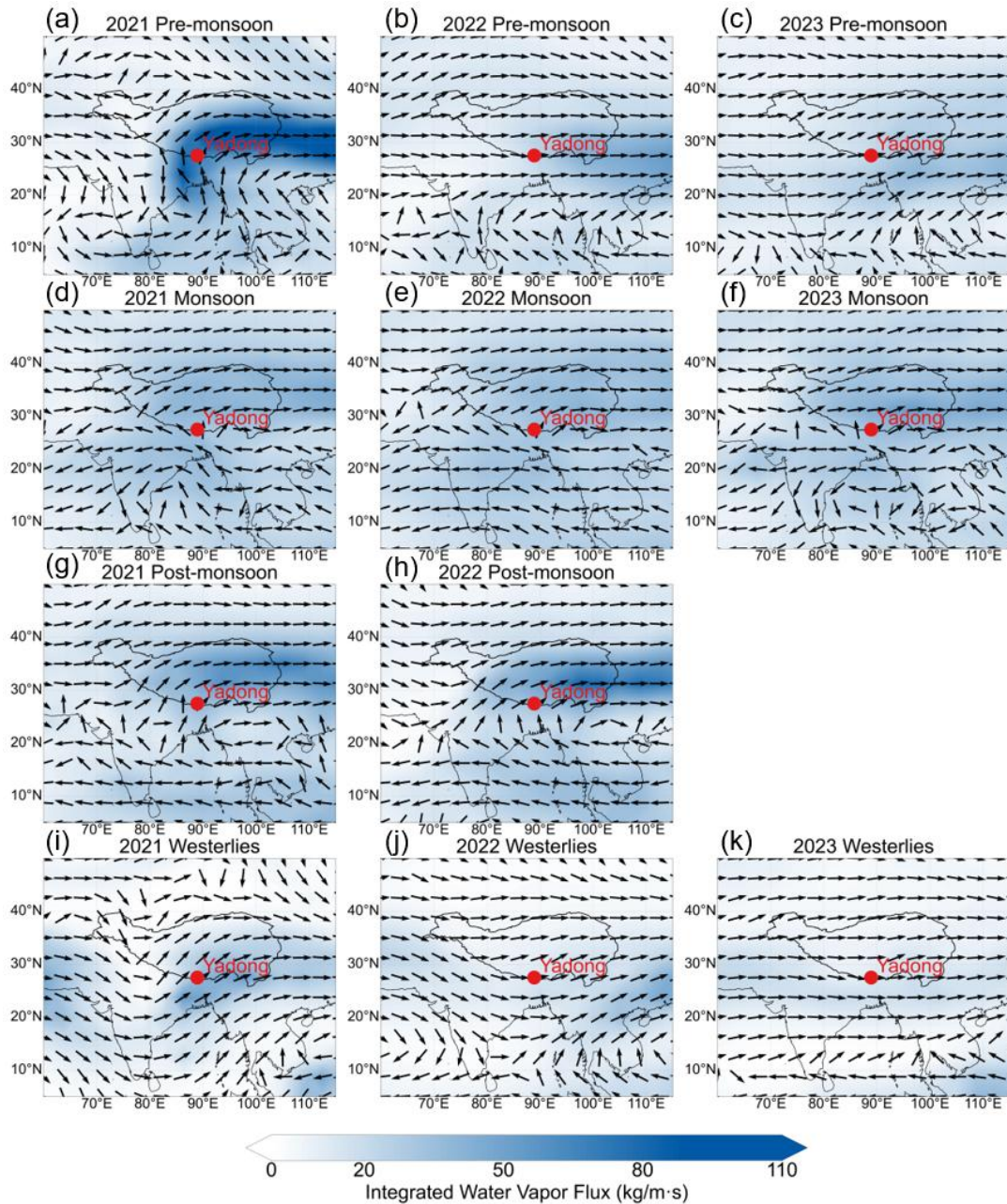
565 At Yadong, the valley terrain and relatively low elevation allow local moisture to
566 remain confined within the planetary boundary layer (PBL). As a result,
567 condensation-level trajectories miss weak westerly intrusions during the non-monsoon
568 season (Fig. S4b-c and i-k), possibly because shallow boundary-layer conditions and
569 topographic sheltering enhance the relative contribution of local moisture signals,

570 while 500 hPa trajectories, representing the mid-troposphere, tend to underrepresent
571 locally recycled moisture (Fig. S5b-c, g-h and i-k). During the monsoon (Fig. S4d-f
572 and S5d-f), strong ISM inflow penetrates the full tropospheric column, leading to
573 consistent source identification across all heights.

