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Relationships between $\delta^{18}O$ in precipitation and surface air temperature in the Urumqi River Basin, east Tianshan Mountains, China

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Abstract. In order to evaluate the dependency of present-day $\delta^{18}O$ in precipitation with temperature, individual precipitation events have been continuously sampled since 1996 at three stations along the Urumqi River Basin, eastern Tianshan mountains, north High China. Both the correlation and the positive slope of $\delta^{18}O$ versus temperature increase with elevation for monthly averages, indicating that on long time scales high altitude precipitation $\delta^{18}O$ should be a reliable indicator of regional temperature fluctuations, and supporting future ice core drilling.

1. Introduction

Reconstructing recent temperature fluctuations at various locations is essential to place the observed XXth century warming in the context of natural climate variability. Past precipitation are archived in ice caps and glaciers and their isotopic composition is related to past temperature changes. The simultaneous collection of precipitation samples and measurement of surface temperature, in a specific region, enables to estimate a regional spatial isotope-temperature relationship [*Dansgaard*, 1964; *Lorius and Merlivat*, 1977; *Peel et al.*, 1988; *Qin et al.*, 1990; *Rozanski*, 1992]. Theoretical approaches have enabled a better understanding of fractionation processes by means of simple isotopic models [*Jouzel and Merlivat*, 1984] or implementation of the water isotope cycle in climate models [*Jouzel et al.*, 1997]. Most of these works have focussed on polar regions, for which large-scale precipitation processes are active and show a $\delta^{18}O$ to temperature slope ranging typically from 0.6 (Greenland) to 0.9 ‰/°C (Antarctic Peninsula).

In order to document recent climate fluctuations at low and mid latitudes, several deep ice core drillings have been achieved in mountain glaciers at very high altitudes in Asia [e.g. *Thompson et al.*, 1989; *Yao et al.*, 1992, 1997a, 1997b] and South America [*Thompson et al.*, 1995, 1998]. Unlike polar regions, these high altitude regions undergo a large convective activity. Local altitude-induced climate and convection cannot be simulated using either simple isotopic models (which are aimed at simulating large scale condensation) or global climate models (due to their horizontal resolution). Local calibrations of the isotope-temperature relationships have to be achieved. The required continuous observation is restricted because of the difficulty to access to these regions and to keep the observation running. For these reasons, the first reports of measurements of oxygen isotope in High Asia (Tibetan Plateau) precipitation started only in 1990 [*Yao et al.*, 1991]. In the northern Tibetan Plateau, a continuous isotope observation network was set on and showed a positive relationship between oxygen isotope and temperature [*Zhang et al.*, 1995; *Yao et al.*., 1996b; *Lide et al.*, 1997].

New ice core deep drillings are planned in the Tianshan, one of the largest mountain systems of central Asia, a climate-sensitive area where meteorological and glacier mass-balance studies show a recent warming trend [*Aizen et al.*, 1997] and an abrupt mid-1970 event [*Cao*, 1998]. In order to document the present-day characteristics of precipitation isotopic composition, a new continuous observation network was set in 1996 in the northern margin of High China, in the Urumqi River basin, located in the east Tianshan (Heaven Mountains) of the Xingjiang Autonomous Region (Figure 1). Three stations were set at different elevations, corresponding to distinct climatic and environmental zones from desert to forest and glacier : 1) the Urumqi Meteorological Station (altitude 900m a.s.l., annual precipitation lower than 100mm), located at the lower reaches of the Urumqi river which disappear in the desert; 2) the Yaojin Bridge Hydrological station (2400m a.s.l., annual precipitation in the range 300-400mm), located in the middle reaches of the river, covered with grassland and forest, and 3) the Daxigou Meteorological Station (4200m a.s.l., annual mostly solid precipitation above 500mm) in the upper glacier reaches of the river.

During the observation period (June 1996 to present at Urumqi, July 1996 to present at Yaojin Bridge, and May 1997 to present at Daxigou), all individual precipitation events were collected (Figure 2) and initial and final meteorological data (temperature, relative humidity, air pressure) were gathered. The isotopic composition of the precipitation is affected by the moisture sources (evaporation conditions) and the subsequent trajectory and rain-out history of the air masses. In winter, Urumqi receives year-round precipitation originating from the westerly flow, which at this extreme continental location have

