Identifying water vapor sources of precipitation in forest and grassland in the north slope of the Tianshan Mountains, Central Asia Postprint

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Abstract

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Full Text

Identifying Water Vapor Sources of Precipitation in Forest and Grassland on the North Slope of the Tianshan Mountains, Central Asia

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Abstract: Identifying water vapor sources in the natural vegetation of the Tianshan Mountains is of significant importance for obtaining greater knowledge about the water cycle, forecasting water resource changes, and dealing with the adverse effects of climate change. In this study, we identified water vapor sources of precipitation and evaluated their effects on precipitation stable isotopes on the north slope of the Tianshan Mountains, China. By utilizing the temporal and spatial distributions of precipitation stable isotopes in forest and grassland regions, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, and isotope mass balance model, we obtained the following results: (1) The Eurasian continent, Black Sea, and Caspian Sea are the major sources of water vapor. (2) The contribution of surface evaporation to precipitation in forests is lower than that in grasslands (except in spring), while the contribution of plant transpiration to precipitation in forests (5.35%) is higher than that in grasslands (3.79%) in summer. (3) The underlying surface and temperature are the main factors that affect the contribution of recycled water vapor to precipitation; meanwhile, the effects of water vapor sources of precipitation on precipitation stable isotopes are counteracted by other environmental factors. Overall, this work will prove beneficial in quantifying the effect of climate change on local water cycles.

Keywords: Tianshan Mountains; Manas River Basin; water vapor sources of precipitation; land cover; precipitation stable isotopes; Hybrid Single-Particle Lagrangian Integrated Trajectory

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1 Introduction

The Tianshan Mountains are considered to be the 'water tower' of Central Asia [**?**, **?**]. Mid-mountain forests and low-mountain grasslands are the major natural vegetation distributions in this region, which facilitate the formation and conservation of water resources [**?**, **?**, **?**]. Identifying water vapor sources in the forest and grassland regions of the Tianshan Mountains will provide more information about the water cycle while enabling the forecasting of future water resource changes. However, there is a lack of observation data in mountain areas [**?**, **?**]. As environmental variables differ significantly in space and time

due to complex terrain, most remote sensing datasets and reanalysis datasets with low spatial resolutions cannot be reliably used in mountain areas [?, ?, ?]. Furthermore, monitoring data are very scarce due to poor accessibility. Thus, the lack of reliable datasets is the major limiting factor for elucidating the water cycle in the region.

A large amount of climatic and hydrological information is recorded in precipitation stable isotopes. They have been widely used in global and regional water cycle studies [?, ?, ?]. Modern precipitation isotopes are stable indicators of water vapor sources, phase change, and water vapor transmission paths [?, ?, ?]. Many studies have analyzed the water vapor sources of precipitation based on stable isotopes, covering regions with different climates such as monsoon [?, ?, ?, ?, ?, ?], temperate marine climate [?, ?, ?], and inland arid climate [?, ?, ?, ?, ?].

Numerous studies have attempted to obtain more information about water vapor sources of precipitation in the Tianshan Mountains based on precipitation stable isotopes. On the north slope of the Tianshan Mountains, water vapor mainly originates from Eurasia [?, ?]; the contribution of recycled water vapor to precipitation is higher in larger oases (Urumqi Oasis) than in smaller oases (Shihezi Oasis and Caijiahu Oasis) [?, ?]. In the Urumqi River Basin, temperature and evaporation decrease with increasing altitude, consequently reducing the fraction of recycled water vapor in precipitation [?, ?]. However, few studies have quantified the contribution of different water vapor sources to precipitation in areas with different land covers.

This study utilizes precipitation stable isotopes in forest and grassland regions, the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, and isotope mass balance model to identify water vapor sources, quantify their contribution to precipitation on the north slope of the Tianshan Mountains in Central Asia, and discuss the factors that affect the water vapor sources of precipitation.

