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Decade-long isotope dataset of rainfall and non-rainfall waters in the central Namib Desert

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Abstract

Drylands are essential Earth System components, and dryland dynamics are strongly controlled by water availability. Long-term ground observations of hydrological parameters are often lacking in most dryland ecosystems. A series of foundational and unique water input data, including both rainfall and non-rainfall (i.e., fog and dew) components, in hyper-arid desert environments have been presented in this database. These observations provide comprehensive isotope measurements of rainfall and non-rainfall water resources, which are essential to evaluate the impacts of extreme climate events on the water cycle. The database comprised three key components: (1) a decade-long (2014−2023) event-based stable isotopes (δ^2H, δ^{18}O, and d-excess) in rainfall and non-rainfall waters at Gobabeb, (2) a two-month spatial isotope dataset (δ^2H, δ^{18}O, and d-excess) of fog collected from the central Namib Desert in 2016 and 2017, and (3) a six-decade (1963−2023) temporal data documenting monthly fog and rainfall amounts as well as annual Kuiseb River flooding events at Gobabeb. The detailed stable isotope data included 585 fog samples, 71 rainfall samples, 115 dew samples, and 13 groundwater samples over the past ten years (2014−2023) in the Namib Desert. Detailed descriptions of the study sites, sampling procedures, analytical methods, and data quality control are provided in this study. The uniqueness of our long-term dataset makes it an important resource for future studies investigating hydrological processes in drylands and their responses to climate change. The DOIs of the dataset can be obtained in the "Data availability" section.

Short Summary

We investigated water availability in the hyper-arid Namib Desert by collecting long-term data on rainfall, fog, and dew inputs. Our research presents a rare, decade-long dataset of stable isotope measurements to better understand how water moves within dryland environments. This work helps scientists quantify changes in the water cycle and improve our understanding of how drylands may respond to a changing climate.

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1 Introduction

Dryland ecosystems, where precipitation is consistently lower than potential evapotranspiration, span approximately 40% of Earth's land surface (Wang et al., 2012; Jiao et al., 2021; Wang et al., 2022). In these water-limited regions, the availability, timing, origins, and predictability of water inputs play a crucial role in regulating ecosystem functions (Wang et al., 2022). While rainfall serves as the primary water source for maintaining vegetation-water relations, nutrient fluxes, biogeochemical recycling, and groundwater recharges in most ecosystems, non-rainfall water, including fog and dew, can constitute a significant or even dominant hydrological input in certain ecosystems (Kaseke et al., 2017; Wang et al., 2017). This has been reported in some coastal deserts, hyper-arid inland regions, and high-altitude mountainous areas, where fog and dew occur with greater frequency and can sometimes surpass rainfall in both frequency and volume (Seely and Henschel, 1998; Cermak, 2018; Henschel, 2021). Understanding the contributions of both rainfall water and non-rainfall water to regional water cycling and their interactions with biotic and abiotic processes is essential for predicting dryland responses to climate variability and improving water resource management (del Río et al., 2018).

Stable isotope ratios of hydrogen and oxygen have been widely used in hydrological research for more than six decades (Craig, 1961; Dansgaard, 1964). Stable isotope analyses provide critical insights into the sources, pathways, and transformations of water within atmospheric and hydrological systems (Scholl et al., 2002; Bowen et al., 2019). Specifically, isotope ratios in water inputs can integrate information on key processes such as atmospheric water cycling (e.g., water vapor origins and atmospheric water balance), land-atmospheric flux processes (e.g., continental recycling and evapotranspiration partitioning), and hydrological recharges (e.g., soil water and/or groundwater recharges) (Zhang and Wang, 2016; Bowen et al., 2019). Over the past two decades, advancements in isotope data compilation and information sharing have significantly enhanced the integration of global isotope observations across diverse water sources, including precipitation, surface water, groundwater, vapor, and tap water (Araguasaraguas et al., 1995; Evaristo and McDonnell, 2017; Zhao et al., 2017; Nan et al., 2019; Tian et al., 2020; Nelson et al., 2021). Large-scale isotopic datasets, such as those from the Global Network of Isotopes in Precipitation (GNIP), Waterisotopes Database (wiDB), National Ecological Observatory Network (NEON), Stable Water Vapor Isotope Database (SWVID), and Water Isotope System for Data Analysis, Visualization, and Electronic Retrieval (WISER), provide invaluable records for assessing water cycle patterns across spatial and temporal scales (Bowen et al., 2019). However, a comprehensive global isotope monitoring network for rainfall and non-rainfall water inputs in dryland ecosystems has yet to be established. This lack of coordinated isotopic data limits our ability to accurately quantify the contributions of different water sources to dryland water balance, evaluate the impacts of climate variability on ecosystem functioning, and inform sustainable water resource management in arid and semi-arid regions. Establishing a standardized, long-term global isotope monitoring framework for dryland rainfall and non-rainfall water inputs would enhance our understanding of moisture dynamics, improve predictive hydrological models, and support more effective adaptation strategies for water-limited environments on a global scale.

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The Namib Desert is a typical non-rainfall-dependent dryland ecosystem, where water deposition from non-rainfall sources significantly exceeds rainfall inputs (Henschel and Seely, 2008; Eckardt et al., 2013; Wang et al., 2017). Accordingly, temporal and spatial observations of the stable isotope data for rainfall and non-rainfall water inputs in such non-rainfall-dependent ecosystems are crucial for unravelling regional water cycling and accurately predicting long-term hydrological trends under changing climate conditions. However, acquiring long-term stable isotope datasets in these ecosystems remains challenging due to the high costs of labor-intensive sampling and the logistical difficulties associated with continuous monitoring in remote and harsh environments. These constraints have contributed to the scarcity of comprehensive isotope records for rainfall and non-rainfall waters, limiting our ability to assess long-term trends and variability in dryland hydrology.

In this study, we provide a series of foundational and unique water input data, including both rainfall and non-rainfall (i.e., fog and dew) components, in the hyper-arid Namib Desert. Building on the FogNet station network, we utilized eight permanent meteorological stations across two transects (west–east from 14.625° E to 15.029° E and north–south from 22.970° S to 23.560° S) and five temporal meteorological stations along a northwest–southeast transect (west–east from 14.721° E to 15.022° E and north–south from 23.016° S to 23.564° S) over the central Namib Desert (Fig. 1). Specifically, we presented a decade-long (2014–2023) event-based stable isotope (δ^2H, δ^{18}O, and d-excess) dataset of rainfall and non-rainfall waters at Gobabeb and two field campaign based spatial isotope datasets (δ^2H, δ^{18}O, and d-excess) of fog collected from the central Namib Desert in 2016 and 2017. The historical water availability (i.e., fog water amount, rainfall amount, and the annual total number of Kuiseb River flooding occurrences) in Gobabeb has also been compiled over the past six decades. Additionally, for researchers interested in meteorological context, hourly meteorological data from eight permanent meteorological stations since October 2014 can be obtained from the Southern African Science Service Centre for Climate Change and Adaptive Land Management (SASSCAL) (available at http://sasscalweathernet.org/ and https://sasscalweathernet.org/w_datarequest_we.php?MIsoCode=NA&MMCS=0#StationAnchor). Users can register on the website by contacting SASSCAL directly via email at oadc-datarequest@sasscal.org, which is required for bulk or customized data requests (e.g., spanning multiple countries, sensors, or long-time periods). These data are external resources and not directly deposited on PANGAEA. The observational isotope datasets provided in this study, together with publicly available meteorological data resources such as SASSCAL across the central Namib Desert, offer valuable opportunities for future research on the processes governing dryland water cycle patterns, spanning from site-specific to regional and global scales, and their responses to climate change.

2 Methods and data quality control

2.1 Study area and field data collections

Field observations and sample collection were conducted in the central Namib Desert, Namibia between 2014 and 2023 (Fig. 1). This study area is situated within the Namib fog zone, where visible fog is present along the Namib coast (Eckardt et al.,

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2013; Kaseke et al., 2017). The central Namib Desert receives less than 25 mm of annual rainfall and 30−180 mm of annual fog amount (Henschel et al., 1998). Rainfall in the Namib Desert exhibited a westward decreasing trend, dropping below 12 mm in the western region (Henschel and Seely, 2008; Eckardt et al., 2013). At the same time, a west−to−east gradient in fog frequency is evident, with fog occurrence declining inland (Kaseke et al., 2018; Andersen et al., 2019). The region lacks perennial rivers, with surface water being largely absent for most of the year (Jacobson and Seely, 1995). Instead, ephemeral rivers, such as the Kuiseb and Swakop rivers, serve as critical hydrological features, transporting runoff from the interior highlands to the Atlantic Ocean during sporadic rainfall events (Jacobson and Seely, 1995; Lange, 2006). These ephemeral rivers periodically recharge shallow alluvial aquifers, which can provide essential water sources for riparian deep-rooted trees and wildlife (Soderberg, 2010; Kaseke et al., 2018).