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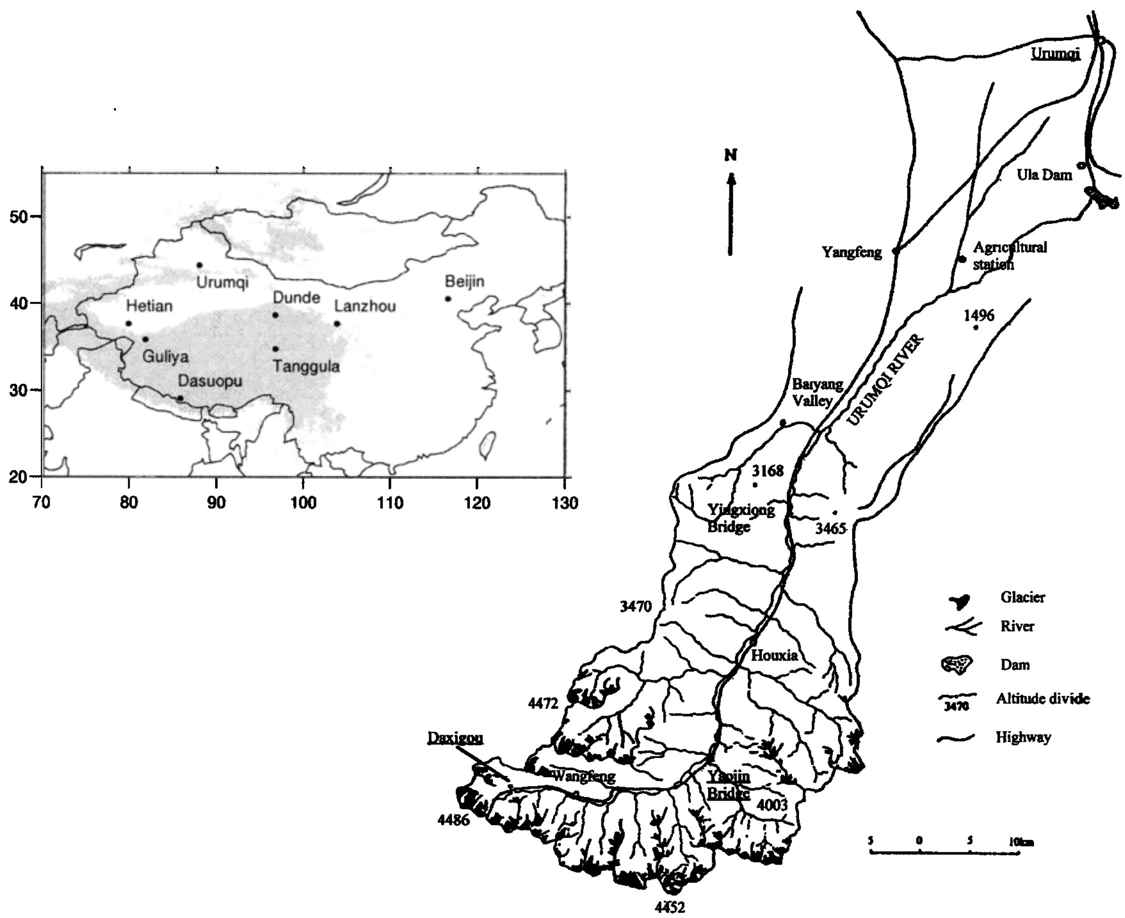

Figure 1. Map of China with shading indicating elevations above 2500m (a) and detailed map of the Urumqi River Basin (b) showing the three stations (Urumqi, Yaojin Bridge and Daxigou).

already undergone a complex rain-out history [*Araguàs-Araguàs et al.*, 1998]. Few winter precipitation events are recorded in the high altitude stations; the mountain ranges act as a barrier for the winter moisture flow. In contrast, the two high altitude stations undergo frequent and large summer precipitation events, due to convection and water recycling. This paper, based on the first set of observations, discusses the isotope-temperature relationships in this valley based on spatial and temporal regressions.

2. Results and discussion

For each station, linear regressions are calculated using temporal fluctuations of $\delta^{18}O$ and temperature fluctuations from all the individual precipitation events (Figure 3 and Table 1). All stations exhibit a clear positive correlation between $\delta^{18}O$ and local temperature. For Yaojin Bridge and Daxigou, a large isotopic dispersion is obvious in warm conditions, resulting from the summer convective activity and local recycling. Evapotranspiration from Yaojin Bridge forest and sublimation from Daxigou glacier imprint the isotopic composition of local vapour, as the evaporated water represents a storage of precipitation during at least several colder months. The highest correlation is therefore obtained for Urumqi, where the desert land surface does not store water from previous seasons and evaporation does not modify the isotopic composition of the vapour.