2 Study Area

The Manas River Basin is situated on the north slope of the Tianshan Mountains in Xinjiang Uygur Autonomous Region, China. The maximum and minimum altitudes are 5131 m and 582 m above sea level, respectively. Areas with altitudes above 3900 m (the snow line) are covered by permanent snow and glaciers. Overall, there are 726 glaciers covering an area of 637.8 km^2 in the basin [?, ?]. The glaciers are an important recharge source for the Manas River [?, ?]. From the foot to the top of the mountain, the land cover comprises oases and deserts, desert steppes, upland meadows, spruce forests, alpine meadows, alpine cushion-like vegetation, and lichen (Fig. 1 [Figure 1: see original paper]).

Fig. 1 (a) Schematic of the study area and hydrological stations used in the study and (b) land cover of the Manas River Basin. Land cover data are from MODIS Land Cover Products (MCD12Q1) (https://lpdaac.usgs.gov/products/mcd12q1v006/).

The area exhibits a typical temperate continental climate with scarce precipitation. The annual mean temperature ranges from 4.7°C to 5.7°C, and mean annual precipitation ranges from 115 mm to 200 mm, concentrated mainly in summer. The altitudes of Honggou station (in the forest area) and Kensiwate station (in the grassland area) are 1472 m and 860 m, respectively (Fig. 1). From August 2015 to July 2016, the annual mean temperature, total precipitation, and potential evapotranspiration were 4.0°C, 570 mm, and 866 mm at Honggou station, respectively; the respective values were 6.2°C, 498 mm, and 916 mm at Kensiwate station.

3.1 Sampling and Analysis

All samples were collected at the above-mentioned hydrological stations (Fig. 1). From August 2015 to July 2016, precipitation and stream water samples were collected at Honggou station and Kensiwate station in the Manas River Basin, and at the hydrological station in the Kashi River Basin (43°48 36 N, 81°54 00 E). Honggou station and Kensiwate station are located in the forest and grassland regions of the Manas River Basin, respectively. The Kashi River station is situated upwind of the Manas River Basin. At Honggou station, 97 precipitation samples and 295 stream water samples were collected; at Kensiwate station, 119 precipitation samples and 295 stream water samples were collected; and at Kashi River station, 127 precipitation samples and 295 stream water samples were collected. Standard Chinese rain gauges with a funnel diameter of 20 cm were used as samplers. Precipitation samples were collected immediately after precipitation events.

From March to October, stream water samples were collected at 14:00 (LST) every day. In other months, stream water samples were collected at 14:00 (LST) every three days. More information about sampling and sample analysis can be obtained from Chen et al. (2019) and Chen et al. (2020).

3.2 Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model

The HYSPLIT model is a complete system for computing air parcel trajectories and simulating dispersion, chemical transformation, and deposition [**?**, **?**, **?**]. In this study, we used the dataset from the Global Data Assimilation System (GDAS) [**?**, **?**] with a spatial resolution of 1°$×$1°. The backward duration was set as 10 d [**?**, **?**]. The lifting condensation level (LCL) was set as the initial modeling height of the air mass; LCL was generally determined from humidity and temperature data [**?**, **?**] and varied with each event.

The HYSPLIT model is widely used to detect the transportation trajectory of water vapor and dust. However, the traditional HYSPLIT model maintains a constant backward duration and starting height without considering meteorological variables that can result in erroneous identification of water vapor sources. It is technically easy to obtain the air mass transportation trajectory

10 d before precipitation. However, it is difficult to precisely determine the time and location at which moisture significantly recharges into the air mass. The actual moisture recharge could occur less than 10 d before precipitation. To determine the water vapor source more precisely, we adjusted the transportation trajectory based on specific humidity [**?**, **?**, **?**, **?**]. For each 6 h interval, if the specific humidity of the following time interval increases by more than 0.2 g/kg compared to that in the previous time interval, the air parcel location at the previous time interval is identified as an evaporative source. In this study, we only modeled the trajectories of Honggou station as the distance between Honggou station and Kensiwate station is less than 1°, although the land cover of these two areas is completely different.

