

Reply to Reviewer 2:

We thank the reviewer for the positive and constructive assessment of the manuscript and for the careful line by line reading. We give a point-by-point reply (in blue) to the reviewer's comments (in italics). Changes that will be made in the revised manuscript are given in red.

The manuscript "Technical note: A new monitoring approach to measure water vapor isotopes in high altitude regions" was an interesting read. It describes the challenges of establishing a continuous water vapour isotope station in the Himalayan region, and the authors are commendably transparent about the setup and the problems encountered.

My main concern is the title, which implies a new monitoring approach, whereas the manuscript presents a new station built on an established approach. After this and the minor issues listed below are addressed, I recommend the manuscript for publication.

Title (Line 1–2): The setup follows established standardized practice, and I could not identify methodological novelty. Please consider using "a new monitoring station" instead of "new monitoring approach" or explicitly state what is new in the approach.

Reply: We agree that the core analytical technique (CRDS on a Picarro L2140-i) and the calibration framework follow established approaches; the novelty of this work lies in the entire high-altitude water vapour isotope set up in the Himalayas, for which a custom-engineered heated air inlet system was built to provide accurate and reliable data collection across various seasons, effectively preventing the fractionation of vapour isotopes as air travels from inlet to the CRDS analyser. The station incorporates dedicated power-backup and lightning-protection systems to support continuous operation under highly variable environmental conditions, such as air temperatures ranging from -1.7 to 30.2 °C (below freezing in winter), intermittent power supply, and precipitation that falls as both rain and snow.

Line 1-2 (Title): We replace approach by station; the new title reads now: "Technical note: A new monitoring station to measure water vapor isotopes in high altitude regions."

Line 22–24: Unclear phrasing. Please state the region directly (e.g., "the Himalayas") and why observations there are limited.

Reply: We thank the reviewer for this comment. The original phrasing ("high altitude, tropics, subtropical -- mid-latitude transition zone") aimed to show that the Himalayas represent a transition between the tropical monsoonal and mid-latitude westerly-influenced zone, which receives precipitation from multiple moisture sources, including the Bay of Bengal (ISM), westerlies and locally recycled moisture. The reason that continuous

monitoring has not been achieved is primarily because of logistical difficulties in setting up a station and technical difficulties of preserving the water vapour isotopes from fractionating as it travels from the inlet to the instrument across various seasons and precipitation forms (solid: snow and liquid: water).

Line 22-24 revised to: Such studies in the Himalayas are limited due to the challenging physical conditions and the diverse forms of precipitation in the region, which originate from three sources of moisture: the Bay of Bengal (ISM), the westerlies, and locally recycled moisture.

Sissu station: The abstract reports two stations, but only Manali is described. Is Sissu the same setup? How does it differ, and why is it not presented in text? Or am I missing?

Reply: Reviewer 1 also pointed out this oversight. We have now clarified in the main manuscript text, details of the two stations. Sissu uses the identical instrument, inlet design, and calibration protocol as Manali (it is in fact the same laboratory unit relocated, not a second independent setup). The instrument was operated continuously at Manali (Figure 1(c)) from 12 June 2024 to 31 October 2025, after which it was relocated to Sissu (Figure 1(f)), operated from 3 to 8 November 2025. The Sissu site, located on the leeward side at a higher elevation (3,120 m a.s.l.), could only be used for a short period due to inaccessibility in winter because of heavy snowfall, and it was intended to capture Western-Disturbance-influenced winter moisture conditions as a contrast to Manali's windward monsoon record. We have modified the manuscript text to state clearly that measurements were conducted at two sites, added the Sissu deployment dates and rationale to the site-description section and updated Figure 1 with a new panel (f) showing Sissu setup as well.

Line 24-26 (Abstract) revised to: ...establishment of the first continuous high-altitude isotope-monitoring laboratory in Northwest Himalayas, at the windward-side site of Manali (32°15'23.17"N, 77°10'58.67"E; 2,050 m a.s.l.; operated from 12 June 2024 to 31 October 2025) and the leeward-side site of Sissu (32°28'44.44"N, 77°07'40.47"E; 3,120 m a.s.l.; operated from 3 to 8 November 2025 following relocation of the instrument).