574 At Ali, the high-elevation arid basin favors limited local recycling and weak
575 low-level monsoon penetration. Consequently, condensation-level trajectories appear
576 more sensitive to pre-monsoon (Fig. S4c) and post-monsoon (Fig. S4h) seasons, when
577 weak winds and enhanced surface-driven convection may amplify short-range
578 continental moisture contributions relative to the westerly. 500 hPa trajectories are
579 dominated by the large-scale westerly and may miss weak ISM-related moisture (Fig.
580 S5d-f) or local sources (Fig. S5a-c) confined to the lower PBL. Nonetheless, during
581 the westerly-dominated season (Fig. S4i-j and S5i-j), all trajectory heights recover
582 consistent source patterns.

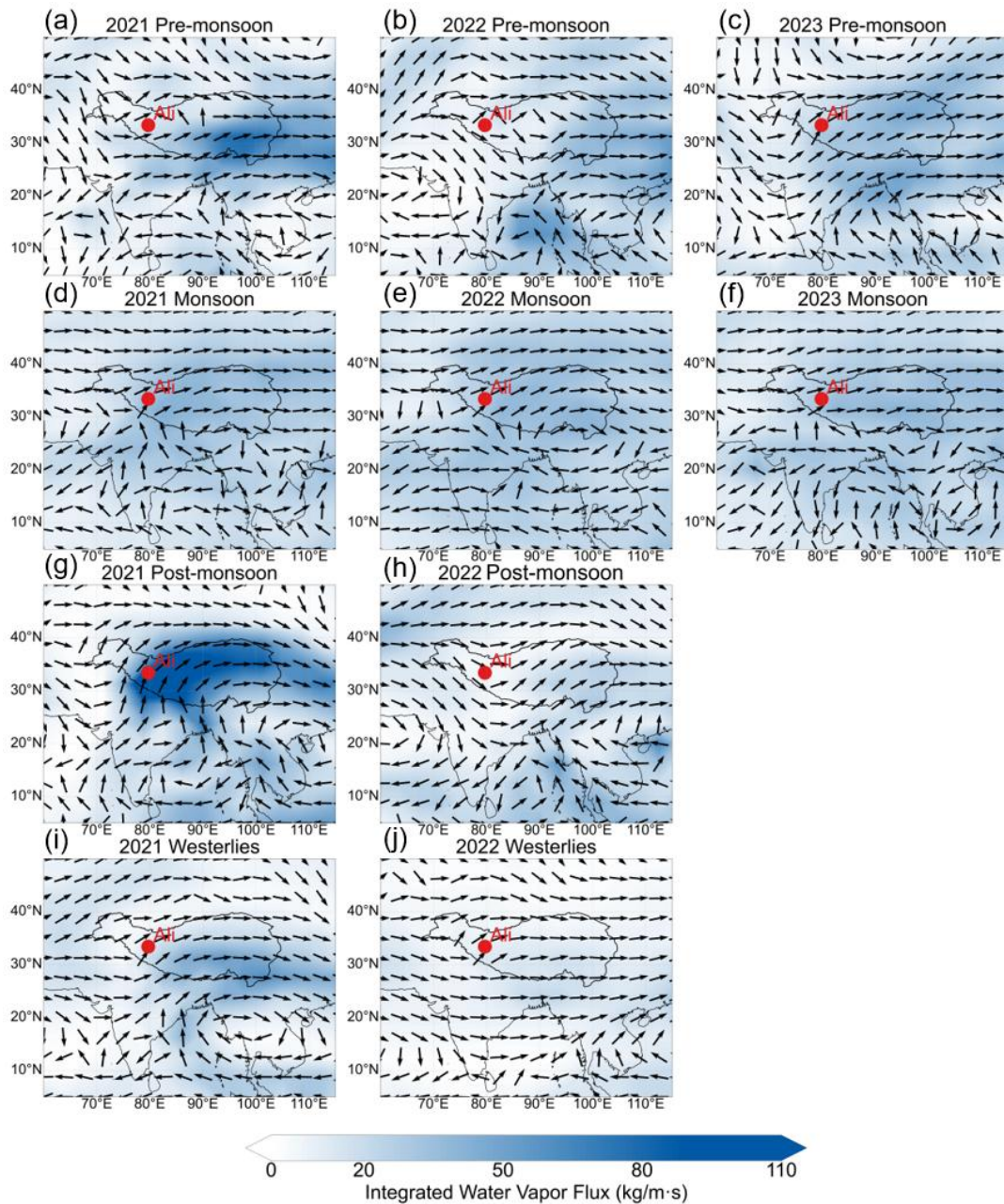
583 Overall, these findings suggest that differences among trajectory heights mainly
584 arise from the interplay between boundary-layer confinement of local moisture and
585 the strength of large-scale circulation. Trajectories at 200 m AGL provide a balanced
586 representation of both large-scale transport and boundary-layer moisture, supporting
587 their use as the primary framework in our analysis.

