https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

Technical note: A new monitoring approach to measure water vapor isotopes in high altitude regions

Gaurav Kumar[1], Yama Dixit[1*], Anubhav Singh[1], Shyam Ranjan[2], Markus Leuenberger[3,4]

[1]Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, India

[2] Shaheed Bhagat Singh College, University of Delhi, India

[3]Climate and Environmental Physics, Physics Institute, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland

[4]Oeschger Centre for Climate Change Research, University of Bern, Hochschulstrasse 4, CH-3012 Bern, Switzerland

*Corresponding author: Yama Dixit (ydixit@iitd.ac.in),

Markus Leuenberger (markus.leuenberger@unibe.ch)

Keywords: water vapor isotopes, triple oxygen isotopes, ^{17}O-excess, Cavity Ring-Down Spectroscopy (CRDS) analyzer, Picarro L2140-i, high-altitude continuous vapor isotope monitoring station, Indian Summer Monsoon (ISM), Western Disturbances (Westerlies).

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

Abstract

Water vapor isotopes provide a comprehensive perspective on the moisture source dynamics for tracing the physical processes in hydrological and climatic studies. Continuous real-time water vapor isotopic measurements using Cavity Ring-Down Spectroscopy (CRDS) techniques are mostly based at stations located in high latitudes and the low-lying tropical regions. Such investigations from high-altitude, tropics, subtropical - mid-latitude transition zone - the Himalayas is limited owing to challenging physical conditions and multiple forms of precipitation occurring in the region. In this study, we report the establishment of the first continuous high-altitude isotope-monitoring laboratory in Northwest Himalayas windward side Manali (2,050 above msl) and leeward side Sissu (3,120 above msl) using the Picarro L2140-i Cavity Ring-Down Spectroscopy (CRDS) analyzer. This instrument enables real-time measurements of $\delta^{17}O$, $\delta^{18}O$, and δ2H in local atmospheric water vapor. Our laboratory setup integrates installation of Picarro analyzer, a heating air inlet system, meteorological sensor, lightning arrester and calibration protocols suited for optimum performance of the instrument in such challenging high-altitude Himalayan environment. Our laboratory setup protocols integrate the best practice and published guidelines with some additional modifications to mitigate the challenges in water vapor isotopic measurements in high altitude environment. A limitation of the current dataset is that no calibration has been performed since July 2025, due to relocation of JRF recruited to Delhi resulting in the unavailability of the trained personnel to carry out routine calibration cycles. We acknowledge this as a significant shortcoming and highlighted here for transparency. In addition to these continuous water vapor isotope measurements, precipitation events are also recorded, which could be helpful in investigating serious calibration problems should they arise.

1. Introduction

The high-altitude and the vast glacial mass of the Himalayan region plays a crucial role in regulating South Asian hydrological cycle with significant implications for sustaining the perennial river systems of the continent (Lepcha et al., 2021). The region's precipitation is derived by two distinct weather systems, Indian Summer Monsoon is the primary source of rainfall for the Central and Lower Western Himalayas mostly active from June to September, and the Western Disturbances (Westerlies) contribute a significant portion of moisture, particularly

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

to the upper and lower Western Himalayan regions in winters from December to March (Bookhagen & Burbank, 2010; Hunt et al., 2025; Saini & Attada, 2025; Singh et al., 2024). Multiple moisture sources and complex topography of the region make it difficult to understand the hydroclimate dynamics of the region (Ranjan et al., 2021). In such scenarios, the stable isotope composition of water vapor is a powerful diagnostic tool to fingerprint moisture pathways and to understand atmospheric processes associated with precipitation systems (Rahul et al., 2016a).

Measurements of water's stable isotopic composition have been instrumental in providing critical insights into the hydrological processes (Bowen et al., 2019; Gat, 1996). The ratios of D/H and $^{18}O/^{16}O$ in water samples are commonly expressed in per-mile (δ) units, using the Vienna Standard Mean Ocean Water (V-SMOW) as reference. The δ value (Eq. 1) shows how much the isotope ratio in the sample differs from the ratio in the standard.

$$\delta\ (‰) = [(\frac{R\_sample}{R\_v-smow}) - 1] \times 1000 \quad \text{………………………. (Eq. 1)}$$

Here, R represents the ratio of the heavier isotope to the lighter isotope ($^{2}H/^{1}H$ or $^{18}O/^{16}O$) for both the sample and the V-SMOW standard.

Derived isotope parameters such as d-excess and ^{17}O-excess defined below provide crucial insights into the relative humidity conditions and ambient evaporation temperature at the moisture source (Bershaw et al., 2020). ^{17}O-excess is more effective than d-excess as a direct tracer of relative humidity at the moisture source because unlike d-excess it is largely insensitive to temperature.

$$d - excess = \delta^{2}H - 8 \times \delta^{18}O \quad \text{………………………………………………. (Eq.2)}$$

$$\delta^{17}O - \text{excess} = \ln(\delta^{17}O + 1) - 0.528 \times \ln(\delta^{18}O + 1) \quad \text{……………………………… (Eq.3)}$$

where, 0.528 is the exponent (θ) for meteoric waters (Luz & Barkan, 2010; Meijer & Li, 1998), that describes the experimentally obtained relationship of the above-mentioned parameters and can be explained by combinations of fractionation factors of equilibrium and kinetic processes. Theoretically and experimentally derived ratio values of equilibrium fractionation factor between liquid and vapor of water are measured to be 0.529 (Barkan & Luz, 2005) and 0.5184 for kinetic processes (diffusion of water vapor in air) (Barkan & Luz, 2007) and were

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

used in many studies among others by Uemura et al., (2010). A slight temperature dependence is still under discussion for the latter ratio as discussed in Bao et al., (2016) and Nyamgerel et al., (2021).

