Global Stable Isotope Dataset for Surface Water

Rui Li[1,2,3], Guofeng Zhu[1,2,3*], Longhu Chen[1,2,3], Xiaoyu Qi[1], Siyu Lu[1,2,3], Gaojia Meng[1,2,3], Yuhao Wang[1,2,3], Wenmin Li[1,2,3], Zhijie Zheng[1,2,3] , Jiangwei Yang[1,2,3] , Yani Gun[1,2,3]

Affiliations:

[1] College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, Gansu, China

[2] Shiyang River Ecological Environment Observation Station, Northwest Normal University, Lanzhou 730070, Gansu, China

[3] Key Laboratory of Resource Environment and Sustainable Development of Oasis, Gansu Province, Lanzhou 730070, Gansu, China

Correspondence to: zhugf@nwnu.edu.cn

Abstract: Hydrogen and oxygen-stable isotopes are widely used as tracers of the water cycle, and surface water is an integral part of the water cycle. Compared with other water bodies, surface water is more susceptible to different natural and anthropogenic factors, and an accurate understanding of surface water changes is of great significance in ensuring regional water security, maintaining ecological balance, and promoting sustainable economic and social development. The spatial and temporal distribution of global surface water stable isotope data is extremely uneven on a global scale due to factors such as observation conditions and instrumental analysis. For this reason, we have compiled and analyzed the stable hydrogen and oxygen isotope data in surface water from 22,389 sampling stations worldwide from 1956 to 2023, with 102,511 data records. The results found: (1) global surface water stable isotopes are gradually depleted from the equator to the poles and from the coast to the interior. However, there are significant differences in the spatial and temporal distributions of surface water isotopes in different regions. (2) The variation of stable isotopes in surface water is controlled by geographic location, topographic conditions, and meteorological factors (especially temperature), and its heterogeneity is considerable. The global stable isotope dataset of surface water provides vital information for an in-depth understanding of the water cycle and climate change. It can provide essential data references for global water resource management and researches. The Global Surface Water Stable Isotope

Dataset is available at https://doi.org/10.17632/fs7rwp7fpr.2 (Zhu, 2024).

Keywords: Stable isotopes; Surface Water; Global Dataset

1.Introduction

Water resources are an essential material basis for human survival and indispensable for maintaining sustainable local socio-economic development, preserving ecological health, and maintaining ecosystem stability (Immerzeel et al., 2020; Mehta et al., 2024). Due to human activity and climate change, global hydrological systems have changed in recent decades, increasing ecological vulnerability and sensitivity to climate change (Chahine, 1992; Liu et al., 2021; Satoh et al., 2022). Hydrogen and oxygen isotopes, as a kind of stable isotopes widely present in the water column (Reckerth et al., 2017; Sprenger et al., 2016), are an important method for conducting water cycle studies and have an essential indicative role in the study of the water cycle (Aggarwal et al., 2007; Joussaume et al., 1984; Vystavna et al., 2021). However, due to restrictions imposed by their conditions in various regions of the world, there are a number of difficulties and constraints in the gathering, integrating, and analysing of current stable isotope data for surface water (Chen et al., 2020; Penna et al., 2018).

Since 1960, the Global Network of Isotopes in Precipitation (GNIP) was created by the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO), with the aim of constructing a worldwide monitoring network focusing on the in-depth study of hydrogen and oxygen isotopes in precipitation (Aggarwal et al., 2012). Compared to global stable isotope monitoring of precipitation, global surface water monitoring is lagging behind. In 2002, the IAEA started building the Global Network of Isotopes in Rivers (GNIR), which aims to study the interactions between surface water and groundwater using stable isotopes in runoff and to identify the effects of climate change on river runoff and the effects of human activity on riverine variability (Halder et al., 2015). Many academics worldwide have studied the stable isotope composition of surface water, Scholars around the world for surface water stable isotope research has achieved many results, a researcher using the U.S. river water stable isotope data, mapped the isotope distribution of U.S. river water, and use the model to analyze the U.S. river water isotope changes (Bowen et al., 2011; Dutton et al., 2005). In addition, the stable isotope composition of surface water is affected by a variety of hydrological processes such as precipitation, evaporation, surface runoff, etc., and can therefore provide valuable information on water cycle processes, water resource management, and the impacts of climate change (Bowen et al., 2019; Darling, 2004; Schulte et al., 2011). The source, flow, accumulation, and change rule of surface water can be thoroughly understood by analysing and interpreting stable isotope data, which can offer a scientific foundation for water resource management, water resource assessment, and ecological and environmental protection (Dudley et al., 2022). In addition, surface water, as a "link" between groundwater and precipitation (Cooley et al., 2021), offers fresh scientific perspectives on a variety of hydrogeological phenomena, including the hydrogeologic evolution of the basin (Bershaw et al., 2016), groundwater-surfac water interactions(Autio et al., 2023), groundwater recharge (Jameel et al., 2023), and precipitation processes (Reckerth et al., 2017).

The establishment of a global stable isotope dataset for surface water is of great significance in the current context of global climate change and water scarcity. The dataset will help integrate and utilize surface water stable isotope data from various regions, improve the accessibility and usability of stable isotope data, and provide more abundant and reliable data support for researchers to carry out global-scale hydrological and environmental studies. In addition, based on the global surface water stable isotope dataset, the analysis of the driving force of meteorological factors on the global surface water stable isotope changes can provide a data basis for research on water resources assessment, climate change adaptation, and optimization of agricultural irrigation. In this work, we present the first global surface water stable isotope dataset, comprising measured, website, and references data. Our goals are as follows: (1) to compile and gather surface water stable isotope data globally; (2) to construct a global surface water stable isotope dataset, and to promote the application of global surface water stable isotope dataset in the hydrological, meteorological, ecological, and other fields.

2. Data and methods

2.1 Compositions of the dataset

The Dataset consists of three main elements: website data (GNIR, http://nucleus.iaea.org/wiser/explore, water isotopes website, http://wateriso.utah.edu/waterisotopes), measured data and references data. The dataset encompasses 22,432 surface water sampling sites across seven continents (Fig.1). Since 2015, an ecohydrological observation system has been implemented in the Shiyang River Basin in the arid zone of Northwest China to systematically gather surface water stable isotope data (Fig. S1), serving as the primary source of measured data.

