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Dataset of Stable Isotopes of Precipitation in the Eurasian Continent

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Abstract: Stable isotopes in precipitation can effectively reveal the process of atmospheric water circulation, serving as an effective tool for hydrological and water resources research, climate change, and ecosystem studies. The scarcity of stable isotope data in precipitation has hindered comprehension of regional hydrology, climate, and ecology due to discontinuities on a temporal scale and unevenness on a spatial scale. To this end, we collated stable hydrogen and oxygen isotope data in precipitation from 1930 stations in Eurasia from 1961 to 2022, totalling 51,752 data records. Stable isotopes in precipitation across various regions of Eurasia, as a whole, decrease with increasing latitude and distance from the coast. In the summer, stable isotopes in precipitation are relatively enriched, while in winter, they are relatively depleted. In recent decades, the stable isotope values of Eurasian precipitation show an overall trend of increasing variation with the advancement of years, which is associated with global warming. Geographical location, underlying surface conditions, seasons, and atmospheric circulation are all factors that determine the characteristics of stable isotopes in precipitation. The dataset of stable isotopes in Eurasian precipitation provides a powerful tool for understanding changes in regional atmospheric water circulation and assists in conducting hydrological, meteorological, and ecological studies in related regions.

Keywords: Eurasian Continent, Climate Change, Stable Isotopes in Precipitation, Atmospheric Circulation, Dataset.

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Introduction

In recent years, the impacts of global climate change have become increasingly severe, particularly the significant increase in the frequency of various types of extreme weather and climate events (Faranda et al., 2023; Liu et al., 2022; Zhang et al., 2016). The World Meteorological Organization's 2022 report on the state of the climate in Asia shows that the rate of warming in Asia is higher than the global average, with droughts, floods, and heatwaves affecting most parts of the world (State of the Climate in Asia 2022). Severe fluctuations in climatic elements can alter water circulation processes, affect development trends of climate change, and even change the evolutionary patterns of ecological environments. Among these, stable isotopes in precipitation are an excellent comprehensive tracer, playing an important role in revealing water cycle processes, climate change information, and mechanisms of water resource use in ecosystems (Bowen et al., 2019; Wang et al., 2022). Therefore, in the face of increasingly complex climate conditions, we need more comprehensive data on stable isotopes in precipitation at various spacetime scales to help understand climate change phenomena.

Stable isotopes in precipitation are intermediate variables in isotope hydrological cycles. They are influenced by factors such as temperature, precipitation, wind speed, relative humidity, and the source of water vapour (Gat, 1996; Jiao et al., 2020). In atmospheric water vapor and precipitation, non-equilibrium fractionation and equilibrium fractionation cause different degrees of variation in δ^2H and δ^{18}O during phase changes (evaporation, condensation) (Craig, 1961). Fractionation is constrained by surrounding climatic conditions, causing hydrogen and oxygen stable isotopes in precipitation to carry a wealth of climate information in their changes. For example, effects like temperature, precipitation volume, and elevation (Dansgaard, 1964; Ma et al., 2023). The "temperature effect" implies that as temperature increases, the values of δ^2H and δ^{18}O gradually increase. This effect is the most prevalent influence on stable isotopes in precipitation; spatial "elevation" and "latitude" effects can be attributed to "temperature effects". Moreover, seasonal variations in stable isotopes in precipitation are also temperature-dependent. Rainfall has a more pronounced effect on hydrogen and oxygen stable isotopes in precipitation in low-latitude areas, often associated with abundant precipitation. The deuterium excess (d-excess = δ^2H - 8× δ^{18}O) reflects the source of water vapour and atmospheric moisture conditions, largely affected by relative humidity, with an average deuterium excess of around 10‰ from oceanic water vapour (Dansgaard, 1964). The complexity of influencing factors determines the diverse applications of stable isotopes in precipitation. The signals of hydrogen and oxygen stable isotopes in precipitation can be recorded by geological carriers (ice cores, tree rings, loess, cave stalactites, etc.) (Eastoe and Dettman, 2016). They provide essential archives for describing historical climate change and water cycles, useful for paleoclimate reconstruction, especially the reconstruction of monsoon climates (Caley et al., 2014). Additionally, stable isotopes in precipitation can identify extreme weather events to understand their water vapour sources and mechanisms (Zhao et al., 2023). The composition of hydrogen and oxygen isotopes in precipitation can be used to infer the proportions of plant transpiration water vapour, surface evaporation water vapour, and advection water vapour (Zhu et al., 2019). Spectral remote sensing technology has advanced the capability to obtain large-scale water vapour stable isotope data through satellite inversion (Shi et al., 2022; Wei et al., 2019), deepening the cooperative effect with stable isotopes in precipitation and yielding good results in meteorological and hydrological research in low-latitude regions. Incorporating stable isotopes in precipitation into atmospheric circulation models has improved our understanding of future climate change. Also, coupling stable isotopes in precipitation with hydrological models reduces model uncertainty (Delavau et al., 2017; Nan et al., 2021; Nelson et al., 2021).

In 1961, the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO) began establishing the Global Network for Isotopes in Precipitation (GNIP), which is the world's primary observation system. To date, research on stable isotopes in precipitation primarily relies on the GNIP database. However, GNIP's observations are very unevenly distributed in time and space. Global and regional-scale research on stable isotopes in precipitation mainly depends on model simulations. The relationship between predicted data from models and actual measured data is "comparative". Although model simulations can compensate for the absence of measured data and are particularly advantageous in revealing the operating mechanisms of large-scale climate systems and water cycles, existing models for stable isotopes in precipitation are often insufficiently accurate. They cannot check long-term trends or characteristics of interannual variation. By integrating independent data to provide a higher density of data, it's possible to enhance the precision of model simulations.