Stable isotopes of atmospheric water vapor offer valuable insights into vapor 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) continental recycling of moisture (Li et al., 2015) and moisture sources. Cavity Ring Down Spectroscopy (CRDS) technique enabling continuous, high-precision measurements are crucial for understanding atmospheric moisture dynamics (Bonne et al., 2020; Deshpande & Gupta, 2004; Galewsky et al., 2016. These advances have enabled long-term vapor isotope monitoring at diverse mid to high latitude sites such as Greenland ice cores, the Atlantic Ocean, and European observatories, leading to global high-resolution data set are pertinent for isotope-enabled climate model evaluation (Galewsky et al., 2016; Steen-Larsen et al., 2013). Despite popular use of CRDS technology for continuous water vapor isotopic measurements from high latitudes, real-time continuous datasets from the tropics is missing. He et al., (2018) and Wei et al., (2019) presented the first continuous water vapor isotopic dataset from Singapore documenting significant changes in vapor isotopes during extreme rainfall events. Previous isotope surveys across the Himalayan and SE Tibetan Plateau demonstrate strong spatial and seasonal water vapor isotope gradients driven by moisture-source changes and orographic effects; these baseline precipitation isotope records (Gao et al., 2011) provide a useful framework for interpreting continuous vapor isotope observations from high-altitude sites.

In India, primarily campaign-based, focused on precipitation rather than vapor isotopic measurements have been carried out (Chakraborty et al., 2016; Deshpande & Gupta, 2004; Tharammal et al., 2023) et al., 2023). For example, the Indian Network of Isotopes in Precipitation (IWIN) program has provided valuable long-term rainwater isotope records across the subcontinent (Deshpande & Gupta, 2004; Sengupta et al., 2020). Similarly, campaign studies during the monsoon season in Bengaluru and the Andaman Islands have investigated rain-vapor interactions and isotopic variability (Rahul et al., 2016b). These datasets lack the continuous vapor-phase measurements needed to capture rapid synoptic-scale variability and diurnal cycles. Specifically, there is a dearth of continuous vapor measurements from the high-altitude regions, primarily because of numerous technical challenges faced at a high-altitude Himalayan region that received precipitation in both solid and liquid forms via multiple moisture sources across seasons.

This study aims to fill this observational gap by establishing the first water vapor isotope- monitoring laboratory

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

in the Western Himalayas. This installation integrates the Picarro L2140-i CRDS analyzer with a customized high-altitude air-inlet system (that preserves the isotopic characteristics of water vapor from the point of entry to the analyzer), meteorological sensor, and custom calibration protocols suited for extreme environments. The laboratory provides real-time, high-precision measurements of $\delta^{18}O$, $\delta^{17}O$, and $\delta^{2}H$ in atmospheric water vapor, enabling the study of diurnal, seasonal and intraseasonal isotopic variability, varied moisture sources (Indian Summer Monsoon & Western Disturbances) and moisture transport pathways.

2. Challenges setting up a high-altitude vapor isotopic laboratory

i. Careful site selection

The water vapor isotope monitoring site is located at Old Manali, Himachal Pradesh, India (32.2396° N, 77.1887° E) at an elevation of 2,050 meters above sea level. The region experiences a bimodal precipitation regime: the Indian Summer Monsoon (July–September) and Western Disturbances (December–March) in the form of solid snow and liquid rain. Mean annual precipitation in Manali exceeds 1,200 mm, with frequent snowfall in winter (starting from December). More than 50% of the rainfall is recorded during Indian Summer Monsoon period (Rao MS, 2014). Ambient temperatures range from −1.7°C in winter to 30°C in summer. Relative humidity varies significantly, with values often below 20% during dry seasons. The strategic location of laboratory setup was chosen in a way such that it lies far away from major human settlement as well as any big water reservoir although the station is in proximity to the Beas River, and several mid-altitude glaciers which also contribute significantly to atmospheric moisture through sublimation/evaporation. Thus, the site is ideal for studying the influence of long range and local moisture sources, moisture recycling and atmospheric processes on isotopic values of atmospheric vapor as it is influenced by both tropical and mid-latitude air masses. Setting up the laboratory at this remote location involved several challenges such as hindrance in continuous power supply and difficulty in procuring laboratory materials, particularly during restricted periods in winter when snow covered roads are blocked.

ii. Instrumental set-up challenges

The isotope ratios of atmospheric water vapor were quantified using a laser based Picarro L2140-i cavity ring-down spectrometer, capable of performing high-precision stable isotope measurements in atmospheric

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

vapor. The instrument provides simultaneous analysis of $\delta^{18}O$, $\delta^{2}H$, and $\delta^{17}O$ which can be used to calculate derived parameters such as d-excess and ^{17}O-excess.