Line 124: inserted new paragraph: The instrument was subsequently relocated to a second site at Sissu, Himachal Pradesh, India (32°28'44.44"N, 77°07'40.47"E]; 3,120 m a.s.l.), on the leeward side of the range, and operated there from 3 to 8 November 2025. The Sissu deployment window was short as the site becomes largely inaccessible once winter snowfall begins, restricting the period in which the instrument could be safely transported, installed, and retrieved before road access closed. One 17-minute

instrumental shutdown was recorded during this five-day period.

Line 131-136 (Figure 1 caption): added the Sissu location to a new panel (f) and referenced the Figure 1(f); revised caption to describe both stations.

Line 52–54: Please introduce D/H and $^{18}\text{O}/^{16}\text{O}$ (and $^{17}\text{O}/^{16}\text{O}$) and use a consistent notation (D vs ^2H) throughout.

Reply: We thank the reviewer for highlighting this. The original sentence introduced only D/H and $^{18}\text{O}/^{16}\text{O}$, omitting $^{17}\text{O}/^{16}\text{O}$ even though $\delta^{17}\text{O}$ in Eq.3 to define ^{17}O -excess, and is one of the three parameters this station is built to measure. We have added $^{17}\text{O}/^{16}\text{O}$ to the introductory sentence, so all three ratios are defined before they are used. We have also standardized notation throughout the manuscript to δD rather than $\delta^2\text{H}$. We have updated the correction and now we are consistently using δD alongside $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$, this keeps the three primary isotope ratios in one uniform notation style throughout the manuscript.

Line 52-54: revise to: "The ratios of $^2\text{H}/^1\text{H}$, $^{18}\text{O}/^{16}\text{O}$, and $^{17}\text{O}/^{16}\text{O}$ in water samples are commonly expressed in per mil (δ) units, using the Vienna Standard Mean Ocean Water (V-SMOW) as reference."

Throughout the manuscript (Abstract Line 27, Eq. 1-3, Table 2 column header, Figure 3 panel titles and caption, Figure 4 caption): replaced every notation of $\delta^2\text{H}$ with δD to maintain consistency.

Line 68–70: Unclear, especially "can be explained by combinations of...". Please clarify.

Reply: We have rewritten the line to make four points explicit. (i) 0.528 is an empirical reference slope. It is the slope of $\ln(\delta^{17}\text{O}+1)$ versus $\ln(\delta^{18}\text{O}+1)$ of global meteoric waters (0.528 ± 0.0001 , (Luz & Barkan, 2010); 0.5281 ± 0.0015 , (Meijer & Li, 1998). We had denoted it θ , but in the literature θ is the exponent of a single fractionation process, $\theta = \ln ^{17}\alpha / \ln ^{18}\alpha$. We now call 0.528 the reference slope λ_{ref} . (ii) The two process exponents are different quantities. For liquid-vapour equilibrium, $\theta_{\text{eq}} = 0.529 \pm 0.001$, constant between 11.4 and 41.5 °C (Barkan & Luz, 2005). For diffusion of water vapour in air, $\theta_{\text{diff}} = 0.5185 \pm 0.0003$, in agreement with the theoretical value of 0.5184 from kinetic gas theory (Barkan & Luz, 2007). (iii) 0.528 is not the average of 0.529 and 0.5185. During equilibrium condensation and rainout, the relevant slope is $(^{17}\alpha_{\text{eq}} - 1)/(^{18}\alpha_{\text{eq}} - 1)$, which stays near 0.528 (0.528 ± 0.001 over 0-30 °C). It differs slightly from θ_{eq} because it uses $\alpha - 1$ instead of $\ln \alpha$ (Barkan & Luz, 2007; Luz & Barkan, 2010). (iv)

The ^{17}O -excess arises during evaporation. Vapour leaving the ocean is fractionated by equilibrium (0.529) and by diffusion through undersaturated air (0.5185). In that sense, we can state that the apparent slope of 0.528 corresponds to a combination of the two fractionation types, i.e. equilibrium and kinetic fractionations. The corresponding values are given above.