We have compiled precipitation stable isotope data from the Eurasian continent since 1961 with the aim of providing more comprehensive data support for the following research areas：

Climate research: Precipitation-stable isotopes exhibit geographical and seasonal variations, which can be used to study climate change and the impact of solar radiation. By comparing and analyzing the stable isotopes of precipitation in different regions of the Eurasian continent, long-term climate trends can be revealed, such as changes in precipitation distribution and the evolution of monsoon systems.

Earth system research: Precipitation stable isotopes are not only influenced by climate and water cycle but also by geological and biological processes. By integrating precipitation stable isotope data from the Eurasian continent, it is possible to investigate in-depth the interactions between different components of the Earth system, such as the interaction between the atmosphere and the ocean, and the water cycle in terrestrial ecosystems. This will contribute to a better understanding of the functioning and changes of the Earth system.

Water cycle research: Precipitation-stable isotopes serve as important indicators of the water cycle and can track the sources, evaporation, and precipitation processes of water. By analyzing the spatial distribution and variations of precipitation stable isotopes on the Eurasian continent, it is possible to understand the processes of water evaporation, precipitation, and recycling, revealing the patterns of water resource distribution and changes. This provides support for water resource management and hydrological modelling.

Paleoclimate reconstruction: Precipitation-stable isotopes exhibit long-term variations, making them useful for reconstructing past climate changes. By analyzing the chronological sequences of precipitation-stable isotopes on the Eurasian continent, it is possible to study paleoclimate changes and ancient environmental evolution, such as changes in precipitation during ice ages, variations in monsoon intensity, and more. This provides historical references and predictions for understanding modern climate change.

1. Study area

The Eurasian continent (10°45'N - 77°44'N, 9°30'W - 169°45'E) spans a vast territory,

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with considerable variations in natural geographic conditions within the region (Fig.1). Significant thermal differences between sea and land have given rise to a typical monsoon climate system on the southeast coast, while interactions between Atlantic moisture and planetary wind systems result in the west coast and wide inland areas being perennially subject to westerly moisture. These two major systems play significant roles in global climate systems (Li et al., 2022; Wang et al., 2010). Moreover, the interactions across multiple heat zones with sea and land provide conditions conducive to a wide variety of climate types. The uplift of the Qinghai-Tibet plateau not only alters the climate patterns dominated by the planetary wind system on the Eurasian continent and the moisture movement paths in the Indian Ocean (An et al., 2001) but also changes the natural surface conditions, such as the numerous rivers including the Yangtze, Yellow, Ganges, and Mekong Rivers, which play a vital role in hydrological processes and human life. The plateau itself forms a relatively complete vertical ecological environment differentiation, enhancing the complexity of the natural environment on the Eurasian continent. Therefore, the research data and studies on climate environmental changes in Eurasia hold significant representativeness in addressing global changes.

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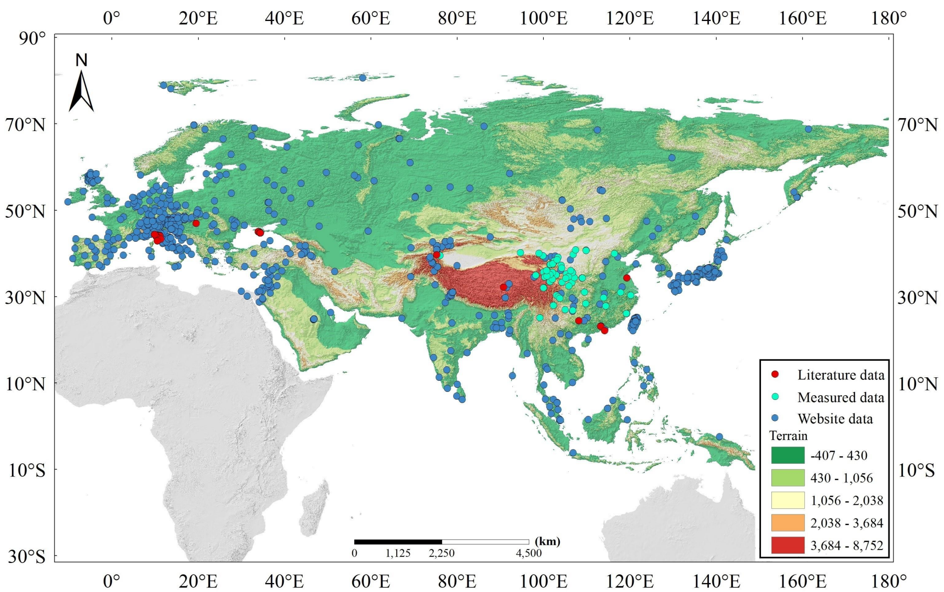

Fig.1 Distribution map of precipitation stable isotope sampling sites in the Eurasian continent

3. Data and methodology

3.1 Data sources and collection

We have collected $\delta^{18}O$ and δ^2H stable isotope data from precipitation at 1,930 sampling points across the Eurasian continent from 1961 to 2022. The dataset includes both measured data and data collected from various sources. The collected data mainly come from the Global Network of Isotopes in Precipitation (GNIP) and the Water Isotope Network operated by the International Atomic Energy Agency (IAEA) (https://waterisotopes.utah.edu/waterisotopes/index.html). In this study, we have compiled a total of 45,782 data records, including 3,676 records from literature sources. The measured data were collected, analyzed, and organized at the Shiyang River Basin Integrated Observation Station of Northwest Normal University in China, comprising 2,297 data records. Additionally, meteorological data used in this study are from the CRU TS v. 4.07 dataset (Harris et al., 2020) and the NCEP-NCAR Reanalysis 1 dataset (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html).