Figure 1: (a) Geographic location of the water vapour isotope measurement laboratory shown on a regional base map of India (Sources: Esri, Garmin, GEBCO, NOAA NGDC; Powered by Esri) (b) Satellite view of the study site representing the actual valley location and its distance from the nearby Beas and Manalsu rivers (Imagery © [Google Earth] 2025, spatial layers and distance vectors prepared using ArcGIS); (c) Laboratory building, with the air inlet system, meteorological sensor, and lightning arrestor mounted on its roof; (d) Isotope measurement room displaying Picarro L2140-i analyser, vacuum pumps, control systems, and the air inlet pipe routed from the roof.

Our isotope measurement laboratory is designed to ensure accurate and reliable data collection across various seasons with both solid and liquid forms of precipitation, starting with a robust air inlet system. One of the major challenges

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

in setting up such a high-altitude isotopic measurement laboratory is fractionation of vapor isotopes on the way from the inlet to the analyser. Our bespoke air inlet system is designed to tackle this issue. The air inlet system is composed of a 6.35 mm outer diameter (4 mm internal diameter) stainless steel tube supported from outside by another SS pipe of OD 42 mm mounted vertically on a rooftop 5.5 meters above the rooftop. The vertical steel pipe stands on a concrete base designed to support heavy mass and remain unaffected by any air deflection. The outer stainless-steel pipe provides stability and robustness to the main air inlet pipe. Vertical height of air inlet is strategically chosen to avoid any near surface contamination. To prevent the intake of debris and large insects, the top of the inlet was fitted with a cylindrical mesh. A precisely engineered screwed cap of larger size (67 mm inner diameter) at the top of the inlet ensures a controlled and uniform suction of air into the analyser through inlet pipe. The cap at the top blocks the rainwater and snow to enter or block the inlet pipe, which is crucial for collecting atmospheric vapor without introducing unfiltered air leaks.

Manali generally experiences a huge ambient temperature range, nearly 30.2°C in summers (March-June) to subzero temperature around (−2°C) observed at the study sight during winters. Consistent with IMD record (IMD, 2005-2025), to balance these temperature variations such that it doesn't reflect in the isotopic data, our customised bespoke heating inlet pipe setup was built to regulate uniform temperature stability throughout all seasons. Inlet line temperature was regulated at 40°C inside and 25°C outside by wrapping two the heating cable around the inlet pipe which was then covered with an Armaflex Insolation (ID 19.2 mm, thickness 7.78 mm) to prevent any further heat loss. The Armaflex, with all internal joints was taped securely and outer surface further covered with aluminium tape, which serves as thermal insulation. High-strength, heat-resistant aluminium tape is best suited for this application, as it prevents loosening due to heat. This temperature setting averts any condensation or freezing of vapor thereby mitigating potential isotopic fractionation that could arise from phase changes. This small, uniform temperature increase is specifically intended to maintain the atmospheric water in vapor state. This process is not expected to cause significant isotopic fractionation, as such effects are most pronounced during phase transitions or due to strong temperature gradients.

The inlet pipe is passed straight through the ceiling slab downwards in the room. From the end of air inlet pipe, further connections are made using Dekabon, a metal-plastic composite tubing (6 mm internal diameter) also wrapped along the heating cable to the Picarro vaporization module (A0211) through a two-way valve. A gentle, continuous slope was maintained from the inlet pipe to the analyzer using the Dekabon tubing, ensuring there were no bends. Avoiding

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

small bends is crucial as they can lead to blocking of the air flow. This inlet system setup is capable of significantly avoiding isotopic fractionations in various extreme season where precipitation occurs both in the form of rain and snow. The two-way valve system is necessary for calibrating the Picarro by switching from the ambient air to zero air gas while injecting the standards. Monthly calibrations of the instrument documents the long-term stability of the instrument and suggest whether any drift correction is needed or not. The instrumental setup was housed in a climate-controlled room, where a 24/7 heating, ventilation and air conditioning system maintained a stable temperature of 25 ± 2°C. To ensure continuous data collection, the system was backed up by a 2 kVA UPS and a 3 kVA gasoline generator, providing uninterrupted power backup. The exhaust of the generator was placed at about 15 metres away from the inlet pipe.

The isotope monitoring setup was complemented with a meteorological instrument (SEM6000) to simultaneously measure ambient meteorological parameters placed on a pole at height ~ 6 m next to air inlet pole. These measurements along with their precision include - ambient air temperature (± 2%), relative humidity (± 2%), barometric pressure (±1 hpa), wind speed and direction (± 2%), rainfall amount (±10%), solar radiation (±5%) and UV index (±5%), particulate matters PM1.0/PM2.5/PM10 (±10%). This inclusive meteorological data is essential for contextualizing the isotopic measurements and understanding the atmospheric dynamics influencing the vapor isotope composition.

iii. Other logistical challenges in a high-altitude laboratory

To prevent the data loss during short power cuts, power backups were installed whose power supply capacity lasts for around 2 hours and for the longer power failures a 3 kVA capacity generator was used. Various electronic safety devices were installed to ensure the safety of all operational instruments from electrical fluctuations, especially abrupt high voltage bursts, which are quite common in Manali. These safety devices include a voltage regulator operating at range of 90 VAC to 300 VAC voltage and a current display unit to monitor the supply, and an RCCB box to mitigate both high and low voltage risks. The electric voltage cutoff threshold was set at around 90 volts - 260 volts, beyond which the electricity supply will automatically cutoff, thereby protecting the instruments from serious damage or heavy loss.