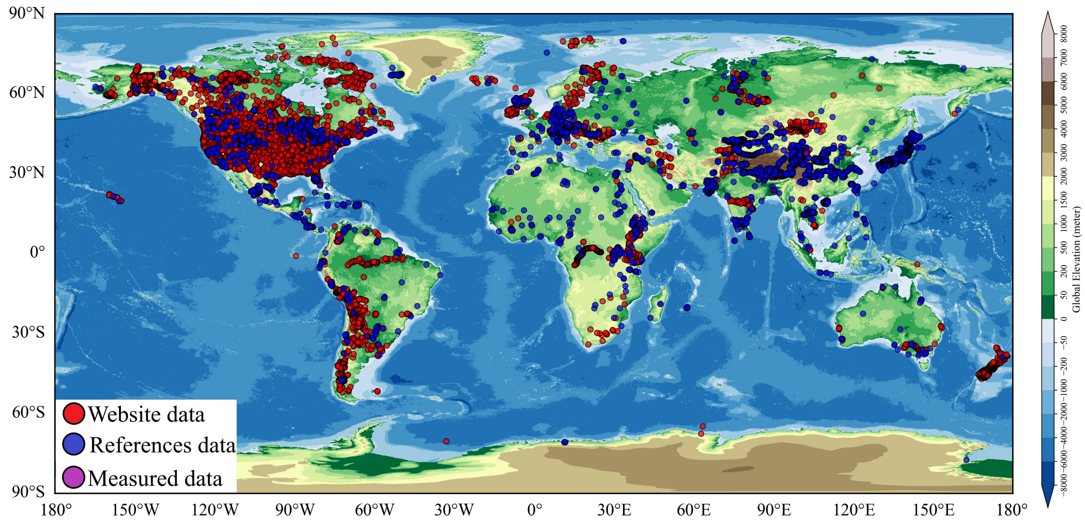

Figure 1 Distribution of sample sites in the global stable isotope dataset for surface water.

Measured data: Surface water sampling sites are chosen whenever feasible at places where the water is moving quickly because stagnant water is frequently impacted by pollution and evaporation. After the sampling bottle was rinsed three times prior to sampling using water from the sampling site, the bottle was placed below the surface of the water with the mouth facing up and filled to a position approximately three-quarters of the bottle's volume. Following the completion of the water sample collection process, the bottles are promptly sealed tightly, their mouths are taped with waterproof tape, and labels bearing the name of the sampling location, the sampling date, and additional information are affixed to the bottles. Every collected water sample was kept in a refrigerator to be frozen in order to avoid data errors caused by evaporation.

References data: We added more information to the database by searching for the terms "isotope," "surface water," and "river" in published papers on Web-of-Science. We chose scholarly articles containing isotope data in textual, tabular, and graphical formats as the primary source of data to enhance the precision of our data. The aforementioned papers explicitly identified the water body type as "surface water." Alongside isotope data, we gathered spatial and temporal informations, including the latitude and longitude of the sampling sites and the exact time of sampling.

Moreover, the meteorological data utilized in this study were sourced from the NCEP-

NCAR reanalysis dataset (https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html) and the CRUTS v. 4.07 dataset (https://crudata.uea.ac.uk/cru/data). The data utilized for the global climate division are derived from Köppen's global climate classification (Peel et al., 2007) (Fig. S2).

2.2 Data processing

2.2.1 Experiment

Prior to the experiment commencing, removing the samples to be analysed from the refrigerator and transferring them to standard 1.5 mL glass sample bottles once they had melted in the room. A filter with a pore size of 0.45 μm and a diameter of 13 mm was then applied to eliminate any contaminants, such as silt and dust, that may have been carried in with the samples during the transfer. All water samples were analyzed for stable isotope values using a liquid water isotope analyzer (DLT-100, Los Gatos Research, USA). During the determination process, each water sample was measured six consecutive times. To prevent residual contamination from affecting the results, the first two measurements were discarded, and the stable isotope value was calculated as the average of the last four measurements. The test results obtained are expressed as thousandths deviation from the Vienna Standard Mean Ocean Water (V-SMOW):

$$\delta_{\text{sample}}(‰) = [(\frac{R_s}{R_v}) - 1] \times 1000$$

Here, R_s represents the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in the collected sample, and R_v is the ratio of $^{18}O/^{16}O$ or $^{2}H/^{1}H$ in the Vienna standard sample. The analytical accuracy for $\delta^{2}H$ and $\delta^{18}O$ is ±0.6‰ and ±0.2‰, respectively.

2.2.2 Data quality

Since the collected data included various problems such as missing values, outliers and obvious duplicate entries as well as sampling date gaps and missing or incorrect latitude and longitude information. Therefore, the collected raw data were pre-processed and data screened to eliminate erroneous data.

In addition, We use the Liquid Water Isotope Analyzer (LWIA) post-analysis software to examine the measured raw isotope data. LGR recommends our customized Post-Processing Software to analyze the data. This software uploads the data files, performs all required normalization and processing, and saves the processed data as readable TXT files. In addition, the

LWIA automatically checks for instrumental fault indications, provides a selection of data filters, displays a variety of graphical displays, and can be configured by the user. With LWIA, we can know which raw data values of the sample are wrong and need to be tested again, and we can see the reasons for the data errors. Additionally, all isotope data were thoroughly examined to ensure each entry included clear "longitude," "latitude," "sampling time," and "isotope" data. Outliers and duplicates were removed (Fig. 2).