In order to smooth the part of the isotopic variability associated with summer convective activity, individual rainfall events are gathered to monthly mean values (Figure 3, Table 1). As expected, this averaging has almost no impact on the isotope temperature relationships at Urumqi (the isotope-temperature relationship obtained during our observation period is similar to the one estimated by IAEA during the period 1986-1992 [*Araguàs-Araguàs et al.*, 1998]). At the two other stations, correlations increase but the monthly averaging gives a large weight to the few individual precipitation events occurring at low temperatures. For instance, in Yaojin Bridge one single precipitation event occurs with extreme low values in isotopes and precipitation in January 1998 and taking into account this event changes the monthly slope from 0.73 to

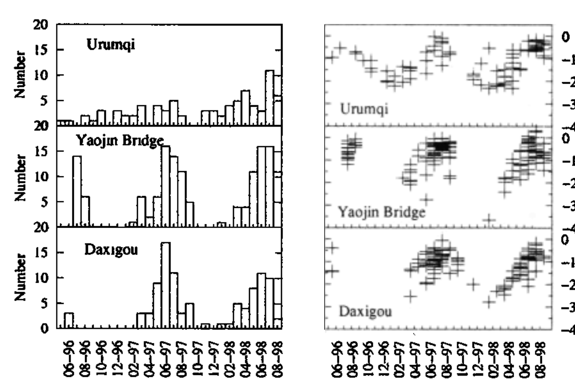

Figure 2. Histogram of the observed precipitation at the three stations and of their isotopic compositions (analytical precision ±0.2‰). From top to bottom, Urumqi, Yaojin Bridge and Daxigou.

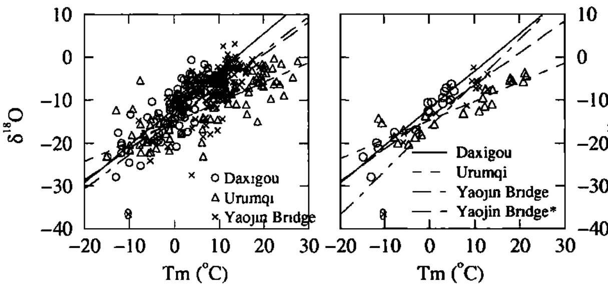

Figure 3. Relationships between $\delta^{18}O$ in precipitation (‰) and mean air temperature (°C) for individual precipitation events (a) and monthly averages (b) at the three stations. For Yaojin Bridge, the impact of the coldest precipitation event (circled square) is evaluated by calculating the regressions with and without (*) this point.

1.02‰/°C. Extending the observational network for several years is required to better document the isotopic composition of precipitation during the dry season. Nevertheless, with monthly means, the highest correlations are obtained at high altitudes (0.92 for Daxigou). From both individual events and monthly values, the $\delta^{18}O$-T slope increases with elevation (0.45‰/°C in Urumqi, versus 0.87‰/°C in Daxigou, Table 1), as already described by Jacob and Sonntag [1991]. High elevation and therefore colder sites show both a better correlation and a larger dependency of temporal fluctuations of $\delta^{18}O$ with temperature, which is expected at the end of a Rayleigh distillation process.

For Yaojin Bridge and Daxigou, very high isotopic values are measured in summer precipitation and are partly responsible for the high isotope temperature slopes; they may result from partial evaporation of the falling droplets or rainfall or from an enriched groundwater moisture source in summer. Deuterium measurements are not available but would help to discriminate between these two physical mechanisms leading to high isotopic values in summer. Araguàs-Araguàs et al. [1998] also noted such high values for Hetian (76.56°E, 37.08°N, 1375 m elevation) and discussed the possibility that summer precipitation may in part originate from diffusive discharge of enriched groundwaters. Isotopic measurements of the groundwaters should be helpful in this respect.

Table 1. Different Estimates of Isotope-Temperature Relationships in the Urumqi River Basin

	Site	Slope (‰/°C) (R^2)	Number of events
T (I)	Urumqi	0.46±0.04 (0.65)	81
T (C)	Urumqi	0.46±0.12 (0.54)	13
T (M)	Urumqi	0.44±0.05 (0.83)	23
T (I)	Yaojin	0.80±0.06 (0.54) *0.73±0.06 (0.51)	138
T (C)	Yaojin	0.61±0.06 (0.62)	13
T (M)	Yaojin	1.02±0.14 (0.80) *0.75±0.09 (0.83)	16
T (I)	Daxigou	0.87±0.06 (0.66)	94
T (C)	Daxigou	1.28±0.19 (0.78)	13
T (M)	Daxigou	0.87±0.06 (0.92)	17
ST (I)	All	0.55±0.03 (0.52)	313
ST (C)	All	0.30±0.14 (0.82)	3
ST (M)	All	0.57±0.05 (0.69)	56
S (JJA)	All	0.22±0.09 (0.86)	3

Different types of estimates (T, temporal; ST, spatio-temporal; S, spatial) obtained from individual events (I, *without including the coldest point), events common to the three sites (C), monthly (M) or summer (JJA) averages

Table 2. Average Summer Characteristics of Precipitation at Each Station.

	$\delta^{18}O$ (‰)	Tm (°C)	Events per month
Urumqi	-5.13	19.4	4.1
Yaojin	-5.85	11.0	13.0
Daxigou	-8.52	4.1	8.1

The local temperature lapse rate is -4.6°C/km.

