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Open Access Earth System Science Data Discussions

Integration of global precipitation stable isotope data

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Abstract: Precipitation plays a crucial role in the hydrological cycle and is vital for water resources management, climate change research, and ecosystem conservation. Precipitation stable isotopes serve as the "fingerprints" of precipitation, which can clearly trace the formation, transport, and subsequent processes of precipitation. However, due to the scarcity of precipitation stable isotope data, we face challenges of temporal discontinuity and spatial heterogeneity when studying it at large to medium scales. Therefore, we compiled precipitation hydrogen and oxygen stable isotope data ($\delta^{18}O$ and $\delta^{2}H$) from 2059 global sites spanning from 1961 to 2023, totaling 141,624 records. Our study indicates significant variations of global precipitation stable isotopes both spatially and temporally. Spatially, the isotopic composition of precipitation in different regions varies significantly due to factors such as geographical location, underlying surface conditions, and atmospheric circulation. Temporally, $\delta^{18}O$ and $\delta^{2}H$ show decreasing trends, while d-excess shows an increasing trend, with the impact of global temperature rise being very apparent. This precipitation stable isotope dataset provides robust support for our understanding of global precipitation changes and climate change. Through further investigation of precipitation stable isotope data, we hope to uncover more mechanisms and influencing factors of precipitation processes, providing a more accurate basis for the assessment and prediction of climate and water resource changes.

1. introduction

With the escalating global climate change, research on the impact of global water cycles and ecosystems on human society has become increasingly important (Anon, 2023; Intergovernmental

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Panel on Climate Change (IPCC), 2023). Precipitation is one of the core components of the Earth's water cycle, and its spatial and temporal variations are crucial for accurate climate modeling and water resources management (Konapala et al., 2020; Bevacqua et al., 2022). Stable isotope technology has become an indispensable tool for understanding hydrological processes. Through analysis of the hydrogen and oxygen isotopic ratios in precipitation, key information such as the source, formation mechanism, and transport pathways of precipitation can be revealed (Cropper et al., 2021; Aggarwal et al., 2016). However, there are currently issues with the global precipitation stable isotope data, such as dispersion, inconsistency, and low accuracy, limiting our in-depth understanding of global climate and hydrological processes. Therefore, this study aims to integrate global precipitation stable isotope data, construct a more comprehensive dataset, fill gaps in existing research, and enhance our understanding of the Earth's hydrological cycle.

During the process of the hydrological cycle, stable isotope fractionation occurs with the phase change of water (Gat, 1996). Light isotopes ($\delta^{16}O$ and $\delta^{1}H$) are more prone to evaporate, while heavy isotopes ($\delta^{18}O$ and $\delta^{2}H$) are more easily enriched (Craig, 1961; Dansgaard, 1964). This difference leads to changes in the isotopic ratios in precipitation, which can be used to trace the source of water and hydrological processes. The stable isotope ratios in precipitation are influenced by temperature, known as the "temperature effect" (Juan et al., 2020). Generally, lower temperatures result in lower abundances of $\delta^{18}O$ and $\delta^{2}H$ in precipitation. The "temperature effect" manifests in two aspects: (1) evaporation from water vapor sources is reflected in the stable isotopes of precipitation in the area (Diekmann et al., 2021), (2) secondary evaporation affects precipitation condensation within clouds before reaching the ground, leading to enrichment of precipitation stable isotopes (more pronounced in arid regions) (Wang et al., 2016). Moreover, an increase in precipitation leads to a decrease in the stable isotope ratios in precipitation, as heavier isotopes are more easily removed during the precipitation process. This phenomenon is particularly evident during long-distance water vapor transport in the atmosphere. Additionally, an increase in precipitation weakens the "temperature effect" of precipitation stable isotopes. The variation in precipitation stable isotopic composition is also influenced by water vapor transport (Toride et al., 2021; Lekshmy et al., 2022). On one hand, there is a "continental effect" in the variation of precipitation stable isotopic composition (Winnick et al., 2014). On the other hand, the reverse altitude effect of water vapor stable isotopes is also reflected in the variation of precipitation stable

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isotopes (Jing et al., 2022). This relationship makes stable isotopes a good proxy for climate. For example, precipitation stable isotopes are used to assess extreme weather events (Ansari et al., 2020; Lin et al., 2023).