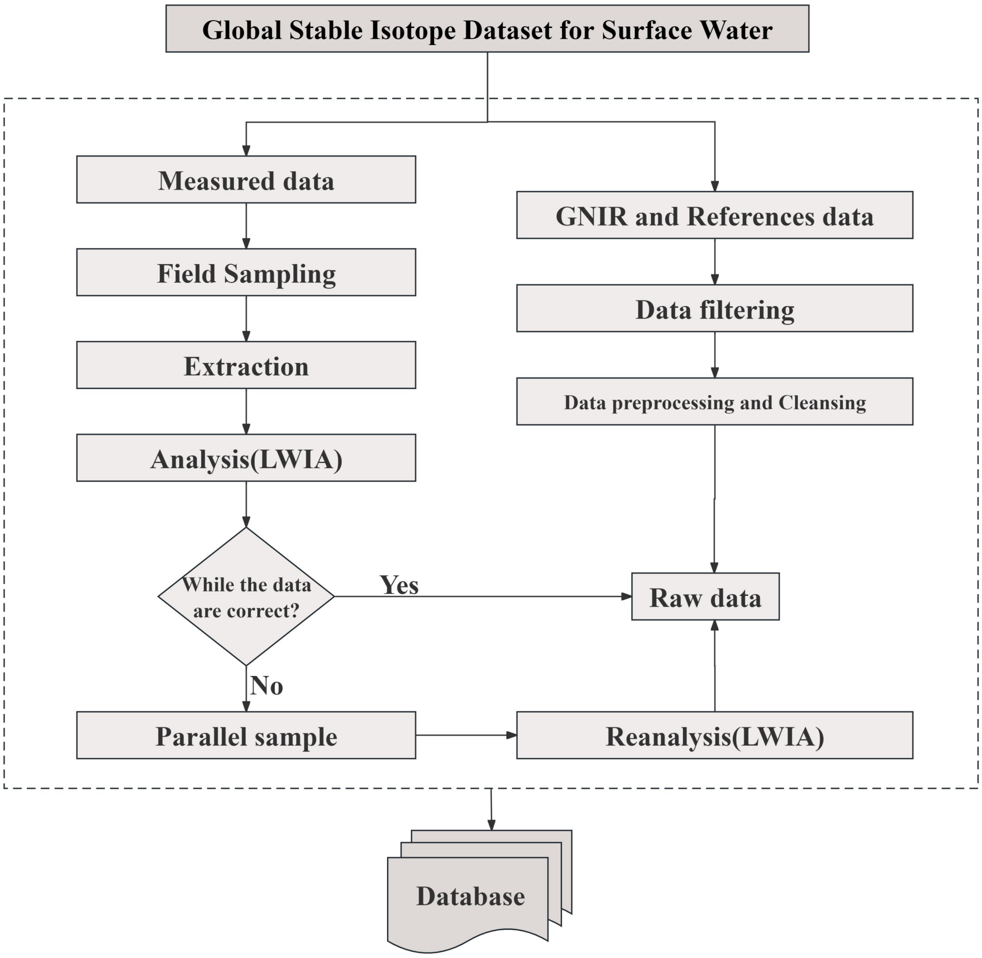

Figure 2 Flow of data processing and construction of global surface water stable isotope dataset.

2.3 Methods

Based on previous studies, a one-way analysis of variance (ANOVA) was used to determine the significance ($p < 0.05$ at a 95% confidence level) of the slopes and intercepts of the linear regression fits for surface water stable isotopes δ^2H and δ^{18}O across different climatic regions (Vystavna et al., 2021). Furthermore, the Random Forest (RF) model can assess the importance of variables. In this study, we employed the RF model to evaluate the impact of various meteorological factors on the stable isotopes of surface water globally. The RF algorithm integrates multiple decision trees to generate a cumulative effect. It predicts regression outcomes based on the average results of these randomized decision trees, employing bootstrapping to minimize the risk of overfitting (Breiman, 2001; Hu et al., 2017). Both root mean square error (RMSE) and mean absolute error (MAE) were utilized to estimate the model's error (Kartal, 2024). The detailed calculation process for RMSE and MAE is described in Text S1 in the Supporting Information.

3. Results and discussions

3.1 Volume, geographic distribution and temporal coverage of datasets

As shown in Fig. 3, a total of 102,561 measurements of stable isotopes of hydrogen and oxygen in surface water were collected for this dataset. This includes 79,525 website data, 1040measured data, and 21,946 references data. Most of GNIR data are primarily concentrated in a few regions, such as the United States and Eastern Europe, and are sparsely distributed globally. To expand our dataset, we incorporated data from published literature. This expanded dataset now covers nearly the entire world with a relatively even distribution, including regions traditionally difficult to access data from, such as Greenland, Antarctica, western Australia, and high-altitude mountainous areas (Fig. 1). In terms of time range, the dataset covers the period from 1956 to 2023, and most of the data are distributed since 1990, which also suggests that the dataset can better characterize the global distribution of stable isotopes in surface water over the past decades.

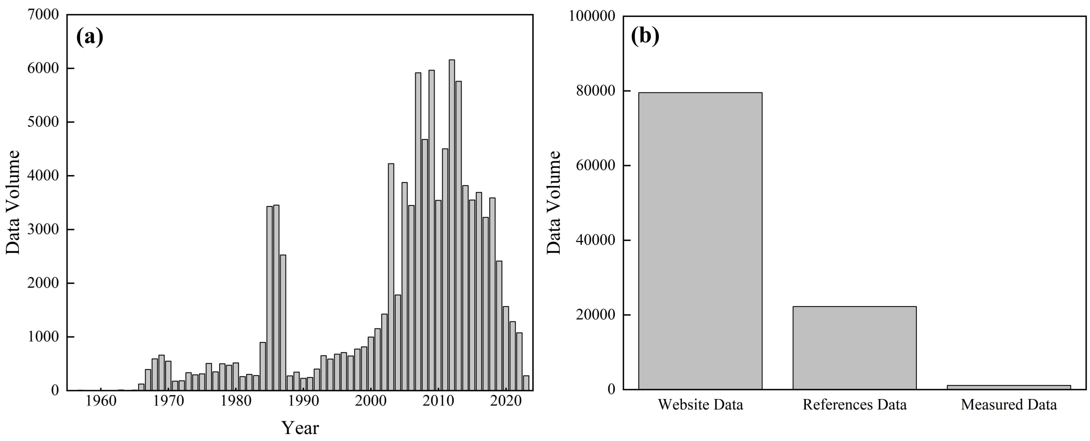

Figure 3 Distribution of global surface water stable isotope dataset. (a) time series distribution; (b) category distribution.

3.2 Spatial and temporal variations of stable isotopes in global surface waters

The variation of δ^2H ranged from -252.48‰ to 79.01‰, and $\delta^{18}O$ ranged from -26.30‰ to

15.41‰ over the whole dataset. On a seasonal scale, global surface water stable isotopes typically exhibit pronounced variations, characterized by higher values in summer and lower values in winter (Fig.4). To better observe these variations across different regions, we classified the globe into five climatic zones—tropical, temperate, arid, continental, and polar, based on the "Köppen climate zones" classification. Across the six climatic zones, stable isotopes of surface water exhibit seasonal variations with higher values in summer and lower values in winter, except in polar climatic zones. The most pronounced variations occur in arid zones, underscoring the influence of meteorological factors on stable isotopes of surface water.

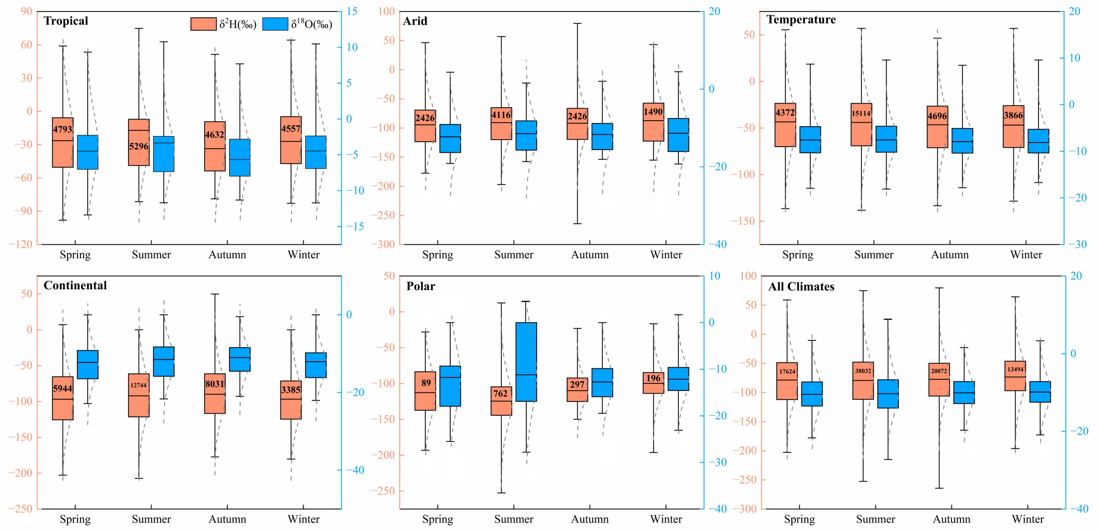

Figure 4 Seasonal variation of δ^2H and δ^{18}O in surface water in different climatic zones (Numbers indicates amount of stable isotope data).

