Deuterium excess in arid zone hydrology-with recent Chinese experiences

Zhonghe PANG[a,b] Yanlong KONG[a,b] Jie LI[a,b] Tianming HUANG[a,b]

[a]Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029, China
[b]School of Earth Science, University of Chinese Academy of Sciences, Beijing, 100049, China

Abstract

Recent investigations on water cycle and climate change issues using stable isotopes in the (semi) arid northwest China are presented with emphasis on the usefulness of the deuterium excess in precipitation and surface water. Deuterium excess has found effective applications in identifying sub-cloud evaporation versus moisture recycling effects in Tianshan and Tarim Basin. Methodologies have been developed based on deuterium excess to quantify recycled moisture in the precipitation of Xinjiang, concluding that the internal moisture cycle is very low. We have achieved a better estimate of dissolution fraction against evaporation in the salinization process of water in the lower Tarim river using a newly established method based on deuterium excess. High frequency monitoring of precipitation has also resulted in the identification of causes responsible for the extreme heavy storm in Beijing in 2012.

Introduction

Research on the mechanism of precipitation isotopic evolution is one of the most important fundamental topics in Isotope Hydrology. Precipitation monitoring in (semi) arid regions are of paramount significance in the investigations on water cycle changes as affected by climate and on water resources in the planning and management for sustainable use. In this paper we intend to demonstrate the usefulness of precipitation monitoring, with emphasis on the use of deuterium excess.

High frequency monitoring of isotopes in precipitation

We conducted monitoring of isotopic composition of precipitation on an eventful basis, sampling simultaneously individual precipitation events at two neighboring stations at high elevation (Houxia at 2100 m a.s.l. and Gaoshan at 3545 m a.s.l.) in the Tianshan Mountains, Northwest China. We analyzed the observed variations of $\delta^{18}O$ and δ^2H with emphasis on the changes of deuterium excess. We evaluated the isotope variations by comparing them with surface air temperature, altitude and season to derive information on the effects of adiabatic cooling, sub-cloud evaporation and moisture recycling processes on the precipitation isotopes under arid climatic conditions.

Consulting the long-term monthly averages of d-excess and temperature of the nearest GNIP (Global Network for Isotopes in Precipitation) station Wulumuqi (Urumqi), a striking similarity was found with the results of the two high-altitude stations concerning the relation between d-excess and temperature. The Wulumuqi (Urumqi) data shows an hysteresis effect which appears to signify seasonal changes in the interplay between sub-cloud evaporation and moisture recycling. Finally, for the first time a negative altitude gradient of the d-excess has been found for all stations including two more GNIP stations in Northwest China but far away from the study area. This 'inverse altitude effect' may manifest a decrease of the recycled fraction in air moisture with altitude.

Quantifying recycled moisture fraction in precipitation using deuterium excess

There is considerable interest in the hydrology community over how changes in land use may affect the precipitation and moisture availability. The contribution of local evapotranspiration, which could be altered by changes in land surface characteristics, to local precipitation, called ''recycling,'' is therefore a key parameter in this assessment.

In this work, we used the isotope data measured on precipitation samples taken from individual precipitation events during a hydrological year from 2003 to 2004 at two observatory stations in the Tianshan Mountains, and the long-term monthly average values of d-excess for the GNIP station Urumqi. The data were corrected

for evaporation effect due to the fact that sub-cloud evaporation of falling raindrops also affects the d-excess of precipitation, in addition to the recycled moisture from the ground.

We developed a method to calculate the remaining fraction (f) of the water-drop mass, which replaces traditional empirical methods and thus can reduce uncertainty in the calculations. The method to quantify recycled moisture fraction is improved by estimating the deuterium excess of advected moisture and by incorporating the calculation of the "f" parameter. For the first time, the uncertainty of using deuterium excess method to quantify moisture recycling is obtained using Monte-Carlo analysis.

Monitoring Isotopes in precipitation during a Storm Event

Previous studies of precipitation isotopes were mainly based on monthly, weekly, and event-based isotope monitoring data. We monitored short-term interval isotope variations within a rainfall event in Beijing. We collected 39 samples during a record-breaking rainstorm in Beijing on 21 July 2012; which was the city's heaviest rainfall in six decades. We then analyzed the data applying the Rayleigh distillation model (RAYDIM) and found new criteria for the screening of mixing process of different moisture sources.