3.2 Data processing steps and quality control

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Data Collection: The data collected includes a variety of issues such as missing values, outliers, and duplicates, as well as gaps in dates and missing or incorrect latitude and longitude information. Therefore, the collected raw data underwent preprocessing and data cleaning. Missing data was interpolated, entries that could not be completed were removed, and duplicate data was eliminated.

Measured Data: Standard rain gauges were used to collect precipitation samples. After each precipitation event, the collected samples were immediately transferred into 100ml high-density sample bottles. To prevent data errors caused by evaporation, the collected water samples were stored in a refrigerator at a temperature of approximately 4°C. Prior to analysis, the precipitation samples were naturally thawed at room temperature. Impurities were filtered out using a 0.45μm filter membrane, and the samples were transferred to 2ml sample bottles. Isotope values were measured using a liquid water isotope analyzer (DLT-100, Los Gatos Research, USA). For any abnormal or values that did not pass the LWIA post-analysis software check, parallel samples were selected for re-measurement to ensure data accuracy (Zhu et al., 2022). The isotopic abundances of ^{18}O and ^{2}H were expressed using the δ notation relative to the International Atomic Energy Agency (IAEA) Vienna Standard Mean Ocean Water (V-SMOW) reference, following the equation:

$$\delta_{\text{sample}}(‰) = [\frac{R_{sample}}{R_{V-smow}} - 1] \times 1000$$

Here, R represents the ratio of the heavier isotope to the lighter isotope (i.e., $^{18}O/^{16}O$ or $^{2}H/^{1}H$). We used the International Atomic Energy Agency (IAEA) standard (V-SMOW2) to validate our isotope measurements, ensuring comparability between isotopic measurements across laboratories and instruments.

In 1982, Ferronsky VI and Polyakov VA conducted a study that found a general distribution of $\delta^{18}O$ and $\delta^{2}H$ values in natural substances, indicating that the range of stable isotope values for hydrogen and oxygen in atmospheric precipitation is typically -400‰ to -30‰ and -60‰ to 10‰, respectively (Ferronsky VI et al., 1982). After data processing, the data generally falls within the reasonable range.

Furthermore, the data has also undergone normality testing, the Mann-Kendall trend test, and change point detection. The results of the Kolmogorov-Smirnov (K-S) test, which

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examines the goodness of fit by comparing observed frequencies with expected frequencies, are not significant, indicating that the data does not strictly follow a normal distribution. However, the histogram of the data distribution and measures of skewness and kurtosis suggest that the data approximately follows a normal distribution. The Mann-Kendall trend test indicates an overall upward trend in the data over the long-term time series. Additionally, the UFK-UBK curve exceeds the 95% confidence interval, indicating that the trend test is not significant. This is mainly due to the increased seasonality and variability of stable isotopes in precipitation, which contribute to the data's non-stationarity. The Mann-Kendall change point test detected three significant change points.