Both outside installations for the water vapor isotope (heated air intake line) and meteorological measurements (meteorological sensor) are installed on the roof of same building on high poles to avoid any near surface

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

contamination in our samples. However, this could attract the thunder lightening therefore a copper lightning arrestor grounded in earth was installed on a high steel pole (1.5 meter higher than inlet pole and Meteorological sensor) over the rooftop to safeguard the whole building along with laboratory setup from potential lightning strikes and induced surges, ensuring enhanced protection of this sensitive instrument and overall electrical stability during extreme weather events.

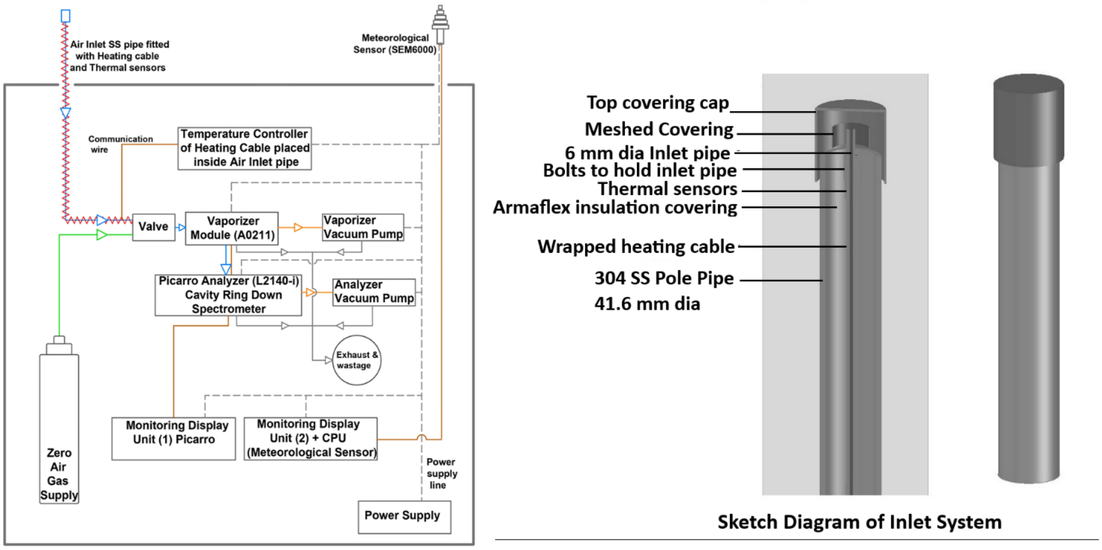

Fig. 2(a) **Fig. 2(b)**

Figure 2(a): Schematic representation of an automated system to continuously measure stable isotopes in-situ water vapor. The setup illustrates the integration of an ambient air intake, regulated by a temperature-controlled heating cable (indicated by the red jagged line) to prevent fractionation, and a Zero Air Gas Supply (green flow line) for calibration. Both streams are managed via a Valve manifold leading to a Vaporizer Module (A0211) and a Picarro L2140-i Cavity Ring-Down Spectrometer. The primary sampling flow is indicated by blue arrows, while the vacuum-driven extraction and exhaust paths are marked by orange and grey arrows, respectively. System data and control signals are transmitted via solid brown communication wires to dual Monitoring Display Units, while the distribution of electricity from the Power Supply to all active components is represented by dashed grey lines. Environmental context is simultaneously captured by an external Meteorological Sensor (SEM6000) linked to a CPU. 2(b): Cross sectional view of the air inlet stainless steel tube.

Table 1: Listing and functions of various components used in the laboratory setup

Component / Accessory	Source / Manufacturer	Function / Use
Picarro L2140-i Analyzer	Picarro Inc. (USA)	Measures $\delta^{18}O$, $\delta^{17}O$, δD in water vapor using CRDS technology.
Auto-sampler Port / Manual Injection Port	Picarro	For isotopic calibration using water standards.
Sample Inlet Septum (2 mm)	Picarro	Provides enveloping in vaporization sample inlet module after liquid sample insertion
Air Pump (Diaphragm)	Picarro/Vaccubrand	Draws ambient air through the inlet system and maintains pressure.