The variations in precipitation isotopes can reveal multiple aspects of the water cycle, including the sources of precipitation, and the processes of evaporation and condensation. Thus, they are widely used in fields such as climate change research, hydrology, paleoclimatology, ecology, and geology (Zhang et al., 2021a; Caley et al., 2014). In climate change studies, stable isotopes of precipitation are used to track changes in past and present climate systems. By analyzing the isotopic ratios in ice cores, tree rings, and lake sediments (Jouzel et al., 1997), it is possible to reconstruct historical climate indicators such as temperature variations, precipitation levels, and evaporation intensity. This method provides an important tool for understanding the dynamics of the climate system, especially in interpreting past climate events in the context of global warming. The modern monitoring of precipitation stable isotopes began in 1961 with the observation network initiated by the International Atomic Energy Agency and the World Meteorological Organization (GNIP), which not only provides a powerful tool for understanding the current climate state but also validates reconstructions of past climates. Furthermore, isotope-supported atmospheric circulation models are becoming an important method for understanding modern and ancient climate changes (Bailey et al., 2018). The improvement of observational data is also clearly important for supporting the development of these models (Brady et al., 2019, p.1). In hydrology, stable isotope technology is used to study water cycle processes, such as the interactions between precipitation, surface water, and groundwater (Liberoff and Poca, 2023). Spatial and temporal variations in isotopic composition can help identify the sources and pathways of water, and assess the sustainability of water resources (Jiao et al., 2020). Through these isotopic studies, a deeper understanding of the dynamic changes in water resources and the complexity of the climate system can be achieved, providing a scientific basis for addressing environmental changes.

In this paper, we introduce the methods and data integration strategies employed in our study, including data sources, quality control, and statistical analysis. We present the constructed global dataset of stable isotopes in precipitation and provide preliminary analyses and validation of this dataset. Finally, we discuss the potential applications of the dataset and directions for future research, aiming to provide more reliable data support for global hydrological cycle studies and to offer

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scientific foundations for addressing climate change and managing water resources.

2. Data sources

This manuscript compiles global precipitation stable isotope data from 1961 to 2023, which includes both field-collected and gathered data types. The collected data is sourced from the International Atomic Energy Agency's (IAEA) Global Network of Isotopes in Precipitation (GNIP) and the Water Isotope Website (https://wateriso.utah.edu/waterisotopes/index.html), encompassing a total of 141,624 data records (Fig. 1). The field-collected data originates from various locations across China, sampled by the Shiyang River Basin Observatory and analyzed by the Isotope Laboratory at Northwest Normal University, totaling 2,921 data records. Additionally, the meteorological data used for analysis in this paper is from TerraClimate—a gridded dataset of global terrestrial surface monthly climate and atmospheric water balance from 1958-2022 (Abatzoglou et al., 2018, p.1958–2015), available at: https://www.climatologylab.org/terraclimate.html. Global average temperature data is provided by NASA's Goddard Institute for Space Studies (GISS). Marine meteorological data from NCEP-NCAR Reanalysis 1 and NOAA Extended Reconstructed Sea Surface Temperature (SST) V4.

3. Data processing steps and quality control

Data Collection: The collected data contained many missing values, anomalies, duplicate entries, as well as missing dates, and errors or absences in geographic coordinates (latitude and longitude). Consequently, the raw data was preprocessed and cleaned. Missing data was interpolated, and data entries that could not be completed, as well as duplicate data, were deleted.

Measured Data: Precipitation samples were collected using a standard rain gauge. Immediately after each precipitation event, the collected precipitation samples were transferred to 100ml high-density sample bottles. To prevent data errors due to evaporation, the collected water samples were stored in a refrigerator at approximately 4°C. At the start of the experiments, the precipitation samples were naturally thawed at room temperature. During sampling, a 0.45μm filter was used to filter impurities, and the samples were transferred to 2ml sample bottles. The isotopic values were determined using a Liquid Water Isotope Analyzer (DLT-100, Los Gatos Research, USA). For each sample, six measurements were taken, discarding the first two results to avoid cross-sample influence. For values that were anomalies or not verified by the LWIA post Analysis software, we reselected parallel samples for measurement to ensure the accuracy of the data. The isotopic

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abundances of ^{18}O and ^{2}H are denoted using the delta (δ) symbol relative to the Vienna Standard Mean Ocean Water (V-SMOW) standard, following the equation:

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

where (R) is the ratio of the heavier isotope to the lighter isotope (i.e.,18O/16O) or (2H/1H). We have validated our isotopic measurements against the International Atomic Energy Agency (IAEA) standard (V-SMOW2) to ensure the comparability of isotopic measurements across different laboratories and instruments.