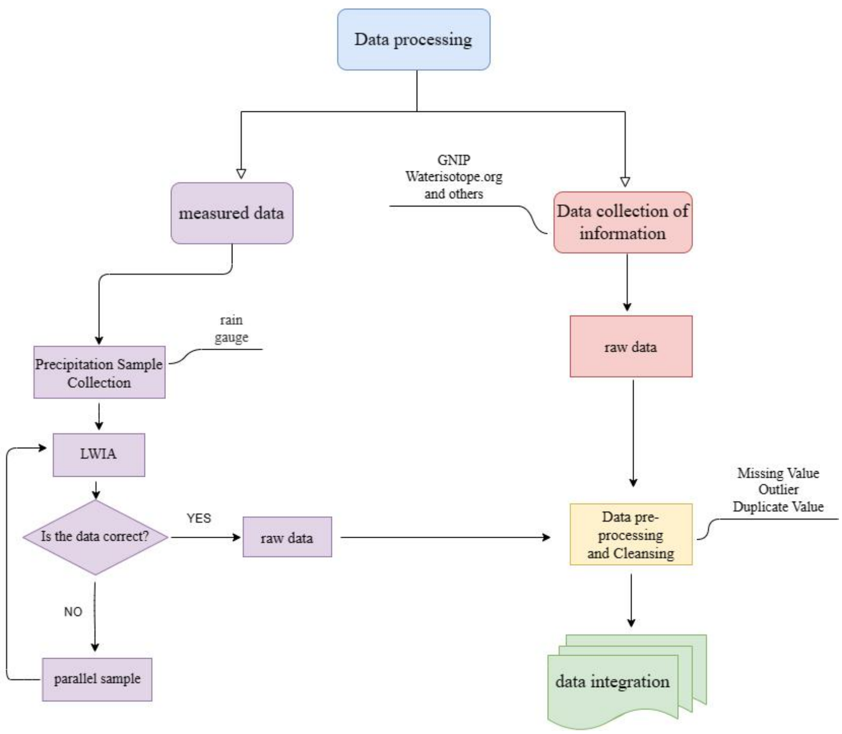

Fig.2 Flowchart of precipitation stable isotope dataset construction

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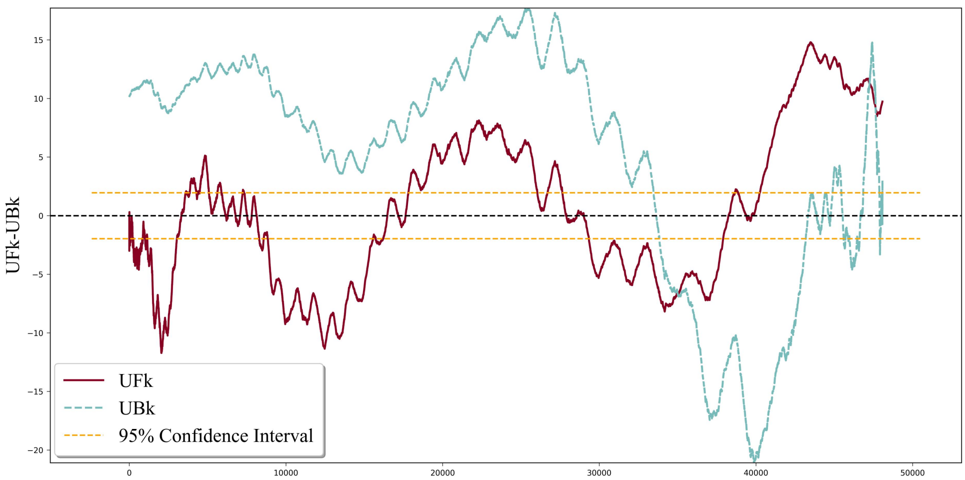

Fig.3 The Mann-Kendall (MK) test for time series analysis.

4. Results and discussion

4.1 Temporal and Spatial Variation Characteristics of Precipitation Stable Isotopes

The hydrogen and oxygen stable isotopes in precipitation on the Eurasian continent range from -332.4‰ to 62.05‰ and -41.4‰ to 23.18‰, respectively. The lower values of stable isotopes reflect both high-altitude and high-latitude regions in terms of spatial distribution. On a temporal scale, they also exhibit seasonal differences, with higher values in summer and lower values in winter (Fig.4). The stable isotopes in precipitation on the Eurasian continent show fluctuations influenced by seasonal factors. Since the 1960s, extreme values of stable isotopes in precipitation have increased over time, indicating the intensification of instability in meteorological elements such as temperature and precipitation. This trend also suggests that the climate environment in the Eurasian continent is experiencing an increase in extreme events under the backdrop of global change. As we face a changing climate environment, the arid region of Central Asia has undergone a warming and moistening process since the 1990s. This is characterized by increasing temperatures and precipitation in the arid region, and even the occurrence of intense floods (Wei et al., 2023). The response of stable isotopes in precipitation to extreme weather events is evident. For example, stable isotopes in precipitation can explain the origin and intensification of extreme rainfall events in Mumbai (Ansari et al., 2020). Stable isotopes in precipitation can detect

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changes in climate and weather anomalies, providing us with valuable information in long-term climate research.

From a spatial perspective, the stable isotopes in precipitation on the Eurasian continent are influenced by an " elevation effect". The hydrogen and oxygen stable isotope values gradually decrease from low to high latitudes (Fig.5). The multi-year average values of δ^2H and δ^{18}O at different latitudes are as follows: from 0°N to 30°N, -30.20‰ and -5.99‰, from 30°N to 60°N, -58.94‰ and -8.77‰, and from 60°N to 90°N, -92.98‰ and -12.69‰. Temperature is the dominant factor influencing the variations in stable isotopes in precipitation on the Eurasian continent. In Southeast Asia, which is influenced by tropical rainforest and monsoon climates, the high temperatures and humidity enhance the "precipitation effect" on stable isotopes. In contrast, regions such as the Arabian Peninsula and Central Asia, under desert climate conditions, experience high temperatures and low rainfall, leading to enhanced evaporative fractionation and the "sub-cloud evaporation" effect, resulting in larger values of stable isotopes in precipitation (Zhu et al., 2021). Additionally, low values of stable isotopes in precipitation are observed in the Qinghai-Tibet Plateau and the Alps in the mid-latitude regions. Overall, these variations are still influenced by temperature. The spatial distribution of topographic features also affects the composition of stable isotopes in precipitation. Compared to regions at the same latitude, the high values of stable isotopes in precipitation extend to higher latitudes along the western coast of the Eurasian continent, indicating higher temperatures in most parts of Europe at the same latitude, especially in coastal areas near the North Pacific. Both regional and global water cycles follow the principle of water balance. With increasing temperatures, the "low-value zones" of stable isotopes in precipitation at high latitudes and altitudes will be more strongly influenced. The substantial reduction of Arctic sea ice is a well-known climate change event (Ding et al., 2017). Additionally, vegetation transpiration and water evaporation will enhance atmospheric water vapour content. The impacts of these changes will be multifaceted, potentially alleviating drought conditions in some regions while intensifying extreme precipitation events, leading to severe climate disasters.

