Near-Surface Soil-Vegetation-Water Evapotranspiration and Water Vapor Isotope Characteristics on a Typical Day in the Yellow River Source Region (Postprint)

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Abstract

Based on in-situ observations of evaporation and its water vapor isotopes, this study investigated the near-surface soil-water-vegetation evapotranspiration characteristics on typical days in Wangjia Township, the source region of the Yellow River, explored the isotopic features of water vapor from soil-vegetation-water evapotranspiration, and calculated the proportions of evapotranspiration and advected water vapor. The results indicate that the peak times of soil and vegetation evapotranspiration exhibit a delayed effect relative to the peak time of water evaporation, and evapotranspiration affects soil water depth up to 20 cm. Significant differences exist in the isotopic values of evapotranspiration water vapor among different observation objects (bare soil, vegetation, water body, mixed). The plant transpiration process exhibits a more intense isotopic fractionation process compared to the soil evaporation process, and the greater the depth of soil water consumed by evapotranspiration, the stronger the fractionation effect. Evaporation causes the observed water vapor δ 18O, δ D, and δ 17O to initially enrich and increase, then stabilize, indicating the existence of an isotopic equilibrium process, while the d-excess continuously decreases during the evaporation process. The hourly Rayleigh fractionation model can effectively reflect the isotopic variation characteristics of evaporative water vapor. Calculations from the water vapor isotopic end-member mixing model show that the near-surface at the observation site is dominated by vegetation-transpired water vapor, with soil evaporation and advected water vapor being comparable in amount. In future water resource allocation and management, greater attention should be paid to the impacts of climate change on soil evapotranspiration.

Characteristics of Near-Surface Soil-Vegetation-Water Body Evapotranspiration and Water Vapor Isotopes on Typical Days in the Yellow River Source Region

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Abstract

Based on in-situ observations of evaporation and water vapor isotopes, this study investigated the characteristics of near-surface soil-vegetation evapotranspiration in Wangjiaxiang, a typical area in the Yellow River source region, and explored the isotopic features of water vapor from soil, vegetation, and water bodies. The study also calculated the proportions of evapotranspiration and migrating water vapor. The results show that the peak times of soil and vegetation evapotranspiration are delayed relative to the peak time of water body evaporation, and the influence of evapotranspiration extends to a soil depth of 20 cm. Significant differences exist in the isotopic values of evapotranspiration water vapor among different observation objects (bare soil, vegetation, water bodies, and mixed conditions). The isotopic fractionation process during plant transpiration is generally stronger than that during soil evaporation, and the fractionation effect intensifies as the depth of soil water consumption by evapotranspiration increases. Evaporation causes the observed water vapor δ^{18}O, δD, and δ^{17}O to initially enrich and then stabilize, indicating the existence of an isotopic equilibrium process, while the d-excess continues to decrease during evaporation. The hourly Rayleigh fractionation model can effectively characterize the changes in the isotopic composition of evaporation water vapor. The results of the endmember mixing model for water vapor isotopes show that near-surface water vapor at the observation site is dominated by evapotranspiration. Future water resource allocation and management should pay greater attention to the impact of climate change on soil evapotranspiration.

Keywords: soil evapotranspiration; water vapor isotopes; Rayleigh fractionation model; Yellow River source region

The Yellow River source region constitutes a crucial runoff generation area for the Yellow River, with studies confirming that over 35% of the Yellow River' s water originates from this region. Against the backdrop of global climate change, the temperature increase rate in the Yellow River source region is significantly higher than in other areas, leading to a decreasing trend in annual runoff. Precipitation is a major component of runoff in the source region, while water vapor serves as the direct source of precipitation. The isotopic characteristics of soil, vegetation, and water body evapotranspiration water vapor in the Yellow River source region and their underlying mechanisms remain insufficiently understood. Currently, the Craig-Gordon model is predominantly used to calculate the isotopic characteristics of soil evapotranspiration water vapor, but the selection of model parameters and their representativeness for actual conditions require further observational verification. Additionally, the isotopic fractionation mechanism of vegetation transpiration remains unclear, and whether different vegetation types exhibit the same isotopic fractionation relationships during transpiration has not been conclusively determined. Although numerous studies have investigated water body evaporation, the isotopic characteristics of evaporation water vapor caused by the coupling of kinetic and equilibrium fractionation cannot yet be precisely calculated and evaluated.