Meanwhile, to better describe the spatial distribution of stable isotopes in global surface water, we conducted interpolation to map their spatial distribution globally (Fig. 5). Generally, δ^2H and δ^{18}O exhibit a consistent trend of gradually decreasing values from equatorial regions to high latitudes and from coastal regions to inland areas of continents such as Eurasia and North America. This trend is especially pronounced in high-latitude and high-altitude regions, where the values are significantly lower. However, some areas do not exhibit a clear pattern in the distribution of δ^2H and δ^{18}O values. This irregularity primarily results from the complex factors influencing runoff generation and water flow concentration processes in various regions. Additionally, the presence of open water bodies, such as lakes and reservoirs, exacerbates this irregular distribution phenomenon.

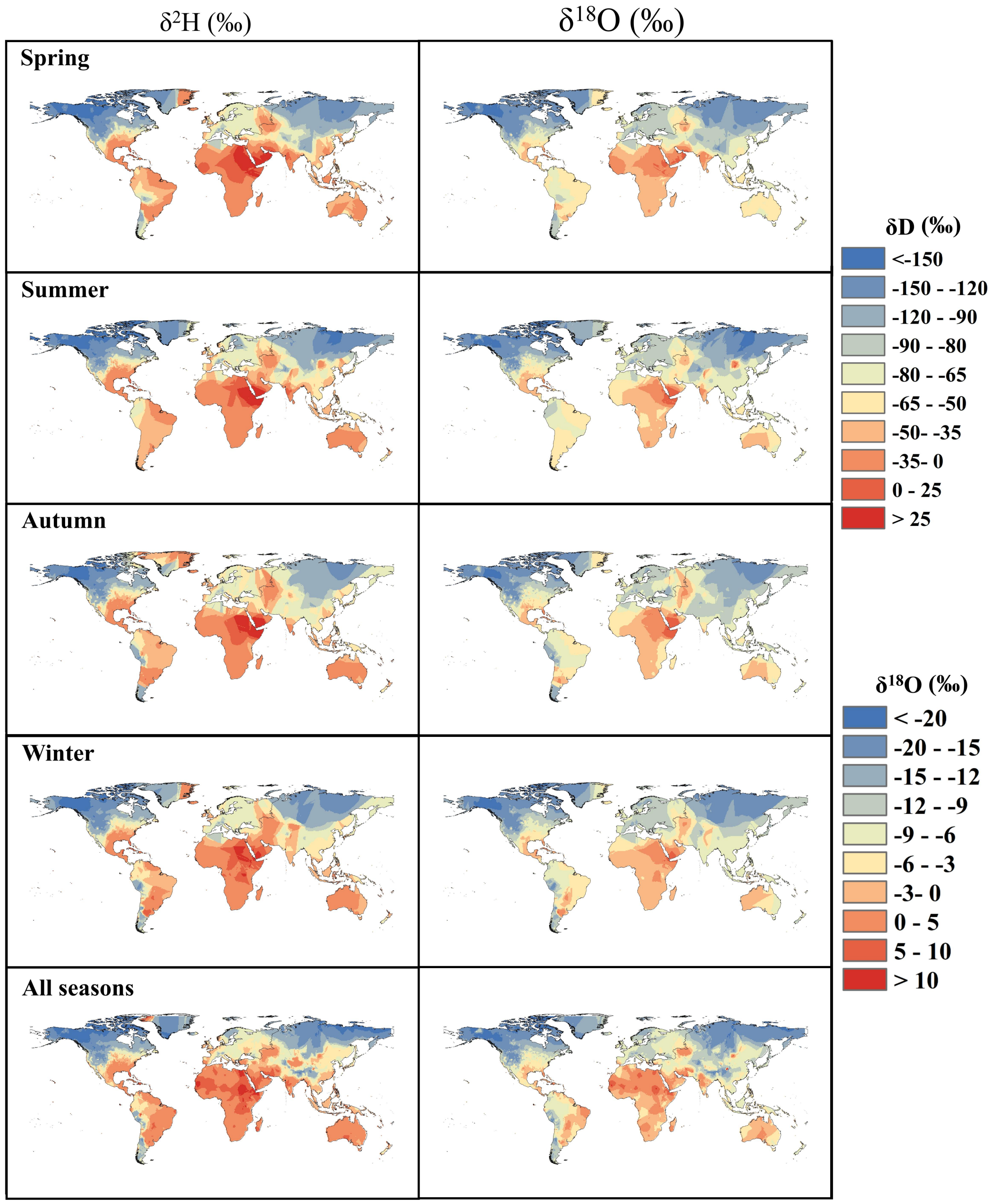

Figure 5 Spatial distribution of global surface water δ^2H and $\delta^{18}O$ in different seasons (Unweighted data, using kriging grid methods).

To better understand the relationship between surface water and precipitation, we compared the spatial interpolation results of surface water isotopes with those of global precipitation isotopes. We found that the isotope distribution in surface water is largely consistent with the isotope distribution in precipitation across most areas (Fig. S3). This consistency primarily arises because surface water is predominantly recharged by precipitation. Moreover, the spatial variation in the isotopic composition of surface water serves as a valuable indicator of its recharge relationship with groundwater and precipitation (Kendall and Coplen, 2001). This is particularly evident in the tropics and at high altitudes, where precipitation serves as the primary source of surface water recharge. In these regions, the spatial distributions of surface water isotopes and precipitation isotopes exhibit a high degree of similarity (Fig. S3).

3.3 Global surface water δ^2H and δ^{18}O correlations

Here, we fit δ^2H and δ18O to surface waters in six climatic zones, the results indicated a strong correlation between δ^2H and δ^{18}O across six various climate zones (Fig. 6). The relationship between δ^2H and δ^{18}O for global surface water is $\delta^2H = 7.92\delta^{18}O + 7.80$ ($R^2 = 0.98$), which is closer to the intercept and slope of the global meteoric water line (GMWL: $\delta^2H = 8\delta^{18}O + 10$), and this confirms once again that the source of recharge of global surface water is precipitation. However, the fitted lines of δ^2H and δ^{18}O for surface water were significantly different in different climatic zones (Fig. 6), and the fitted lines of δ^2H and δ^{18}O exhibited the lowest intercept and slope under arid climate ($\delta^2H = 7.50\ \delta^{18}O + 3.30$, $R^2 = 0.98$), which also suggests that under arid climate, the surface water experienced significant evapotranspiration, which led to the isotopic enrichment of surface water, δ^2H and δ^{18}O values were higher compared to other climatic zones. In the coldest polar climate zone, the fitted line of δ^2H and δ^{18}O is $\delta^2H=5.57\delta^{18}O+17.18$ ($R^2=0.95$), and the higher slope and intercept indicate that under the influence of the cold climate, the surface water undergoes little evaporation, and the presence of surface water may be in the form of snow and ice, resulting in significantly lower values of δ^2H and δ^{18}O compared to the other climate zones.