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

SS 316 Inlet Pipe OD: 42 mm ID: 36 mm	Local vendor	To provide it with a firm structure to standalone
SS Inlet Tube (20ft) OD: 06 mm, ID: 04 mm	Local vendor	Delivers ambient air from elevated sampling point to analyzer.
Inlet Heating Cable	Eltherm / Omega	Prevents condensation or freezing in the inlet during winter.
Inlet Tube Insulation Jacket (Armaflex) OD: 35.8 mm, ID: 19.2 mm, Thickness: 7.78 mm	Local	Ensures thermal stability of air in transit.
Dust and Insect Pre-Filter (PTFE)	Whatman/Sigma-Aldrich	Filters debris before air enters analyzer.
SEM6000 Meteorological Sensor	Sentec	Measures T, RH, Pressure, Wind, Gust, PM1/2.5/10, Solar, UV radiation, Rain.
Uninterruptible Power Supply (UPS)	V-Guard	Protects instruments from power outages.
PC with Picarro Software/ Meteorological Software SEM6000	Picarro/Institute	Controls instrument, logs and visualizes data.
Standards STO8, B-slap, Dye III, MW97	Collaborator	Isotopic calibration and accuracy assurance.
Zero air Gas Cylinder (99.99%)	Local gas supplier	Used to flush, purge, or maintain dry conditions inside instrument parts.
Dual-Stage Regulator for Zero air gas Cylinder	Swagelok / Parker / Local	Maintains constant low pressure gas delivery to Picarro ports.
1/8-inch SS Tubing	Swagelok / Online/Local	Used for high-purity gas line from regulator to Picarro.
1/8- to 1/4-inch SS Adaptor	Swagelok / Local	Connects with different diameter fittings in gas line.
1/8-inch SS Tee Connector	Swagelok / Local	Allows branching of gas or vapor flow lines.
1/8-inch SS Ferrules (10 sets)	Swagelok / Local	Sealing and connection of tubes. 1/8"
1/4-inch SS Ferrules (5 sets)	Swagelok / Local	Sealing and connection of tubes. 1/4"
Manual Water Injection Syringe	Hamilton	Used for calibrating with known water standards.
Heater-Controller for Inlet Cable	Omega / Custom	Controls heating cable for air inlet, ensures temperature is maintained above dew point.
Thermal Sensor (RTD/PT100)	Omega / Online	Monitors inlet temperature during heating.
Power Extension, Stabilizer	Local	Ensures safe and steady power supply.

Table 2: Water standard and their isotope signatures expressed on the V-SMOW scale**,** Tap water Bern (ST-O8), Bern-Slap (B-Slap), Dye III melted ice (Dye-III), Ocean water (MW 97)

Assigned values	**δ^{18}O**	**δ^{2}H**	**δ^{17}O**	**^{17}O - excess**
ST-O8	-10.95	-77.46	-5.78	0.01872

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

B-Slap	-55.34	-263.29	-29.21	0.4122
Dye-III	-27.39	-209.28	-14.54	0.010649
MW 97	-0.3	-2.19	-0.16	-0.00316

iv. Long-term data quality control

The instrumental calibration was performed every month from July 2024 with a total of 8 calibrations conducted over the initial study period using internal standards of University of Bern, ST-O8, B-Slap, Dye-III, and MW 97 listed in table 2. The calibration has been performed always in same order with ten injections per standard targeting 20,000 ppm H_2O. The four standards range from enriched values close to V-SMOW (MW97) over medium (STO-8 and DYE-3) to very depleted values (BSLAP). The accuracy and bias of instrument's response was validated by comparing measured isotopic values against the assigned standard values (Table 2). The slope of this comparison indicates the instrument's response accuracy, aiming for a 1:1 match. The intercept reveals any systematic measurement bias. A high $R^2 > 0.99$ for $\delta^{18}O$, $\delta^{17}O$, and δ^2H (Figure 3) confirms a strong correlation between Picarro measurements and the assigned standards values, signifying a robust calibration potential. These eight calibrations were performed over a period of 8 months from July 2024 to Feb 2024 to control the instrument stability. The results from all eight calibrations demonstrate high consistency and instrument stability throughout the measurement period. Yet, the factory calibration for the oxygen isotopes are rather bad as the slopes are significantly below 1 in contrast to hydrogen isotopes.

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

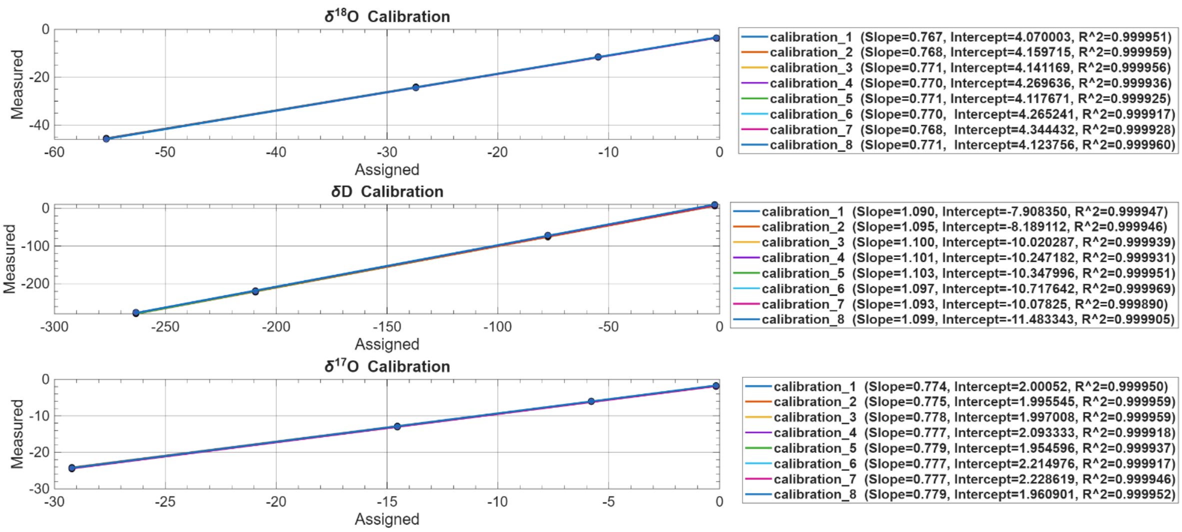

Figure 3. Picarro L2140-i laboratory calibration measurements. The results of 8 calibration experiments performed using four standards is shown. The calibration was done on a roughly monthly basis with a total of 8 calibrations from July 2024 to Feb 2025. High correlation coefficient values of the linear regression fit line indicate instrument's stability and stability over time. The slope deviating significantly from 1 ($d^{17}O$, $d^{18}O$) document a rather poor base calibration of the instrument. The agreement between the eight calibrations are excellent, which is also documented by the fact that only one line per parameter is visible.