In-situ observation is a crucial means of understanding water vapor isotope variations. This study focuses on two key questions: (1) Whether the isotopic differences in evapotranspiration water vapor among different objects (bare soil, grassland, and water bodies) can be observed and distinguished; and (2) The characteristics and influencing factors of evapotranspiration water vapor isotope variations for different objects on typical days. Based on these objectives, the study focuses on the isotopic characteristics of evapotranspiration water vapor from bare soil, grassland, and water bodies. A water vapor isotope in-situ monitoring station was established in the Yellow River source region to observe and analyze the isotopic characteristics of water vapor from soil, vegetation, and water bodies. Using an hourly Rayleigh fractionation model, the isotopic values of evaporating water bodies and their generated water vapor were calculated, and the proportions of soil evapotranspiration and migrating water vapor were analyzed. The research results provide important reference value for understanding the isotopic fractionation mechanisms of evapotranspiration water vapor in alpine grasslands.

1.1 Study Area

[Figure 1: see original paper] The water system of the source region of Yellow River and the locations of observation points

The study area is located in Wangjiaxiang, Zeku County, in the Yellow River source region. This area features a continental plateau climate with an average annual temperature of approximately -2.4°C. Spring and autumn are contiguous, the grass growing season is only 120 days, and the region experiences long winters without summer. The average annual rainfall is about 437.2 mm, with annual sunshine hours of 2509 h. The main river is the Ba River, with a length of 10 km, flowing westward from east to west and joining the Yellow River at Tongde County. The observation site location is shown in Figure 1. The geographical coordinates of the observation point are (35°22 56.1390 N, 101°01 23.5495 E). The observation area is a pastoral zone with main grass species including star grass, needlegrass, and bluegrass, which are typical plant types in alpine meadows. Therefore, the isotopic data obtained in this study can well represent the evapotranspiration water vapor isotopic characteristics of typical grasslands in the Yellow River source region.

1.2.1 Observation Equipment

In-situ observations of evapotranspiration water vapor isotopes were conducted in Wangjiaxiang, Zeku County. The water vapor isotope monitoring system was designed with five channels, as shown in Figure 2. The first four channels were for monitoring transpiration water vapor from grassland, evaporation water vapor from bare soil, evaporation water vapor from water bodies, and mixed water vapor, respectively. Each channel inlet was positioned approximately 15 cm above the monitoring object. The fifth channel monitored near-surface atmospheric water vapor isotopes at 1.5 m height, representing the mixed isotopic values of evapotranspiration water vapor from different objects (grassland, bare soil, water bodies) and migrating water vapor.

[Figure 2: see original paper] Field observation scenes and equipments

The first channel inlet was fixed inside an organic glass tube with a diameter of 10 cm to restrict water vapor movement from non-observation directions and avoid affecting the isotopic values of the target water vapor. Below the first channel was an evaporation pan with an outer diameter of 150 mm, inner diameter of 71 mm, and height of 73 mm. During the experiment, the initial water height was 10 cm, using groundwater collected the day before the experiment. Water samples were collected every 2 hours in 50 mL glass bottles (sealed after excluding excess air), totaling 13 samples. The evaporation pan and its water were weighed before and after sampling to calculate water evaporation at different times, using a weighing instrument with 0.01 g precision. The sampling and weighing process was controlled within 2 minutes, after which the evaporation pan was returned to its original position. The collected liquid water samples were stored at low temperature and transported to Qinghai University for isotopic analysis.