Four stages of the storm event were identified with corresponding isotopic characteristics: 1) heavy isotope depletes as rain increases, 2) heavy isotope enriches as rain decreases, 3) heavy isotope quickly depletes as rain increases, and 4) isotopes remain constant as storm event terminates.

The correlation between $\delta^{18}O$ and the residual vapor fraction f with time as the storm proceeds for stage 1 and combined stages 3 and 4 is evident, following the RAYDIM, indicating that rainout is the main reason for the strong depletion of heavy isotope in precipitation. The residual vapor fraction calculated by dividing total water vapor by the amount of precipitation is compared to the result calculated from the RAYDIM. The incursion of a new air mass with enriched heavy isotopes was the main cause for the isotope enriching trend during stage 2. Diverse isotopic values for two different air masses were calculated with a RAYDIM and an isotopic mixing model.

Combined with $\delta^{18}O$ of precipitation at nearby stations belonging to the Global Network of Isotopes in Precipitation (GNIP), southwest trajectory in the initial rain stage and a mixture with southeast trajectory in the later stage, were identified with a transient rain in between, during which period the two trajectories merged. The comparison of deuterium excess further confirmed the isotopic evidence.

This model also indicates that 29% of the initial vapor from the southwest trajectory was precipitated in stage 1, followed by a mixing process with new moisture from southeast. In stage 3, up to 56% of mixed moisture was precipitated, among which, 65%–100% was from the southeast moisture. These results are comparable to meteorological information but the isotopic mixing model is more quantitative than the meteorological trajectories method mentioned above.

Deuterium excess in determining sources of water salinisation

Understanding the water salinisation mechanism is the basis for regional salt management. Mineral dissolution, evaporation and transpiration are the main factors controlling natural water salinity in arid inland basins; however, it is difficult to differentiate the two sources. Because evaporation enriches water bodies with heavy isotopes, some studies have used the relationship between $\delta^{18}O$ and $\delta^{2}H$, and relationship between $\delta^{18}O$ (or $\delta^{2}H$) and salinity to determine the sources of salinity and the evapoconcentration effect. However, the method only works when the isotopic composition of the initial water body is known or exclusive and usually does not work at large scale basins with different isotopic composition in the initial water.

We developed a deuterium excess method to calculate the evaporation loss. In the paper, the relationship between the residual water fraction (f) and deuterium excess (d) was derived from the Rayleigh distillation equation. When we know the salinity of initial water (S_0) and a given water body (S), the contribution of evapoconcentration (S_0/f) and mineral dissolution and/or transpiration ($S-S_0/f$) and then can be determined. The deuterium excess ($d=\delta^{2}H-8*\delta^{18}O$) is used for the first time as a tool to identify sources of salinisation in the arid Tarim river water. Because deuterium excess decreases during evaporation and is unrelated to the isotopic composition of the initial water (in arid basins, rivers are derived from mountainous area as initial water, which have similar deuterium excess values), it is a potential tool for determining the contribution of the evapoconcentration of a given water body.

Evaluating the sensitivity of glacier-river flows to climate change

Global warming will inevitably lead to increased volume of glacier/snow-melt water, and increased mountainous discharge, which is essentially the total water resources available in an arid region. To what extent this will occur highly depends on the sensitivity of a river water system to such changes.

In this work, the magnitude and variability of water system's response to climate change impacts have been assessed through a detailed analysis of discharge composition of two selected typical glacier rivers originated from Tianshan Mountains, Xinjiang Uygur Autonomous Region in West China, which is considered as the water tower of Central Asia. Here we demonstrated climate change in the last 60 years using meteorological data (1951–2009) in the region and calculated the discharge composition in the selected glaciers river of Urumqi River and Kumalak River using isotope hydrograph separation as well as other conservative tracers.

We found that: (1) Both of the temperature and precipitation show a remarkable rise before and after year 1990 and these changes are much more significant in North Xinjiang than it is in South Xinjiang. (2) During the same period, the annual discharge change of Urumqi River in the North increased about 10.0% and Kumalak River in South Xinjiang increased about 38.7%. (3) Urumqi River is recharged by less than 9% of ice-melt water, while Kumalak River contains more than 57% of ice-melt water in their discharges. (4) The extent of glacier input to a water system governs its sensitivity towards climate change.

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