588 Thus, monsoon-season convergence of $\delta^{18}\text{O}$ values (-10.7‰ at Yadong, -13.3‰
589 at Ali) reflects a shared ISM moisture source, whereas the westerlies-season
590 divergence of $\delta^{18}\text{O}$ is largest (-9.6‰ at Yadong, -21.8‰ at Ali) due to differing
591 moisture regimes.



592

593 **Figure 5. The magnitude and direction of seasonal mean integrated water vapor**
 594 **flux (500-200 hPa) over Yadong on rainy days from 25 May 2021 to 23**
 595 **September 2023 (308 days) across seasons using ERA5 reanalysis data (the blue**
 596 **shading and the direction of the black arrows indicate the magnitude and**
 597 **direction of water vapor flux).**



598

599 **Figure 6 The magnitude and direction of seasonal mean integrated water vapor**
 600 **flux (500-200 hPa) over Ali on rainy days from 31 May 2021 to 18 September**
 601 **2023 (69 days) across seasons using ERA5 reanalysis data (the blue shading and**
 602 **the direction of the black arrows indicate the magnitude and direction of water**
 603 **vapor flux).**

604

605 Figures 5 and 6 show the seasonal mean vertically integrated water vapor flux in
 606 the 500–200 hPa layer on rainy days at Yadong and Ali, respectively, illustrating the

607 seasonal variability in both the magnitude and direction of moisture transport
608 associated with precipitation events at the two sites. The specific rainy days included
609 in the analysis are listed in Table S3. At Yadong, southwesterly moisture transport
610 dominated during late May (pre-monsoon) 2021, with the maximum vertically
611 integrated water vapor flux reaching $77.5 \text{ kg m}^{-1} \text{ s}^{-1}$ (Fig. 5a), accompanied by
612 relatively depleted precipitation isotopic values ($\delta^{18}\text{O} = -9.3 \text{ ‰}$). In 2022 and 2023,
613 Yadong was controlled by dry westerly, resulting in a reduction in water vapor flux to
614 $24.6 \text{ kg m}^{-1} \text{ s}^{-1}$ (Fig. 5b) and $23.3 \text{ kg m}^{-1} \text{ s}^{-1}$ (Fig. 5c), respectively, and
615 corresponding increase in the average $\delta^{18}\text{O}$ values of 9.3 ‰ and 10.0 ‰ compared to
616 2021. During the monsoon season, the dominant circulation shifted from westerlies to
617 monsoon, with water vapor flux increasing to $32.5 \text{ kg m}^{-1} \text{ s}^{-1}$, and the average $\delta^{18}\text{O}$
618 value decreasing by $\sim 8.0 \text{ ‰}$ relative to the pre-monsoon season (Fig. 5d-f). In the
619 post-monsoon season, water vapor flux reached a seasonal high of $39.6 \text{ kg m}^{-1} \text{ s}^{-1}$
620 (Fig. 5g-h), while the average $\delta^{18}\text{O}$ decreased by an additional 12.2 ‰ . During the
621 westerlies season, westerly carried dryer moisture to this region, resulting in a
622 reduction in water vapor flux to $22.2 \text{ kg m}^{-1} \text{ s}^{-1}$ (Fig. 5i-k), and a 13.3 ‰ increase in
623 average $\delta^{18}\text{O}$ values compared to the post-monsoon.