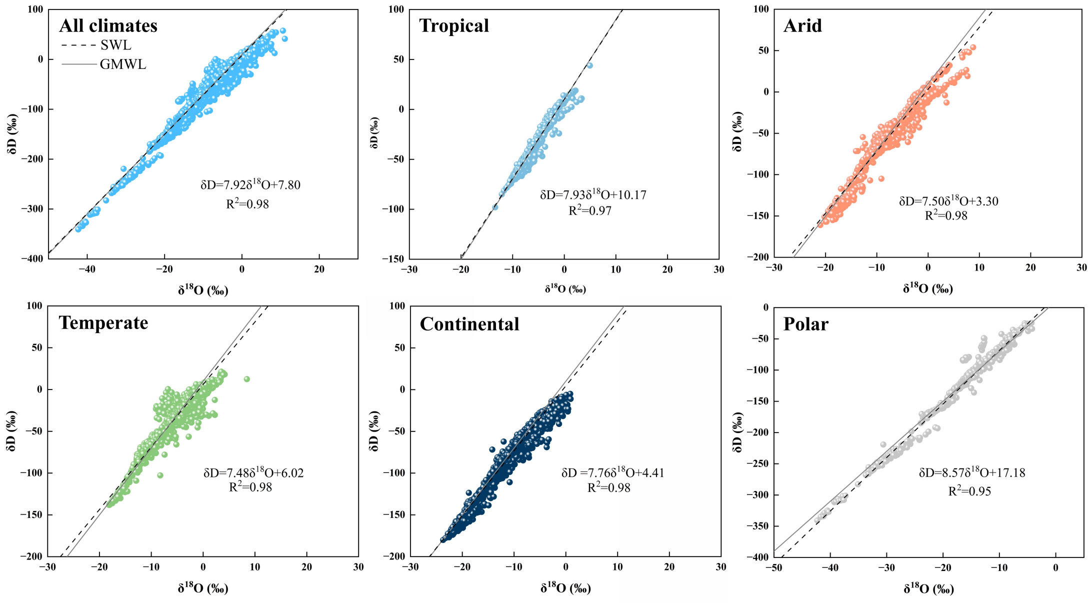

Figure 6 Relationship between δ^2H and $\delta^{18}O$ in different climatic zones.

3.4 Controlling factors for stable isotopes in surface water

For precipitation stable isotopes, there is a significant "latitude effect" and "continent effect (Dansgaard, 1964)," this pattern of variation is also observed in the stable isotopes of surface water, characterized by a gradual decrease in stable isotope values from low to high latitudes and from coastal to arid inland areas. However, in low-latitude regions near the equator, where surface water is primarily recharged by precipitation and climatic factors do not vary significantly along latitude, there is no significant spatial variation in the stable isotopes of surface water.

Additionally, numerous studies have demonstrated that the stable isotope composition of surface water is predominantly influenced by climatic factors (Araguás-Araguás et al., 1998; Dansgaard, 1964; Wang et al., 2017). To assess the importance of various meteorological variables on the stable isotopes of surface water globally, we employed a RF model. The RF regression analysis fitted to the stable isotopes of surface water indicated a strong model fit for both the training and test sets. This suggests that variables such as temperature, precipitation, potential evapotranspiration, vapor pressure, wind speed, and relative humidity possess significant explanatory power for the stable isotopes of surface water (Fig. 7). The validation results of the RF model demonstrate excellent prediction performance for both $\delta^{18}O$ and δ^2H, with $\delta^{18}O$ showing better prediction accuracy than δ^2H, as indicated by smaller RMSE and MAE values (Table S1). Among the six meteorological factors considered, temperature exerts the strongest influence on surface water stable isotopes. Potential evapotranspiration also exhibits a strong controlling effect, suggesting that temperature and evapotranspiration are the primary factors governing changes in global surface water stable isotopes. Additionally, relative humidity and wind speed demonstrate high explanatory power for variations in surface water stable isotopes. Previous studies have indicated that wind speed and relative humidity significantly influence evaporation from water bodies (Gallart et al., 2024; Skrzypek et al., 2015), which can subsequently impact surface water stable isotopes. While vapor pressure and precipitation offer weaker explanations for variations in surface water stable isotopes, these factors can largely be attributed to the residence time of surface water and the local hydrological cycle. The residence time of surface water and the characteristics of the local hydrological cycle vary significantly across different regions. Large open water bodies typically have longer residence times and slower hydrological cycles, resulting in a more enriched isotopic composition of surface water (Feng et al., 2016). In contrast, water bodies with faster hydrological cycles, such as rivers, may exhibit different isotopic compositions (Ala-aho et al., 2018). However, interpreting these patterns on a large scale requires further investigation and validation.