Event-based fog samples were collected from 13 stations in total. Specifically, the temporal fog water samples were collected from the Gobabeb−Namib Research Institute between 2014 and 2023, while the spatial fog samples were collected from all 13 stations during two periods: June 10−19, 2016, and June 27−July 10, 2017. The Gobabeb−Namib Research Institute (−23°33′39.3″ S, 15°02′24.6″ E) is located downstream of the Kuiseb River catchment, which originates in the eastern Khomas Highlands and flows westward toward Walvis Bay. Situated on the outer edge of the Namib fog zone, it lies approximately 60 km inland from the South Atlantic Ocean (Eckardt et al., 2013; Kaseke et al., 2017). During periods of flooding events, the rainfall in the upper-east Kuiseb watershed (approximately 350 mm per year) can temporarily provide additional moisture to the lower-lying region of Gobabeb in the west Kuiseb catchment (Soderberg, 2010; Kaseke et al., 2018). The multi-year (1962−2022) average annual flooding occurrence in the Kuiseb River is 17.3 days (Mizuno and Yamagata, 2005; Morgan et al., 2020). The 13 stations collectively covered an area of approximately 1,700 km², with a complete roundtrip visit spanning about 250 km (Kaseke et al., 2018). In particular, eight permanent meteorological stations across two transects (west−east from 14.625° E to 15.029° E and north−south from 22.970° S to 23.560° S) were part of the FogNet meteorological station network over the central Namib Desert. Additionally, five temporary meteorological stations were deployed along a northwest−southeast transect (west−east from 14.721° E to 15.022° E and north−south from 23.016° S to 23.564° S) to enhance the spatial coverage of the fog dataset. Before each roundtrip field campaign, we inspected the fog collector at the Gobabeb–Namib Research Institute and monitored real-time meteorological data (leaf wetness and relative humidity) from other stations to identify fog events across the central Namib Desert (Kaseke and Wang, 2022). If fog was present, we immediately conducted sampling roundtrips to all 13 sites using alternating routes (Gobabeb–Aussinanis–Coastal MET–Gobabeb). These measures optimized sampling efficiency, minimized unnecessary trips, and reduced evaporation effects and sampling bias. The Standard Fog Collectors (SFCs), designed according to Schemenauer and Cereceda (1994), were used to collect event-based fog water samples for isotopic analysis. All the captured fog water ran down from the bottom of the collectors into a 1 L glass bottle anchored to the ground through a pipe sealed at both ends to minimize water evaporation.

The temporal event-based dew samples were opportunistically collected at the Gobabeb−Namib Research Institute from 2014 to 2023. Dew was captured using a dew collector consisting of a 1 m^2 metal sheet covered by a glass plate, inclined at 30°, and elevated 0.5 m above the ground. The glass plate cools to or below the dew point, enabling condensation to form and

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accumulate in a trough at its lower edge. A connected pipe channels the collected moisture into a storage container. To minimize evaporation effects, all dew samples were collected before dawn (Tian et al., 2021).

The temporal rainfall samples were collected using a Young Model 52202 tipping-bucket rain gauge from 2014 to 2023. To eliminate evaporation effects on water samples, all rainfall samples were collected immediately after each event or, if the event ended after midnight, at the earliest possible time in the morning (Tian et al., 2021).

During the study period 2014−2023, groundwater samples were also opportunistically collected from two boreholes downstream of the Kuiseb River, which is close to the Gobabeb–Namib Research Institute (Kaseke et al., 2017).

The temporal event-based fog water at the Gobabeb–Namib Research Institute was opportunistically and equably collected across seasons during the period 2014−2023. Figure 2 presents the monthly mean number of foggy days from 1963 to 2016 and the actual coverage and consistency of our isotope dataset for temporal fog samples throughout the study period (2014–2023). The multi-year (2014−2023) average of the annual fog water sampling coverage exceeded 65% (Fig. 3) (Li et al., 2025a, in press). Throughout the study period from 2014 to 2023, we made every effort to opportunistically and comprehensively collect event-based rainfall and dew water samples at the Gobabeb–Namib Research Institute.

At the Gobabeb–Namib Research Institute, a total of 696 temporal water samples were collected between 2014 and 2023, comprising 497 fog samples, 71 rainfall samples, 115 dew samples, and 13 groundwater samples. Additionally, 88 event-based spatial fog water samples were collected from the 13 stations across the central Namib Desert during June–July 2016 and 2017. All the collecting water samples were transferred into a 15 ml Qorpak French square bottle and sealed with a Black Phenolic Pulp/Vinyl Lined Cap. They were stored in the refrigerator at the Gobabeb−Namib Research Institute until shipment to the Indiana University Indianapolis Ecohydrology Lab for isotope analysis.

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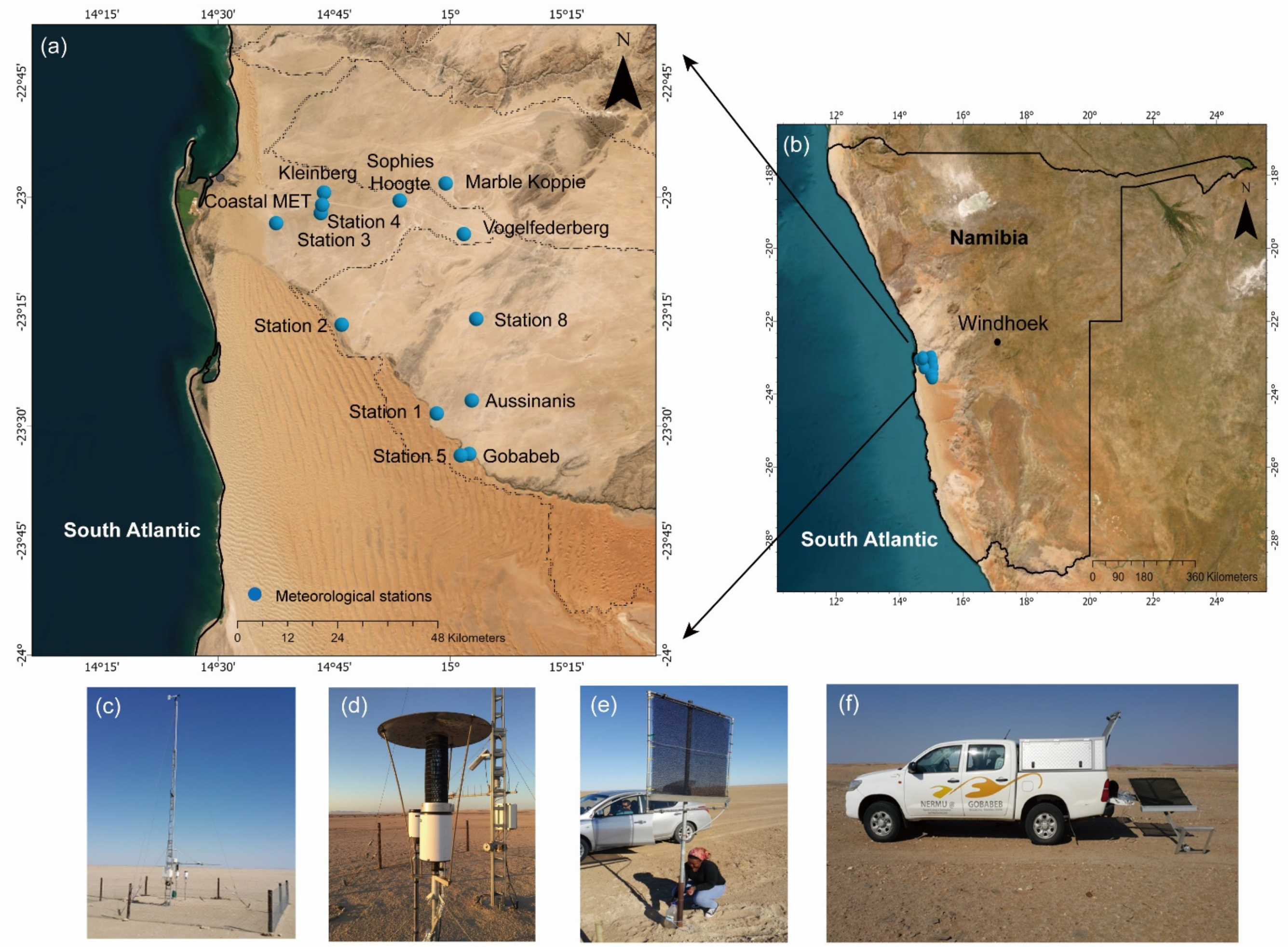

Figure 1: Location of the study area and meteorological stations/sampling sites over the central Namib Desert. The 13 blue dots in panels **(a)** and **(b)** are meteorological stations and sampling sites. Maps in panels **(a)** and **(b)** created using ArcGIS Pro with basemap layers from Esri and elevation data from NASA's Shuttle Radar Topography Mission (SRTM) (public domain). Panels **c-d** are pictures showing typical setups of the automated weather stations at Gobabe, Aussinanis, station 8, Vogelfederberg, Marble Koppie, Sophies Hoogte, Kleinberg, and Coastal Met. Panels **(e)** and **(f)** are pictures taken in meteorological stations 1−5.