Preliminary results:

The monthly mean of the water vapor isotope values is represented in Figure 4 over a period of 16 months (June 2024 – September 2025) to demonstrate the preliminary data recorded at our station which shows the capability of our laboratory setup to capture longer-term atmospheric variability. The resulting time series of $\delta^{18}O$, $\delta^{17}O$, δ^2H and ^{17}O-excess in atmospheric water vapor shows distinct isotopic values during different seasons of the year possibly reflecting changes in moisture source, ambient meteorological conditions and transport pathways of the air mass reaching the study site. These monthly averages (Figure 4) are preliminary and are therefore not yet used for detailed climatological analysis. But based on the long-term stability of the system as illustrated by Figure 3, we expect that the results are robust and can be used for detailed investigations with different temporal resolutions. The least robust parameter is ^{17}O-excess, which calls for an in-depth analysis.

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

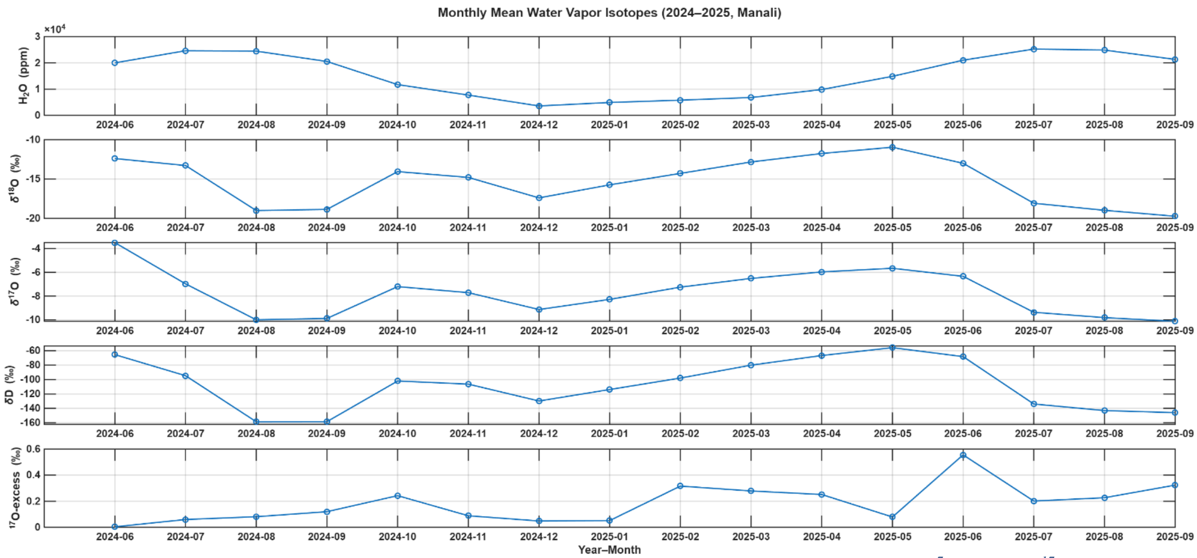

Figure 4. Monthly mean values of near-surface water vapour concentration and isotopic measurements ($\delta^{18}O$, $\delta^{17}O$, $\delta^{2}H$ and ^{17}O-excess) measured and recorded using the Picarro TL2140-i over a period of 16-months (June 2024 – September 2025) in Manali.

5. Conclusion

In this study, we present the prerequisites, challenges and mitigation techniques in establishing a continuous isotope monitoring system in a high-altitude Himalayan region. The instrument was calibrated once every month with four known- internal calibration standards to check instrument's accuracy over a range of isotopic values. The calibration results demonstrate that the instrument is stable over time and performs reliably under varying environmental conditions, providing reliable high-resolution continuous $\delta^{17}O$, $\delta^{18}O$, and $\delta^{2}H$ data.

This laboratory setup lays the foundation for integrated atmospheric-hydrological studies, model validation, and long-term climate reconstructions. The data generated from the instrument will be crucial in providing an improved understanding of the hydrological cycle in the region.

Supplement link: NA

Author contributions: Gaurav Kumar: Conceptualization, writing original draft; Yama Dixit: Supervision, Funding acquisition, Writing – review & editing. Anubhav Singh: Writing original draft & editing Methodology. Shyam Ranjan: review & editing. Markus Leuenberger: Supervision, Funding acquisition, Writing – review & editing

Competing interests: The authors declare that they have no conflict of interest.

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

Acknowledgements: We gratefully thank and acknowledge the Ministry of Earth Sciences (MoES), Government of India, for providing financial support under the project (MOES/INDO-SWISS/3/2022-PC-1). This work was also supported by the Swiss National Science Foundation (SNF) under grant number (IZINZ2_209542). We thank IIT Delhi and University of Bern for technical and infrastructural support. We would also like to acknowledge Mr. Peter Nyfeler for providing technical support in setting up the laboratory through online video calls.

Financial support: Ministry of Earth Sciences (MoES), Government of India and Swiss National Science Foundation (SNF, IZINZ2_209542), Switzerland.