3.3 Isotope Mass Balance Model

The contributions of upwind water vapor, evaporation vapor, and transpiration vapor to precipitation can be quantified via the isotope mass balance model [**?**, **?**, **?**]:

$$2222pvtrtrevevadvadvHHHHfffδδδδ = ++$$

where f_{tr}, f_{ev}, and f_{adv} denote the fractions of transpiration, surface evaporation, and advection moisture in precipitation (%), respectively. Additionally, δ_{pv}, δ_{tr}, δ_{ev}, and δ_{adv} denote the concentration of stable isotopes in precipitation vapor, transpiration vapor, surface evaporation vapor, and upwind water vapor (‰), respectively. H and O denote the stable hydrogen isotope and stable oxygen isotope, respectively.

The concentration of stable isotopes in precipitation vapor (δ_{pv}) is calculated with the following equation [**?**, **?**]:

where δ_p denotes the concentration of precipitation stable isotope (‰) and k represents an adjusting factor. The value of k ranges from 0.5 to 1.0; it equals 0.5 for regions with significant seasonal variation and 1.0 for regions with no significant seasonal variation [**?**, **?**, **?**]. We take k as 0.5 in this study as the seasonal variation is significant in the study area. ε^+ denotes the equilibrium fractionation factor between water and water vapor:

where α^+ denotes the equilibrium fractionation factor calculated based on temperature [**?**, **?**]:

where T denotes temperature (K).

The concentration of stable isotopes in surface evaporation vapor (δ_{ev}) is calculated using the Craig-Gordon model [**?**, **?**]:

where δ_s denotes the concentration of stable isotopes in surface evaporation vapor (‰), h denotes relative humidity (%), ε denotes the total fractionation coefficient, and ε_k denotes the kinetic fractionation factor.

The concentration of stable isotopes in evaporation vapor (δ_s) is calculated by following Skrzypek et al. (2015), Gibson et al. (2016), and Diamond and Jack (2018):

The total fractionation coefficient (ε) is defined as the sum of equilibrium fractionation factor and kinetic fractionation factor [**?**, **?**]:

Based on the studies by Gat (1996) and Gonfiantini (1986), the kinetic fractionation factor (ε_k) is expressed as follows:

$$18181818pvtrtrevevadvadvOOOOfffδδδδ = ++trevadv++ = 1fffppv3110–kkδεδε+−+× = +1–εα+++ =$$

The concentration of stable isotopes in upwind water vapor (δ_{adv}) is calculated with the Rayleigh fractionation formula:

where $\delta_{pv–adv}$ denotes the concentration of stable isotopes in precipitation water vapor from the upwind regions (‰) and F denotes the residual water fraction of raindrops after evaporation as they fall to the ground (%), which is calculated using precipitation water vapor [**?**, **?**].

Under steady-state conditions, the concentrations of stable isotopes in transpiration vapor (δ_{tr}) from plants are unfractionated when compared to the source water utilized by the plants; thus, these can be measured using xylem water [**?**, **?**]. In the Manas River Basin, local plants either utilize groundwater or surface water that has been transformed by precipitation and snow/glacier meltwater. Conversely, stream water in the Manas River is a combination of precipitation, snow/glacier meltwater, and baseflow [**?**, **?**]. In this study, we denoted the concentration of stable isotopes in stream water as δ_{tr}.

4.1 Transportation Trajectory of Precipitation Water Vapor

The air mass mainly originates from the west and northwest, with no significant seasonal variations (Figs. 2 and 3). Based on the air mass transportation trajectory, precipitation water vapor in the Manas River Basin mainly originates from the following four sites: (1) the Arctic Ocean; (2) the Atlantic Ocean; (3) the Mediterranean Sea, Black Sea, and Caspian Sea; and (4) the Eurasian continent. We also observed a few precipitation events wherein the air mass is sourced from the east or the Red Sea and Persian Gulf in the southwest; these events occurred in summer and winter.