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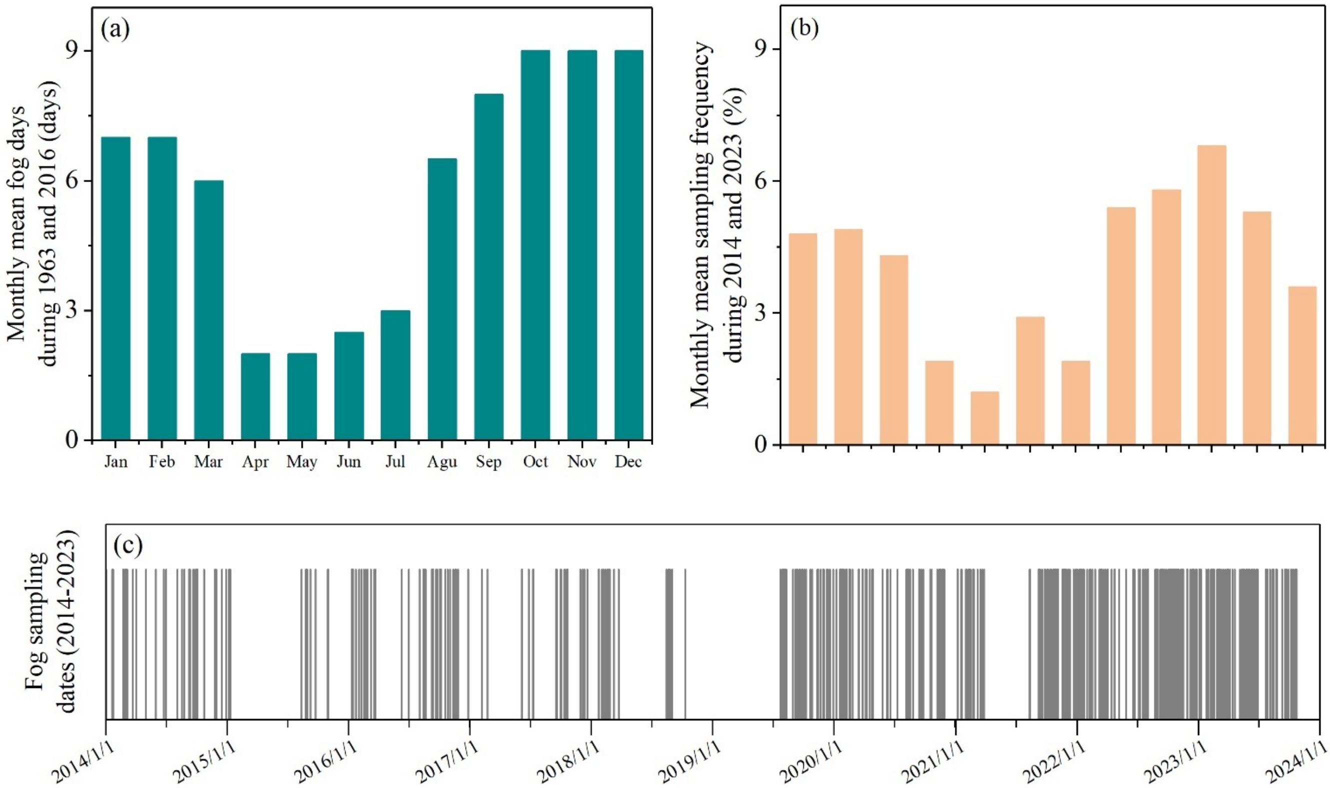

160 **Figure 2: Monthly mean foggy days during 1963 and 2016 and the actual coverage and consistency of our isotope dataset at the Gobabeb−Namib Research Institute throughout the study period (2014–2023). a.** Monthly mean number of foggy days from 1963 to 2016. **b.** Monthly sampling frequency of fog water during the study period from 2014 to 2023. **c.** Fog sampling dates during the study period from 2014 to 2023. The monthly mean fog days between 1963 and 2016 were derived from Spirig et al. (2019).

Table 1. Altitude, latitude, longitude, and climate of the meteorological stations.

Sites	Permanent (P) or Temporary (T)	Altitude (m.a.s.l.)	Latitude	Longitude	Distance from the coast (km)	Annual temperature (°C)	Annual precipitation (mm)
Coastal MET	P	94	-23.0563	14.625	18.3	16.1	12.8
Kleinberg	P	184	-22.9893	14.7279	22.2	16.7	11.3
Soophies Hoogte	P	334	-23.0068	14.8908	38.5	18.1	22.6
Marble koppie	P	421	-22.9695	14.9897	47.0	19.2	18.5
Vogelfederberg	P	501	-23.08	15.0289	55	19.1	15.0
Station 8	P	487	-23.2653	15.05563	58.4	18.9	14.0
Aussinanis	P	405	-23.4435	15.0459	56.5	20.6	14.3
Gobabeb	P	406	-23.5603	15.0404	55.2	19.6	15.3

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Station 1	T	361	-23.4719	14.97056	50.5	--	--
Station 2	T	215	-23.278	14.76598	28.3	--	--
Station 3	T	184	-23.0344	14.72111	22.6	--	--
Station 4	T	183	-23.0164	14.72389	22.0	--	--
Station 5	T	430	-23.5636	15.02222	53.1	--	--

2.2 Isotope analysis and isotope-based fog classification

A Los Gatos Research In.c GLA431 series analyzer (Los Gatos Research Inc., Mountain View, CA, USA) was utilized to measure the stable isotopic composition (δ^2H, $\delta^{18}O$, and d-excess) of fog, rain, and groundwater samples over the study period. Before isotope analysis, all water samples were filtered using a centrifuge (Diersing et al., 2025). The isotopic ratios of water samples are denoted by "δ", representing the per mil (‰) deviation relative to the Vienna Standard Mean Ocean Water (VSMOW) standard. This is expressed as follows in Equation (1):

$$\delta = (R_{sample}/R_{standard} - 1) \times 1000‰ \quad , \tag{1}$$

where R_{sample} represents the isotope ratio of water samples, and $R_{standard}$ is the defined isotope ratio of the working standard water samples.

The instrument's measurement precision was 0.8‰ for δ^2H and 0.2‰ for $\delta^{18}O$ (Kaseke and Wang, 2022). We measured the stable isotopic compositions of five standard water samples (LGR#1 to LGR#5) interspersed among every five water sample measurements to improve the accuracy of the Triple Water Vapor Analyzer's performance. Additionally, each analysis run began and ended with measurements of all five LGR standard water samples (Diersing et al., 2025). The standard δ^2H values of LGR#1 to LGR#5 are −154.0‰, −123.7‰, −97.3‰, −51.6‰, and −9.2‰, respectively. The standard $\delta^{18}O$ values of LGR#1 to LGR#5 are −19.49‰, −12.64‰, −13.39‰, −7.94‰, and −2.69‰, respectively. To further minimize potential contamination between water samples, the instrument syringe was flushed with deionized water after every eight water samples.

The stable isotopes (δ^2H and $\delta^{18}O$) are widely recognized as effective tracers for identifying different water sources, including the three primary fog types: advection fog (originating from oceanic moisture), radiation fog (formed from local sources), and mixed fog (a combination of both) (Kaseke et al., 2017). This classification is based on the principle that fog forms as a primary condensate under equilibrium fractionation, meaning its isotopic composition generally aligns with the meteoric water line. Deuterium excess, calculated as $d = \delta^2H - 8\delta^{18}O$, serves as a secondary isotopic parameter influenced by kinetic fractionation during oceanic evaporation. Although oceanic vapor initially condenses into sea fog with a d-excess matching that of the Global Meteoric Water Line (GMWL) (i.e., 10‰), advection fog undergoes non-equilibrium evaporation and exchanges with ambient vapor during inland transport. These processes are particularly pronounced in hyper-arid regions, where unsaturated and dry air conditions prevail (Dansgaard, 1964). In the coastal deserts of southwest Africa, located within the subtropical high-pressure belt, advection fog is primarily influenced by the upwelling of cold deep waters associated with

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the Benguela Current and southwesterly winds (Olivier, 1995). Synthesis of stable isotope data indicates that kinetic effects during evaporation can cause the initial condensate, formed over regions with cold ocean currents, to align along a line with a slope of less than 8 and a reduced d-excess of approximately 7‰ (Dansgaard, 1964). In this study, we assume that condensation occurs under equilibrium conditions, whereas landward advection involves non-equilibrium processes. Consequently, advection fog in the central Namib Desert is typically characterized by d-excess values exceeding 7‰. Another secondary isotope parameter, the line-conditioned excess (lc-excess), defined as lc-excess = $\delta^2H_{sample} - LMWL_{slope} \times \delta^{18}O - LMWL_{intercept}$, quantifies the deviation of fog water isotopes from the local meteoric water line (LMWL). A positive lc-excess suggests mixing between local meteoric water and oceanic sources, whereas a negative value indicates evaporative effects on the local meteoric water. Radiation fog, which forms from local moisture sources, is anticipated to plot on or slightly below the LMWL due to evaporation. In contrast, mixed fog, influenced by both oceanic and local water, is expected to exhibit isotopic characteristics intermediate between the GMWL and LMWL. Specifically, we classify fog water samples with an lc-excess below 0.5‰ as radiation fog based on isotopic signatures. Samples with a d-excess lower than 7‰ and an lc-excess exceeding 0.5‰ are identified as mixed fog, reflecting a combination of marine and continental moisture sources.