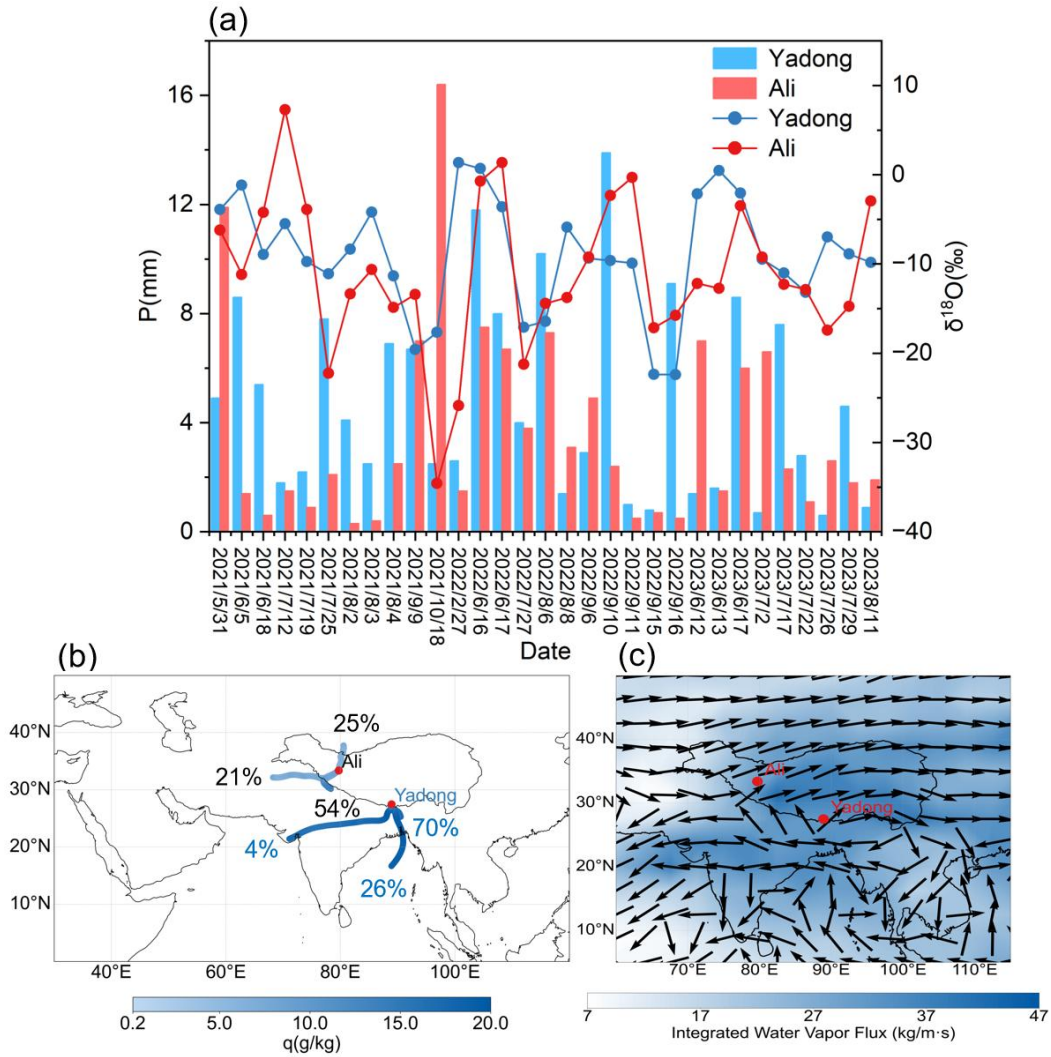
624 During the pre-monsoon period (Fig. 6a-c), Ali was dominated by the westerly,
625 with a relatively low water vapor flux of $18.6 \text{ kg m}^{-1} \text{ s}^{-1}$ and an average $\delta^{18}\text{O}$ value of
626 -8.4 ‰ . During the monsoon season (Fig. 6d-f), the region transitions to monsoon
627 dominance, resulting in an increase in water vapor flux to $36.5 \text{ kg m}^{-1} \text{ s}^{-1}$ and a
628 corresponding decrease in the average $\delta^{18}\text{O}$ by 4.9 ‰ . During the post-monsoon
629 season, substantial interannual variability was observed. In 2021 (Fig. 6g), the region
630 remained under the monsoon influence, with the maximum water vapor flux reaching
631 $98.6 \text{ kg m}^{-1} \text{ s}^{-1}$. In contrast, the region shifted to westerly dominance in 2022 (Fig.
632 6h), leading to a sharp decline in water vapor flux to $5.5 \text{ kg m}^{-1} \text{ s}^{-1}$, and an increase in
633 the average $\delta^{18}\text{O}$ of 13.6 ‰ compared to 2021. During the westerlies season,
634 persistent westerly influence resulted in a further decrease in water vapor flux to 11.5
635 $\text{ kg m}^{-1} \text{ s}^{-1}$, accompanied by an increase in average $\delta^{18}\text{O}$ of 4.9 ‰ relative to the

636 post-monsoon season.

637 Both methods consistently indicate that Yadong is dominated by monsoon-derived
638 moisture during the pre-monsoon (2021), monsoon, and post-monsoon seasons, and
639 by westerly-sourced moisture during the westerlies season. In contrast, Ali is
640 influenced by monsoon moisture during the monsoon season and by westerly
641 moisture during the westerlies season. These consistent results demonstrate the
642 robustness of our moisture source attribution.

