Below-Cloud Secondary Evaporation Effects on Stable Isotopes in Precipitation in the Yellow River Basin (Postprint)

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Abstract

The phenomenon of sub-cloud secondary evaporation during raindrop descent from cloud base to ground surface affects isotopic ratios in raindrops; clarifying variations in stable isotopes during precipitation is crucial for investigating watershed hydrological cycles. Based on data from the Global Network of Isotopes in Precipitation (GNIP), isotopic data from relevant literature, and meteorological data, we first established the Local Meteoric Water Line (LMWL) to qualitatively analyze the relationship between sub-cloud secondary evaporation and various meteorological elements in the Yellow River Basin, and subsequently employed a modified Stewart model to quantitatively calculate the evaporation residual ratio (f) and the difference in D-excess between cloud-base and surface precipitation (Δd). The results demonstrate: (1) The LMWL equation for the Yellow River Basin is 2H=7.01 18O+1.25 (n=293, R2=0.92), with both slope and intercept smaller than those of the Global Meteoric Water Line (GMWL), indicating that raindrops are influenced by sub-cloud secondary evaporation during their descent. Rainfall events of 0–10 mm exert significant influence on sub-cloud secondary evaporation; higher temperatures or lower water vapor pressure and relative humidity intensify sub-cloud secondary evaporation. (2) Seasonally, f and Δd increase progressively from spring through winter, while sub-cloud secondary evaporation decreases. Spatially, the Meng-Gan, Meng-Zhong, and Jin-Shan-Gan regions, as well as Xi' an in the Weihe River region, exhibit substantial interannual variability in sub-cloud secondary evaporation, whereas the Southern Qinghai region, Qilian-Qinghai Lake region, Pingliang, Changwu, Huashan in the Weihe River region, and the Lu-Huai region show minimal interannual differences. (3) The linear relationship between Δd and f in precipitation assumes different values across various meteorological element ranges; given that meteorological conditions differ among regions, the specific

meteorological conditions of the study area must be considered when applying empirical formulas.

Full Text

Preamble

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1. Introduction

1.1 Study Area

The Yellow River Basin extends from 95°53 to 119°05 E and 32°10 to 41°50 N, covering a drainage area of 7.93×10 km^2 with a main stream length of 5,464 km. The basin encompasses diverse climate zones, including arid, semi-arid, and semi-humid regions [Figure 1: see original paper]. The multi-year average precipitation is 451 mm [19-20]. Precipitation stable isotope samples were collected across various climate zones, including alpine, semi-humid, semi-arid, arid, and extreme arid regions, as well as different precipitation types such as convective rain, frontal rain, and orographic rain [21].

1.2 Data Sources

Isotopic data (^{2}H and ^{1} O) for precipitation were obtained from the Global Network of Isotopes in Precipitation (GNIP) database (https://nucleus.iaea.org/wiser/gnip.php) and literature sources [22-25] for 13 sampling sites across the Yellow River Basin, including stations at Xining, Lanzhou, Yinchuan, Baotou, Taiyuan, Zhengzhou, Xi' an, Yan' an, Changwu, Tianshui, Minhe, Xifeng, and Hequ .

Meteorological data, including monthly precipitation, air temperature, vapor pressure, and relative humidity, were acquired from the China Meteorological Administration (http://data.cma.cn). A 1 km resolution Digital Elevation Model (DEM) was obtained from the Geospatial Data Cloud (http://www.gscloud.cn). The Local Meteoric Water Line (LMWL) was derived using Ordinary Least Squares Regression (OLSR) with the Isotopic Water Line Freeware from the Australian Nuclear Science and Technology Organisation (ANSTO). The improved Stewart model was employed to calculate the evaporation remaining ratio (f) and D-excess difference (Δd) from cloud base to ground [11, 29-30].

1.3 Calculation Methods

The OLSR method was used to establish the LMWL. The isotopic composition of precipitation is influenced by below-cloud secondary evaporation, which affects both the slope and intercept of the LMWL. The Stewart model quantifies these effects by calculating the remaining fraction of raindrops (f) and the change in D-excess (Δd) during descent.