2.3 Literature data collection

In addition to the decade-long (2014−2023) isotope dataset of rainfall and non-rainfall waters, we compiled a six-decade (1962−2023) temporal record of historical water availability at the Gobabeb−Namib Research Institute based on literature-derived dataset, public-available meteorological observations, and our measurement records. This dataset includes monthly and annual fog amounts, monthly and annual rainfall amounts, and annual Kuiseb River flooding occurrence days.

From 1966 to 2002, the daily amount of fog water was measured at the Gobabeb − Namib Research Institute using a Grunow-type fog collector, which consisted of a cylindrical wire mesh screen (10 cm in diameter, 22 cm in height, collecting area of 691.15 cm^2) mounted above a standard rain gauge (Henschel et al., 1998; Henschel and Seely, 2008). Beginning in 1997 and continuing through 2002, SFCs were introduced for fog monitoring. SFCs featured a 1 m^2 vertical polyethylene mesh screen (10,000 cm^2 surface area) positioned above a horizontal 1 m funnel to capture event-scale fog deposition (i.e., daily fog amount) (Henschel et al., 1998; Henschel and Seely, 2008). To ensure consistency across instruments, Henschel et al. (1998) developed a linear regression model (R^2 = 0.62) linking fog water amounts from the Grunow and SFC systems. This model was subsequently used to convert the Grunow-type fog amount measurements (1966–1996) into SFC-equivalent units. The adjusted monthly Grunow dataset can be accessed in Henschel et al. (1998), while raw monthly SFC data from 1997–2002 are documented in both Henschel et al. (1998) and Henschel and Seely (2008). Notably, the original monthly Grunow-type fog amount data and the applied regression equation were not presented in Henschel et al. (1998). Between October 2006 and December 2015, daily fog amount dataset was measured again at Gobabeb using SFCs. From January 2016 to December 2022, additional event-scale fog water amount measurements were intermittently recorded using a 1 m^2 SFC as a backup. Since October 2014, hourly fog water amount has also been recorded using a Juvik-type louvered cylindrical fog collector (12.5 cm

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in diameter, 40.6 cm in height, 1,594.36 cm^2 area), mounted on a Young Model 52202 tipping-bucket rain gauge. The SASSCAL provides easy and open access to the hourly Juvik-type fog amount data via http://sasscalweathernet.org/ and https://sasscalweathernet.org/w_datarequest_we.php?MIsoCode=NA&MMCS=0#StationAnchor. To maintain the integrity of fog data from the SASSCAL station, spurious fog events—typically arising from rainfall, drizzle, or high winds—were excluded in cases where fog occurred alongside rain or when relative humidity dropped below 70%. Additionally, during 2020–2021, a regression relationship ($R^2 = 0.78$, $p < 0.05$) was established between daily fog water amounts collected by the SFC and those measured by the Juvik-type fog collector. This regression was then applied to harmonize SFC-derived fog water amount data from 1966–2002 and October 2006–September 2014, converting them into Juvik-equivalent units. To address the missing monthly fog data from January 2003 to September 2006, interpolation techniques were employed. Specifically, average daily fog amounts per month were derived from datasets spanning October 2006 to December 2022, using both monthly fog amount and fog frequency. Monthly fog frequency during the gap period was obtained from Henschel (2021), allowing estimation of fog water amounts for the missing months based on observed fog frequency and the previously derived daily averages. In sum, the long-term monthly fog amount record (1966–2022) from the Gobabeb − Namib Research Institute was not substantially influenced by the type of fog collection instrument used.

The monthly and annual rainfall data at the Gobabeb−Namib Research Institute from September 1962 to December 2002 are available at Henschel and Seely (2008), and monthly and annual rainfall amount data from January 2003 to December 2023 are available at the FogNet station network via http://sasscalweathernet.org/ and https://sasscalweathernet.org/w_datarequest_we.php?MIsoCode=NA&MMCS=0#StationAnchor. The dataset of annual Kuiseb River flooding occurrence days downstream of the Kuiseb River catchment from 1964 to 2022 is available at Mizuno and Yamagata (2005) and Morgan et al. (2020).

2.4 Statistical analysis

The one-way analysis of variance (ANOVA) was applied to examine differences in each variable across water types, between fog and non-fog seasons, among different types of fog, and across the six decades ($p < 0.05$). We applied the Structural Changes Detection (SCD) method from the R package 'strucchange' to identify statistically significant breakpoints ($p < 0.05$) in the annual fog amount data from 1966 to 2023. To assess trends within the time segments defined by these breakpoints, we subsequently employed the Mann–Kendall trend test.

3 Data descriptions and evaluation

3.1 Monthly and annual total of moisture in Gobabeb over the past six decades

The long-term (1966−2023) average of the annual total fog amount was 103.4 ± 53.7 mm, with peak monthly totals of 11.9 mm in August and 9.5 mm in September (Fig. 3a). Seasonally, fog deposition showed a distinct contrast between the first and

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second halves of the year. The multi-year average of the monthly total fog amount from June to December (with a mean value of 8.9 mm) was significantly higher compared to that between January and May (with a mean value of 4.3 mm). The long-term annual fog deposition record revealed a significant increasing trend from 1966 to 1996 ($p < 0.05$). However, no statistically significant trend was observed between 1997 and 2023 ($p > 0.05$). Notably, the multi-year average of the annual total fog deposition during the earlier period (1966–1996) (mean of 131.8 ± 53.7 mm) was substantially higher compared to the more recent period (1997–2023), which experienced a marked decline to 70.7 ± 30.2 mm (Fig. 3a).

In comparison, the multi-year (1963−2023) average of the annual total rainfall amount was 30.2 ± 35.6 mm (Fig. 3b). Rainfall exhibited a distinct seasonal pattern, with a peak monthly total of 5.5 mm occurring in March. Unlike fog deposition, rainfall was more concentrated in the first half of the year. The multi-year average of the monthly total rainfall from January to May (mean of 3.3 mm) exceeded that from June to December (mean of 2.0 mm) (Fig. 3b). This pattern reflects a climatic regime in which fog serves as the primary moisture source during the period from June to December, while rainfall, though infrequent, plays a more significant role in the first half of the year.

The multi-year (1964−2022) average of the annual total occurrence days of Kuiseb River flooding was 16.2 ± 24.8 mm (Fig. 2c).