Line 68-73 revised to: where 0.528 is the reference slope (λ_{ref}) of the $\ln(\delta^{17}\text{O}+1)$ – $\ln(\delta^{18}\text{O}+1)$ relationship of global meteoric waters (Luz & Barkan, 2010; Meijer & Li, 1998). This slope arises from equilibrium condensation during rainout, for which $(^{17}\alpha_{\text{eq}} - 1)/(^{18}\alpha_{\text{eq}} - 1)$ remains close to 0.528 over 0-30 °C (Barkan & Luz, 2007), whereas the fractionation exponent of liquid-vapour equilibrium itself, $\theta_{\text{eq}} = \ln ^{17}\alpha_{\text{eq}} / \ln ^{18}\alpha_{\text{eq}}$, is 0.529 ± 0.001 (Barkan & Luz, 2005). Diffusion of water vapour in air has a lower exponent, $\theta_{\text{diff}} = 0.5185 \pm 0.0003$ (theoretical value 0.5184; (Barkan & Luz, 2007) . Because θ_{diff} is smaller than λ_{ref} , vapour evaporated over the ocean, which is fractionated by both processes, acquires a positive ^{17}O -excess. This excess depends mainly on relative humidity and is largely preserved during subsequent rainout (Barkan & Luz, 2007; Uemura et al., 2010).

Line 83–84: The text states that continuous records are missing, then cites data from Singapore and the Himalayas. Do the authors mean that the data are sporadic or campaign-based? Please clarify.

Reply: We would like to clarify that the cited studies are not continuous *water vapour* records but sporadic, short-duration vapour and rain isotope records. To the best of our knowledge there are no realtime long-term continuous vapour isotope measurements available from the Himalayas. Specifically:

- He et al., 2018 is a continuous, real-time CRDS-based study of precipitation (rainfall) isotopes during tropical convective events in Singapore, not a water vapor dataset. Our original description of it as a “continuous water vapor isotopic dataset” was incorrect. We now cite it as an example of continuous tropical *precipitation* monitoring.
- Wei et al., 2019 is a global database of high-temporal-resolution vapor isotope measurements. We have removed it from the Singapore sentence and now cite it as evidence that continuous vapor records are concentrated at low-elevation, predominantly mid-latitude sites, with the tropics and high-altitude regions under-represented.
- Gao et al., 2011 is a precipitation-isotope study (observations combined with isotope-enabled modeling) over the South Tibetan Plateau, not a continuous vapor time series; we cite it for spatial and seasonal context only.

The gap we describe is therefore the absence of continuous, high-temporal-resolution water vapor monitoring in the tropical and high-altitude monsoon domain. Continuous precipitation sampling (He et al., 2018) and discrete precipitation surveys (Gao et al., 2011) exist, but neither resolves the sub-diurnal vapor-phase variability targeted here. We have restructured this section so that the distinctions between water vapor and precipitation, and between continuous and discrete/campaign-based datasets, are now explicit throughout. The revised text appears below:

Line Number 83–89 (merged with the restructuring below): Please see the combined revision under Line Number 75–99 immediately below, which resolves this comment together with the paragraph-redundancy comment.

Line 75–99: The two paragraphs convey largely the same message. Please merge them or clarify the distinct purpose of each

Reply: We have now merged the two paragraphs. The two paragraphs as written both move from (i) global capability of CRDS vapour monitoring, to (ii) its scarcity in specific regions, to (iii) the India-specific observational gap. Running the same argument at two different geographic scales without signaling the change in scale. We have now merged them into a single paragraph that moves from global, to tropical, to India-specific, to Himalaya-specific, and also naming whether the cited work is vapour-phase or precipitation-phase, and continuous or campaign-based, and ending in one clear statement of the gap that our station addresses.