6. References:

Bao, H., Cao, X., & Hayles, J. A. (2016). Triple Oxygen Isotopes: Fundamental Relationships and Applications. *Annual Review of Earth and Planetary Sciences*, *44*. https://doi.org/10.1146/annurev-earth-060115-012340

Barkan, E., & Luz, B. (2005). High precision measurements of 17O/16O and 18O/16O ratios in H2O. *Rapid Communications in Mass Spectrometry*, *19*(24). https://doi.org/10.1002/rcm.2250

Barkan, E., & Luz, B. (2007). Diffusivity fractionations of H216O/H 217O and H216O/H218O in air and their implications for isotope hydrology. *Rapid Communications in Mass Spectrometry*, *21*(18). https://doi.org/10.1002/rcm.3180

Bershaw, J., Hansen, D. D., & Schauer, A. J. (2020). Deuterium excess and 17O-excess variability in meteoric water across the Pacific Northwest, USA. *Tellus, Series B: Chemical and Physical Meteorology*, *72*(1). https://doi.org/10.1080/16000889.2020.1773722

Bonne, J. L., Meyer, H., Behrens, M., Boike, J., Kipfstuhl, S., Rabe, B., Schmidt, T., Schönicke, L., Steen-Larsen, H. C., & Werner, M. (2020). Moisture origin as a driver of temporal variabilities of the water vapour isotopic composition in the Lena River Delta, Siberia. *Atmospheric Chemistry and Physics*, *20*(17). https://doi.org/10.5194/acp-20-10493-2020

Bookhagen, B., & Burbank, D. W. (2010). Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research: Earth Surface*, *115*(3). https://doi.org/10.1029/2009JF001426

Bowen, G. J., Cai, Z., Fiorella, R. P., & Putman, A. L. (2019). Isotopes in the water cycle: Regional- to global-scale patterns and applications. In *Annual Review of Earth and Planetary Sciences* (Vol. 47). https://doi.org/10.1146/annurev-earth-053018-060220

Deshpande, R. D., & Gupta, S. K. (2004). *National Programme on Isotope Fingerprinting of Waters of India (IWIN)-a New Initiative.*

https://doi.org/10.5194/egusphere-2026-220
Preprint. Discussion started: 23 June 2026

Deshpande, R. D., Maurya, A. S., Kumar, B., Sarkar, A., & Gupta, S. K. (2010). Rain-vapor interaction and vapor source identification using stable isotopes from semiarid western India. *Journal of Geophysical Research Atmospheres*, *115*(23). https://doi.org/10.1029/2010JD014458

Galewsky, J., Steen-Larsen, H. C., Field, R. D., Worden, J., Risi, C., & Schneider, M. (2016). Stable isotopes in atmospheric water vapor and applications to the hydrologic cycle. In *Reviews of Geophysics* (Vol. 54, Issue 4). https://doi.org/10.1002/2015RG000512

Gao, J., Masson-Delmotte, V., Yao, T., Tian, L., Risi, C., & Hoffmann, G. (2011). Precipitation water stable isotopes in the South Tibetan plateau: Observations and modeling. *Journal of Climate*, *24*(13). https://doi.org/10.1175/2010JCLI3736.1

Gat, J. R. (1996). Oxygen and hydrogen isotopes in the hydrologic cycle. *Annual Review of Earth and Planetary Sciences*, *24*. https://doi.org/10.1146/annurev.earth.24.1.225

He, S., Goodkin, N. F., Jackisch, D., Ong, M. R., & Samanta, D. (2018). Continuous real-time analysis of the isotopic composition of precipitation during tropical rain events: Insights into tropical convection. *Hydrological Processes*, *32*(11). https://doi.org/10.1002/hyp.11520

Hunt, K. M. R., Baudouin, J. P., Turner, A. G., Dimri, A. P., Jeelani, G., Pooja, Chattopadhyay, R., Cannon, F., Arulalan, T., Shekhar, M. S., Sabin, T. P., & Palazzi, E. (2025). Western disturbances and climate variability: A review of recent developments. In *Weather and Climate Dynamics* (Vol. 6, Issue 1, pp. 43–112). Copernicus Publications. https://doi.org/10.5194/wcd-6-43-2025

Landais, A., Risi, C., Bony, S., Vimeux, F., Descroix, L., Falourd, S., & Bouygues, A. (2010). Combined measurements of 17Oexcess and d-excess in African monsoon precipitation: Implications for evaluating convective parameterizations. *Earth and Planetary Science Letters*, *298*(1–2). https://doi.org/10.1016/j.epsl.2010.07.033

Lepcha, P. T., Pandey, P. K., & Ranjan, P. (2021). Hydrological significance of Himalayan surface water and its management considering anthropogenic and climate change aspects. *IOP Conference Series: Materials Science and Engineering*, *1020*(1). https://doi.org/10.1088/1757-899X/1020/1/012013

Li, S., Levin, N. E., & Chesson, L. A. (2015). Continental scale variation in 17O-excess of meteoric waters in the United States. *Geochimica et Cosmochimica Acta*, *164*. https://doi.org/10.1016/j.gca.2015.04.047

Luz, B., & Barkan, E. (2010). Variations of 17O/16O and 18O/16O in meteoric waters. *Geochimica et Cosmochimica Acta*, *74*(22). https://doi.org/10.1016/j.gca.2010.08.016