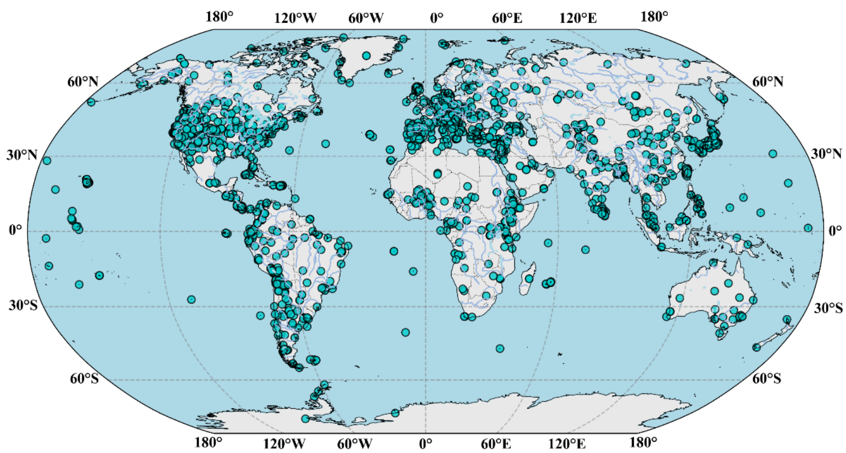

Fig. 1 Global distribution of precipitation stable isotope sites

4. Results and discussion

4.1 Spatial distribution of stable isotopes in precipitation

The spatial distribution of global terrestrial $\delta^{2}H$ and $\delta^{18}O$ exhibits a clear latitudinal correlation, characterized by isotopic values becoming progressively depleted from low to high latitudes (Fig. 2). This variation is primarily controlled by temperature, especially on a global scale. In the low latitudes, often influenced by tropical rainforest and monsoon climates, the high temperatures and humidity intensify the "amount effect" in precipitation's stable isotopes, while weakening the "temperature effect" (Eastoe and Dettman, 2016). Conversely, in the arid climates of northern Africa, the Arabian Peninsula, and Central Asia, the high temperatures and dry conditions promote evaporation fractionation and "below-cloud secondary evaporation," leading to relatively enriched isotopic values in precipitation in these regions. In mid to low latitude mountainous areas, such as

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the Tibetan Plateau, the Alps, and the Andes in South America, precipitation stable isotope ratios are generally low, reflecting the unique climatic and precipitation processes at high altitudes. Additionally, in Western Europe, particularly in coastal areas near the North Atlantic, the isotopic high values extend to higher latitudes, reflecting the region's higher temperatures. Seasonally, the Northern Hemisphere experiences lower stable isotope values in precipitation during winter and spring, while values are relatively enriched during summer and autumn, correlating with seasonal climate changes. The Southern Hemisphere presents a unique case, as most regions are tropical and land areas are relatively smaller, leading to less pronounced seasonal variations in precipitation stable isotopes. The composition of stable isotopes in global precipitation is influenced by multiple factors, including latitude, climate type, seasonal variations, and topography, which together determine its complex spatial and temporal distribution patterns.

In the oceans near the equator, we observe high values of δ^2H and $\delta^{18}O$ isotopes, which directly reflect the region's high evaporation rates and rapid moisture exchange. In contrast, in polar regions, δ^2H and $\delta^{18}O$ are generally lower (Fig. 2). This distribution pattern is consistent with the spatial differentiation of stable isotopes' "latitudinal gradient" on land. Specifically, the North Atlantic and Western Pacific regions exhibit isotopic enrichment or depletion distinct from other areas at similar latitudes, revealing possible climatic peculiarities or special atmospheric circulation patterns in these regions. In the North Atlantic, the observed isotope values are higher than in other areas at the same latitude, which can be attributed to the intensified non-stationary climate variations due to the North Atlantic Oscillation (NAO) (Schurer et al., 2023). Additionally, it is associated with rising sea surface temperatures (Karnauskas et al., 2021). In contrast, in Southeast Asia, observed isotope values are lower than in other regions at the same latitude, which correlates with increased precipitation in the area. With global warming, we not only observe an increase in total precipitation but also an intensification of precipitation extremes (Zhang et al., 2021b). Due to the tropical monsoon climate and strong convective weather systems, the region experiences more rainfall, which in turn enhances the "amount effect" of stable precipitation isotopes.