Fig. 2 [Figure 2: see original paper] Spatial and temporal distributions of raw and adjusted trajectories of Honggou station for each precipitation event from August 2015 to July 2016 in (a) spring, (b) summer, (c) autumn, and (d) winter. The satellite-derived land cover is downloaded from Natural Earth (http://www.naturalearthdata.com).

After correction of the transportation trajectory based on specific humidity, the length of all trajectories decreased. The precipitation water vapor in the Manas River Basin is mainly derived from the Eurasian continent, Black Sea, and Caspian Sea. The frequency of precipitation events where water vapor originated directly from the Atlantic Ocean and Arctic Ocean is very low (Fig. 2).

Our results are consistent with those of previous studies; that is, precipitation water vapor on the north slope of the Tianshan Mountains mainly originates from the west and northwest [**?**, **?**, **?**, **?**, **?**, **?**]. After adjusting the trajectories, we found that precipitation water vapor mainly originates from the Eurasian continent, Black Sea, and Caspian Sea (irrespective of season). Only a few precipitation events occurred in winter and summer wherein water vapor originated from the North Atlantic and Arctic.

However, previous studies have indicated that water vapor sources of precipitation vary significantly with seasons. The water vapor sources of summer precipitation, especially rainstorms, are mainly the North Atlantic and Arctic oceans [**?**, **?**, **?**]. There are two major reasons for the difference between our results and previous research. First, all precipitation events have been elucidated in our study; however, Dai et al. (2007) and Huang et al. (2017) only researched rainstorms as the Tianshan Mountains are far from the ocean and exhibit low air humidity. Precipitation in this region ranges from light to moderate. Second, only the mid-mountain zone covered by grasslands and forests has been considered in our study, whereas Dai et al. (2007) and Huang et al. (2017) studied the entire Xinjiang Uygur Autonomous Region, China. The mid-mountain zone is wetter than the plains and basins in Xinjiang, while being a major site for water resource formation and conservation in Central Asia [**?**, **?**, **?**]. Thus, locally evaporated water is an important water vapor source for light to moderate precipitation in the mid-mountain zone.

Fig. 3 [Figure 3: see original paper] Distribution of water vapor sources from different directions at Honggou station during August 2015 to July 2016. Here, the summer half-year occurs from April to September, while the winter half-year ranges from October to March in the next year.

4.2 Contribution of Recycled Water Vapor

Table 1 shows the contribution of each water vapor source to precipitation in the Manas River Basin. At higher altitudes and lower temperatures, the potential evaporation is lower in forests than in grasslands. However, the actual evaporation is higher in forests than in grasslands because snow covers a larger area for a longer duration in forests in spring. The contribution of evaporation water vapor is higher in the forests (3.67%) than in the grasslands (2.46%). Given the lower altitude and higher temperature in other seasons, evaporation is more intensive in grasslands than in forests.

Conversely, because of lower altitude and higher temperature in spring, vegeta-

tion exhibits higher growth in grasslands than in forest areas; the contribution of transpiration water vapor to overall precipitation in the grasslands (1.70%) exceeds that in forests (0.42%). In winter, the temperature is always lower than 0.00°C, while plant transpiration is weak in both grasslands and forests. However, in summer and autumn, plant transpiration is more intensive in forests than in grasslands, while the contribution of transpiration water vapor is higher in forests (5.35% and 1.12% in summer and autumn, respectively) than in grasslands (3.79% and 0.95% in summer and autumn, respectively).

4.3 Factors Affecting the Contribution of Recycled Water Vapor

On a global scale, transpiration water vapor from plants constitutes a major part of recycled water. It accounts for almost 39%$±10±$15% of total land evapotranspiration [**?**, **?**]. In the Urumqi River Basin, an increase in altitude causes the land cover to comprise oases, forests, and grasslands at Urumqi station, Houxia station, and Gaoshan station, respectively. The contribution of recycled water vapor to precipitation decreases with increasing altitude [**?**, **?**]. In the northwestern Tibetan Plateau, the contribution of recycled water vapor to precipitation increases with rising temperature, especially in areas with adequate water for evapotranspiration such as the Qinghai Lake and areas covered by snow and glacier [**?**, **?**, **?**].