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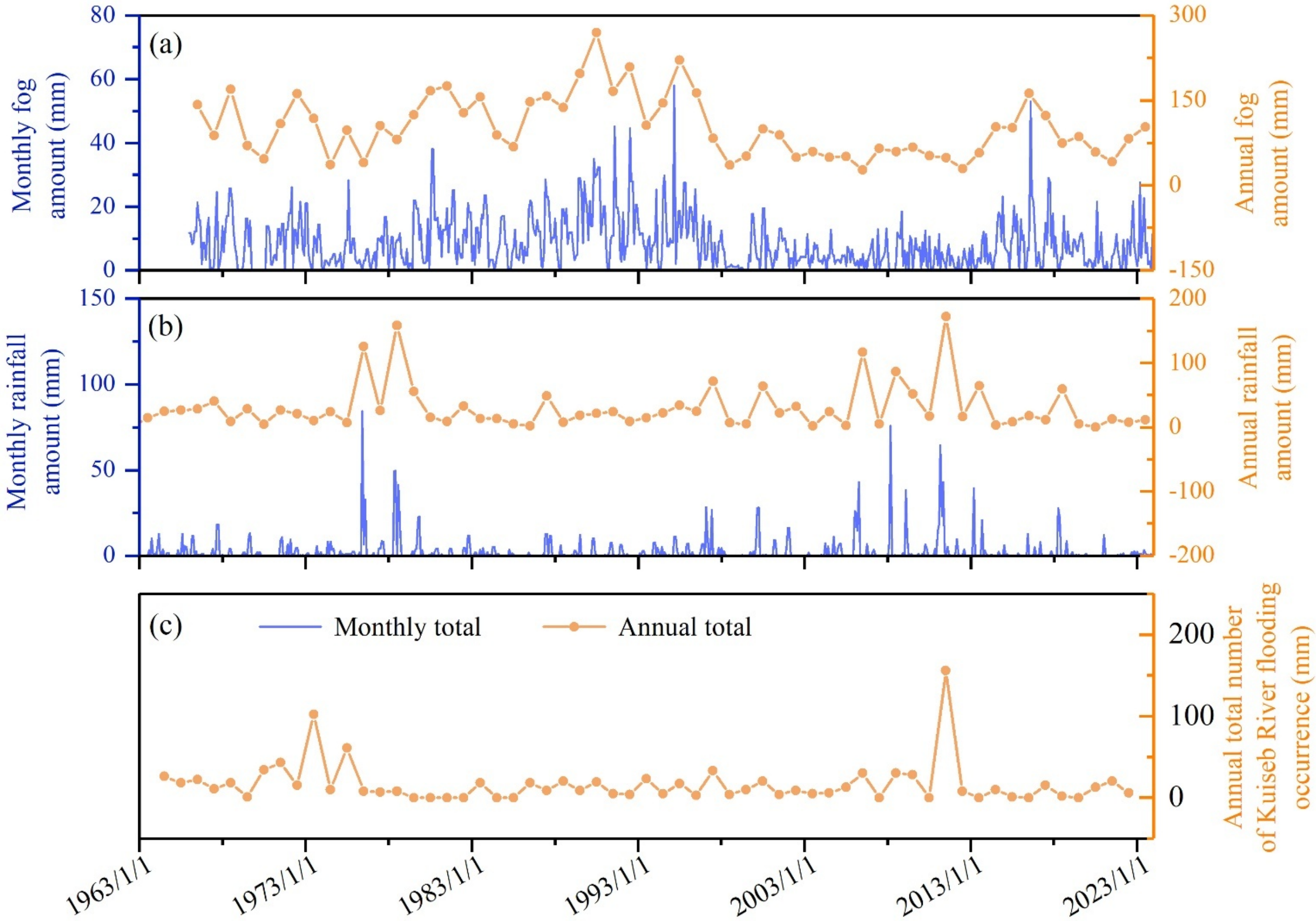

Figure 3: The monthly and annual total of moisture at Gobabeb from 1962 to 2023. a. Monthly and annual amount of fog. **b.** Monthly and annual amount of rainfall. **c.** Annual total number of Kuiseb River flooding occurrences.

3.2 Decade-long stable isotope compositions of rainfall, fog, and dew samples at Gobabeb

The LMWL ($\delta^2H = 5.8*\delta^{18}O - 5.2$, $R^2 = 0.93$, $p < 0.05$) was fitted by the stable isotopic compositions of rainfall water and groundwater at the Gobabeb–Namib Research Institute during the study period 2014−2023 (Fig. 4). The decade-long (2014−2023) averages of δ^2H, $\delta^{18}O$, d-excess, and lc-excess in the sampled rainfall water were −1.0 ± 21.9 ‰, 0.5 ± 3.6 ‰, −5.4 ± 12.0 ‰, and 1.0 ± 8.1 ‰, respectively (Fig. 4).

The decade-long (2014−2023) averages of δ^2H, $\delta^{18}O$, d-excess, and lc-excess in the sampled fog water at the Gobabeb–Namib Research Institute were −2.7 ± 10.8 ‰, −0.3 ± 2.1 ‰, −0.2 ± 9.8‰, and 4.3 ± 6.6 ‰, respectively (Fig. 5). The radiation fog water line, expressed as $\delta^2H = 5.2*\delta^{18}O - 8.6$ ($R^2 = 0.90$, $p < 0.05$), was derived from the stable isotopic

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compositions of the sampled radiation fog water at the Gobabeb–Namib Research Institute during the studied period 2014−2023 (Fig. 6). Similarly, the advection fog water line, given by $\delta^2H = 6.3*\delta^{18}O + 8.2$ ($R^2 = 0.89$, $p < 0.05$), was established using the stable isotopic compositions of the sampled advection fog water at the same site and time period (Fig. 6). Additionally, the mixed fog water line, defined as $\delta^2H = 5.8*\delta^{18}O + 0.4$ ($R^2 = 0.91$, $p < 0.05$), was fitted based on the stable isotopic compositions of the sampled mixed fog water at the Gobabeb–Namib Research Institute from 2014 to 2023 (Fig. 6). During the study period (2014–2023), radiation fog, advection fog, and mixed fog accounted for 26.5%, 20.4%, and 53.1% of the total sampled fog water at the Gobabeb–Namib Research Institute, respectively (Fig. 6).

Based on the multi-year averages of monthly fog amount and monthly total foggy days over the last decade, our previous study (Li et al., 2025a, in press) identified the period from April to July as the non-fog season, while the periods from August to December and from January to March were classified as the fog season. Figure 7 presents the dual-isotope plots and corresponding water lines for the three types of fog water during the fog season and non-fog season from 2014 to 2023. The slope of the radiation water line during the fog season, expressed as $\delta^2H = 5.2*\delta^{18}O – 8.6$ ($R^2 = 0.91$, $p < 0.05$), was relatively higher than that during the non-fog season, calculated by $\delta^2H = 4.5*\delta^{18}O – 10.2$ ($R^2 = 0.80$, $p < 0.05$). This suggests that radiation fog during the non-fog season may experience stronger sub-cloud evaporation than during the fog season. In contrast, the slope of the advection water line during the fog season, fitted by $\delta^2H = 6.2*\delta^{18}O + 8.0$ ($R^2 = 0.84$, $p < 0.05$), was relatively lower than that during the non-fog season, expressed as $\delta^2H = 6.5*\delta^{18}O + 8.8$ ($R^2 = 0.91$, $p < 0.05$). During the fog season from 2014 to 2023, radiation fog, advection fog, and mixed fog accounted for 26.4 %, 19.1 %, and 54.5 % of the total sampled fog water at the Gobabeb–Namib Research Institute, respectively (Fig. 7). In contrast, during the non-fog season over the same period, the proportions of radiation fog, advection fog, and mixed fog were 21.8 %, 51.3 %, and 26.9 %, respectively, contributing to the total sampled fog water at the site.

The decade-long (2014−2023) averages of δ^2H, $\delta^{18}O$, d-excess, and lc-excess in the sampled dew water at the Gobabeb–Namib Research Institute were −8.3 ± 11.2 ‰ and −1.2 ± 2.3 ‰, 1.3 ± 10.9 ‰, and 3.9 ± 7.1 ‰, respectively (Fig. 8).

The decade-long (2014−2023) average of δ^2H in both rainfall water and fog water at the Gobabeb–Namib Research Institute was significantly higher than that in dew water at the same site and period ($p < 0.05$) (Fig. 9). No significant difference in δ^2H values between rainfall water and fog water was found ($p > 0.05$). In comparison, the decade-long (2014−2023) average of $\delta^{18}O$ in rainfall water was significantly higher than that in fog water ($p < 0.05$). Additionally, the decade-long average of $\delta^{18}O$ in fog water was much higher compared to dew water ($p < 0.05$) (Fig. 9). The decade-long averages of both d-excess and lc-excess in fog water and dew water were significantly higher than that in rainfall water ($p < 0.05$) (Fig. 9). There was no significant difference in d-excess and lc-excess between fog water and dew water ($p > 0.05$).