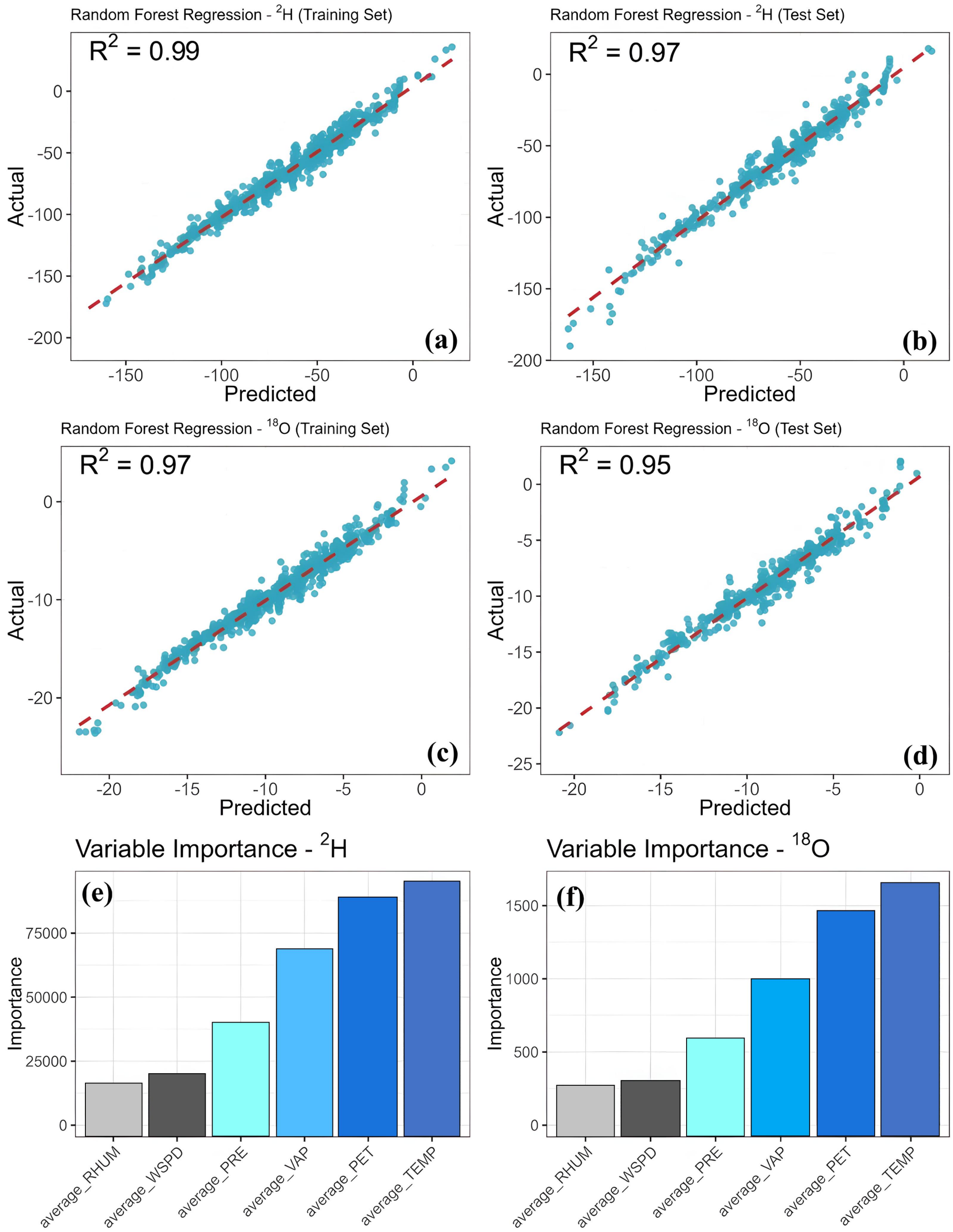

Figure 7 The relationship between δ2H and $\delta^{18}O$ and meteorological factors was analyzed using RF model. (a) δ^2H regression results for the training set. (b) δ^2H regression results of the test set. (c) $\delta^{18}O$ regression results of the training set. (d) $\delta^{18}O$ regression results of the test set. (e) Effect of meteorological factors on δ^2H. (f) Effect of meteorological factors on $\delta^{18}O$.

Simultaneously, for lakes, reservoirs, and other large open water bodies, the controls on surface water stable isotopes can be more complex. Studies have demonstrated that global stable isotope variations in lakes result from the combined effects of solar radiation, evapotranspiration, catchment area size, and other factors (Vystavna et al., 2021). These controls vary across different regions, contributing to diverse stable isotopic compositions in surface waters worldwide. For instance, in arid zones, solar radiation primarily controls stable isotopic variations in lakes, whereas in temperate climatic zones, evaporation and transpiration play a dominant role. Consequently, the controlling factors for surface water stable isotopes vary significantly across different regions. However, overarching patterns suggest that geographic and meteorological factors collectively govern the stable isotopic changes in surface water within a region.

3.5 Challenges and limitations in the construction of surface water isotope datasets and future research directions

At present, due to the limitations of sampling techniques and methods, there may be significant differences in sampling methods and frequencies across various geological environments and hydrogeological conditions. These differences can affect the comparison and analysis of the data. Constructing a comprehensive isotope dataset for surface water requires careful consideration of spatial and temporal coverage to ensure data accuracy and comparability (Ankor et al., 2019). However, due to cost, labor, and equipment constraints, as well as the harsh natural conditions in sampling areas, it is challenging to achieve continuous observation of different watersheds over long time series. This limitation results in some incompleteness of the data in terms of spatial and temporal scales (Penna et al., 2014). In addition, the accuracy of current stable isotope data has yet to be harmonized due to issues such as sample preservation, analytical techniques, and instrumental accuracy. These challenges may lead to problems in the comparability and overall reliability of the data.

In the future, establishing harmonized standards for data collection, storage, and sharing will be essential for creating a global isotope database for surface water. Additionally, integrating data from different sources, times, and locations will be necessary to develop a more comprehensive global isotope database for surface water (Chen et al., 2024). With advances in artificial intelligence, there is a growing trend towards integrating isotope data with hydrologic modeling (Gierz et al., 2017; Nelson et al., 2021). This integration promises to enhance our understanding of hydrologic processes and improve water resource management practices. Furthermore, it facilitates improvements in the spatial and temporal coverage of data, offering more robust insights into water dynamics and interactions within ecosystems. Meanwhile, within the context of global change, climate change, and isotopes are becoming increasingly integrated and interdisciplinary. In the longer term, there is potential to develop a comprehensive understanding and application of isotope datasets for surface water. This development will rely on integrating expertise from disciplines such as geology, hydrology, meteorology, and others, fostering a holistic approach to studying and managing water resources in a changing climate.

4. Data availability

The Global Surface Water Stable Isotope Dataset is now publicly available and the data can be found at 10.17632/fs7rwp7fpr.2 (Zhu, 2024).

5. Conclusion

The global surface water stable isotope dataset provides crucial information for advancing our understanding of the water cycle, climate change, and environmental monitoring. In this study, we established a global surface water stable isotope dataset by combining measured data and reference data from existing station data. This approach enriched the dataset and enabled comprehensive analysis across different regions and climatic zones. The results reveal pronounced spatial and temporal variations in the stable isotope composition of global surface water, with significant differences observed in the isotopic composition of surface water across different climates. The variations in global surface water isotopes are influenced by a combination of geographic and meteorological factors, with temperature and evapotranspiration among the climatic factors exhibiting strong explanatory power for the isotopic composition of surface water. Observations of stable isotopes in global surface water play a crucial role in enhancing our understanding of the global water cycle, climate change, and water resource management. They provide essential data support for interdisciplinary research, helping to uncover connections between hydrological processes, climate variability, and environmental changes worldwide. Although we have enriched this dataset as much as possible, there are still regions with sparse data, such as Siberia and Eastern Europe. In the future, efforts should focus on strengthening observations in these challenging areas where data availability is limited. Improving the resolution of global surface water stable isotope data can be achieved by integrating interdisciplinary approaches and leveraging artificial intelligence methods. This approach will help fill data gaps, enhance accuracy, and provide more comprehensive insights into global water dynamics and environmental changes.

ACKNOWLEDGEMENTS

This research was financially supported by the National Natural Science Foundation of China (42371040, 41971036), Key Natural Science Foundation of Gansu Province (23JRRA698), Key Research and Development Program of Gansu Province (22YF7NA122), Cultivation Program of Major key projects of Northwest Normal University (NWNU-LKZD-202302), Oasis Scientific Research achievements Breakthrough Action Plan Project of Northwest normal University (NWNU-LZKX-202303). The authors would like to thank Gabriel J. Bowen et al. for their contributions to the wiDB database and the International Atomic Energy Agency for their outstanding contributions with respect to the GNIR dataset. Finally, the authors thank all the researchers and institutions that provided data.