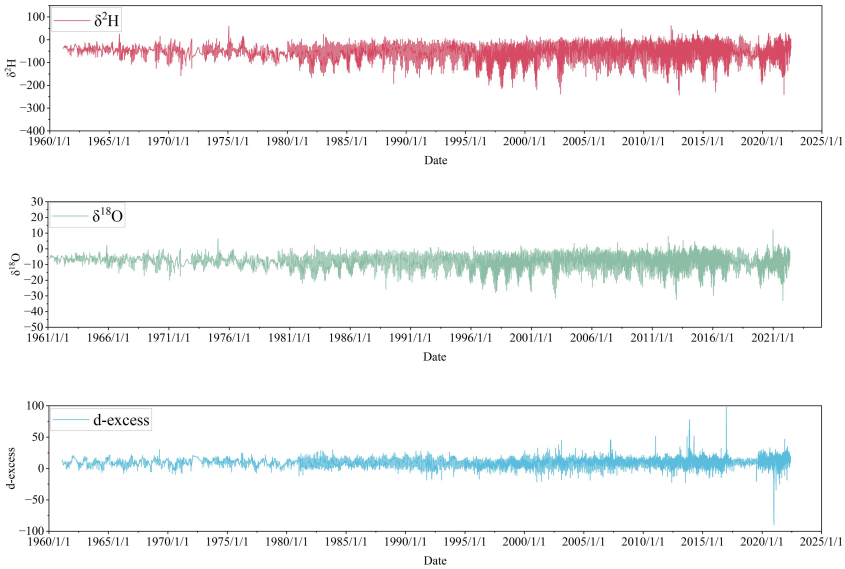

Fig.4 The time series variations of δ^2H, $\delta^{18}O$, and d-excess in the Eurasian continent.

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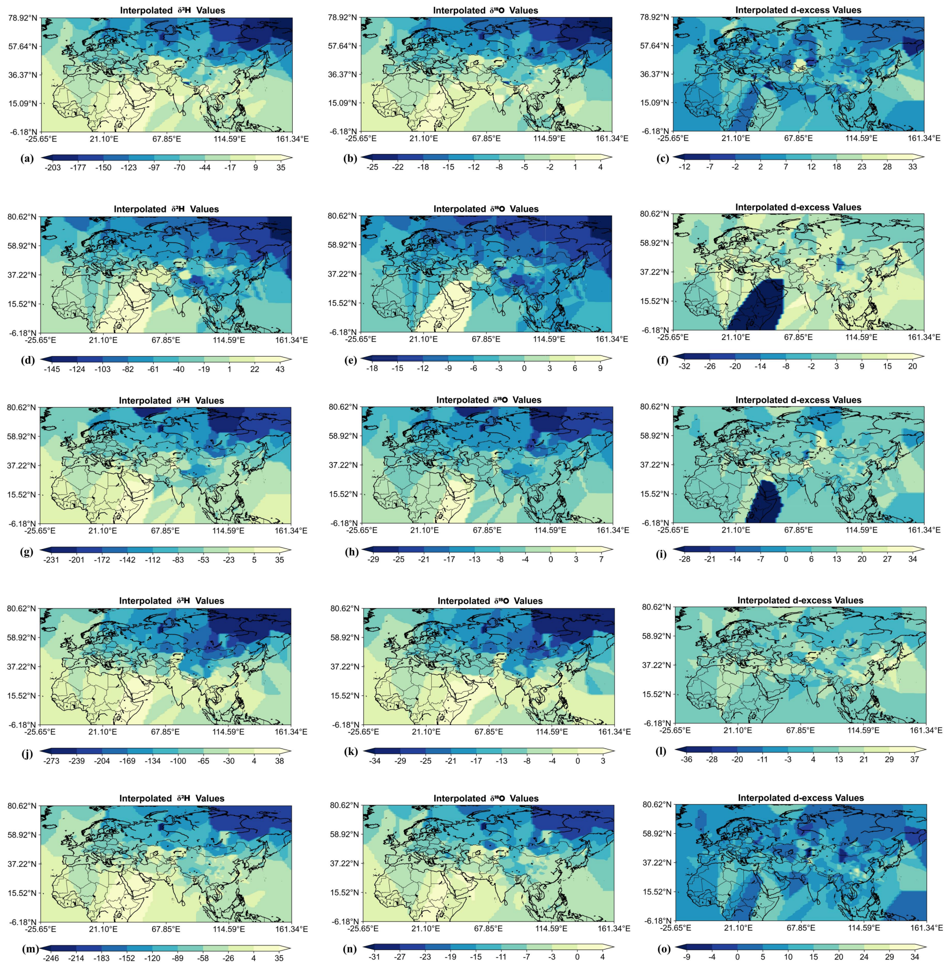

Fig.5 The spatial variations of δ²H, δ¹⁸O, and d-excess in the Eurasian continent. Panels (a), (b), and (c) display the spatial distribution of isotope values in the spring season. Panels (d), (e), and (f) show the spatial distribution of isotope values in the summer season. Panels (g), (h), and (i) present the spatial distribution of isotope values in the autumn season. Panels (j), (k), and (l) exhibit the spatial distribution of isotope values in the winter season. Panels (m), (n), and (o) display the spatial distribution of isotope values averaged over multiple years.