643 These results demonstrate that seasonal and interannual variations in
644 ISM-westerly patterns exert strong control over both moisture transport and
645 precipitation isotope compositions at both Yadong and Ali. The systematic inverse
646 relationship between water vapor flux and $\delta^{18}\text{O}$ values reflects the fundamental
647 influence of moisture source regions and transport pathways on isotopic signatures,
648 with monsoon-sourced moisture consistently producing higher flux and more depleted
649 isotopic signatures compared to westerly-transported moisture. The pronounced
650 interannual variability observed during the post-monsoon season, particularly the
651 contrasting circulation patterns between 2021 and 2022, highlights the sensitivity of
652 precipitation stable isotopes to large-scale atmospheric dynamics.

653 **3.5 Moisture Sources on Simultaneous Rainy Days**



654

655 **Figure 7. Comparative analysis for simultaneous rainy days at Yadong and Ali,**
 656 **including $\delta^{18}O$ and precipitation amount, backward trajectories, and mean**
 657 **integrated water vapor flux (500-200 hPa) during the monsoon season. (a) $\delta^{18}O$**
 658 **and P on simultaneous rainy days at Yadong and Ali, bars represent precipitation**
 659 **amount and points represent $\delta^{18}O$ values; backward trajectories on simultaneous**
 660 **rainy days at Yadong (b) and Ali (c) during the monsoon season; integrated**
 661 **water vapor flux from 500 hPa to 200 hPa on simultaneous rainy days at Yadong**
 662 **(d) and Ali (e) during the monsoon season.**

663

664 During the monsoon season, simultaneous precipitation events were recorded on
 665 28 days at both Yadong and Ali, whereas only 3 such days were observed during the
 666 non-monsoon season (Fig. 7a). During the monsoon season, the average $\delta^{18}O$ values

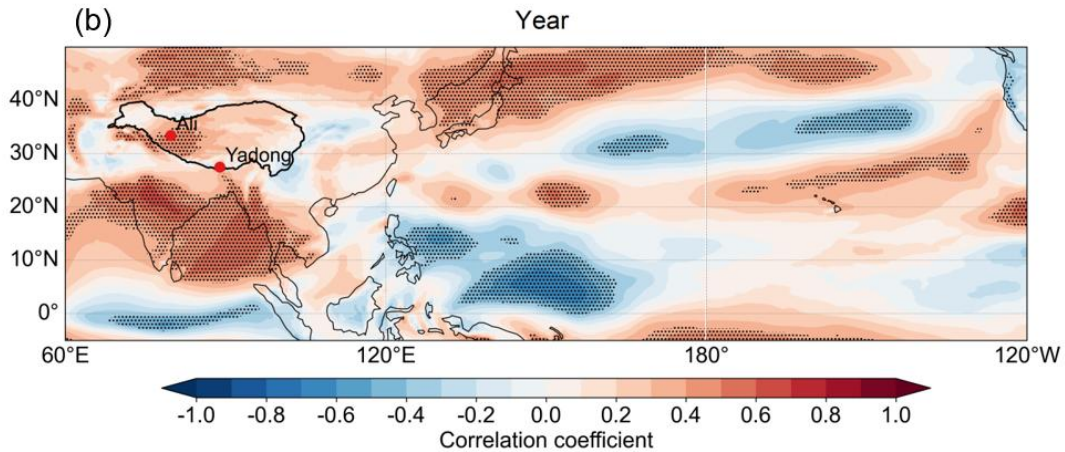
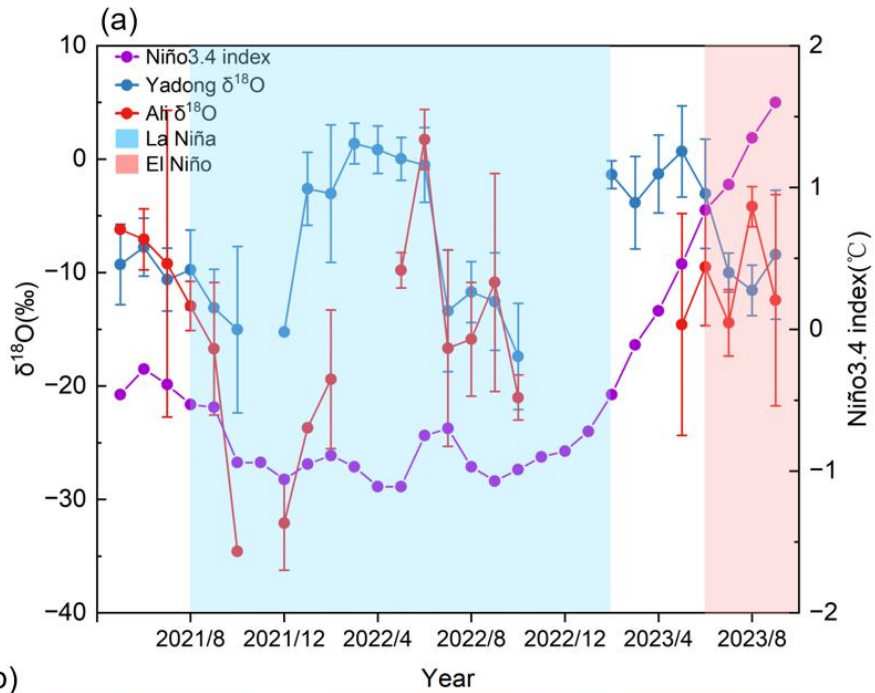
667 for simultaneous precipitation days at Yadong and Ali were -9.3 ‰ and -9.4 ‰ ,
668 respectively, with corresponding average d-excess values of 9.2 ‰ and 13.9 ‰ .
669 Precipitation amounts at Yadong (137.9 mm) exceeded those at Ali (84.9 mm) by 53
670 mm , likely resulting from Yadong's more southeastward location and 1280 m lower
671 altitude under the ISM influence.