Due to the different temporal slopes depending on the elevation of the site, the calculations based on spatio-temporal fluctuations for all sites lead to weak correlations with temperatures (R^2=0.69 for monthly values) and a resulting isotope-temperature slope intermediate between low and high altitude values (about 0.5 ‰/°C).

To evaluate the impact of altitude on the isotopic content, it is necessary to evaluate the spatial isotope-temperature slope from annual characteristics of each station. Due to the restricted observational period, winter precipitation cannot be considered as significantly sampled at high elevation sites and we have to use the summer characteristics of the three sites (Table 2). The relationship between the summer isotopic values and summer temperatures leads to a spatial isotope-temperature slope of 0.22‰/°C (R^2= 0.86 but for only 3 points), more than half weaker than the spatio-temporal gradient obtained previously and almost four times weaker than the temporal gradient obtained at Daxigou (Table 1). This low spatial slope compared with the global estimate (typically 0.6‰/°C) can be explained by a simple isotopic model taking into account the presence of liquid water remaining in the cloud (Figure 4 and its caption). If all the liquid water precipitates (open system cloud, Rayleigh model), the theoretical isotope-temperature slope is 0.54‰/°C in the temperature range of 0 to +20°C; but if all the liquid is kept into the cloud (closed system, important for convective clouds), the simulated slope decreases to 0.29‰/°C. This crude simulation supports the interpretation that the observed low spatial slope is due to convective cloud droplets reevaporation cycles.

An alternative approach to evaluate the impact of altitude on the isotope-temperature relationship is to consider the 13 precipitation events occurring simultaneously at the three stations, assuming that they correspond to synoptic processes affecting the whole Urumqi River basin. The resulting slope of 0.30‰/°C (correlation coefficient 0.82) is intermediate between the summer spatial slope (0.22‰/°C) and the spatio-temporal slope calculated from all stations and all events (0.55‰/°C). During these common events, a temporal slope can be evaluated for each station: 0.46‰/°C at Urumqi, 0.61‰/°C at Yaojin Bridge and 1.28‰/°C at Daxigou (Table 3). We explain the non linear amplification of isotope-surface temperature changes with altitude by the cloud orography lifting [*Siegenthaler and Oeschger,* 1980]. This should be verified by measurements of cloud altitude along Urumqi River Basin.

3. Conclusion

This study is based on continuous precipitation sampling and isotopic analysis (369 individual events) for three sites representative of climate, land-surface and altitude characteristics of the Urumqi River Basin. Temporal

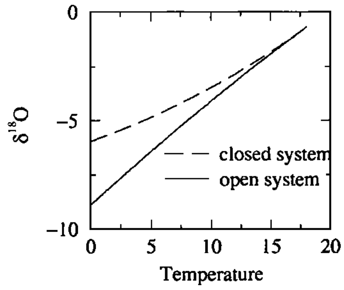

Figure 4. Simulation of $\delta^{18}O$ in the liquid phase (‰) versus temperature (°C) calculated with an isotopic model for an isolated air mass initially at 20°C and 900hPa (Urumqi summer conditions) along its trajectory to a final temperature of 4°C and a pressure of 650hPa (Daxigou summer conditions). The evolution of the isotopic composition in the liquid phase δ_L depends on the mass of liquid water in the cloud m_L, the mass of water vapour m_V, the fractionation coefficient α, following Jouzel (1986) :

$$d\delta_L = (1+\delta_L)\,\frac{(\alpha-1)\frac{dmv}{mv}+\frac{d\alpha}{\alpha}}{1+\alpha\frac{mL}{mv}}$$

Two extreme cloud behaviors are calculated : the closed cloud system, dashed line (all the liquid water is kept in the cloud) and the open cloud system, solid line (Rayleigh model, all condensate precipitates and m_L=0).

fluctuations of $\delta^{18}O$ in precipitation at each site show a significant positive correlation with temperature fluctuations. Due to the strong contribution of local recycling to summer convective events, individual events show a weak linear correlation with temperature fluctuations at high altitudes. When monthly averaging is performed, the correlation increases dramatically and is really good (0.92) for the highest location (4200m a.s.l.). The impact of temperature change on the isotopic content is much stronger at high elevations (0.8 to 1.0) compared with the low elevation site (0.4), possibly due to cloud orographic lifting. The spatial distribution of mean $\delta^{18}O$ among the three sites also shows a positive correlation with temperature reflecting the lower altitude-temperature dependency. The low spatial slope can be explained by the role of liquid droplets in the convective clouds.

These observations, which should be extended in time and include deuterium excess measurements, clearly show that $\delta^{18}O$ is a reliable indicator of temperature in the high Asia, and that the highest sensitivity to temperature should be obtained at the highest possible elevations. We now face the challenge of obtaining deep ice cores from Tianshan mountain glaciers.

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