4.2 Seasonal changes in atmospheric precipitation lines and precipitation stable isotopes

The temporal and spatial variations of stable isotopes in precipitation are significantly influenced by meteorological factors, showing a high level of consistency with the climate regions they are in. Therefore, we classified the 12 climate zones in Eurasia according to the

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Köppen climate classification and used the least squares method to fit the atmospheric precipitation lines (Fig.6). Köppen initially divided the world into five climate zones, with four of them based on temperature (Beck, H.E., et al., 2018). These include the equatorial climate zone (represented by A), the warm-temperate climate zone (represented by C), the cold-temperate climate zone (represented by D), and the polar climate zone (represented by E). All arid regions were separately classified as a climate zone, known as the dry climate zone (represented by B). The atmospheric precipitation lines for different climate types show that the tropical climate in type A exhibits relatively small differences in precipitation compared to other climate types. The variation in slope and intercept of the atmospheric water lines is determined by the combined effects of precipitation amount and temperature, with convective precipitation weakening the influence of temperature effects. Types B and C climates exhibit lower slopes and intercepts in their atmospheric precipitation lines. Stable isotopes in arid climates are influenced by secondary evaporation below the clouds, resulting in strong fractionation processes and relatively enriched stable isotopes in precipitation. Under temperate climate conditions, the differences in stable isotope composition among different climate regions become greater. In the Mediterranean region, which is controlled by the Cs climate (summer-dry, warm), the slope and intercept are the lowest, indicating that temperature increase dominates the hydrogen and oxygen stable isotope fractionation in precipitation, suggesting a tendency towards aridity in this region under long-term average conditions. In polar climates, the atmospheric precipitation lines exhibit higher slopes and intercepts. In the polar climate environment, the influence of unbalanced fractionation processes after the condensation of water vapour within cloud systems is relatively small, resulting in a slope that is closer to 8. The differences in stable isotopes of precipitation among different climate types indicate the relationship between precipitation and temperature. The characteristics of high temperatures and low rainfall create a dry atmospheric environment, and enhanced evaporation leads to a lower slope due to increased unbalanced fractionation processes.

The seasonal variation of hydrogen and oxygen stable isotopes in precipitation on the Eurasian continent generally exhibits a pattern of higher values in summer and lower values in winter (Fig.7). The d-excess, which represents the deviation of the deuterium excess from

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the global average, is lower in summer and higher in winter, indicating seasonal changes in the source and transport distance of water vapor (Zhang et al., 2021). Furthermore, there are regional differences in the seasonal variation of d-excess. This overall suggests that the summer climate in the Eurasian continent is more humid, while the winter climate is drier. However, the d-excess values, relative to δ^2H and $\delta^{18}O$, exhibit a more stable pattern and are distributed around the global average. This indicates that the moisture in the vast regions of the Eurasian continent is strongly influenced by oceanic water vapour. The state of the oceans and large-scale atmospheric circulation changes can have a profound impact on the climate environment of the Eurasian continent.

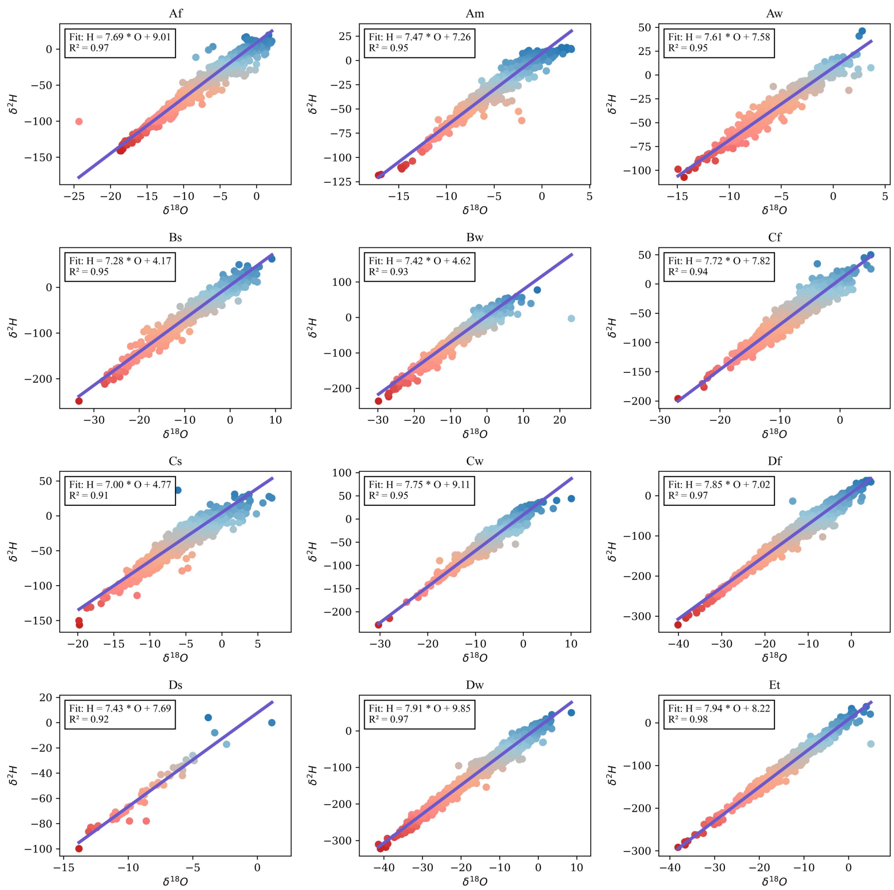

Fig.6 Different atmospheric precipitation lines in various climate zones. The subgraph titles represent the following climate zones: Af for Tropical Rainforest Climate, Am for Tropical Monsoon Climate, Aw for Tropical Savanna Climate, Bs for Steppe Climate, Bw for Desert Climate, Cf for Temperate Oceanic Climate, Cs for Mediterranean Climate, Cw for Humid Subtropical Climate, Df for Continental Subarctic

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Climate, Ds for Subarctic Continental Climate, Dw for Subarctic Monsoon Climate, and Et for Tundra Climate.