The water vapor isotope measurement device used a high-precision liquid water and water vapor isotope analyzer (GLA431-TIWA) combined with a multiplexer. The isotope analyzer had a time resolution of 2 seconds, with analysis precisions of 0.5‰ and 0.1‰ for δD and δ^{18}O, respectively. Different observation channels were controlled by electromagnetic valve switching with a switching time of less than 1 second. The isotope analyzer was located about 20 m from the in-situ monitoring sampling inlet. A micro-meteorological station observed meteorological parameters at 1.5 m height, measuring 7 parameters: temperature (\$$\pm0.3°C), humidity(\pm0.25\pm0.1m\cdot s\hat{}\{-1\}), winddirection(withnorthas0°andclockwiseaspositive), lightintensity, pressure(\pm0.2kPa), andrainfall(\pm$ mm), with a time resolution of 1 minute.

To monitor soil evaporation, soil samples were collected using ring knives (70 mm × 52 mm × 50 mm). Based on different vegetation biomass gradients, three observation points were established (Figure 3). The biomass (wet weight) on the ring knives was 3.44 g, 3.87 g, and 4.18 g, respectively. Soil weight (including ring knife weight) was observed every 2 hours (weighing time within 2 minutes) before being returned to the original position. After observation, soil samples at different depths (0–40 cm, with 2 samples collected at each depth) were collected to detect soil water isotopic values. Additionally, vegetation samples were collected to detect plant water hydrogen and oxygen isotopic values.

[Figure 3: see original paper] On-site photo of ring knife sampling

1.2.2 Experimental Observation Process

Observations were conducted on August 15, 2023, from 8:00 to 20:00. The water vapor isotope observation sequence was: bare soil evaporation water vapor, grassland transpiration water vapor, water body evaporation water vapor, mixed water vapor, and atmospheric water vapor. Each channel observation time was set to 15 minutes. Before water vapor isotope observation, time correction was performed using a standard water vapor source with known isotopic values to calibrate the monitored water vapor isotopic values. After the experimental observation, the instrument performed concentration dependence correction, setting 5 water vapor concentration gradients to correct concentration deviations.

1.3.1 Water Vapor Isotope Data

Water vapor isotope observations require time correction and concentration dependence correction. Time correction establishes a functional relationship between observed and true values of standard water vapor sources to correct observation values. Concentration dependence correction uses standard water vapor sources with known concentration gradients to establish a linear relationship between concentration and deviation values for correction. In this study, the actual observed water vapor concentration ranged between 10,000–20,000 ppm (based on instrument observations). The deviation between measured and true values caused by concentration was 0.5‰ for δD and 0.1‰ for δ^{18}O, with a time correction of 303 seconds. Additionally, due to channel switching, the first 303 seconds of data from each channel observation were discarded to ensure accurate isotopic values.

1.3.2 Soil Water and Vegetation Water Processing

Soil water and vegetation water extraction used an automatic vacuum condensation extraction system (LI2100) produced by Beijing Lica United Tech. The extraction temperature was set to 205°C with an extraction time of 120 minutes. After extraction, test tubes were removed, sealed, melted at room temperature, and then transferred to sample bottles using disposable syringes for liquid water isotopic measurement. During extraction, known standards were included to correct deviations produced during the soil water and vegetation water extraction process.

2.1 Daily Meteorological Parameters and Evapotranspiration Variation

Humidity and pressure showed a trend of first decreasing then increasing over time, while temperature showed the opposite pattern, with turning points at 14:00. Temperature increased from 13.51°C at 9:00 to a maximum of 22.25°C at 18:00, then decreased. Relative humidity and pressure decreased from 71.81% and 66.81 kPa at 9:00 to minimum values of 44.09% and 66.58 kPa at 18:00, then gradually increased to 56.84% and 66.62 kPa by the end of the experiment. Light intensity was 7970 lux at 9:00, reaching a maximum of 140,532 lux at 14:00, then fluctuating and decreasing to 2468 lux by 20:00. Wind speed showed fluctuating changes, maintaining above 1.50 $m \cdot s^{-1}$, with speeds above 2.82 $m \cdot s^{-1}$ from 9:00–14:00, peaking at 3.58 $m \cdot s^{-1}$ at 15:00, and maintaining above 3.33 $m \cdot s^{-1}$ afterward. Wind direction was primarily southeasterly before 17:00, then shifted to northeasterly. The variations in temperature and light intensity characterize the diurnal temperature changes dominated by solar radiation under clear-sky conditions, indicating that this study well represents typical weather conditions.