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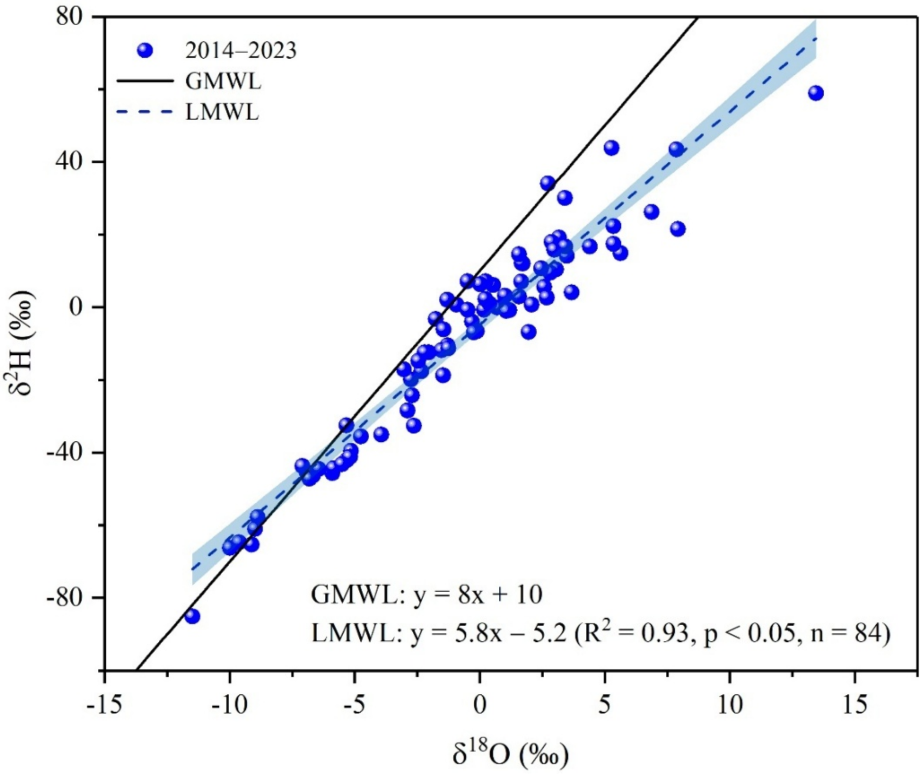

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Figure 4: Local meteoric water line (LMWL) and global meteoric water line (GMWL). The LMWL is fitted by the stable isotope compositions of rainfall water and groundwater collected from Gobabeb, in the central Namib Desert, from 2014 to 2023.

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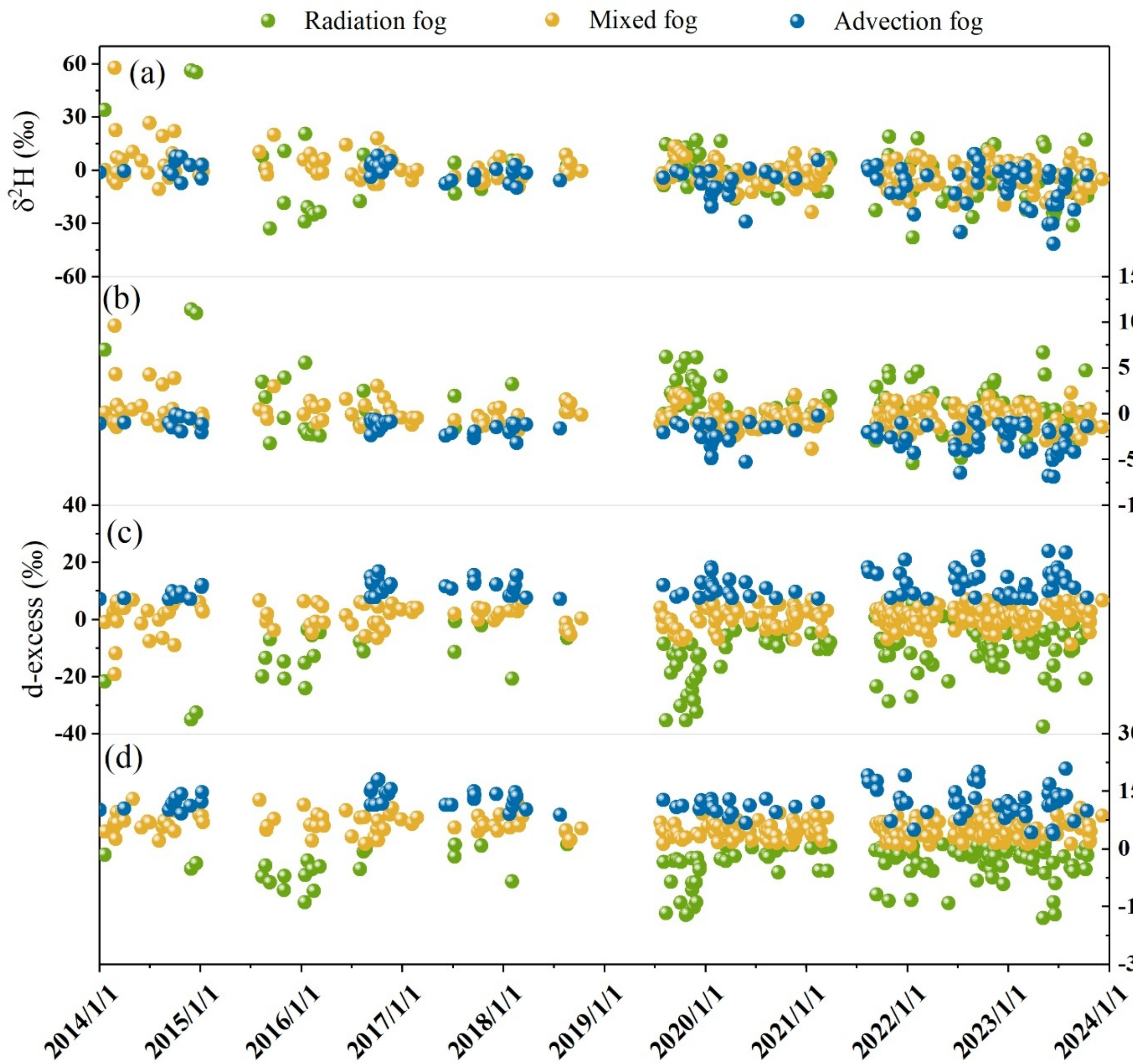

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Figure 5: Stable isotope compositions (δ^2H, $\delta^{18}O$, d-excess, and lc-excess) of radiation fog, mixed fog, and advection fog during 2014 and 2023 at the Gobabeb–Namib Research Institute.

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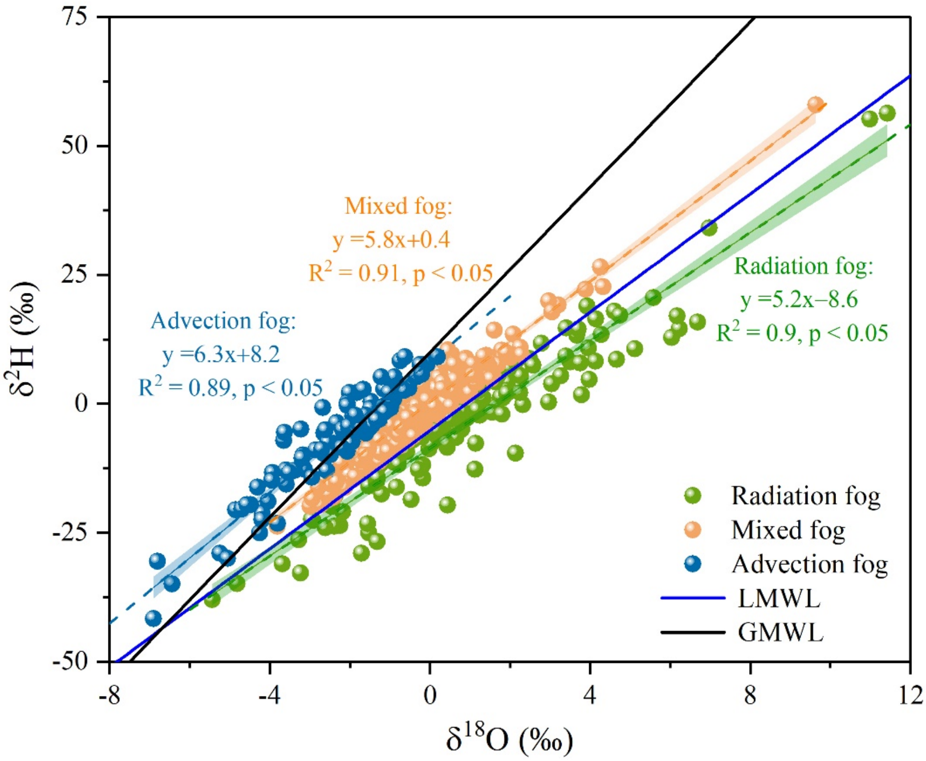
325 

Figure 6: Dual-isotope plots of radiation fog, mixed fog, and advection fog during 2014 and 2023 at the Gobabeb–Namib Research Institute.