For similar land cover, the contribution of recycled water vapor increases with altitude and vegetation/water area. At Shihezi City, Caijiahu Town, and Urumqi City located on the north slope of the Tianshan Mountains, the land cover comprises artificial oases and the oasis area increases successively. The altitude of the Urumqi oasis (935 m) exceeds that of the Shihezi oasis and the Caijiahu oasis (440 m for both). The contribution of recycled water vapor is highest in the Urumqi oasis and lowest in the Shihezi oasis [**?**, **?**]. In the Shiyang River Basin of China, as altitude increases, the land cover changes from artificial oasis to desert and then to forest; consequently, the contribution of recycled water increases [**?**, **?**]. In the Manas River Basin, as altitude increases, the land cover changes from desert steppe to forest; the contribution of recycled water vapor increases with rising altitude in summer but decreases in other seasons (Table 2).

Table 2 Comparison of studies on recycled water vapor estimated based on stable water isotopes in Northwest China

Study area	Station	Latitude	Longitude	Altitude	Proportion (%)	Landcover	Reference
Urumqi River Basin	Urumqi	43°47 N	86°37 E	935 m	0.6$±1.7	*Oasis*	*Kongetal.*(2013)
	Houxia	43°17′*N*	87°11′*E*	1			

Study area	Station	Latitude	Longitude	Altitude	Proportion (%)	Landcover	Reference
Manas River Basin	Honggou 2015–2016 (spring)	43°43 N	85°44 E	1472 m	3.67	Forest	This study
	Honggou 2015–2016 (summer)	43°43 N	85°44 E	1472 m	5.35	Forest	This study
	Honggou 2015–2016 (autumn)	43°43 N	85°44 E	1472 m	1.12	Forest	This study
	Honggou 2015–2016 (winter)	43°43 N	85°44 E	1472 m	0.42	Forest	This study
	Kensiwate 2015–2016 (spring)	43°58 N	85°57 E	860 m	1.70	Grassland	This study
	Kensiwate 2015–2016 (summer)	43°58 N	85°57 E	860 m	3.79	Grassland	This study
	Kensiwate 2015–2016 (autumn)	43°58 N	85°57 E	860 m	0.95	Grassland	This study
	Kensiwate 2015–2016 (winter)	43°58 N	85°57 E	860 m	0.00	Grassland	This study

4.4 Effect of Water Vapor Source on Stable Isotopes in Precipitation

Water vapor can significantly affect the composition of precipitation stable isotopes [?, ?, ?]. At Postojna, Slovenia, located in Central Europe, $\delta^{18}O$ and $\delta^{2}H$ values of precipitation water vapor from the continent are lower than those from the ocean. Under the effect of evapotranspiration and post-condensation exchange between raindrops and atmospheric water vapor, there are similarities in $\delta^{18}O$ and $\delta^{2}H$ values of precipitation water vapor from different oceans [?, ?]. In the Sydney Basin of Australia, the $\delta^{18}O$ value of precipitation is higher for water vapor sourced from the continent compared to that sourced from the ocean. However, given the effect of sub-cloud evaporation and mixing, the d-excess values of precipitation are similar for continental and oceanic water vapor [?, ?].

Conversely, in the East Asian monsoon region, strong convection in the source region of water vapor and long-distance transport of water vapor tends to reduce the weight of stable isotopes in water vapor and decrease the $\delta^{18}O$ value of precipitation [?, ?]. Given the low relative humidity in the source region of water vapor, non-equilibrium evaporation tends to be intensive during water vapor transportation and results in high d-excess values [?, ?]. In the Indian Ocean monsoon zone, water vapor is sourced from the ocean in the monsoon season and from the continent in other seasons. The concentration of precipitation stable isotopes is lower in the monsoon season than in other seasons [?, ?, ?, ?, ?].

For oases in the hinterland of Eurasia located on the north slope of the Tianshan Mountains, increases in oasis area augment the intensity of evaporation and transpiration, expand the fraction of recycled water vapor in precipitation, and decrease the concentration of precipitation stable isotopes [?, ?]. All the aforementioned studies indicate that stable isotopes in precipitation change with water vapor source.