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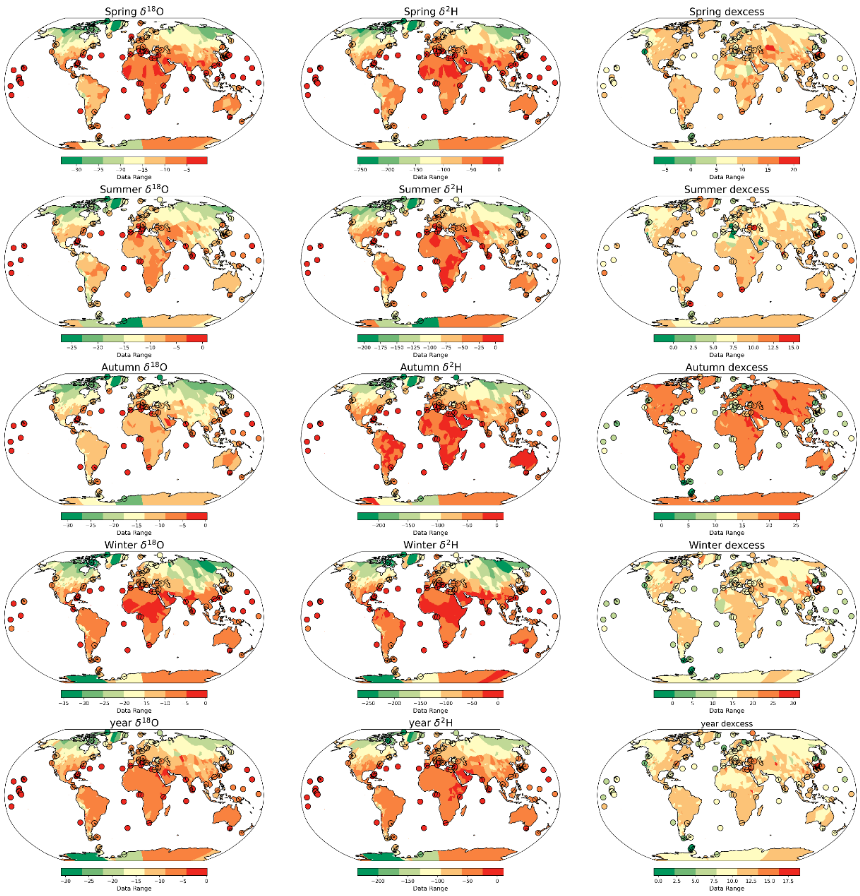

Fig. 2 Spatial distribution of precipitation stable isotopes (where dots represent isotope values at sampling sites near the ocean and coast.)

4.2 Stable isotope time series of precipitation in different climatic zones

Based on the Köppen climate classification (Beck et al., 2018), time series of the stable isotopic values of precipitation (weighted averages) were constructed for different climatic zones (Fig. 3). Tropical (A) and desert climates (B) exhibit high values of stable isotopes in precipitation. Since 1960, the tropical and temperate climate zones have shown steady fluctuations in stable isotopic values of precipitation, while arid climate zones have experienced significant volatility. Without considering the changes in stable isotopes under extreme conditions, this suggests that tropical and temperate climates have a relatively stable hydrothermal combination relationship. During the period 1985-1995, the stable isotopic values of desert climate precipitation were lower than those of the temperate zone, indicating a trend of decreased temperatures or increased precipitation in