Water body evaporation at different times was greater than soil and vegetation evapotranspiration. Soil evapotranspiration with different biomass levels showed consistent trends, but peak evaporation times were delayed compared to water bodies. Water body evaporation, influenced by meteorological parameters, showed an increasing then fluctuating pattern over time (Figure 5), with two evaporation peaks of 0.80 mm and 0.53 mm at 13:00 and 17:00, respectively. Soil evapotranspiration with different biomass levels showed consistent trends with two peaks of 0.44 mm and 0.45 mm, both delayed by 1 hour compared to water body peaks.

[Figure 4: see original paper] Temporal variation of meteorological parameters

[Figure 5: see original paper] Temporal variation of water body and soil evapotranspiration

2.2 Soil and Water Body Isotope Variations

Soil water isotopes showed an initial increase then decrease with depth, with a turning point at 20 cm. From the surface to 20 cm depth, $\delta^{18}O$ increased from -10.2‰ to -8.5‰, then gradually decreased to -9.8‰; δD increased from -68.3‰ to -58.2‰, then gradually decreased to -65.1‰; d-excess increased from 13.2‰ near the surface to 15.6‰, then decreased to 13.5‰, and finally increased to 14.8‰. The increase in soil water isotopes with depth from 0–20 cm indicates that evaporation affects soil water isotopic enrichment in this layer. From 20–40 cm, isotopes showed a decreasing trend with depth, suggesting connection between soil water and groundwater. At 40 cm depth, soil water isotopic values were -9.6‰ for $\delta^{18}O$ and -64.2‰ for δD, close to the groundwater isotopic values of -9.8‰ and -65.1‰, respectively. The d-excess showed an increasing trend at 0–10 cm depth, indicating regulation by plant roots in this layer.

Water body isotopes showed an initial enrichment then stabilization over time. According to the rate of isotopic temporal change, water body evaporation can be divided into two stages: 8:00–11:00 and 11:00–20:00. In the first stage, due to lower temperatures and smaller evaporation rates, the temporal growth rates of δ^{18}O and δD were 0.15‰ h^{-1} and 1.2‰ h^{-1}, respectively, with d-excess decreasing at 0.3‰ h^{-1}, indicating equilibrium fractionation control. In the second stage, influenced by temperature and solar radiation, evaporation was larger, causing greater isotopic variations with temporal growth rates of 0.35‰ h^{-1} for δ^{18}O, 2.8‰ h^{-1} for δD, and -0.8‰ h^{-1} for d-excess, showing significant kinetic fractionation.

[Figure 6: see original paper] Soil water isotope variation with depth at the observation site

2.3 Temporal Variation of Evapotranspiration Water Vapor Isotopes from Soil-Vegetation-Water Body

Grassland, bare soil, and water body evapotranspiration water vapor hydrogen and oxygen isotopes showed a pattern of initial fluctuating increase then stabilization over time (except for the initial grassland value), while mixed water vapor isotopes showed a decreasing then increasing pattern, and d-excess showed a decreasing trend throughout. The isotopic fluctuations of grassland, bare soil, and water body evapotranspiration water vapor were basically consistent (Figure 8), indicating that isotopes were mainly controlled by the evaporation process. The d-excess showed a decreasing pattern consistent with evaporating water bodies. Mixed water vapor isotopic values showed a significant decrease at 12:00–14:00, indicating sufficient influence from external migrating water vapor, which was corroborated by observed wind speed and evapotranspiration rates.