The evaporation remaining ratio f is calculated as:

$$f = \frac{Q_1}{Q_2}$$

where Q and Q represent water vapor pressure and saturation vapor pressure, respectively, as functions of temperature (T), dew point (D), and relative humidity (RH) [11]. Following Wang et al. [10], parameters Q and Q were optimized for local conditions. Based on Kinzer [32], raindrop diameters in the Yellow River Basin typically range from 1.0–4.0 mm, with evaporation rates of 0.8-3.3 mm, yielding an average value of DC = 2.49 mm.

The D-excess change Δd is calculated as:

$$\Delta d = 18400\left(1 - \frac{h}{P}\right)$$

where t is air temperature, P is atmospheric pressure, and h is water vapor pressure (hPa) [33]. The Magnus-Teten formula was used for saturation vapor pressure calculations [34].

1.4 Stewart Model Framework

The D-excess difference between cloud base and ground is calculated using the Stewart model [5, 14]:

$$\Delta d = \delta^2 H - 8\delta^{18} O$$

where ^{2}H and ^{1} O represent the isotopic composition of precipitation samples. The model parameters (, ,) were derived from Stewart [14] and optimized based on local meteorological conditions [26-28]. The mass balance equation is:

$$\Delta d = \frac{(f^{\beta} - 1) - 8(f^{\gamma} - 1)}{1 - f}$$

where f is the evaporation remaining ratio, and , are fractionation factors.

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2. Results

2.1 Isotopic Characteristics and LMWL

The LMWL for the Yellow River Basin based on 293 samples is:

$$\delta^2 H = 7.01\delta^{18} O + 1.25 \quad (n = 293, R^2 = 0.92)$$

Both the slope (7.01) and intercept (1.25) are lower than the Global Meteoric Water Line (GMWL: ^{2}H = 8 ^{1} O + 10), indicating significant influence of below-cloud secondary evaporation .

Precipitation events of 0-10 mm/month show the strongest evaporation effects, with slopes decreasing from 6.92 (0-5 mm) to 6.64 (5-10 mm) and intercepts ranging from 4.26‰ to -2.85‰. For precipitation >10 mm, the LMWL slope is 6.82 with an intercept of -2.55‰. The 0-10 mm precipitation category accounts for 96.04% of all events, making it the dominant control on the overall LMWL.

2.2 Meteorological Controls on Isotopic Composition

The relationship between Δd and meteorological factors reveals that: - **Temperature**: Higher temperatures correlate with greater sub-cloud evaporation, with Δd increasing by 1.27‰ per °C when relative humidity <50% - **Precipitation amount**: Events of 5-10 mm show a Δd increase of 1.24‰ per °C, while 0-5 mm events show 1.12‰ per °C - **Relative humidity**: Strong negative correlation with Δd, particularly for precipitation <10 mm

The spatial distribution of f and Δd shows clear seasonal patterns [FIGURE:2, FIGURE:3]. From spring to winter, f values gradually increase while Δd decreases, indicating reduced sub-cloud evaporation in colder months.

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3. Discussion

Key findings demonstrate that:

1. **Sub-cloud secondary evaporation significantly affects precipitation isotopes** in the Yellow River Basin, as evidenced by the LMWL slope (7.01) and intercept (1.25) being substantially lower than GMWL values.
2. **Precipitation amount is the primary control**: The 0-10 mm category dominates the isotopic signal, with 96% of events showing strong evaporation effects. The relationship between Δd and f varies by precipitation intensity, requiring locally calibrated parameters.
3. **Strong seasonal and spatial variability**: The Inner Mongolia-Gansu, Central Inner Mongolia, and Shanxi-Shaanxi-Gansu sub-regions exhibit the largest inter-annual variability in sub-cloud evaporation, while northern Qinghai, Qilian Mountains, and Shandong-Huaihe sub-regions show more stable patterns [Figure 4: see original paper].
4. **Meteorological thresholds**: When relative humidity falls below 50%, temperature effects become pronounced (1.27‰/°C). For precipitation >95% of events, Δd values cluster between -10‰ and -5‰, indicating consistent evaporation effects across the basin.

The improved Stewart model, incorporating local lifting condensation level (LCL) estimates and optimized parameters, provides robust quantification of below-cloud processes. The linear relationships between Δd and meteorological factors should be applied according to local climate zones and precipitation regimes.

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