Meijer, H. A. J., & Li, W. J. (1998). The use of electrolysis for accurate δ17O and δ18O isotope measurements in water. *Isotopes in Environmental and Health Studies*, *34*(4). https://doi.org/10.1080/10256019808234072

Nyamgerel, Y., Han, Y., Kim, M., Koh, D., & Lee, J. (2021). Review on applications of17O in hydrological cycle. *Molecules*, *26*(15). https://doi.org/10.3390/molecules26154468

Rahul, P., Ghosh, P., Bhattacharya, S. K., & Yoshimura, K. (2016a). Controlling factors of rainwater and water vapor isotopes at Bangalore, India: Constraints from observations in 2013 Indian monsoon. *Journal of Geophysical Research*, *121*(23). https://doi.org/10.1002/2016JD025352

Rahul, P., Ghosh, P., Bhattacharya, S. K., & Yoshimura, K. (2016b). Controlling factors of rainwater and water vapor isotopes at Bangalore, India: Constraints from observations in 2013 Indian monsoon. *Journal of Geophysical Research*, *121*(23). https://doi.org/10.1002/2016JD025352

Ranjan, S., Ramanathan, A. L., Keesari, T., Singh, V. B., Kumar, N., Pandey, M., & Leuenberger, M. C. (2021). Triple Water Vapour–Isotopologues Record from Chhota Shigri, Western Himalaya, India: A Unified Interpretation based on δ17O, δ18O, δD and Comparison to Meteorological Parameters. *Frontiers in Earth Science*, *8*. https://doi.org/10.3389/feart.2020.599632

Rao MS, G. K. (2014). Isotopic Observations from Two Stations of North India to Investigate Geographical Effects on Seasonal Air Moisture. *Journal of Earth Science & Climatic Change*, *05*(02). https://doi.org/10.4172/2157-7617.1000180

Saini, R., & Attada, R. (2025). Indian summer monsoon precipitation and extremes over the Indian Himalayas in WRF dynamically downscaled (HARv2) reanalysis. *Climate Dynamics*, *63*(3). https://doi.org/10.1007/s00382-025-07648-1

Sengupta, S., Bhattacharya, S. K., Parekh, A., Nimya, S. S., Yoshimura, K., & Sarkar, A. (2020). Signatures of monsoon intra-seasonal oscillation and stratiform process in rain isotope variability in northern Bay of Bengal and their simulation by isotope enabled general circulation model. *Climate Dynamics*, *55*(5–6). https://doi.org/10.1007/s00382-020-05344-w

Singh, A., Kumari, A., Sharma, B., Senthilnathan, R., & Dixit, Y. (2024). Assessing the hydroclimate changes in Western Himalayas during the Little Ice Age. *Holocene*, *34*(5). https://doi.org/10.1177/09596836231225727

Steen-Larsen, H. C., Johnsen, S. J., Masson-Delmotte, V., Stenni, B., Risi, C., Sodemann, H., Balslev-Clausen, D., Blunier, T., Dahl-Jensen, D., Ellehøj, M. D., Falourd, S., Grindsted, A., Gkinis, V., Jouzel, J., Popp, T., Sheldon, S., Simonsen, S. B., Sjolte, J., Steffensen, J. P., … White, J. W. C. (2013). Continuous monitoring of summer surface water vapor isotopic composition above the Greenland Ice Sheet. *Atmospheric Chemistry and Physics*, *13*(9). https://doi.org/10.5194/acp-13-4815-2013

Surma, J., Assonov, S., Herwartz, D., Voigt, C., & Staubwasser, M. (2018). The evolution of 17O-excess in surface water of the arid environment during recharge and evaporation. *Scientific Reports*, *8*(1). https://doi.org/10.1038/s41598-018-23151-6

Tharammal, T., Bala, G., & Nusbaumer, J. M. (2023). Sources of water vapor and their effects on water isotopes in precipitation in the Indian monsoon region: a model-based assessment. *Scientific Reports*, *13*(1). https://doi.org/10.1038/s41598-023-27905-9

Uechi, Y., & Uemura, R. (2019). Dominant influence of the humidity in the moisture source region on the 17 O-excess in precipitation on a subtropical island. *Earth and Planetary Science Letters*, *513*. https://doi.org/10.1016/j.epsl.2019.02.012

Uemura, R., Barkan, E., Abe, O., & Luz, B. (2010). Triple isotope composition of oxygen in atmospheric water vapor. *Geophysical Research Letters*, *37*(4). https://doi.org/10.1029/2009GL041960

Voigt, C., Herwartz, D., Dorador, C., & Staubwasser, M. (2021). Triple oxygen isotope systematics of evaporation and mixing processes in a dynamic desert lake system. *Hydrology and Earth System Sciences*, *25*(3). https://doi.org/10.5194/hess-25-1211-2021

Wei, Z., Lee, X., Aemisegger, F., Benetti, M., Berkelhammer, M., Casado, M., Caylor, K., Christner, E., Dyroff, C., García, O., González, Y., Griffis, T., Kurita, N., Liang, J., Liang, M. C., Lin, G., Noone, D., Gribanov, K., Munksgaard, N. C., … Yoshimura, K. (2019). A global database of water vapor isotopes measured with high temporal resolution infrared laser spectroscopy. *Scientific Data*, *6*. https://doi.org/10.1038/sdata.2018.302