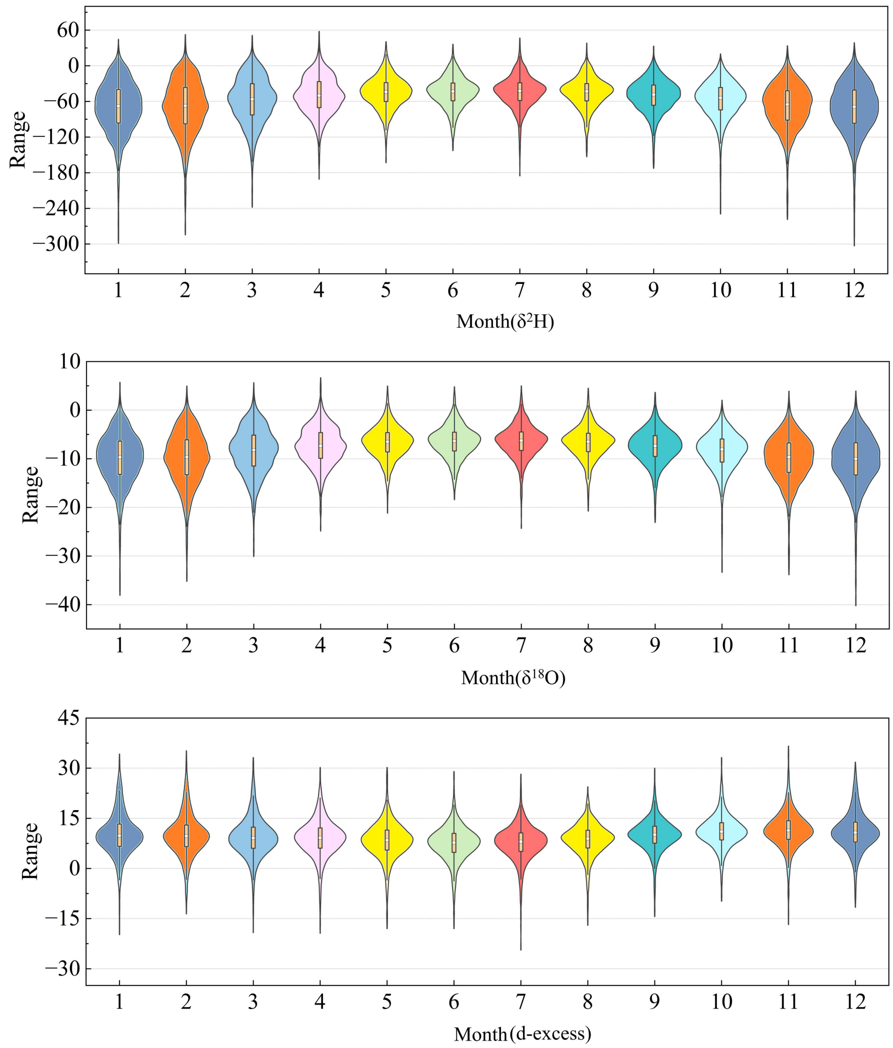

Fig.7 Seasonal Distribution and Variations of Stable Isotopes in Precipitation

4.3 Drivers of stable isotope variation in precipitation in Asia and Europe

Meteorological variables accompany the fractionation process of stable hydrogen and oxygen isotopes in precipitation, impacting the composition of stable isotopes (Sun et al., 2019). We utilized a random forest regression model to assess the importance of

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meteorological variables in the Eurasian continent on stable isotopes. Random forest regression is a non-parametric method used to solve prediction problems. It predicts regression problems based on the average results of random decision trees, which use bootstrapping to eliminate the possibility of overfitting (Erdélyi et al., 2023). The random forest regression analysis of the fitted stable isotopes of hydrogen and oxygen showed good goodness of fit for both the training and testing sets, indicating that temperature, precipitation, potential evapotranspiration, vapour pressure, wind speed, and relative humidity have a high explanatory power for stable isotopes of hydrogen and oxygen (Fig.8). The composition of stable isotopes in precipitation is greatly influenced by meteorological variables. However, due to the spatial resolution of reanalysis meteorological data, the resampling process of meteorological variables increased the repetition values, resulting in an improved variance explanation rate for the dependent variable. Among the six variables considered, temperature has the strongest explanatory power for the variation of stable isotopes of hydrogen and oxygen, and potential evapotranspiration also has a relatively strong explanatory ability, indicating that temperature change primarily drives the variation of stable isotopes in precipitation in the Eurasian continent. The relative humidity is the ratio of actual vapour pressure to saturated vapour pressure, but there is a significant difference in the explanatory power of vapour pressure and relative humidity on stable isotopes. Vapour pressure has a wider range of variation in the atmosphere, thus it may have greater variability in the regression model, leading to a larger impact on predicting stable isotopes in precipitation. Relative humidity, on the other hand, is a relative indicator with a relatively smaller range of variation, so it may have a weaker predictive ability for stable isotopes in precipitation in the regression model. The driving factors for the variation of stable isotopes in precipitation in the Eurasian continent include climate change, seasonal variations, topography and landforms, as well as water cycle processes, which collectively influence the isotopic composition of precipitation. Atmospheric circulation directly affects the source of water vapor and the path of moisture, while other factors primarily influence the composition of stable isotopes in precipitation by altering temperature. For example, potential evapotranspiration plays a crucial role in explaining the variation of stable isotopes in precipitation. However, the control of meteorological variables on stable isotopes in precipitation varies between regions. Studies