Conflict of Interest Statement

The authors declare no conflicts of interest.

Author contributions statement

Guofeng Zhu and Rui Li: Writing-Original draft preparation. Siyu Lu and Longhu Chen: Data curation. Xiaoyu Qi: Writing-Reviewing and Editing. Gaojia Meng and Yuhao Wang: Methodology. Wenmin Li: Investigation. Zhijie Zheng, Jiangwei Yang and Yani Gun: Software

Reference

Aggarwal, P. K., Alduchov, O., Araguás Araguás, L., Dogramaci, S., Katzlberger, G., Kriz, K., Kulkarni, K. M., Kurttas, T., Newman, B. D., and Purcher, A.: New capabilities for studies using isotopes in the water cycle, EoS Transactions, 88, 537–538, https://doi.org/10.1029/2007EO490002, 2007.

Aggarwal, P. K., Alduchov, O. A., Froehlich, K. O., Araguas-Araguas, L. J., Sturchio, N. C., and Kurita, N.: Stable isotopes in global precipitation: A unified interpretation based on atmospheric moisture residence time, Geophysical Research Letters, 39, 2012GL051937, https://doi.org/10.1029/2012GL051937, 2012.

Ala-aho, P., Soulsby, C., Pokrovsky, O. S., Kirpotin, S. N., Karlsson, J., Serikova, S., Manasypov, R., Lim, A., Krickov, I., Kolesnichenko, L. G., Laudon, H., and Tetzlaff, D.: Permafrost and lakes control river isotope composition across a boreal Arctic transect in the Western Siberian lowlands, Environ. Res. Lett., 13, 034028, https://doi.org/10.1088/1748-9326/aaa4fe, 2018.

Ankor, M. J., Tyler, J. J., and Hughes, C. E.: Development of an autonomous, monthly and daily, rainfall sampler for isotope research, Journal of Hydrology, 575, 31–41, https://doi.org/10.1016/j.jhydrol.2019.04.074, 2019.

Araguás-Araguás, L., Froehlich, K., and Rozanski, K.: Stable isotope composition of precipitation over southeast Asia, J. Geophys. Res., 103, 28721–28742, https://doi.org/10.1029/98JD02582, 1998.

Autio, A., Ala-Aho, P., Rossi, P. M., Ronkanen, A.-K., Aurela, M., Lohila, A., Korpelainen, P., Kumpula, T., Klöve, B., and Marttila, H.: Groundwater exfiltration pattern determination in the sub-arctic catchment using thermal imaging, stable water isotopes and fully-integrated groundwater-surface water modelling, Journal of Hydrology, 626, 130342, https://doi.org/10.1016/j.jhydrol.2023.130342, 2023.

Bershaw, J., Saylor, J. E., Garzione, C. N., Leier, A., and Sundell, K. E.: Stable isotope variations (δ18O and δD) in modern waters across the Andean Plateau, Geochimica et Cosmochimica Acta, 194, 310–324, https://doi.org/10.1016/j.gca.2016.08.011, 2016.

Bowen, G. J., Kennedy, C. D., Liu, Z., and Stalker, J.: Water balance model for mean annual hydrogen and oxygen isotope distributions in surface waters of the contiguous United States, J. Geophys. Res., 116, G04011, https://doi.org/10.1029/2010JG001581, 2011.

Bowen, G. J., Cai, Z., Fiorella, R. P., and Putman, A. L.: Isotopes in the Water Cycle: Regional- to Global-Scale Patterns and Applications, Annu. Rev. Earth Planet. Sci., 47, 453–479, https://doi.org/10.1146/annurev-earth-053018-060220, 2019.

Breiman, L.: Random Forests, Machine Learning, 45, 5–32, https://doi.org/10.1023/A:1010933404324, 2001.

Chahine, M. T.: The hydrological cycle and its influence on climate, Nature, 359, 373–380, https://doi.org/10.1038/359373a0, 1992.

Chen, L., Wang, Q., Zhu, G., Lin, X., Qiu, D., Jiao, Y., Lu, S., Li, R., Meng, G., and Wang, Y.: Dataset of stable isotopes of precipitation in the Eurasian continent, Earth Syst. Sci. Data, 16, 1543–1557, https://doi.org/10.5194/essd-16-1543-2024, 2024.

Chen, Y., Helliker, B. R., Tang, X., Li, F., Zhou, Y., and Song, X.: Stem water cryogenic extraction biases estimation in deuterium isotope composition of plant source water, Proc. Natl. Acad.

Sci. U.S.A., 117, 33345–33350, https://doi.org/10.1073/pnas.2014422117, 2020.

Cooley, S. W., Ryan, J. C., and Smith, L. C.: Human alteration of global surface water storage variability, Nature, 591, 78–81, https://doi.org/10.1038/s41586-021-03262-3, 2021.

Dansgaard, W.: Stable isotopes in precipitation, Tellus, 16, 436–468, https://doi.org/10.1111/j.2153-3490.1964.tb00181.x, 1964.

Darling, W. G.: Hydrological factors in the interpretation of stable isotopic proxy data present and past: a European perspective, Quaternary Science Reviews, 23, 743–770, https://doi.org/10.1016/j.quascirev.2003.06.016, 2004.

Dudley, B. D., Yang, J., Shankar, U., and Graham, S. L.: A method for predicting hydrogen and oxygen isotope distributions across a region's river network using reach-scale environmental attributes, Hydrol. Earth Syst. Sci., 26, 4933–4951, https://doi.org/10.5194/hess-26-4933-2022, 2022.

Dutton, A., Wilkinson, B. H., Welker, J. M., Bowen, G. J., and Lohmann, K. C.: Spatial distribution and seasonal variation in^{18}O/^{16}O of modern precipitation and river water across the conterminous USA, Hydrological Processes, 19, 4121–4146, https://doi.org/10.1002/hyp.5876, 2005.

Feng, X., Lauder, A. M., Posmentier, E. S., Kopec, B. G., and Virginia, R. A.: Evaporation and transport of water isotopologues from Greenland lakes: The lake size effect, Quaternary Science Reviews, 131, 302–315, https://doi.org/10.1016/j.quascirev.2015.07.029, 2016.

Gallart, F., González-Fuentes, S., and Llorens, P.: Technical note: Isotopic fractionation of evaporating waters: effect of sub-daily atmospheric variations and eventual depletion of heavy isotopes, Hydrol. Earth Syst. Sci., 28, 229–239, https://doi.org/10.5194/hess-28-229-2024, 2024.

Gierz, P., Werner, M., and Lohmann, G.: Simulating climate and stable water isotopes during the L ast I nterglacial using a coupled climate-isotope model, J Adv Model Earth Syst, 9, 2027–2045, https://doi.org/10.1002/2017MS001056, 2017.