Line 75-99: merged: Stable isotopes of atmospheric water vapour offer valuable insight into vapour formation conditions (Uechi & Uemura, 2019), mixing of moisture from different sources (Surma et al., 2018; Voigt et al., 2021), raindrop re-evaporation (Deshpande et al., 2010; Landais et al., 2010) and continental-scale moisture recycling (Li et al., 2015). Cavity ring-down spectroscopy (CRDS) has enabled continuous, high-precision vapour-phase measurement of these signals, but such monitoring remains concentrated at low-elevation, predominantly mid- to high-latitude sites such as the Greenland ice sheet, the Atlantic Ocean and European observatories (Galewsky et al., 2016; Steen-Larsen et al., 2013; Wei et al., 2019). Continuous vapour-phase records remain particularly scarce in the tropics, where continuous high-resolution monitoring has so far targeted precipitation rather than vapour: (He et al., 2018), for example, used a CRDS-based diffusion-sampling system to continuously measure the isotopic composition of rainfall during tropical convective events in Singapore. In the Himalaya and southeastern Tibetan Plateau, isotope studies have likewise relied on discrete precipitation sampling combined with isotope-enabled modelling (Gao et al., 2011), which resolves strong spatial and seasonal gradients in precipitation isotopes driven by moisture-source changes and orographic effects but, being precipitation-phase and non-

continuous, cannot capture diurnal vapour-phase variability. The same vapour-versus-precipitation, continuous-versus-discrete distinction holds across India more broadly: the Indian Network of Isotopes in Precipitation (IWIN; Deshpande & Gupta, 2004; Sengupta et al., 2020) provides valuable long-term precipitation isotope records, and monsoon-season studies at Bengaluru have examined rain-vapour interactions over single seasons (Rahul et al., 2016). None of these constitutes a continuous vapour-phase record, and this gap is most acute in the high-altitude Himalaya, where severe logistical and instrumental challenges have, until now, precluded continuous monitoring.

Line 117–120: Please give distances to the rivers, glaciers, and nearest settlement.

Reply: The distances to the Beas and Manalsu rivers (310 m and 260 m respectively) are already shown as measured vectors in Figure 1(b) but, as highlighted by the reviewer correctly, they were not stated in the main text. The distance to the nearest significant settlement, 487 m west, and to the nearest glacier, 4,582 m east, is now added in the manuscript.

Line Number 117-120 revise to: the station lies approximately 310 m west to the Beas River and 260 m north to the Manalsu River (Fig. 1b) and was deliberately located away from any major human settlement and large water reservoir; the nearest significant settlement (Manali town) lies approximately 487 m west, and several mid-altitude glaciers lie within approximately 4,582 m east of the site contributing to atmospheric moisture through sublimation/evaporation.

Line 177–180: The precision for some is in percentage, while others are in their units. Please write all in physical units (e.g., temperature in °C or K, wind direction in degrees).

Reply: Agreed, and we thank the reviewer for identifying the ambiguity. On re-checking the precision, we found that the percentages in the original text were inconsistent in unit, and, for two quantities, did not match the specification: Air temperature is specified as ± 0.5 °C (not ± 2 %) and wind direction as $< 3^\circ$ (not ± 2 %). Barometric pressure (± 1 hPa) was already in physical units. Relative humidity is now written as ± 2 % RH to make clear it is absolute percentage points of RH. For wind speed, rainfall, solar radiation, UV index and particulate matter, accuracy lies relative to the reading. We therefore report that relative accuracy together with the instrument resolution in physical units and the equivalent absolute uncertainty at a representative value is updated in the manuscript.