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desert climates during this time. Polar (D) and arctic climates (E) exhibit lower stable isotopic values in precipitation compared to other climatic zones. There is a process of hydrothermal exchange between high and low latitudes; the high temperatures at low latitudes cause the precipitation reaching the ground to be enriched in heavy isotopes, and as water vapor is transported to higher latitudes, the heavy isotopes are progressively stripped away. Additionally, the lower temperatures in high-latitude areas result in weaker sub-cloud secondary evaporation. Therefore, δ18O and δ2H in high-latitude precipitation are relatively depleted. From 1975 to 1985, cold climate zones showed a continuous increase in $\delta^{18}O$ and $\delta^{2}H$ values, and an upward trend has also been observed since 2015, indicating an intensifying influence of temperature in cold and arctic climate zones. It can be inferred that under the backdrop of global warming, cold and arctic climate zones might contribute more water vapor to the global hydrological cycle, significantly impacting global climate and water resource patterns. These analyses may obscure some information (e.g., the classification of climate zones also varies by distance, such as between the Northern and Southern Hemispheres), leading to less apparent linear trends in isotopic changes across different climates. However, the dataset of stable isotopes in precipitation we constructed also reflects the differences among various climatic zones, allowing for more precise tracing of global precipitation and a deeper understanding of the global water cycle.

The ocean is the core source of global terrestrial precipitation, and over the past several decades, the isotopic ratios of $\delta^{2}H$ and $\delta^{18}O$ over the ocean have exhibited significant interannual fluctuations, showing a general declining trend (Fig. 4). At the same time, the d-excess values have displayed an increasing trend. A possible explanation for this phenomenon is that regional differences in precipitation rates lead to a decrease in the stable isotopic ratios of precipitation, while the dominant trend remains driven by isotopic fractionation due to rising temperatures.

Stable isotopes in precipitation are positively correlated with atmospheric temperature changes recorded in historical climate data. This correlation demonstrates the potential of stable isotopes as indicators of global climate change, particularly in identifying the response of precipitation processes and water vapor sources to climatic factors. However, the years with rising temperatures do not always correspond to the years with changes in stable isotopic ratios (weak correlation), reflecting the complexity of factors affecting stable isotopes in precipitation, indicating that a single indicator (such as global average temperature) cannot fully explain climate changes in all regions.

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Stable isotopes can serve as comprehensive climate proxy indicators. Moreover, d-excess exhibits temporal characteristics different from those of δ^{2}H and δ^{18}O, reflecting changes in different atmospheric water vapor sources and dry-wet conditions.

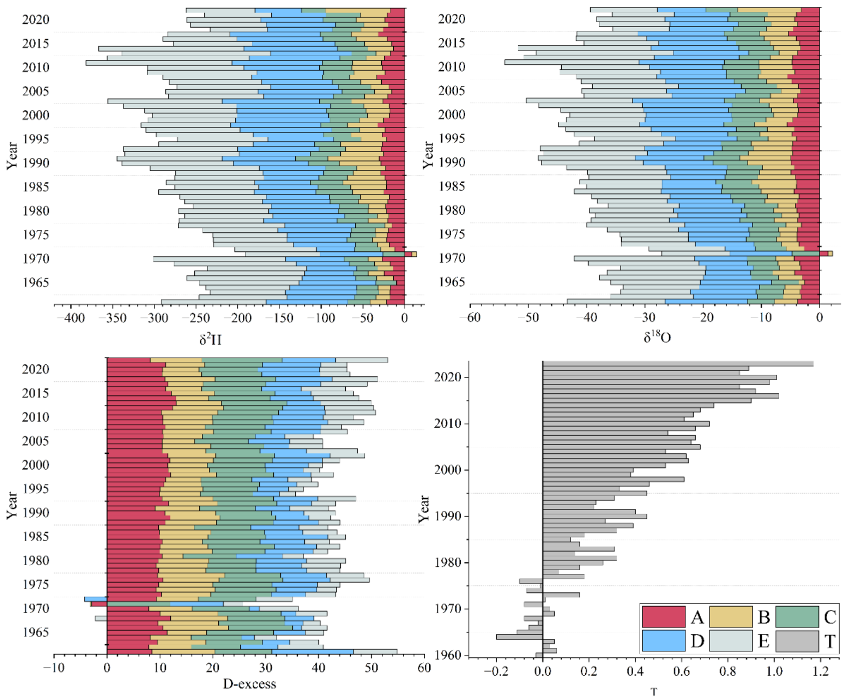

Fig. 3 Temporal trends of stable isotopes of precipitation in different climatic zones, A for tropical climate, B for arid climate, C for temperate climate, D for boreal climate, E for polar climate, and T for global average temperature (°C).