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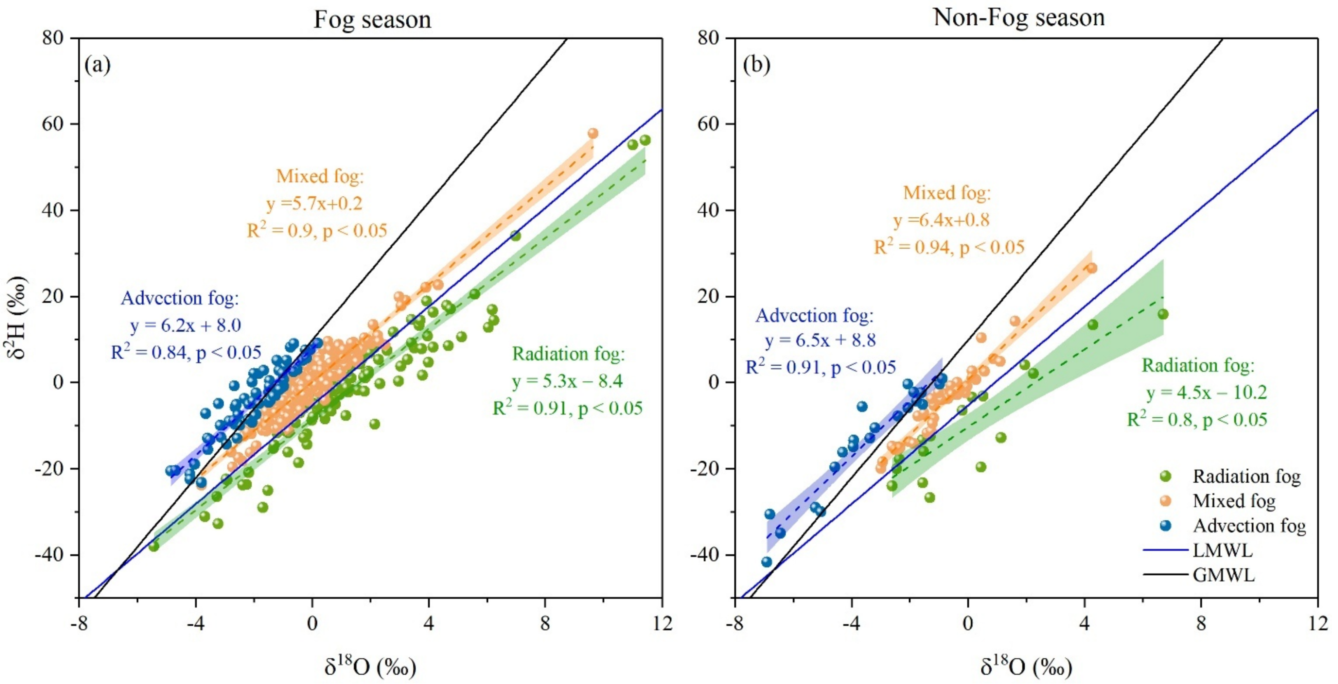

Figure 7: Dual-isotope plots of radiation fog, mixed fog, and advection fog during fog season (from April to July) (a) and non-fog season (from August to March) (b) between 2014 and 2023 at the Gobabeb–Namib Research Institute.

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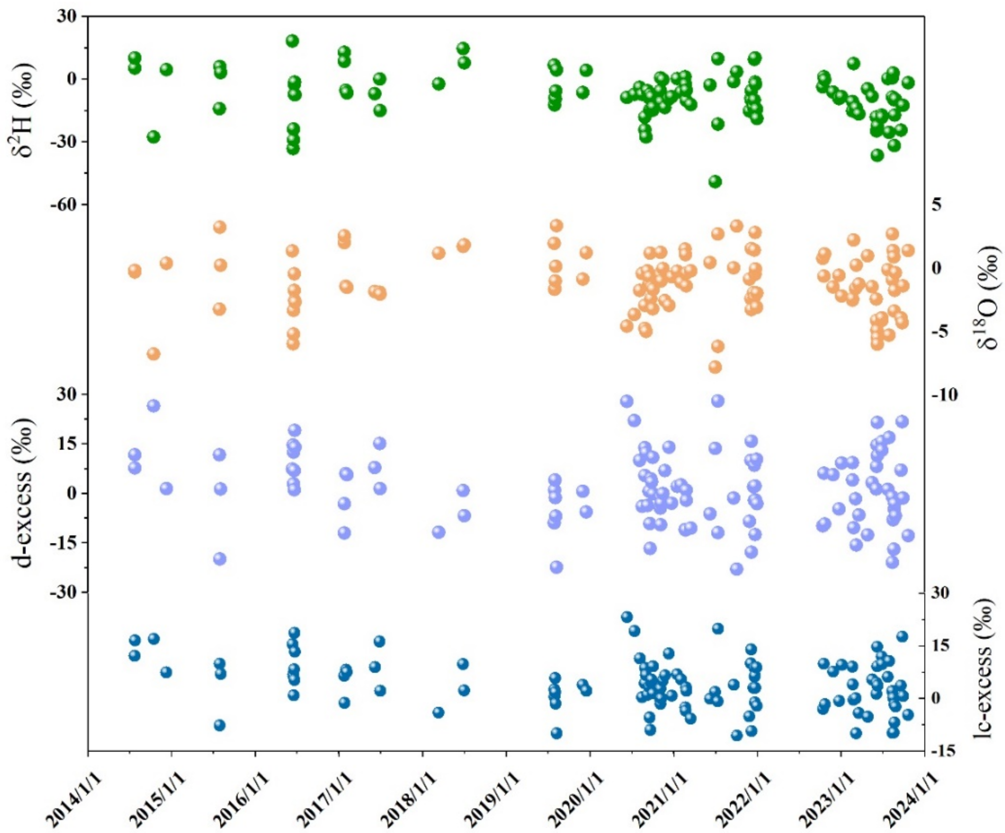

340 **Figure 8: Stable isotope compositions (δ^2H, $\delta^{18}O$, d-excess, and lc-excess) of dew water samples between 2014 and 2023 at the Gobabeb–Namib Research Institute.**

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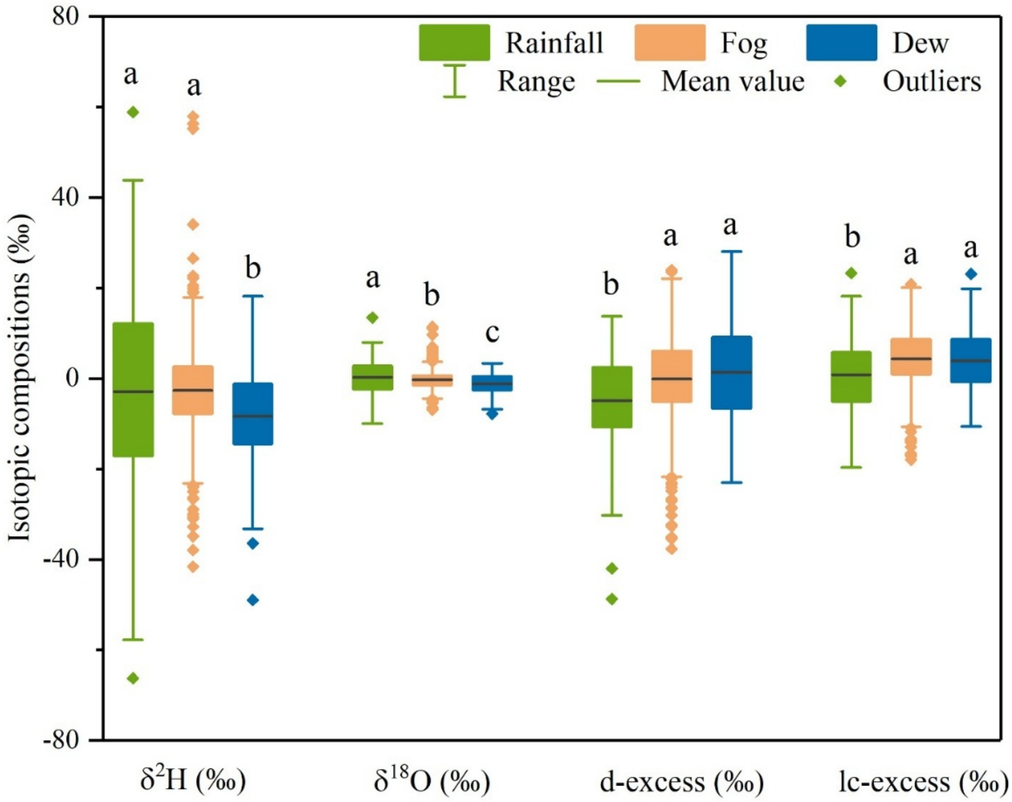

345 **Figure 9: Comparison of stable isotope compositions (δ^2H, $\delta^{18}O$, d-excess, and lc-excess) of rainfall, fog, and dew water samples during 2014 and 2023 at the Gobabeb–Namib Research Institute.**

3.3 Spatial fog distribution over the central Namib Desert

The radiation fog water line, expressed as $\delta^2H = 5.4*\delta^{18}O - 6.8$ ($R^2 = 0.94$, $p < 0.05$), was derived from the stable isotopic compositions of the sampled radiation fog water from 13 stations across the central Namib Desert during the studied period 2016−2017 (Fig. 10). Similarly, the advection fog water line, given by $\delta^2H = 5.1*\delta^{18}O + 13.8$ ($R^2 = 0.34$, $p < 0.05$), was established using the stable isotopic compositions of the sampled advection fog water at the same site and period (Fig. 10). The mixed fog water line, defined as $\delta^2H = 5.9*\delta^{18}O + 0.6$ ($R^2 = 0.81$, $p < 0.05$), was fitted based on the stable isotopic compositions of the sampled mixed fog water over the central Namib Desert from 2016 to 2017 (Fig. 10).