Significance tests on water vapor isotopic values from different observation objects revealed significant differences (significance level > 0.05), indicating different isotopic fractionation mechanisms. The hydrogen and oxygen isotopes showed enrichment over time, with δ^{18}O increasing from -20.5‰ to -12.3‰ (increment of 8.2‰) and δD increasing from -158.2‰ to -95.6‰ (increment of 62.6‰), while d-excess decreased from 15.8‰ to 2.1‰. The large initial water vapor isotopic values were likely due to nighttime water vapor condensation, which was also evidenced by the high initial d-excess values.

[Figure 7: see original paper] The temporal variation of isotopic composition in evaporating water bodies

[Figure 8: see original paper] Isotope temporal variation characteristics of different observed objects (channels)

[Figure 9: see original paper] Temporal changes in the mean isotopic composition of water vapour for different observation objects (channels)

3.1.1 Comparison of Observed and Theoretical Water Body Isotope Values

According to the Rayleigh fractionation model, the isotopic values of evaporating water bodies satisfy the following relationship:

$\delta\text{D} = (1 + \delta\text{D}_0) \times \text{f}\hat{}(\text{ W-V})$
$\delta^{18}\text{O} = (1 + \delta^{18}\text{O}_0) \times \text{f}\hat{}(\text{ W-V})$

where W-V is the enrichment coefficient, which can be calculated based on temperature-dependent relationships; and f is the fraction of water remaining. Based on these equations, calculated water body isotopic values showed large deviations from observed values, particularly for δD, with a maximum deviation of 15.2‰. As evaporation continued, the calculation deviation further expanded.

Using an hourly Rayleigh fractionation model (i.e., calculating with the Rayleigh model each hour, where the initial water body value for each hour is calculated from the previous hour using the Rayleigh model, and the evaporation rate also uses the current hour' s rate), the calculated water body isotopic values better matched observations, with the maximum deviation reduced to 6.8‰, an absolute reduction of 55%. However, the deviation for δD showed little improvement, indicating that natural water body evaporation involves significant kinetic fractionation.

[Figure 10: see original paper] Comparison of calculated and observed hydrogen and oxygen isotope values in evaporating water bodies

3.1.2 Comparison of Observed and Theoretical Water Vapor Isotope Values

Based on mass conservation during evaporation, the isotopic relationship between evaporating water bodies and water vapor is:

$\delta\text{v} = (1 + \delta\text{W}) / \alpha - 1$

where δ represents isotopic values (‰), and subscripts W and v represent liquid water and water vapor, respectively. Using the hourly Rayleigh fractionation model to calculate water vapor isotopic values, the calculated values were larger than observed values, with peak deviations of 8.5‰ for δ^{18}O and 65.2‰ for δD. Using the hourly Rayleigh fractionation model, the calculation deviation decreased from an initial 12.3‰ to 3.2‰ for δ^{18}O and from 95.6‰ to 28.5‰ for δD. The calculation conditions better matched observation conditions, and using meteorological parameters to fit enrichment coefficients for water vapor isotope calculations could reflect kinetic fractionation processes to some extent, bringing calculated values closer to observations.

[Figure 11: see original paper] Comparison of calculated and observed hydrogen and oxygen isotope values in water vapour

3.2 Variation and Mechanism of Isotopic Enrichment Coefficients in Soil-Vegetation Evapotranspiration

The hydrogen and oxygen isotopic enrichment coefficients during soil evaporation and vegetation transpiration are positively correlated with soil depth, and plant transpiration shows stronger isotopic fractionation effects. To explore the variation characteristics of isotopic fractionation coefficients, we assumed that as evaporation proceeds, soil water consumption gradually increases from the surface to 20 cm depth below ground, with a potential depth increase rate of 3.33 cm · h^{-1} from 10:00-16:00.