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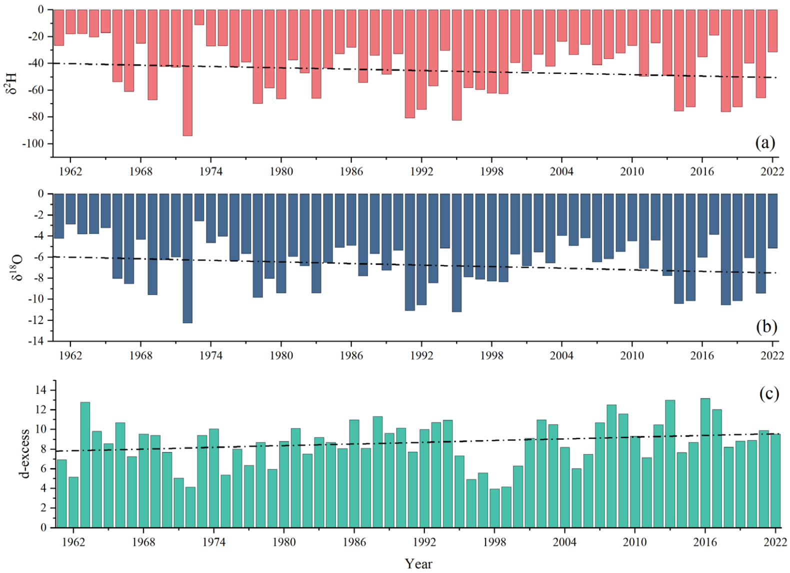

Fig. 4 Temporal trends in stable isotopes of precipitation over the global ocean

4.3 Local Meteoric Water Lines in different regions

The Global Meteoric Water Line (GMWL) describes the global annual average relationship between the ratios of hydrogen and oxygen isotopes ($\delta^{18}O$ and $\delta^{2}H$) in precipitation. GMWL was originally defined by Harmon Craig in 1961 as $\delta^{2}H = 8\delta^{18}O + 10$. GMWL is considered the "expected" equilibrium relationship, assuming the slope is generated by the ratio of equilibrium fractionation factors. Based on this dataset, the fitted equation for the global atmospheric precipitation line is: $\delta^{2}H = 7.95\delta^{18}O + 9.40$. The lower intercept and slope compared to the past might indicate a change in the temperature environment of evaporation and condensation in the precipitation process, which could be related to changes in the global average temperature (Fig. 3d). Factors such as accelerated hydrological cycles, climate models, and changes in precipitation sources could have impacts (Dangendorf et al., 2019; Koutsoyiannis, 2020). On one hand, a faster conversion from evaporation to precipitation and shorter atmospheric residence time might reduce the polarization of fractionation effects, partly explaining the decreased slope. On the other hand, evaporation from oceans generally contains more heavy isotopes, altering the global average isotope ratio.

The slope and intercept variability of Local Meteoric Water Lines (LMWL) across different continents and oceans (excluding Antarctica) reflect the diversity of hydroclimatic conditions and

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isotopic fractionation (Putman et al., 2019) (Fig.5). Fitted using the least squares method, these precipitation lines' variability in slope and intercept are primarily driven by humidity changes and also reflect the combined effects of temperature, precipitation, and other meteorological factors, revealing regional climatic differences. In Asia, the slope of LMWL is closest to the global average (8‰), indicating a more uniform hydrothermal combination under its temperate climate conditions. In contrast, Africa's LMWL slope is the lowest, closely related to its extensive arid and tropical climates. The stable isotopes of oceanic precipitation exhibit characteristics of equilibrium fractionation, particularly in the Pacific and Atlantic Oceans, which not only span multiple thermal zones but also serve as the primary moisture sources for most terrestrial regions. The Indian Ocean's LMWL slope is lower due to most sampling points being near the equator, mainly related to its low-latitude temperature characteristics. The slopes and intercepts inside the polar circles are lower, a phenomenon associated with the global warming trend, which promotes the anomalous performance of stable isotopes in high-latitude precipitation, further substantiating our earlier inference about increased moisture supply from cold and polar regions under global warming.