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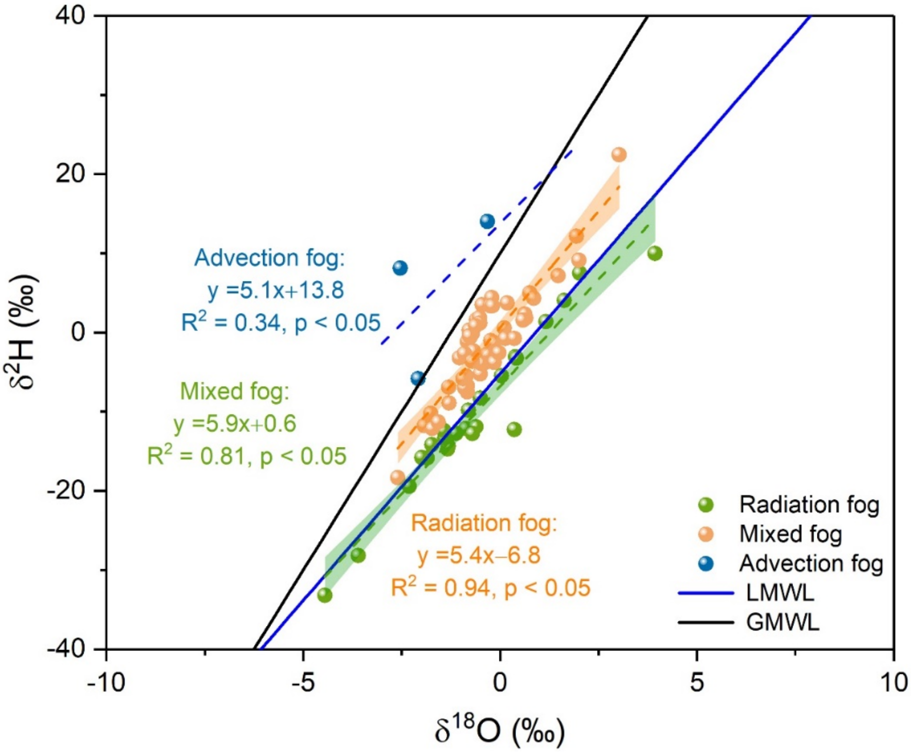

355 **Figure 10: Dual-isotope plot of radiation fog, mixed fog, and advection fog in June−July 2016 and 2017 from all 13 stations across the central Namib Desert.**

4 Data availability

360 The data and metadata have been deposited at Pangaea (https://www.pangaea.de/), a service provided by Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research (AWI), and the Center for Marine Environmental Sciences, University of Bremen (MARUM). The Digital Object Identifier (DOI) of the decade-long isotope dataset of rainfall and non-rainfall waters in the central Namib Desert is https://doi.pangaea.de/10.1594/PANGAEA.981180 (Li et al., 2025b). Additionally, the DOI of the historical water availability at Gobabeb is https://doi.pangaea.de/10.1594/PANGAEA.981208 (Li
365 et al., 2025c). The information on site metadata can be found in Fig. 1 and Table 1.

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5 Discussion

Drylands are critical components of the Earth System, and dryland dynamics are strongly controlled by water availability. However, long-term ground-based observations of hydrological inputs remain scarce in most dryland ecosystems. Here, we provide foundational and unique ecosystem data on the water cycle, including both rainfall and non-rainfall components, in hyper-arid desert environments. A decade-long (2014−2023) event-based isotope dataset from Gobabeb and a two-month spatial fog isotope dataset (2016−2017) from the central Namib Desert can offer novel insights into the spatiotemporal variability of rainfall and non-rainfall water sources and their role in sustaining this hyper-arid ecosystem. These long-term isotope datasets are particularly exceptionally rare and unique in dryland environments, where continuous, high-resolution isotope records of non-rainfall water inputs are largely absent (Kaseke et al., 2017; Yuan and Li, 2023). This isotope dataset establishment marks a significant advancement in dryland hydrological research, providing an invaluable resource for understanding sources, pathways, and transformations of water within atmospheric and hydrological patterns in water-limited landscapes (Scholl et al., 2011; Feigenwinter et al., 2020; Diersing et al., 2025). Moreover, these datasets enhance our understanding of how different water sources interact with biotic and abiotic processes, contributing to the broader hydrological cycle in global arid regions (Wang et al., 2017; Kidron and Starinsky, 2019; Sun et al., 2024).

Climate projections for the region indicate potential shifts in coastal water resource regimes due to global warming and natural climate variability (Seely and Henschel, 1998; del Río et al., 2018; Andersen et al., 2019; del Río et al., 2021; Wang et al., 2022). The long-term record of water availability at Gobabeb, including fog and rainfall amounts and Kuiseb River flooding occurrences, offers a valuable framework for assessing historical water variability in the context of global climate change. The combination of an extensive isotope dataset with long-term water availability records can significantly enhance its value for evaluating climate variations on the availability and variability of local water resources (Bengtsson, 2010; Bowen et al., 2019). Additionally, integrating isotope monitoring with remote sensing products further strengthens this approach by enabling spatiotemporal assessments of moisture sources, transport pathways, and atmospheric water dynamics (Andersen et al., 2019; Spirig et al., 2019). Furthermore, the availability of hourly meteorological data from eight permanent stations across the central Namib Desert during the study period (2014–2023) offers a valuable opportunity for complementary analyses. Researchers can leverage these data to refine models of fog and precipitation dynamics, assess spatial heterogeneity in water inputs, explore the influence of atmospheric circulation patterns on local moisture regimes, and provide valuable insights to policymakers for improving water resource management under global warming. The synchronous access to these meteorological datasets via https://sasscalweathernet.org/w_datarequest_we.php?MIsoCode=NA&MMCS=0#StationAnchor can also facilitate cross-disciplinary investigations, enabling a more comprehensive evaluation of climate-induced changes in such a hyper-arid desert ecosystem.

Integrating stable isotope datasets into regional and global hydrological models can improve the accuracy of water budget estimations in dryland ecosystems (Wang et al., 2012; Dee et al., 2023). Furthermore, sustained monitoring and the incorporation of isotope-based observations with climate models are essential for making robust and quantitative predictions of future changes in water availability and their ecological implications (Bowen et al., 2019). Although large-scale isotopic datasets of precipitation, surface water, groundwater, vapor, and tap water have expanded rapidly over the past two decades (Araguasaraguas et al., 1995; Evaristo and McDonnell, 2017; Tian et al., 2020; Nelson et al., 2021), a comprehensive global isotope monitoring network that encompasses both rainfall and non-rainfall water inputs in dryland ecosystems remains absent. The lack of a global non-rainfall water isotope monitoring network remains a significant limitation in quantifying the relative contributions of fog, dew, and rainfall to dryland water balances (Yuan and Li, 2023). Our study underscores the need for standardized and long-term isotope monitoring frameworks to improve predictive hydrological models. The uniqueness of our dataset provides an invaluable baseline for future research on dryland water cycling, offering insights that can be applied to other arid environments worldwide. Such efforts would provide essential data to inform sustainable water management strategies, particularly in water-scarce environments where non-rainfall water plays a critical role.

6 Conclusions

This comprehensive hydrological database integrates long-term (2014−2023) and spatially distributed (~1700 km^2) isotope measurements of both rainfall and non-rainfall water resources across the central Namib Desert. In this dataset, we included a total of 784 event-based water isotope observations collected during the period 2014−2023 in the study area. Additionally, it also presents long-term monthly fog and rainfall amounts, along with the annual Kuiseb River flooding occurrences over the past six decades (1963−2023). This dataset can enhance our understanding of dryland water cycle dynamics, particularly in non-rainfall-dependent ecosystems like the central Namib Desert. The crucial role of fog and dew in sustaining biological and ecological functions reinforces the need for continued monitoring efforts. The rarity and uniqueness of our long-term dataset make it an essential resource for future studies investigating hydrological processes in drylands and their responses to climate change. We further underscore the need for standardized and long-term non-rainfall water isotope monitoring frameworks in arid regions. Establishing such a globally coordinated non-rainfall water isotope monitoring network would also facilitate cross-regional comparisons and improve our ability to predict dryland responses to climate variability. The insights gained from this database contribute to the broader understanding of hydrological processes in arid environments and provide a foundation for more effective climate adaptation strategies in water-limited and non-rainfall-dependent regions.

Author contributions. YL and LW conceived the idea of the study, EM and LW collected and processed the data, YL wrote the manuscript, and EM and LW edited the manuscript. All authors contributed to the manuscript discussion and revision.

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

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