672 In contrast, during the non-monsoon season, concurrent precipitation events
673 exhibited a reversal of the monsoon-season pattern. The average $\delta^{18}\text{O}$ values on
674 concurrent precipitation events were -6.0 ‰ and -22.8 ‰ , respectively, with
675 d-excess averages of 10.7 ‰ and 20.7 ‰ , and precipitation amounts of 10.0 mm and
676 29.8 mm , respectively. The large differences in $\delta^{18}\text{O}$ (16.8 ‰) and d-excess (10.0 ‰)
677 indicate distinct moisture sources, with Yadong influenced by more local or recycled
678 moisture and Ali influenced by more continental or long-distance transported westerly
679 moisture.

680 Backward trajectory analysis supports further these findings. During
681 monsoon-season simultaneous events, the ISM transports large amounts of
682 high-humidity moisture to Yadong, along with contributions from local surface
683 evapotranspiration (Fig. 7b and S6). In contrast, Ali's moisture primarily originates
684 from local evapotranspiration (Fig. 7b), supplemented by high-humidity ISM input
685 and smaller contributions from low-humidity westerly winds (Fig. S6), indicating that
686 the ISM simultaneously influences both Yadong and Ali at the synoptic scale. This
687 conclusion is further supported by water vapor flux analysis (Fig. 7c), exhibiting
688 pronounced high flux of $33.0\text{ kg m}^{-1}\text{ s}^{-1}$ at Yadong and $36.2\text{ kg m}^{-1}\text{ s}^{-1}$ at Ali. The
689 strength and coherence of monsoonal moisture transport across both regions highlight
690 the ISM's crucial role in controlling precipitation isotopic signatures during
691 simultaneous events at the southern and western TP.

692

693 **3.6 The Influence of ENSO events**



694

695 **Figure 8. Concurrent time series of the monthly Niño 3.4 index and monthly**
 696 **amount-weighted $\delta^{18}\text{O}$ at Yadong and Ali, and the spatial correlation between the**
 697 **monthly Niño 3.4 index and monthly mean integrated water vapor flux (surface**
 698 **to 200 hPa) from May 2021 to September 2023. (a) Time series of the monthly**
 699 **Niño 3.4 index and monthly amount-weighted $\delta^{18}\text{O}$ values at Yadong and Ali**
 700 **from May 2021 to September 2023. El Niño and La Niña periods are highlighted**
 701 **in red and blue shading, respectively. (b) Spatial correlation between the monthly**
 702 **Niño 3.4 index and monthly mean integrated water vapor flux (surface to 200**
 703 **hPa) during the same period. The correlation coefficient reveals regions of**
 704 **enhanced or suppressed moisture transport associated with ENSO phases.**

705

706 The period from August 2021 to January 2023 was characterized by La Niña
707 conditions, while June to September 2023 coincided with an El Niño phase.
708 Precipitation $\delta^{18}\text{O}$ values at Yadong and Ali during the monsoon seasons reflect a
709 clear ENSO imprint. During the monsoon season in 2021, average $\delta^{18}\text{O}$ values at
710 Yadong and Ali were -11.2‰ and -17.2‰ , respectively. During the same period in
711 2022 (La Niña events), $\delta^{18}\text{O}$ values are consistent with those in 2021, while in 2023
712 (El Niño), $\delta^{18}\text{O}$ increased sharply to -8.9‰ at Yadong and -9.1‰ at Ali,
713 respectively. The most pronounced increases in $\delta^{18}\text{O}$ occurred between the La Niña
714 and El Niño monsoon seasons indicate that ENSO noticeably influences the
715 interannual variability of precipitation stable isotopes at both sites, which is consistent
716 with previous studies (Gao et al., 2018) (Fig. 8a).