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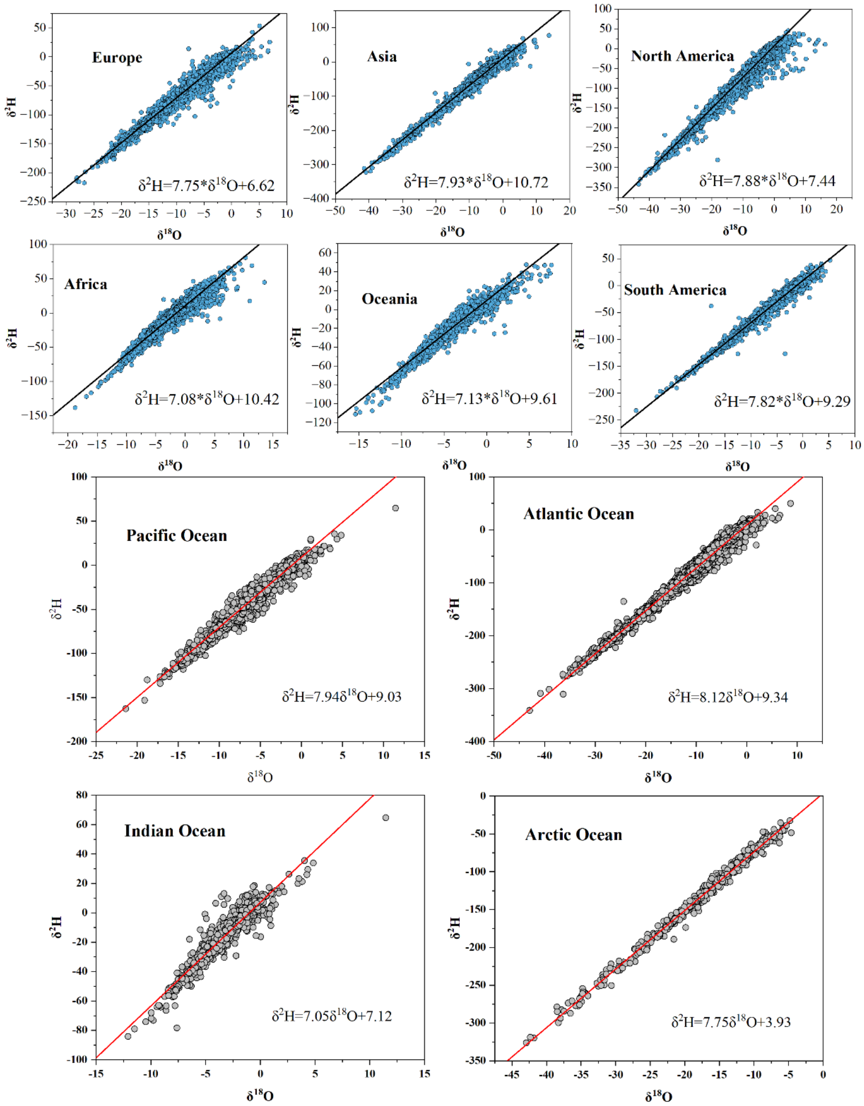

Fig. 5 Local atmospheric precipitation lines on land and at sea

4.4 Precipitation stable isotopes and meteorological elements

By analyzing the correlations between stable precipitation isotope variables ($\delta^{18}O$, $\delta^{2}H$, D-excess) and key meteorological elements (including wind speed, vapor pressure, highest and lowest temperatures, precipitation, potential and actual evapotranspiration) (Fig. 6), results indicate significant negative correlations between the isotopic variables $\delta^{18}O$ and $\delta^{2}H$ with wind speed (ws)

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and vapor pressure (vap), with correlation coefficients of -0.76 and -0.78, respectively. This suggests that under conditions of increasing wind speeds and vapor pressures, the proportions of hydrogen and oxygen isotopes in precipitation are significantly reduced. This reflects the enhanced fractionation effects of isotopes during increased evaporation and the mixing process of atmospheric moisture. Particularly, the negative correlation of D-excess with wind speed (-0.48) is lower than that of $\delta^{18}O$ and $\delta^{2}H$, pointing to D-excess being controlled by multiple factors, including the initial isotopic composition of water vapor and its subsequent transformation in the atmosphere. In contrast, the correlation of D-excess with meteorological variables is generally weaker, reflecting the uniqueness and complexity of D-excess in the evaporation and precipitation recycling process. Additionally, precipitation (ppt) shows a positive correlation with potential and actual evapotranspiration (pet and aet), suggesting that increased precipitation may lead to higher water availability, thus enhancing the surface's capacity for evapotranspiration. This also demonstrates that stable precipitation isotopes are highly reliable indicators for assessing global evapotranspiration. Moreover, the relative independence of D-excess from meteorological elements offers a unique perspective for exploring different mechanisms in water vapor sourcing and the water cycle process. These findings provide valuable insights for further understanding the application of isotope data in environmental and climate research.