Based on observed water vapor and water body isotopic values, enrichment coefficients were calculated using the definition formula and then used to establish multiple linear regression relationships with meteorological parameters:

H = 1.46\$$\times 10^{\{-4\}T + 3.55\times 10}$\{-2\}$RH - 1.16\times 10^{\{-4\}WV(n = 24, R}$\{2\}\$ = 0.905, p = 0.05)
O = 1.49\$$\times 10^{\{-4\}T + 7.70\times 10}$\{-2\}$RH - 4.22\times 10^{\{-4\}WV(n = 24, R}$\{2\}\$ = 0.868, p = 0.05)

Using these regression-derived enrichment coefficients, the calculated water vapor isotopic values showed consistent trends with observations, with the same peak times. The average deviations were 2.1‰ for δ^{18}O and 16.8‰ for δD, representing reductions of 65% and 60% respectively compared to the hourly Rayleigh fractionation model.

At the same depth, vegetation transpiration enrichment coefficients were greater than soil evaporation enrichment coefficients, indicating stronger isotopic fractionation during vegetation transpiration. The hydrogen and oxygen isotopic enrichment coefficients during vegetation transpiration were 381.81\$$\pm 16.23 and 33.66 \pm 2.31, respectively, while during soil evaporation they were 3352.30 \pm 175.26 and 446.65 \pm$\$ respectively. This demonstrates that vegetation transpiration produces more pronounced isotopic fractionation than soil evaporation.

3.3 Partitioning of Evapotranspiration Water Vapor and External Migrating Water Vapor

Based on the endmember mixing model and combined with water vapor isotopes and measured evapotranspiration, the near-surface soil and vegetation evapotranspiration accounts for 71% of total atmospheric water vapor. Using grassland transpiration isotopes, the calculated evapotranspiration water vapor proportion ranged from 55%-93%; using bare soil evaporation isotopes, the proportion ranged from 56%-92%; using water body evaporation isotopes, the proportion ranged from 61%-96%; and using mixed water vapor isotopes, the proportion ranged from 63%-89%. The results from different isotope calculations showed good consistency.

Assuming that mixed water vapor is formed by evaporating water bodies and external migrating water vapor, the water body evaporation water vapor proportion calculated using δ^{18}O ranged from 52%-92%, while that calculated using δD ranged from 53%-93%. The δ^{18}O-calculated evapotranspiration water vapor proportion ranged from 58%-96%, showing slightly higher values. Integrating the results from soil, vegetation, and water body calculations, the mean evapotranspiration water vapor proportion was 71%, consistent with existing research conclusions. This conclusion is significant for understanding soil water migration and its dynamic processes. In future water resource allocation and management, full consideration should be given to this portion of water resources and the potential impacts of climate change on internal circulation rates and water resources.

4 Conclusions

Based on in-situ observations of evaporation and water vapor isotopes, this study investigated daily-scale soil-vegetation evapotranspiration characteristics, summarized the variation patterns of evapotranspiration water vapor isotopes from different objects, calculated water body and water vapor isotopic values, and quantified the proportions of soil evapotranspiration and migrating water vapor. The main conclusions are:

1) During the evapotranspiration process, soil evapotranspiration shows a delayed effect relative to water body evaporation, with the influence extending to a soil depth of 20 cm. Different observation objects show distinct evapotranspiration water vapor isotopic values, all exhibiting an initial increase then stabilization pattern, indicating the existence of isotopic equilibrium processes and different fractionation mechanisms.

2) Theoretical calculations further demonstrate that the Rayleigh fractionation model shows large deviations in describing water body and water vapor isotopic values. Using an hourly Rayleigh fractionation model, the deviation for water body δ^{18}O was reduced by 55%. Combined with meteorologically-derived enrichment coefficients, the hourly Rayleigh fractionation model reduced the average deviation for water vapor δ^{18}O by 65% and for δD by 60%.

3) During soil evaporation and plant transpiration, hydrogen and oxygen isotopic enrichment coefficients gradually increase with soil depth, and plant transpiration exhibits stronger isotopic fractionation effects than soil evaporation.

4) Based on the endmember mixing model and combined with water vapor isotopes and measured evapotranspiration, near-surface soil and vegetation evapotranspiration accounts for 71% of total atmospheric water vapor. Future water resource allocation and management should fully consider this portion of water resources and the potential impacts of climate change on internal circulation rates and water resources.

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Note: Figure translations are in progress. See original paper for figures.