717 To further explore the underlying mechanisms, spatial correlation analysis was
718 conducted between the monthly Niño 3.4 index and the monthly mean integrated
719 water vapor flux (surface to 200 hPa) for May 2021 to September 2023 (Fig. 8b).
720 Results show that significant positive correlations ($p < 0.05$, H_0 : no spatial linear
721 correlation) existed over Ali, the AS, Indian subcontinent, BOB, and Bangladesh. In
722 contrast, significant negative correlations appeared over the equatorial Indian Ocean
723 and western equatorial Pacific, pointing to major shifts in regional moisture transport
724 pathways during ENSO events.

725 During El Niño events, warm sea surface temperature anomalies (SSTA) develop
726 in the eastern equatorial Pacific, which reduce the east–west SST gradient. This
727 weakens the Walker circulation, and results in westerly wind anomalies in the
728 equatorial Pacific (Bjerknes, 1969). Concurrently, SSTs in the western equatorial
729 Pacific decrease, leading to suppressed surface evaporation and moisture advection,
730 along with anomalously weak convection over that region. In contrast, the region
731 south of the southern TP, including Bangladesh, the BOB, the Indian subcontinent,
732 and the AS, experience increased temperature, enhanced surface evaporation and
733 moisture advection, and anomalous convection, accompanied by low-level easterly
734 wind anomalies (Yao et al., 2024). Together, these anomalies form a zonal–vertical

735 atmospheric circulation pattern (Wang et al., 2024). Additionally, cooling in the
736 equatorial Indian Ocean suppresses surface evaporation and moisture flux, and
737 weakens southerly wind anomalies toward the TP. These circulation changes result
738 in reduced ISM moisture transport to both Yadong (from 43 % in 2022 to 36 % in
739 2023) and Ali (from 9 % in 2022 to 0 % in 2023), while contributions of local
740 evapotranspiration and short-distance transport from south moist continental surface
741 increased relatively (from 57 % in 2022 to 63 % in 2023 at Yadong and from 54 % in
742 2022 to 74 % in 2023 at Ali) (Fig. 4e-f and 8b). This leads to more enriched $\delta^{18}\text{O}$
743 values at Yadong and Ali during El Niño years (Cui et al., 2025).

744 The atmospheric circulation patterns during La Niña events are essentially the
745 inverse of those during El Niño (Cai and Tian, 2016). La Niña strengthens the Walker
746 circulation, with elevated SSTs in the western equatorial Pacific leading to enhanced
747 surface evaporation, increased water vapor flux, and strong anomalous convection. At
748 the same time, SSTs rise in the equatorial Indian Ocean, enhancing surface
749 evaporation and northward moisture advection, resulting in increased ISM moisture
750 transport to both Yadong and Ali. This process contributes to significant $\delta^{18}\text{O}$
751 depletion during La Niña events at Yadong and Ali (Fig. 4e-f and 8b).

752

753 **4 Summary and Conclusions**

754 This study characterized event-based precipitation stable isotopes ($\delta^{18}\text{O}$, δD) at
755 Yadong and Ali from May 2021 to September 2023 to investigate climate controls of
756 variability in precipitation stable isotopes on the TP across daily, synoptic, seasonal,
757 and interannual scales. We characterize the influence of shifting moisture sources
758 under westerly and ISM transport regimes, and the differential impact of El Niño and
759 La Niña events on precipitation isotopes.

760 Our results show that $\delta^{18}\text{O}$ and δD at Yadong and Ali converge during the
761 monsoon season but diverge sharply during the westerlies season, reaching
762 differences of up to 12.2 ‰ and 118.8 ‰, respectively. While d-excess values remain
763 similar during the pre-monsoon and monsoon seasons, they diverge significantly in

764 the post-monsoon and westerlies seasons, reaching respective differences of 11.6 ‰
765 and 21.4 ‰.