Halder, J., Terzer, S., Wassenaar, L. I., Araguás-Araguás, L. J., and Aggarwal, P. K.: The Global Network of Isotopes in Rivers (GNIR): integration of water isotopes in watershed observation and riverine research, Hydrol. Earth Syst. Sci., 19, 3419–3431, https://doi.org/10.5194/hess-19-3419-2015, 2015.

Hu, X., Belle, J. H., Meng, X., Wildani, A., Waller, L. A., Strickland, M. J., and Liu, Y.: Estimating $PM_{2.5}$ Concentrations in the Conterminous United States Using the Random Forest Approach, Environ. Sci. Technol., 51, 6936–6944, https://doi.org/10.1021/acs.est.7b01210, 2017.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A. B., Viviroli, D., Wada, Y., Xiao, C., Yao, T., and Baillie, J. E. M.: Importance and vulnerability of the world's water towers, Nature, 577, 364–369, https://doi.org/10.1038/s41586-019-1822-y, 2020.

Jameel, Y., Stahl, M., Michael, H., Bostick, B. C., Steckler, M. S., Schlosser, P., Van Geen, A., and Harvey, C.: Shift in groundwater recharge of the Bengal Basin from rainfall to surface water, Commun Earth Environ, 4, 14, https://doi.org/10.1038/s43247-022-00650-z, 2023.

Joussaume, S., Sadourny, R., and Jouzel, J.: A general circulation model of water isotope cycles in the atmosphere, Nature, 311, 24–29, https://doi.org/10.1038/311024a0, 1984.

Kartal, V.: Machine learning-based streamflow forecasting using CMIP6 scenarios: Assessing performance and improving hydrological projections and climate change, Hydrological Processes, 38, e15204, https://doi.org/10.1002/hyp.15204, 2024.

Kendall, C. and Coplen, T. B.: Distribution of oxygen-18 and deuterium in river waters across the United States, Hydrological Processes, 15, 1363–1393, https://doi.org/10.1002/hyp.217, 2001.

Liu, M., Vecchi, G., Soden, B., Yang, W., and Zhang, B.: Enhanced hydrological cycle increases ocean heat uptake and moderates transient climate change, Nat. Clim. Chang., 11, 848–853, https://doi.org/10.1038/s41558-021-01152-0, 2021.

Mehta, P., Siebert, S., Kummu, M., Deng, Q., Ali, T., Marston, L., Xie, W., and Davis, K. F.: Half of twenty-first century global irrigation expansion has been in water-stressed regions, Nat Water, https://doi.org/10.1038/s44221-024-00206-9, 2024.

Nelson, D. B., Basler, D., and Kahmen, A.: Precipitation isotope time series predictions from machine learning applied in Europe, Proc. Natl. Acad. Sci. U.S.A., 118, e2024107118, https://doi.org/10.1073/pnas.2024107118, 2021.

Peel, M. C., Finlayson, B. L., and McMahon, T. A.: Updated world map of the Köppen-Geiger climate classification, Hydrol. Earth Syst. Sci., 11, 1633–1644, https://doi.org/10.5194/hess-11-1633-2007, 2007.

Penna, D., Ahmad, M., Birks, S. J., Bouchaou, L., Brenčič, M., Butt, S., Holko, L., Jeelani, G., Martínez, D. E., Melikadze, G., Shanley, J. B., Sokratov, S. A., Stadnyk, T., Sugimoto, A., and Vreča, P.: A new method of snowmelt sampling for water stable isotopes, Hydrological Processes, 28, 5637–5644, https://doi.org/10.1002/hyp.10273, 2014.

Penna, D., Hopp, L., Scandellari, F., Allen, S. T., Benettin, P., Beyer, M., Geris, J., Klaus, J., Marshall, J. D., Schwendenmann, L., Volkmann, T. H. M., Von Freyberg, J., Amin, A., Ceperley, N., Engel, M., Frentress, J., Giambastiani, Y., McDonnell, J. J., Zuecco, G., Llorens, P., Siegwolf, R. T. W., Dawson, T. E., and Kirchner, J. W.: Ideas and perspectives: Tracing terrestrial ecosystem water fluxes using hydrogen and oxygen stable isotopes – challenges and opportunities from an interdisciplinary perspective, Biogeosciences, 15, 6399–6415, https://doi.org/10.5194/bg-15-6399-2018, 2018.

Reckerth, A., Stichler, W., Schmidt, A., and Stumpp, C.: Long-term data set analysis of stable isotopic composition in German rivers, Journal of Hydrology, 552, 718–731, https://doi.org/10.1016/j.jhydrol.2017.07.022, 2017.

Satoh, Y., Yoshimura, K., Pokhrel, Y., Kim, H., Shiogama, H., Yokohata, T., Hanasaki, N., Wada, Y., Burek, P., Byers, E., Schmied, H. M., Gerten, D., Ostberg, S., Gosling, S. N., Boulange, J. E. S., and Oki, T.: The timing of unprecedented hydrological drought under climate change, Nat Commun, 13, 3287, https://doi.org/10.1038/s41467-022-30729-2, 2022.

Schulte, P., Van Geldern, R., Freitag, H., Karim, A., Négrel, P., Petelet-Giraud, E., Probst, A., Probst, J.-L., Telmer, K., Veizer, J., and Barth, J. A. C.: Applications of stable water and carbon isotopes in watershed research: Weathering, carbon cycling, and water balances, Earth-Science Reviews, 109, 20–31, https://doi.org/10.1016/j.earscirev.2011.07.003, 2011.

Skrzypek, G., Mydłowski, A., Dogramaci, S., Hedley, P., Gibson, J. J., and Grierson, P. F.: Estimation of evaporative loss based on the stable isotope composition of water using Hydrocalculator, Journal of Hydrology, 523, 781–789, https://doi.org/10.1016/j.jhydrol.2015.02.010, 2015.

Sprenger, M., Leistert, H., Gimbel, K., and Weiler, M.: Illuminating hydrological processes at the soil-vegetation-atmosphere interface with water stable isotopes, Reviews of Geophysics, 54, 674–704, https://doi.org/10.1002/2015RG000515, 2016.

Vystavna, Y., Harjung, A., Monteiro, L. R., Matiatos, I., and Wassenaar, L. I.: Stable isotopes in global lakes integrate catchment and climatic controls on evaporation, Nat Commun, 12, 7224, https://doi.org/10.1038/s41467-021-27569-x, 2021.

Wang, S., Zhang, M., Crawford, J., Hughes, C. E., Du, M., and Liu, X.: The effect of moisture source and synoptic conditions on precipitation isotopes in arid central Asia, JGR Atmospheres, 122, 2667–2682, https://doi.org/10.1002/2015JD024626, 2017.

Zhu, G.: Global Stable Isotope Dataset for Surface Water, Mendeley Data [data set], https://doi.org/10.17632/fs7rwp7fpr.1, 2024.