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on two precipitation stations in Crimea have shown weak correlations between temperature, precipitation, and stable isotopes in precipitation. The complex natural environment determines that no single factor has a dominant control over the stable isotopes in precipitation in that region, and the composition of stable isotopes in precipitation is influenced by both local and distant factors (Dublyansky et al., 2018). In the eastern coastal region of China, the relative enrichment of stable isotopes in precipitation is due to the proximity to the evaporative source of the ocean, leading to an increased abundance of heavy isotopes (Zhang et al., 2021). In the arid region of central Asia, there is a strong correlation between stable isotopes in precipitation and temperature, and the enrichment or depletion of stable isotopes in precipitation reflects the trend of temperature change (Zhu et al., 2023). In summary, the meteorological control factors of the composition of stable isotopes in precipitation vary in different regions. There is a strong relationship between stable isotopes in precipitation and meteorological variables, and stable hydrogen and oxygen isotopes may be considered essential climate response variables, which will contribute to describing the hydrological cycle and better predicting the response of future climate change and ecosystem changes.

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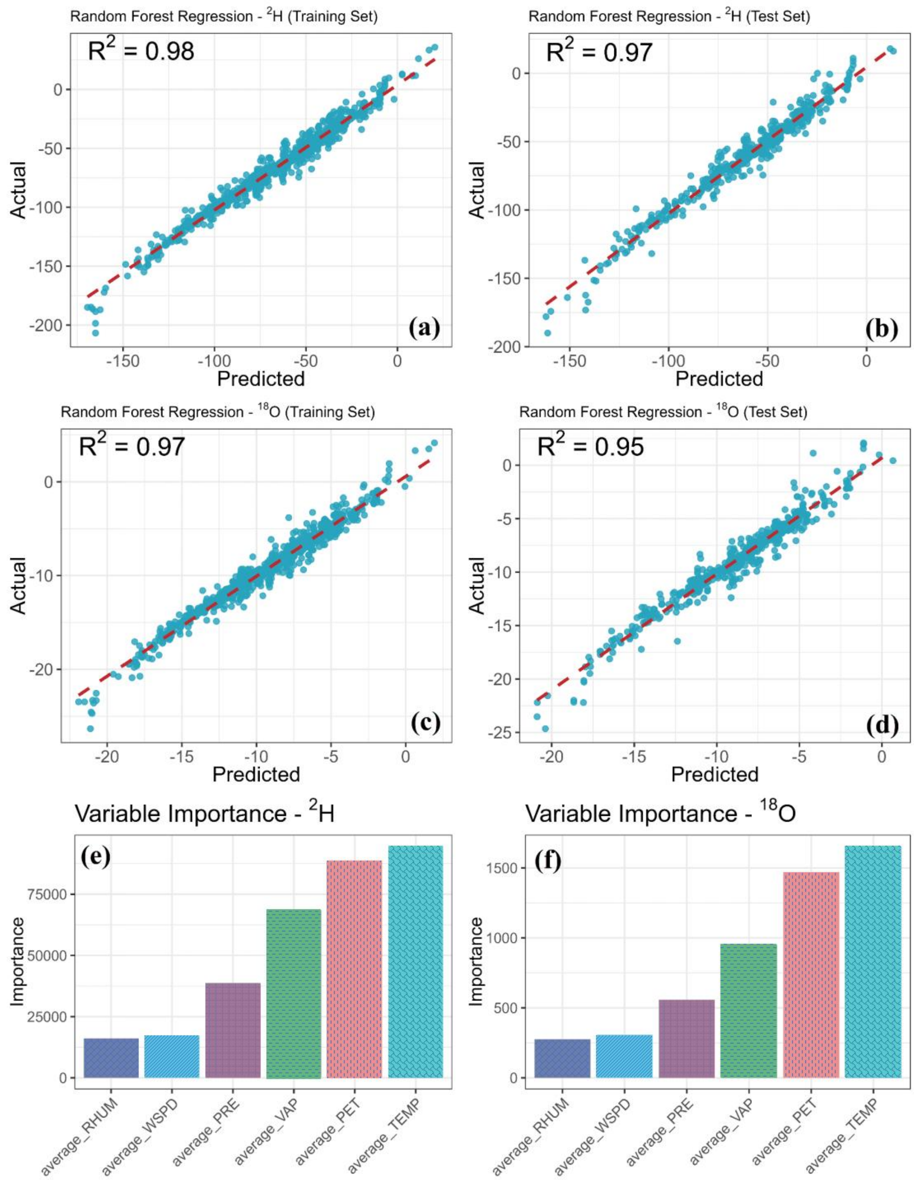

Fig.8 Results of Random Forest Regression Analysis for δ^2H and δ^{18}O in Relation to Meteorological Variables.a: Regression results for the training set of δ^2H, b: Regression results for the testing set of δ^2H, c: Regression results for the training set of δ^{18}O, d: Regression results for the testing set of δ^{18}O, e: Importance of meteorological variables for δ^2H, f: Importance of meteorological variables for δ^{18}O

Data Availability

Zhu, Guofeng (2023), “Dataset of Stable Isotopes of Precipitation in the Eurasian Continent”, Mendeley Data, V1, doi: 10.17632/rbn35yrbd2.1

Author contribution Statement

Longhu Chen: Conceptualization and Writing-Original draft preparation; Qinqin Wang: Writing and Data processing; Guofeng Zhu: Writing review and editing; Xinrui Lin: Modification; Dongdong Qiu: Modification; Yinying Jiao: data processing; Siyu Lu: Experiment; Rui Li: Methodology; Gaojia Meng: Visualization; Yuhao Wang: Visualization.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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