Line 178- 183 revise to: These measurements, along with their manufacturer-specified accuracy, include: ambient air temperature (± 0.5 °C), relative humidity (± 2 % RH), barometric pressure (± 1 hPa), wind speed (± 2 % of reading, e.g., ± 0.2 m s⁻¹ at 10 m s⁻¹; resolution 0.01 m s⁻¹), wind direction ($< 3^\circ$; resolution 1°), rainfall intensity (± 10 % of reading, e.g., ± 1 mm h⁻¹ at 10 mm h⁻¹; resolution 0.01 mm), solar radiation (± 5 % of reading, e.g., ± 25 W m⁻² at 500 W m⁻²; resolution 1 W m⁻²), UV index (± 5 % of reading, e.g., ± 0.5 at an index of 10; dimensionless), and particulate matter PM1.0/PM2.5/PM10 (± 10 % of reading, e.g., ± 10 µg m⁻³ at 100 µg m⁻³; resolution 1 µg m⁻³).

Line 236–237: Why do the oxygen-isotope slopes deviate strongly from 1, unlike hydrogen? Please discuss possible causes and whether such deviations are expected for this instrument.

Reply: We thank the reviewer for this comment and agree that our original sentence was too strong and insufficiently explained. The raw measurement slopes of the instrument against the assigned values of our liquid standards are below unity for $\delta^{18}\text{O}$ (0.767-0.771) and $\delta^{17}\text{O}$ (0.774-0.779) and above unity for $\delta^2\text{H}$ (1.090-1.103). This means that the isotope scale of the analyser (factory calibration) differs from the VSMOW-SLAP scale. It does not mean that the instrument was unstable or poorly calibrated. This scale difference is removed by the linear VSMOW regression described in the new Section 2.v (Step 3), in which the raw $\delta^{17}\text{O}$ and $\delta^{18}\text{O}$ values are mapped onto the VSMOW scale using the standards of all calibrations. The resulting scale factors (1.290 for $\delta^{17}\text{O}$ and 1.302 for $\delta^{18}\text{O}$) are the inverses of the raw slopes. Normalizing raw data to VSMOW-SLAP by linear regression on standards of known composition is the standard procedure for this type of analyser (e.g., Hutchings & Konecky, 2023). The relationship between raw and assigned values was highly linear in all calibrations ($R^2 > 0.99$; Fig. 3), and the slopes varied by only about 0.5 % ($\delta^{18}\text{O}$, $\delta^{17}\text{O}$) and 1.2 % ($\delta^2\text{H}$) between the eight calibrations. The deviation of the slopes from unity therefore reflects a stable and correctable scale difference, not a poor base calibration.

Applications: The claimed benefit to hydrological studies is stated; however, it is not substantiated as to how this station might aid in that field. Please add concrete use cases with references.

Reply: The conclusion currently asserts hydrological relevance; to make it more clear with the application part this setup helps to elevate the understanding as following:

First, because Manali and Sissu sit on opposite (windward/leeward) sides of the Pir Panjal range and are influenced by both the Indian Summer Monsoon and Western Disturbances, the paired continuous vapour records from the two sites can directly

partition the relative moisture contribution of these two systems to the regional water balance, extending the water budget framework of (Bookhagen & Burbank, 2010) and the moisture-source review of (Hunt et al., 2025) from a precipitation-only to a vapour-resolved basis. Second, isotope-enabled climate and reanalysis models are typically evaluated against precipitation isotopes alone, for lack of continuous vapour observations at process-relevant (sub-daily) resolution in this region (Galewsky et al., 2016); this station's continuous $\delta^{18}\text{O}$, $\delta^{17}\text{O}$, $\delta^2\text{H}$ and derived ^{17}O -excess record provides exactly that missing vapour-phase target for model-data comparison. Third, the group has previously interpreted a triple-water-isotope ($\delta^{17}\text{O}$, $\delta^{18}\text{O}$, $\delta^2\text{H}$) record from Chhota Shigri, also in the Western Himalaya, against meteorological parameters to reconstruct hydroclimatic conditions (Ranjan & Leuenberger, 2021); a continuous, ground based vapour-isotope baseline from Manali/Sissu provides the modern data against which that and future Himalayan paleoclimate archives can be more robustly interpreted. We have added these three application as example case studies to the conclusion.

Citations:

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