766 Our results also show that meteorological controls shift seasonally: 1)
767 precipitation amount effects dominate during monsoon ($R = -0.28$ to -0.32), while
768 temperature controls prevail during westerly seasons ($R = 0.51-0.79$); 2) during the
769 monsoon, both sites reflect moisture mixing, rainout effect, and sub-cloud
770 evaporation, closely aligned with $\delta^{18}\text{O}$ changes; however, during the westerlies season,
771 Yadong is influenced primarily by local evaporation, whereas Ali is shaped by
772 Rayleigh fractionation and long-range continental transport, resulting in pronounced
773 $\delta^{18}\text{O}$ differences (-9.6 ‰ vs. -21.8 ‰); 3) atmospheric moisture at both sites are
774 primarily supplied by the seasonally shifted ISM and westerly, accompanied by local
775 and mid-latitude dry sources at Yadong and long-distance continental moisture at Ali,
776 explaining the seasonal convergence and divergence in $\delta^{18}\text{O}$ patterns; 4) $\delta^{18}\text{O}$
777 variations in 28 simultaneous precipitation events during the monsoon season suggest
778 ISM dominance at both sites during these events.

779 Our results further confirm that interannual variability in precipitation $\delta^{18}\text{O}$ at both
780 sites is clearly linked to ENSO, with $\delta^{18}\text{O}$ enrichment of 2.8 ‰ (Yadong) and 5.1 ‰
781 (Ali) from 2022 La Niña to 2023 El Niño monsoon seasons. This enrichment results
782 from changes of moisture transport related with ENSO events. During El Niño events,
783 weakened Walker circulation and reduced ISM moisture transport increase the relative
784 contributions of local evapotranspiration and short-distance transport from southern
785 moist continental surfaces, leading to precipitation $\delta^{18}\text{O}$ enrichment. Conversely, La
786 Niña events strengthen the Walker circulation and enhance ISM moisture transport
787 through elevated western Pacific and Indian Ocean SSTs, resulting in significant
788 precipitation $\delta^{18}\text{O}$ depletion at both sites.

789 Our results demonstrate that ISM circulation homogenizes isotopic signatures
790 across the southern and western Tibetan Plateau, while westerly dominance amplifies
791 regional differences through distinct moisture pathways. The seasonal transition from
792 amount-controlled to temperature-controlled isotopic variability reflects fundamental

793 changes in precipitation isotopic mechanisms. The pronounced ENSO sensitivity
794 indicates that tropical Pacific variability significantly modulates regional hydrological
795 processes through altered moisture transport patterns.

796 Our findings align with previous studies showing ISM dominance in summer
797 isotopic patterns across the Tibetan Plateau, but provide new quantitative constraints
798 on seasonal moisture source transitions. The documented ENSO influence on
799 precipitation isotopes (2.8–5.1 ‰ variability) exceeds previously reported values from
800 limited observations, highlighting the importance of multi-year datasets for capturing
801 interannual climate impacts. Our q - δ analysis advances understanding of site-specific
802 responses to sub-cloud evaporation and moisture recycling that were sparsely resolved
803 in earlier regional studies.

804 This study provides critical observational constraints for atmospheric moisture
805 transport and regional climate sensitivity in the Tibetan Plateau. The quantified ENSO
806 sensitivity of precipitation isotopes offers new insights on regional paleoclimate
807 records interpretation. The 3-year sampling period, however, limits our ability to
808 assess decadal-scale variability and multi-ENSO cycle impacts. Future work should
809 extend observations to capture longer-term climate oscillations and validate these
810 findings across broader spatial scales. Additionally, the mechanisms driving the
811 observed local evapotranspiration changes during ENSO events require further
812 investigation through integrated land-atmosphere modeling approaches.

813

814 **Data availability:**

815 The ERA5 dataset is the latest reanalysis dataset published by the European
816 Centre for Medium-Range Weather Forecasts (ECMWF) available at
817 <https://doi.org/10.24381/cds.bd0915c6> (Hersbach et al., 2023). The Global Data
818 Assimilation System (GDAS) has been published by the National Centers for
819 Environmental Prediction (NCEP) (<ftp://arlftp.arlhq.noaa.gov/archives/gdas1/>, NCEP,
820 2024). The monthly Oceanic Niño Index (ONI) provided by the National Oceanic and
821 Atmospheric Administration Climate Prediction Center (NOAA CPC)

822 (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php)
823 . The precipitation isotopic compositions dataset will be available on the Zenodo
824 research data repository after manuscript publication.

825

826 **Author contributions:**

827 **LK:** data curation, formal analysis, writing (original draft preparation). **GJ:** data
828 curation, conceptualization, methodology, supervision, writing (review and editing),
829 funding acquisition. **YJJ:** data curation. **NXW:** data curation. **ZAB:** writing (review
830 and editing), project administration. **CGBR:** data curation. **WYQ:** data curation.
831 **LYG:** data curation.

832

833 **Competing interests:**

834 The contact author has declared that none of the authors has any competing interests.

835

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850

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