However, in the Manas River Basin, no significant relationship between precipitation stable isotopes and the distance of water vapor transport is observed (Figs. 4 and 5). In inland arid areas, which comprise complex water vapor sources and exhibit low relative humidity, sub-cloud evaporation and exchange between precipitation water vapor and ambient moisture are very intensive. This could counteract the information regarding water vapor source in precipitation stable isotopes [?, ?, ?, ?]. Under the effect of altitude and with increases in contributions of recycled water vapor to precipitation due to increased transpiration intensity in forests compared to grasslands, precipitation stable isotopes in forests are lower than those in grasslands. However, it is difficult to separately quantify the effect of altitude and land cover.

Fig. 4 [Figure 4: see original paper] Relationship between $\delta^{18}O$ and back-tracking time of precipitation vapor (a and b) and the relationship between d-excess and back-tracking time of precipitation vapor (c and d) at Honggou station from August 2015 to July 2016. (a) and (c) denote the summer half-

year; (b) and (d) denote the winter half-year. The boxes represent the 25%–75% percentiles, and the line through the box represents the median (50th percentile). The whiskers indicate the 90th and 10th percentiles, and points above and below the whiskers indicate the 95th and 5th percentiles. Different lowercase letters in the figure indicate significant differences among the five back-tracking times ($P<0.05$).

Fig. 5 [Figure 5: see original paper] Relationship of moisture transport distance with $\delta^{18}O$ (a) and d-excess (b) in precipitation.

4.5 Uncertainty Analysis

Statistical uncertainty and model uncertainty are the two major sources of uncertainty used to evaluate the contribution of different water vapor sources to precipitation. Statistical uncertainty is caused by variations in tracer concentrations. Model uncertainty is caused by violations of underlying assumptions [**?**, **?**, **?**].

With respect to the isotope mass balance model, end-member selection and calculations are the two major sources of uncertainty [**?**, **?**, **?**]. In this study, δ_{pv}, δ_s, δ_{ev}, and δ_{adv} were calculated with δ_p based on different hypotheses, which are not always tenable in the field. Determining the concentration of stable isotopes in transpiration water vapor (δ_{tr}) from plants is another important source of uncertainty. Its basic theory is that under steady state, the concentrations of stable isotopes in transpiration vapor (δ_{tr}) from plants are unfractionated when compared to source water utilized by local plants [**?**, **?**]. There are significant spatial and temporal variations in the source water utilized by plants. Moreover, water isotope monitoring has not been performed consistently to date in the Tianshan Mountains. Data obtained for one year are not sufficient and may lead to loss of information [**?**, **?**].

For the HYSPLIT model, the dataset used is one of the most important sources of uncertainty. The resolution of the data used by the HYSPLIT model is 1°$×$1°. Since the Tianshan Mountains exhibit highly complex terrain, valuable information is smoothed out.

5 Conclusion

Based on the spatial and temporal variations of precipitation stable isotopes in forests and grasslands in the Manas River Basin, we analyzed the water vapor sources of precipitation and quantified the contribution of each water vapor source to precipitation. This is of great importance for accurately forecasting water cycle processes and local water resources in arid areas under the background of climate change.

The Eurasian continent, Black Sea, and Caspian Sea are the major water vapor sources of precipitation in the basin. Significant seasonal changes in the contribution of recycled water vapor to precipitation are observed. In spring, the

contribution of evaporation water vapor is higher in forests than in grasslands. In summer, the contribution of transpiration water vapor is higher in forests (5.35%) than in grasslands (3.79%). Land cover and temperature are the major factors affecting the contribution of recycled water vapor to precipitation. Furthermore, the water vapor sources of precipitation do not have a significant effect on precipitation stable isotopes.

Although water stable isotopes can offer more hydrological information regarding past, present, and future changes in the water cycle of arid areas, high-resolution monitoring is needed in the future.

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