Over the oceans, the correlation between precipitation stable isotopes and meteorological variables is generally weak due to several factors. Firstly, global weather systems dictate the distribution of precipitation stable isotopes. Secondly, extreme weather events over the oceans, such as typhoons and intense convective events (Wang et al., 2021), significantly impact the fractionation of stable isotopes, resulting in notable variations in isotopic compositions under these conditions. These factors collectively contribute to greater spatial variations in precipitation stable isotopes over the oceans compared to those on land, with the influence of specific regional meteorological factors being less apparent. Moreover, compared to terrestrial areas, the scarcity of data over the ocean limits a detailed understanding and precise matching of the relationship between isotopes and meteorological elements, thus affecting the assessment of their correlation. The ocean is a crucial component of the global water cycle, and enhancing the observation of stable isotopes in oceanic precipitation can not only provide more detailed clues about global climate change but also help improve the accuracy of assessments of global climate trends and water resource distribution.

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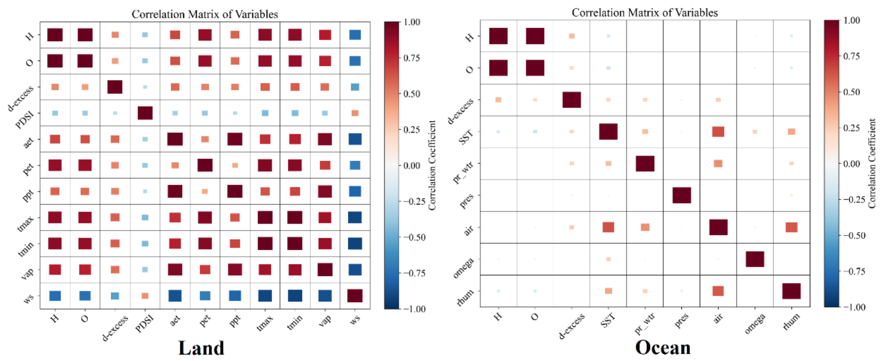

Fig. 6 Correlation of precipitation stable isotopes with meteorological elements

5. Summary and outlook

The global dataset of precipitation stable isotopes is a highly valuable tool for analyzing and simulating trends in climate and water resources. By relying on this re-integrated dataset, we can detect the impacts of climate change on precipitation quantity, frequency, and spatial distribution, thereby gaining a deeper understanding of the evolutionary trends in the global climate system. Precipitation stable isotope data is not only useful for monitoring climate change but also provides critical support for studies on the hydrological cycle. Through dataset analysis, we can understand the sources, transport pathways, and deposition processes of precipitation within the hydrological cycle, revealing the patterns and influencing factors of hydrological cycles in different regions. This new dataset is significant for water resource management. By analyzing precipitation stable isotope data, we can assess the availability of water resources, guide their rational development, utilization, and conservation. Additionally, this dataset can be used to optimize water resource allocation schemes to address the challenges brought about by climate change and human activities on the balance of water supply and demand. We hope to further utilize these data resources to deepen our understanding of the complexity of global climate and hydrological cycles, providing scientific decision support for addressing climate change and achieving sustainable water resource management. Moreover, compared to terrestrial areas, there is relatively less precipitation stable isotope data over the oceans, and future efforts should focus on enhancing the observation of stable isotopes in oceanic precipitation.

Data Availability

Data described in this manuscript can be accessed at Mendeley Data under

10.17632/9gxtc4xzv9.1 (Zhu, 2024).

Author contribution Statement

Longhu Chen: Conceptualization and writing-original draft preparation; Qinqin Wang: Data processing; Guofeng Zhu: Writing review and editing; Rui Li: Methodology; Siyu Lu: Experiment; Xinrui Lin: Validation; Dongdong Qiu: Methodology; Gaojia Meng: Visualization; Yinying Jiao: Data processing; Yuhao Wang: Visualization; Jing Liu: Modification; Yutong He: Modification; Yanan Li: Modification.

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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